İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

A NOVEL COMMUNICATION APPROACH FOR WIRELESS MOBILE SMART OBJECTS

Ph.D. Thesis by

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LIST OF ACRONYMS

ACK	**:** Acknowledgement
AODV	**:** Ad hoc On-Demand Distance Vector Routing Protocol
BLR	**:** Beaconless Routing Algorithm
CBF	**:** Constraint Based Forwarding
CBR	**:** Constant Bit Rate
CLR	**:** Clear
CO	**:** Cooperating Objects
CPU	**:** Central Process Unit
CSMA	**:** Carrier Sense Multiple Access
CTF	**:** Clear To Forward
CTS	**:** Clear To Send
DDB	**:** Dynamic Delayed Broadcasting Protocol
DFD	**:** Dynamic Forwarding Delay
DREAM	**:** A Distance Routing Effect Algorithm For Mobility
DSDV	**:** Destination Sequenced Distance Vector Routing
DSR	**:** Dynamic Source Routing
DVM	**:** Dynamic Velocity Monotonic
EAR	**:** Event Area
ECM	**:** Electronic Counter Measures
FSR	**:** Fisheye State Routing
GDBF	**:** Guaranteed Delivery Beaconless Forwarding
GPS	**:** Global Positioning System
GPSR	**:** Greedy Perimeter Stateless Routing
ID	**:** Identification
IEEE	**:** Institute of Electrical and Electronics Engineers
LAN	**:** Local Area Network
LAR	**:** Location Aided Routing
MA	**:** Multiple Access
MAC	**:** Multiple Access Control

MANET	**:** Mobile Ad Hoc Networks
MET	**:** Minimum Energy Tree
MS-SWR	**:** Stateless Weighted Routing with Multiple Sinks
NADV	**:** Normalized Advance
NFL	**:** Neighborhood Feedback Loop
PRADA	**:** Probe-Based Distributed Protocol For Knowledge Range Adjustment
PTKF	**:** Partial Topology Knowledge Forwarding
QoS	**:** Quality of Services
RAM	**:** Ransom Access Memory
RAP	**:** A Real-Time Communication Architecture for Large-Scale WSN
RERR	**:** Route Error
RTF	**:** Request To Forward
RTS	**:** Request To Send
SNGF	**:** Stateless Non-Deterministic Geographic Forwarding
SPEED	**:** A Stateless Protocol for Real-Time Communication in Sensor Networks
SWAN	**:** Service Differentiation in Stateless Wireless Ad Hoc Network
SWR	**:** Stateless Weighted Routing
SYNC	**:** Synchronization
TCP	**:** Transmission Control Protocol
TDMA	**:** Time Division Multiple Access
TTL	**:** Time-To-Live
UAV	**:** Unmanned Aerial Vehicle
UDP	**:** User Datagram Protocol
VMS	**:** Velocity Monotonic Scheduling
WISE	**:** Wireless Integration Sublayer Extension
WSN	**:** Wireless Sensor Networks

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LIST OF SYMBOLS

$\mathbf{w_i}$	**:** Weight of node *i*
$\mathbf{r}$	**:** Radius
$\mathbf{r_i}$	**:** Radius of node *i*
$\mathbf{R_s}$	**:** Sensing range
$\mathbf{R_c}$	**:** Transmission range
π	**:** *Pi* number
λ	**:** Threshold value
θ_A	**:** Angle at point *A*
$\boldsymbol{\sigma}$	**:** Node density

KABLOSUZ GEZGİN AKILLI NESNELER İÇİN BİR ÖZGÜN İLETİŞİM YAKLAŞIMI

ÖZET

Telsiz ağlar, 1970'lerde ortaya çıkışlarından itibaren bilgisayar endüstrisinde çok yaygınlaşmıştır. Telsiz ağlar gezgin kullanıcılara nerede olduklarına bağlı olmadan her yerde iletişim kurma ve bilgiye erişim imkanı sağlar. Hiçbir sabit altyapıya gerek duymadan bu imkanı sağlayan tasarsız ağların zaman içinde gelişmesiyle, askeri, ticari ve özel maksatlar için tercih edilir hale gelmiştir. Diğer yandan, insan ihtiyaçlarına paralel olarak malzeme, elektronik ve bilgisayar bilimi ve mühendisliğindeki bilimsel ve teknolojik gelişmeler ağ elemanlarını daha küçük ve ucuz hale getirdikçe birçok uygulamanın vazgeçilmez parçaları olmuşlardır. Bu ağ elemanları, taşıyıcılara (örneğin gemiler, uçaklar, büyük araçlar, arabalar, insanlar, hayvanlar, vb.) monteli nesneler veya kendi taşıyıcısı olan (aktörler, duyargalar) nesneler olabilir. Fakat bu ağ elemanları ve uygulamalarında bir takım zorluklar yaşanmaktadır.

Bu tezde, gezgin tasarsız ve duyarga ağlardaki yaşanan zorlukları ve beklentileri dikkate alarak, gezgin tasarsız ve duyarga ağlar için yeni bir özgün, durumsuz veri akış yaklaşımı ve yönlendirme algoritması önerilmektedir. Durumsuz Ağırlıklı Yönlendirme (DAY, "Stateless Weighted Routing – SWR") algoritması olarak adlandırdığımız bu algoritma, diğer yöntemlere göre daha az yönlendirme yükü, daha az enerji tüketimi, daha az yol oluşturma gecikmesi sağlamaktadır. Veri, varışa doğru, çoklu yollar üzerinden taşınmaktadır. Çoklu yol oluşturma, güvenirliği sağlamakta, boşluk problemini büyük oranda çözmekte ve en kısa yolu da içeren daha gürbüz yollar oluşmasını sağlamaktadır. DAY aynı zamanda büyük ölçekli ağlarda da uygulanabilir. Bu amaçla, birden fazla veri toplanma düğümü (sink) içeren sürümü olan Çoklu Veri Toplanma Düğümlü- Durumsuz Ağırlıklı Yönlendirme (ÇVTD-DAY - "Multiple Sink-Stateless Weighted Routing - MS-SWR") yöntemi de büyük ölçekli tasarsız ve duyarga ağları için önerilmiştir. ÇVTD-DAY yöntemi, DAY yönteminde herhangi bir yöntemsel ve algoritmik değişiklik yapmadan birden fazla veri toplanma düğümünün olduğu ağlarda uygulanabilir.

Hem DAY, hem ÇVTD-DAY'nin başarımı benzetimler ile ölçüldü. Elde edilen sonuçlar, DAY 'nin gezgin tasarsız ve duyarga ağlar için istenenleri karşıladığını, karşılaştırılan diğer yöntemlere göre üstün olduğunu ve olası en iyi çözüme yakınlığını, öte yandan ÇVTD-DAY'nin de büyük ölçekli ağlarda uygulanabilir olduğunu göstermektedir.

A NOVEL COMMUNICATION APPROACH FOR WIRELESS MOBILE SMART OBJECTS

SUMMARY

Wireless networks have become very popular in the computing industry after their emergence in the 1970's. Wireless networks provide mobile user with ubiquitous communication capability and information access regardless of location. Mobile ad hoc networks, that manage it without a need to infrastructure networks, as evolved in time, become more preferable for military, commercial and special purposes. On the other hand, parallel to the human requirements, technological advances in materials, electronics, and computer science and engineering made network components smaller and cheaper as they become indispensable for various applications in mass numbers. These network components involves a wide variety of objects such as objects mounted on crafts/platforms (e.g. ships, aircrafts, trucks, cars, humans, animals), and objects that have their own platforms (e.g. actuators, sensor nodes). However, these network components and their involved applications exhibit some challenges to implement. By considering the challenges and expectations of mobile ad hoc networks and sensor network, we propose a novel stateless data flow approach and routing algorithm namely Stateless Weighted Routing (SWR) for mobile ad hoc and sensor networks. The SWR has low routing overhead providing very low energy consumption, and has low route construction delay than other proposed schemes. Multiple paths to the destination are established for data transmission. Constructing multiple paths provides reliability, eliminates the void problem substantially, and provides more robust routes including the shortest path. The SWR is applicable to large scale networks. We propose the multiple-sink version of the SWR that is namely MS-SWR, to be used in large scale ad hoc and sensor networks with multiple sinks. The MS-SWR can be used with multiple sinks without any functional and algorithmic modification in the SWR protocol.

The performance of the SWR and the MS-SWR are evaluated by simulations. The performance of the system shows that the SWR satisfies the requirements of mobile ad hoc networks and outperforms the existing algorithms. The SWR is also tested against a hypothetic routing scheme that finds the shortest available path with no cost in order to compare the performance of the SWR against such an ideal case. Tests also indicate that MS-SWR is scalable for large scale networks.

1. INTRODUCTION

Technological advances in wireless communications and nanotechnologies made use of sensor-involved applications and systems in a wide-range application area. As network components get smaller and cheaper, they become indispensable for various applications in mass numbers. Application areas can be extended from battlefield or security applications such as target detection to humanitarian applications such as disaster recovery, pollution detection, search and rescue, and food agriculture. They are progressively utilized nowadays, and are planned to be used intensively in the near future because of their cost-effectiveness. Therefore, ad hoc and sensor networks appear a common research and interest area in recent years. Moreover, the limitations on the resources of the components of these types of networks keep the interest both to propose new techniques and to optimize the proposed ones which use these resources.

Sensor networks are composed of tiny sensor nodes. Their size limits the size of sensor node's components such as Central Processing Unit (CPU), Random Access Memory (RAM) and battery. On the other hand, in some sensor networks applications, thousands of sensor nodes are deployed at once. Therefore, to balance their cost-effectiveness and to reduce the cost per sensor node, the capacity of the sensor node components should remain low. The size and capacity limitations require techniques which use these resources efficiently. Of these limited resources, energy takes the importance due to the following reasons. Energy exhausting methods and amounts affect the performance of the system. Energy exhausted nodes cannot be used anymore. Their absence leaves gaps in the network and cause unwanted results. Moreover, energy depletion at nodes may define the lifetime of the system. Therefore, energy becomes the most valuable and critical resource in wireless sensor networks.

In addition to the limitations given above, the performance of ad hoc and sensor networks is degraded due to the properties of wireless transmission medium. Collisions, link breakages, bandwidth limitations, etc. affect the consumption of these limited resources. Therefore, new techniques are required to cope with these resource limitations and properties of wireless transmission medium.

The performance metrics e.g. scalability, lifetime of the system, mainly depend on the techniques used in MAC-layer and network layer. Although a number of approaches and algorithms were proposed to enhance the overall system performance, their contributions remain partial subject to particular performance metrics.

MAC protocols propose solutions to share and access the transmission medium efficiently, fairly and reliably. Density and the number of network components, properties of the wireless medium make the problem more challenging in MAC layer. There are many approaches proposed in this sub-area and still continues to keep its importance. Network layer use the services of MAC-layer. Packets which are passed from network layer to MAC layer are transmitted through the physical layer for accessing to the wireless transmission medium. Decisions to transmit or retransmit (relay) a received packet are taken in the network-layer by the applied routing algorithm. The effectiveness of the routing algorithm, therefore, affects the performance of the system. Due to the limitations of sensor nodes and properties of the wireless transmission medium, routing algorithms must present solutions to use these resources efficiently and should consider the properties of the wireless medium.

Routing algorithms used in fixed networks cannot be used in wireless networks. Resource limitations in WSN make the problem more challenging. Therefore, routing schemes have always been the most studied and the most challenging research area in Wireless Sensor Networks and Ad Hoc Networks.

In this thesis, the challenges of wireless mobile ad hoc and sensor networks and a survey of proposed routing protocols and schemes are laid out. The structures and behaviors of the proposed algorithms and schemes are described, and their properties, advantages and drawbacks are emphasized. As each proposed scheme presents a new valuable approach, they suffer from specific drawbacks. Some of these drawbacks are common to all these proposed schemes.

Most of the routing algorithms try to convey the data to the destination by keeping routing tables of the existing topology. However, such approaches show poor performance on Wireless Sensor Networks (WSN) due to resource limitations and link failures peculiar to wireless links and mobile nodes. They introduce routing overhead, reduce performance and lifetime of the network, and suffer from the scalability problem.

As known, the essential aim of a routing function is to convey data to the destination. This is usually achieved by keeping routing tables of existing topology. However, because of the features such as mobility, energy limitations, and link failures peculiar to wireless links and mobile nodes, trying to keep up-to-date routing information or tables produces overhead, reduces performance and lifetime of the network, and introduces scalability problem.

Routing without tables can be achieved by using location information of the nodes retrieved from GPS or by applying a localization algorithm. Geographical routing protocols use only local topology information and have not any update overhead. Therefore, they provide scalability in mobile networks with respect to conventional routing protocols. Although position-based routing is not a brand-new idea it is flourished with the emergence of wireless and mobile networks and it is called *geographical routing* [1-8].

1.1 Contribution of the Thesis

A novel stateless data flow approach and routing algorithm namely *Stateless Weighted Routing (SWR)* for mobile ad hoc and sensor networks is proposed in this thesis. Nodes do not have to be aware of either local or global topology information. Thus, routing is achieved without keeping tables. Nodes' geographical positions are sufficient for the routing process.

The proposed algorithm:

- provides scalability since neither routing tables nor beaconing is used.
- simplifies the routing process by designing an appropriate algorithm which utilizes a weight metric.
- decreases calculations, delay, and resource requirements (such as processor and memory) at nodes since a weight metric is used instead of time consuming operations on routing tables.
- decreases energy consumption by;

- not beaconing,
- considering the remaining energy levels at nodes,
- limiting the number of relaying nodes.

- provides reliability by establishing multiple paths.
- executes routing process completely in the network layer, independent of the MAC layer underneath.

In wireless ad hoc and sensor networks, however, as the network size grows, the challenges described above become more challenging. The use of multiple sinks (multi-sink) has been suggested as a solution for large scale networks [9, 10]. In large scale networks with a large number of sensor nodes, multiple-sinks (gateways) should be used to provide scalability. However, deploying more sink nodes does not solve the problem directly and evenly. Although energy-efficient protocols should be adapted for multi-sink networks, protocols may not be energy-efficient anymore for large scale networks due to an increase in the number of nodes.

A multiple-sink version of the SWR, MS-SWR, is proposed for large scale ad hoc and sensor networks with multiple sinks. MS-SWR can be used with multiple sinks without any essential modification in the protocol. In addition to the properties of the SWR given above, the MS-SWR is scalable in large-scale ad hoc and sensor networks.

The performance of the SWR and the MS-SWR are evaluated by simulation. The evaluated performance of the system shows that the SWR and the MS-SWR have low routing overhead, provide very low energy consumption, and have low route construction delay than other proposed schemes. Data is carried on multiple paths to the destination. Constructing multiple paths provides reliability, eliminates the void problem substantially, and provides more robust routes including the shortest path. Evaluations also show that MS-SWR is scalable for large scale networks.

1.2 Publications

- Müjdat Soytürk, Turgay Altılar. “The Challenges and The Approaches For The Geographic Routing Protocols in Wireless Sensor Networks”, IEEE TEHOSS, October 2006.

In this paper, the challenges and the proposed solutions and approaches for the geographic routing protocols for wireless ad hoc and sensor networks are surveyed.

- Müjdat Soytürk, Turgay Altılar. “Source-Initiated Geographical Data Flow for Wireless Ad Hoc and Sensor Networks”, IEEE WAMICON’06, Florida, U.S.A., December 2006.

  In this paper, a stateless data flow approach for ad hoc and sensor networks is presented. Data flows from source to the destination without external information by the aid of the nodes’ own position information.

- Müjdat Soytürk, Turgay Altılar. “A Novel Stateless Energy-Efficient Routing Algorithm for Large-Scale Wireless Sensor Networks with Multiple Sinks”, IEEE WAMICON’06, Florida, U.S.A., December 2006.

  In this paper, a novel stateless energy-efficient routing algorithm for wireless sensor networks with multiple sinks (MS-SWR) is presented. MS-SWR is based on the SWR protocol and works with any number of sink nodes without any modification in the protocol.

- Müjdat Soytürk, Turgay Altılar. “Stateless Data Flow Approach with Void Avoidance for Wireless Ad Hoc and Sensor Networks”, International Symposium on Wireless Pervasive Computing, ISWPC'07, Puerto Rico, February 2007.

  In this paper, void recovery method and algorithm for SWR protocol are presented. The algorithm is peculiar to SWR and guarantees the delivery of data to the destination. Usage of some parameters to shape the data flow toward the sink are described.

- Müjdat Soytürk, Turgay Altılar. "A Routing Algorithm for Mobile Multiple Sinks in Large-Scale Wireless Sensor Networks", International Symposium on Wireless Pervasive Computing, ISWPC'07, Puerto Rico, February 2007.

  In this paper, mobile sinks are used with MS-SWR protocol to reduce the energy consumption in routing and to extend the lifetime of the network for large scale wireless sensor networks. It is shown that mobile sinks usage enhances the energy related performance metrics.

- Müjdat Soytürk, Turgay Altılar. "3M Real-Time Communication Approach for an Instantly Deployable Sensor Networks for Battlefield Area Surveillance", IEEE MILCOM, submitted in June 1, 2007 and under review.

  In this paper, multiple paths, multiple sink, and multicasting approaches in the proposed routing algorithm will be presented.

1.3 Structure of the Thesis

In Chapter 2, the properties and the structure of mobile ad hoc and sensor networks, and the challenges it posed are described. A review of the existing routing schemes for mobile ad hoc and sensor networks is presented in the rest of this section. The review is organized according to the classification of the proposed routing schemes. Major contributions and the drawbacks of these routing schemes are identified.

A novel approach, SWR, is proposed in Chapter 3 to overcome seen shortcomings of existing schemes, by using the identified properties and drawbacks of the proposed schemes in Chapter 2. The design criteria, methodologies, parameters, and the structure of the proposed approach, is presented in this chapter. The proposed system architecture is defined in this chapter. This chapter also includes Stateless Weight Routing (SWR) approach, the algorithms and the parameters used.

In Chapter 4, the approaches proposed to enhance some performance metrics are presented. Known common challenges and approaches in the literature to enhance these performance metrics as well as methods and approaches proposed and their effects on these performance metrics are described.

The simulation environment and the performance result of the proposed approaches are presented in Chapter 5.

The proposed approach is concluded in the last chapter.

2. SMART OBJECTS AND ROUTING ALGORITHMS

Advances in wireless networks and improvements on transistors and micro-technologies led many research areas. Ongoing studies in wireless ad hoc and sensor networks have been branched to new research areas such as sensor-actuator networks, pervasive computing, wireless mesh networks, ubiquitous computing, sentient computing, sentient objects, cooperating smart objects. All of these research areas are related to each other. Moreover, a few of them are called interchangeably. The common property of these research areas is that the use of ad hoc and/or sensor nodes in their system architecture. A developing and dominating research area which is the collection of these research areas is *Cooperating Objects (CO)*. The enabling technologies of Cooperating Objects are shown in Figure 2.1. The definition of Cooperating Objects was given in [11]: *COs are entities that are composed of sensors, actuators and COs, capable of communicating and interacting with each other and with the environment in a smart and autonomous way to achieve a specific goal*.

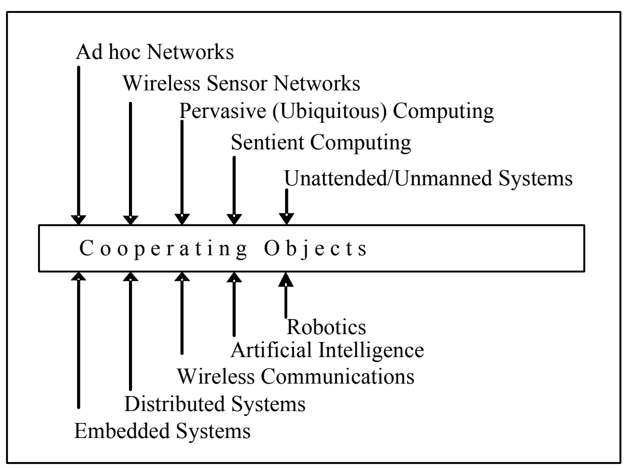


Figure 2.1: Enabling technologies for Cooperating Objects [11].

COs is a composition of the outcomes of enhancement, research and development in various disciplines. Technologies in the upper part of Figure 2.1 are the application areas, while the lower part is the research areas which are all the enabling technologies.

A cooperating object is primarily composed of physical components including their attributes and their related functions. Sensor nodes, actuator nodes, relay nodes, sink nodes and even previously defined cooperating objects are the examples for such objects. A cooperating object can be either unattended or unmanned with autonomous operation capability. Although autonomous operating capability requires intelligence, the degree of the intelligence depends on the desired operations and expected behavior and performance of the system as well as the hardness of the operation.

In this thesis, smart object term is used interchangeably with cooperating objects, since cooperating objects should act smartly with the embedded level of intelligence. However, to satisfy the integrity of the definitions and the proposed approaches in this thesis with [11], cooperating objects term is preferred in the rest of this thesis.

In this section, the definitions, challenges and related studies about cooperating objects are given. The definitions of wireless sensor networks and ad hoc networks are also given, since these types of networks are the enabling technologies of the cooperating objects [11]. Routing protocols for the wireless sensor networks are surveyed, because the cooperating objects networks mostly use sensor nodes.

2.1 Definitions [12]

"Sensor: A transducer that converts a physical phenomenon such as heat, light, sound, or motion into electrical or other signals that may be further manipulated by other apparatus.

Sensor node: A basic unit in sensor network, with on-board sensors, processor, memory, wireless modem and power supply. It is often abbreviated as node. When a node has only a single sensor on board, the node is sometimes also referred to as sensor.

Routing: process of determining a network path from a packet source node to its destination.

Data-centric: approaches that name, route, or access a piece of data via properties, such as physical location, that are external to a communication network. This is to be contrasted with address-centric approaches, which use logical properties of nodes related to the network structure.

Geographic routing: routing of data based on geographical attributes such as locations or regions. Note that this is an example of data-centric networking.

Collaborative networking: Sensors cooperatively processing data from multiple sources in order to serve a high-level task. This typically requires communication among a set of nodes.

Task: Either high-level system tasks which may include sensing, communication, processing and resource allocation, or application tasks which may include detection, classification, localization, and tracking.

Detection: The process of discovering the existence of a physical phenomenon. A threshold-based detector may flag a detection whenever the signature of a physical phenomenon is determined to be significant enough compared with threshold.

Classification: The assignment of class labels to a set of physical phenomena being observed.

Localization and tracking: The estimation of the state of the physical entity such as a physical phenomenon or a sensor node from a set of measurements. Tracking produces a series of estimates over time.

Resource: Resources include sensors, communication links, processors, on-board memory, and node energy reserves. Resource allocation assigns resources to tasks, typically optimizing some performance objective.

Sensor tasking: The assignment of sensors to a particular task and the control of sensor state for accomplishing the task.

System performance goal: The abstract characterization of system properties. Examples include scalability, robustness, and network longevity, each of which may be measured by a set of evaluation metrics."

2.2 Challenges

The followings describe the challenges and these challenges are documented as an internal report of a previous collaborative study in [11].

2.2.1 Goal management

"The challenges as to the goal management are twofold, namely system wide challenges and object level challenges. Generation of a mission plan constitutes the system wide challenges, including decomposition and allocation of missions to objects, timing, determination of hierarchy between the objects if man-in-the-loop is not possible, and synthesis of the results. Problem solving and planning techniques of distributed artificial intelligence can be applied to these challenges, and the mission plan can be generated in advance by a central authority. Autonomous operation of the objects is the source of object level challenges. These involve determination of subtasks, synchronization of tasks, task switching, and resolving task conflicts. Various techniques of expert systems and machine learning can be utilized by the objects for the object level challenges.

2.2.2 Deployment

COs may benefit from the existing objects in the environment, like network of sensors or ubiquitous devices, or they may deploy new sensor or actuator objects. In the latter case, objects can be rapidly and randomly deployed without a plan, or an effective deployment plan can be generated for a good coverage of the operation area. This is a matter of optimization, and might be solved centrally in advance or by the deploying CO during the operation. COs should be powered on before deployment, and they might get self-organized after the deployment.

2.2.3 Resource limitations

Wireless sensor networks are generally characterized by limited onboard energy supply, as well as resources such as storage, communication and processing capabilities. In the case of ad-hoc networks sensor nodes create their infrastructure dynamically, which takes a considerable time and energy. Following successful establishment of the structure data is passed through the sensors to reach the requestor or kind of a data sink. Use of a data aggregator could be encouraged to reduce energy spent for data communication. Data aggregators will also have the responsibility of communicating between other data aggregators and the actuators introduced in the operation area.

By the help of data aggregators sensors will spent less energy to deliver their findings. Since these aggregators will be the gateways for the sensor information flow less time and energy will be spent to create and maintain routing tables. Use of smart data aggregators in the architecture will provide a secure environment for communication and data diffusion. In order to achieve a cooperative success of all these devices, programs, algorithms and also protocols running on should be energy aware and efficient.

2.2.4 Intelligence

Wireless networked sensors which introduced a new way of retrieving information from the surrounding environment will soon be everywhere of our daily lives similar to Internet. These sensors will be smart enough to process information other than just being an access to raw information sooner.

In order to create smart devices from the existing sensors and actuators, some form of intelligence needed to be embedded in them [13].

2.2.5 Mobility

Mobility is considered as continuous change of positions of nodes with respect to each other. Change of relative positions effects routing and requires continues position update which degrades the performance of the system. In spite of some of the objects have no moving capability, they can move to another location by the transporting objects (e.g. boat objects). Some of the objects move only in one-dimensional space (e.g. sensor node objects under the water), some of the objects move in two-dimensional space (e.g. boat objects), and some move in three-dimensional space (e.g. helicopters). Movement requirement may differ from 1 mile-per-hour (e.g. robots) to 40 miles-per-hour (e.g. torpedo carrying boat) – 70 miles-per-hour (e.g. UAV). Some objects move to take their next location, while some objects move to preserve their location against wind or current. Mobility affects the network connectivity and causes more communication overhead. Mobility also makes the localization problem more challenging.

2.2.6 Real-time operation

Most of the CO scenarios will require a real-time response to sensor readings. In these types of applications, a postponed act on crucial information may result in a catastrophe. Furthermore, sensed or received data from the network must still be valid at the time of actuation [14].

From the perspective of real-time considerations, CO networks will add new challenges to the ones that encountered in wireless sensor networks due to coordination, cooperation and collaboration issues, which are the defining characteristics of these networks. These considerations will require more powerful processing capabilities, as well as broader communication bandwidth. Moreover, current protocols used in WSNs will most probably not fit well for these more intelligent and cooperative networks, and thus have to be revised.

2.2.7 Synchronization

Cooperation among the objects requires synchronization. Synchronization of clocks is essential for communications, actuation and localization of objects. Some communication protocols rely on strict time synchronization. Similarly, the time when the data is sensed or when the message is received is vital for the initiation of an action. Objects moving or acting together must also be synchronized in time. Centralized or decentralized approaches to clock synchronization are available. Both methods can be employed in the case of mobile and immobile objects with diverse capabilities. On the other hand, synchronization of tasks is another challenge. It involves real-time synchronization of tasks distributed among heterogeneous objects when there is a precedence relation among their sub-tasks. Inter-task dependencies require efficient coordination and synchronization between the objects.

2.2.8 Localization

Localization is another challenge to deal with. Many localization techniques are proposed for wireless sensor networks and for mobile ad hoc networks. Some of these techniques can be applied in COs, for example, robots can have GPS to locate themselves, and ships have GPS and other locating devices. However, GPS cannot be mounted to tiny and dispensable objects such as sensor nodes to avoid cost-increase. Other position estimation and calculation techniques can be applied, but these techniques need calibration. On the other hand, localization-incapable objects can get their location information from the hosted objects during the transportation. Furthermore, when they are deployed to the operation area, these objects can estimate their locations relatively to the accurate location information of these GPS-mounted objects. Information may be critical in some cases with accuracy in millimeters (currently not possible in WSNs) or may be as slack as the directions east, west, north and south.

2.2.9 Communication

Communication is the central part of a CO system. Communication resides in every object-level and network-wide functions such as routing, synchronization, data sharing, registration/deregistration, security, mission planning, localization, and coordination. Due to limited bandwidth and energy, communication needs bearer considerations for efficient usage of these limited resources. These are common challenges in wireless sensor networks and mobile ad hoc networks. However, there are new additional challenges because of different traffic requirements and varying capabilities of cooperating objects. Some of these new challenges are cross product of other challenges. Objects may require real-time traffic with a propagation delay less than 100 micro second. For real-time traffic, propagation delay is very important, and in some cases much more important than power consumption. For instance, a rudder must react to the sensed data coming from sensors within 10-20 microseconds. End-to-end reliability and seamless integration of heterogeneous objects are other aspects to consider. Therefore, new technologies and architecture designs are needed.

2.2.10 Security

Most of the CO applications are mission-critical and it is inevitable for these applications to meet physical and data security requirements. However, researches on WSNs so far mainly focused on making this new technology feasible and usable rather than addressing security issues encountered on these networks. Due to the unique characteristics of WSNs, such as wireless communications, limited power consumption, scarce processing capabilities and storage, heterogeneity, deployment in vast numbers and low node fault tolerance, they are subject to serious security challenges [15]. Especially, wireless nature of these networks opens them to eavesdropping and denial of service attacks [16].

CO applications inherit all these security challenges from WSNs. Further, coordination, cooperation and collaboration will require much more data traffic to flow in the network, thus make these challenges even worse. Tackling with them will need more processing time, storage and power consumption, which will conflict with the real-time operation requirements, limited storage and power source. Cooperation among the COs is established on delicate basis, thus compromising a single component in the CO hierarchy may result in collapsing down of the whole cooperation.

2.2.11 Scalability and heterogeneity

Depending on the application, typical CO networks will be composed of large number of autonomous nodes. As the definition implies, complexity of these nodes falls into a broad range of possibilities, starting from simple sensors or actuators to high level objects composed of large number of components or other objects. Thus, nodes in the network will be diverse in variety of aspects, such as hardware they are consisted of, software they make use of, power and processing capabilities they deploy. Furthermore, most of the application scenarios will require deployment of new nodes to be able to compensate the changing conditions and maintain the cooperation. On the other hand, due to various reasons, such as power saving considerations, some of the COs may want to enroll and dis-enroll the network on timely basis.

If node density is high and operation area is wide, it is a large-scale system, which is highly decentralized and subject to many faulty conditions stemming from the environment, such as noise [16]. Maintaining the connectivity of the nodes that usually operate under harsh conditions in such a wide area will be very cumbersome.

All these defining characteristics of CO networks introduce new challenges to scalability and heterogeneity, as well as maintaining the ones inherited from WSNs. New schemes have to be developed to achieve cooperation among vast number of heterogeneous objects. [11]"

2.3 Routing Protocols

The routing protocols for the wireless sensor networks can be categorized as two: Structured-based categorization, and functional categorization. In the structured-based categorization, the protocols are classified as flat, hierarchical and location-based protocols. In the functional categorization, the protocols are classified as; multi-sink routing protocols, query-based routing protocols, negotiation-based routing protocols, QoS-based routing protocols. One more categorization can be done according to the behavior of the protocols. According to the behavior, they can be classified as proactive, reactive and hybrid.

2.3.1 Structured-based categorization

The structured-based categorization is well explained in [17]. The preliminary proposed routing protocols for mobile networks were adaptations of routing protocols those used in fixed networks. These protocols used in fixed networks outperform worse results in dynamic networks since they were designed for fixed networks. As the network becomes dynamic, the overload of routing processes increases. Network resources can be exhausted rapidly or may become unusable, if this overload uncontrolled.

New techniques are proposed for mobile networks. Previously proposed routing techniques are surveyed to highlight the reasons why they are not applicable to mobile environments. These routing techniques can be classified as flat routing and hierarchical routing according to their structure.

2.3.1.1 Flat routing techniques

In flat-routed algorithms, each node maintains routing information to some or all of nodes in the network in one or more tables. The size of tables can be manageable in a small sized network. However, for larger networks, the size of routing tables, communication load and process time for routing increases significantly. Table updating and processing time cause an overhead in the network. Therefore, flat routing algorithms are not scalable for large networks. There are many flat routed protocols proposed in the literature such as [18];

- Sensor Protocols for Information via Negotiation (SPIN)
- Directed Diffusion
- Rumor Routing
- Minimum Cost Forwarding Algorithm
- Gradient-Based Routing
- Information-Driven Sensor Querying and Constrained Anisotropic Diffusion Routing

- COUGAR
- ACQUIRE
- Energy Aware Routing
- Routing Protocols with Random Walks

A detailed explanation of the protocols are given in [18].

2.3.1.2 Hierarchical routing techniques

In large networks, hierarchical routing techniques are used for scalability. The main advantage of hierarchical routing is that it minimizes the routing table size, hence decreases the routing process time significantly. A network is consisting of end-point nodes and switches. Switches manage routing function. Communicating entities are the end-point nodes, and each end-point node in case, acts as a switch and manages routing process for its neighbors.

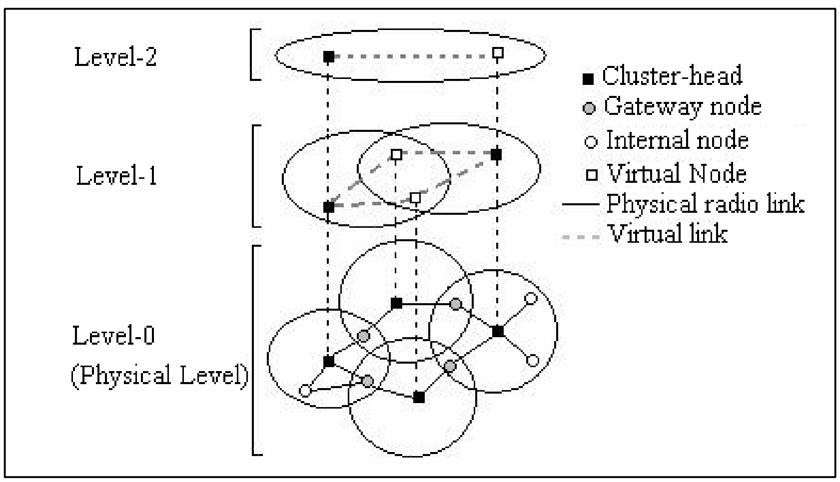


Figure 2.2: A hierarchical network.

In a hierarchical network, the lowest level consists of end-point nodes (Figure 2.2). Neighboring end-points organize into clusters and at each cluster a node is selected as cluster-head. Cluster-heads act as switches. Cluster-heads also organize into clusters to make the upper level and at each cluster; a node is selected as cluster-head for that level. Clustering approach continues until a reasonable sized cluster is established at the highest level.

At each level, a node in a cluster only maintains the routing information of the members of that cluster. For the nodes in different clusters, routes are established via cluster-heads, being also a member of upper level cluster. Therefore routing table size and routing process load decrease. The established route may not be the optimal route.

Some hierarchical routing protocols in the literature are listed as follows [18]:

- LEACH Protocol
- Power-Efficient Gathering in Sensor Information Systems
- Threshold-Sensitive Energy Efficient Protocols
- Small minimum energy communication network (MECN)
- Self-Organizing Protocol
- Sensor Aggregates Routing
- Virtual Grid Architecture Routing
- Hierarchical Power-Aware Routing
- Two-Tier Data Dissemination

2.3.2 Behavior-based categorization

Traditional routing algorithms tend to exhibit their least desirable behavior under highly dynamic conditions. Routing protocol overhead typically increases dramatically with increased network dynamics. If the protocol overhead is uncontrolled, it can easily overwhelm network resources. Furthermore, traditional routing protocols require substantial inter-nodal coordination or global flooding in order to maintain consistent routing information and avoid routing table loops. These techniques increase routing protocol overhead and convergence times. Consequently, although they are well adapted to operate in environments where bandwidth is plentiful and the network links are relatively stable, the efficiency of these techniques conflict with routing requirements in WSN and MANETs. Therefore, new routing strategies are required for WSN and MANETs that are capable of effectively managing the tradeoff between responsiveness and efficiency. The following definitions present the most commonly used means of classifying routing protocols that have been designed for WSN and MANETs:

- ***Proactive Routing*** is defined as a strategy in which routes are continuously maintained for all reachable network destinations. This approach requires periodic dissemination of routing updates to reflect the up-to-date state of the network.

- ***Reactive Routing*** is defined as a strategy in which routes are established and maintained on a demand basis—only communication is required. This approach requires procedures to acquire new routes and to maintain routes following topology changes.
- ***Hybrid Routing*** is defined as a strategy, which selectively applies either proactive or reactive routing techniques, based upon either a predefined or an adaptive criteria.

2.3.3 Proactive routing protocols

Proactive routing protocols periodically distribute routing information throughout the network in order to pre-computed paths to all possible destinations. Hence, each node maintains a priory calculated routing information to all destinations, regardless as to whether or not a particular node actually requires reaching such destination, or lies along a path of another node that does. All nodes update these tables to maintain a consistent and up-to-date view of the network. When the network topology changes, nodes propagate update messages throughout the network in order to maintain consistent and up-to-date routing information about the whole network. These routing protocols differ in the method by which the topology change information is distributed across the network and the number of necessary routing-related tables. Although this approach can ensure higher quality routes in a static topology, it does not scale well to large, highly dynamic networks. This routing strategy is also referred to as table-driven routing, because protocols that adopt this strategy attempt to maintain consistent information in routing tables distributed throughout the network.

2.3.4 Reactive routing protocols

Reactive routing has been proposed as a means of achieving a better balance between responsiveness and efficiency. The objective of reactive routing is to minimize the reaction of the routing algorithm to topology changes by maintaining a limited set of routes—those required for on-going communications. The idea is that by selectively limiting the set of destinations to which routes are maintained, less routing information needs to be routinely exchanged and processed. Consequently, less bandwidth is consumed by routing information, less computation is required to process routing information, and less memory is consumed by routing tables. Based on this technique, routing is expected to response more rapidly to topology changes, and additional network resources are expected to be available for transmission and processing of application data.

In a reactive routing strategy, paths are maintained on a demand-basis using a query-response process. This involves a variation of controlled flooding referred to as a directed broadcast, in which a query, or route request packet is selectively forwarded along multiple paths toward a target destination. The search process dynamically constructs one, or multiple paths from the source node to the destination. This strategy limits the total number of destinations to which routing information must be maintained, and, consequently, the volume of control traffic required to achieve routing. The shortcomings of this approach include the possibility of significant delay at route setup time, the large volume of far reaching control traffic required to support the route query mechanism, and reduce path quality. Furthermore, despite the objective of maintaining only desired routes, the route query could propagate to every node in a network during the initial path setup causing each node to establish paths even when they are only required by certain sources. Finally, most reactive strategies do not discover optimal paths, and the paths typically become increasingly less optimal following each topology change.

2.4 Aim of the Routing Algorithms

The main aim of the routing function is to convey the valuable information to the destination. In infrastructured-wired networks, this function is achieved by keeping routing tables of existing topology. These routing tables are kept at every network element and have to be updated to reflect topology changes. In wireless and mobile networks, similar routing approaches have been developed. However, because of the features such as mobility, energy constraints, and link failures peculiar to wireless links and mobile nodes, trying to keep up-to-date routing information causes overhead, reduces performance and lifetime of the network, and introduces scalability problem.

Scalability of a routing protocol is affected by two dominant factors [1]: rate of topological changes and number of nodes in network. At formerly proposed protocols for mobile ad hoc networks, routing is accomplished by keeping up-to-date whole network topology, failing to be scalable and efficient [18]. Succeeding proposed protocols used the hierarchical structure and local topology knowledge to achieve scalability [18]. Furthermore, they used data aggregation, query-based and energy-based approaches. While most of them compensate specific requirements, they are not suitable for different environments and varying performance metrics such as scalability, energy, network lifetime, and real-time data transfer. The main reasons of inefficiency are keeping local/global routing tables up-to-date at nodes and excessive energy consumption in routing process.

Routing without tables can be achieved by using location information of the nodes retrieved from GPS or by applying a localization algorithm. Position-based routing is not a new idea as used formerly, but has gained importance during the emergence of wireless and mobile networks and has been classified as a geographical routing. In geographic routing protocols, nodes know their actual or relative positions with respect to a reference point, and share this information with their immediate neighbor nodes for routing process. Geographic routing protocols use only local topology information and have not global update overhead. Therefore, scalability in mobile networks with respect to conventional routing protocols becomes possible.

2.5 Geographical Routing Protocols

Geographical routing protocols have been researched since 80's. The taxonomy for position based routing algorithms for ad hoc networks is given in [2] and [8]. Surveys of the proposed protocols are given in [2-4, 12, 19, 20]. The proposed protocols for ad hoc networks can be adapted to sensor networks since ad hoc and sensor networks share similar properties considering routing process. However, other essential properties of sensor networks should be considered for the adaptation of the proposed ad hoc network protocols. First of all, sensor nodes have limited power, memory and processing capabilities. Second of all, sensor nodes and wireless links may become up and down during the operation. Moreover, for mobile sensor networks in which frequent topology changes occur, local stateless algorithms that do not require global topology information are candidates. As stated previously, sensor nodes may get down unpredictably at any time, forcing to deploy nodes in large numbers. By the way, the phenomena can be sensed by more than one node nearby. These properties enforce us to use data-centric approach in WSN. Therefore, the most appropriate protocols for sensor networks are those that discover routes on demand using scalable techniques, while avoiding the overhead of storing routing tables globally or locally and avoiding the overhead of updating these tables according to the topology changes.

In geographic routing protocols, nodes know their actual or relative positions with respect to a reference point, and share this information with immediate neighbor nodes for routing process. Geographic routing protocols utilize only local topology information and have not any update overhead. Therefore, they provide scalability in mobile networks with respect to conventional routing protocols.

Geographic routing protocols use either greedy or beaconless scheme for routing. In the greedy scheme, nodes select the best next node on the route by using the local topology information [1-4]. By periodic beaconing or event-based beaconing, nodes acquire location information of their neighbor nodes. The transmitting node, selects a node according to either distance-based or angle-based scheme. In distance-based scheme, the objective is to select a neighbor that is closest to the destination. In angle-based scheme, the objective is to select a node closest to a virtual line between the transmitting node and the destination. Collecting local topology information in both beaconing schemes consumes more energy than beaconless schemes due to reduced number of transmissions in the latter one. On the other hand, beaconless routing protocols propose solutions to be implemented at the MAC layer [5-8]. In those solutions, RTS and CTS packets are also used for implementing the routing protocol that increases the complexity of the MAC layer. However, sorting the routing problem out at the MAC layer is against the well-defined layered communication protocol. Besides that, those solutions become MAC layer dependent.

2.5.1 Stateful geographical routing protocols

Formerly proposed protocols use the greedy approach either distance or angle as the metric. GPSR [1] requires a priori local topology information. Nodes broadcast periodically the beacon messages independent of data packets to provide this information. Receiving neighbor nodes update their neighborhood tables accordingly. Upon a transmission request, the best next node is selected by calculating the distances of neighbor nodes. Beaconing introduces communication overhead and consumes energy. Continuous table updating introduces processing overhead and buffers overflow due to periodic beaconing [69]. While the GPSR finds the shortest paths, it may experience the local minima problem. GPSR proposes the perimeter-forwarding mode to circumvent holes in network. However, perimeter forwarding increases the communication overhead and energy consumption. On the other hand, it causes to deplete energies of the boundary nodes, which makes holes grow larger. The next node selection is based on proactive table keeping, which is affected from the mobile environment. The next node selection also introduces a computational delay at each node to find the best neighbor node.

LAR [21] is a routing protocol based on source routing, employing the position information to enhance the route discovery phase. The route request packets are flooded within the request zone that includes the expected zone of the target. LAR uses flooding and the position information is used to restrict the flooding to a certain area. Flooding introduces communication overhead and consumes energy. On the other hand, due to source routing, it is sensitive to mobility causing reconstruction of the route, which degrades the performance metrics. LAR also keeps network-wide topology information, which is memory inefficient.

DREAM [22] is a proactive routing protocol using location information. In DREAM, each node maintains a location table of each node in the network. Each node periodically broadcast its position to inform neighbor nodes. Period is adjusted according to the speed of the nodes. On a packet to send, source node calculates the direction toward the destination and selects a set of next node candidates, then sends the packet to these nodes. If the set is empty, the packet is flooded to the entire network. Periodic beaconing and flooding, in case of empty next node candidate set, introduce communication overhead and energy consumption. It introduces the drawbacks introduced in GPSR. In addition to these, it requires memory greater than GPSR due to network-wide topology information requirement.

Another strategy for greedy forwarding is compass routing, which selects the neighbor closest to the straight line between the sender and destination. [23] uses the angle metric rather than distance to select the next node. In addition to the drawbacks of distance-based greedy approaches (e.g. GPSR), it does not avoid loops.

[24] discusses the trade-off between the topology information cost and the communication cost and introduces optimal topology knowledge range for each node to make energy efficient geographical routing decisions. It introduces two approaches, PTKF (Partial Topology Knowledge Forwarding) and PRADA (Probe-Based Distributed Protocol For Knowledge Range Adjustment), to decrease the topology information cost. However, the proposed algorithms do not consider the voids.

[25] introduces QoS for delay-sensitive applications proposing an event-driven protocol similar to GPSR. Therefore, drawbacks are similar to the GPSR. On the other hand, only the transmission energy is considered in the energy consumption model. [26] considers the link breakages and proposes a new link metric called NADV (Normalized Advance) to select the next node for constructing more robust routes. It estimates the link costs by using another new sublayer WISE (Wireless Integration Sublayer Extension) on top of MAC layer. It considers only the transmission energy in the energy consumption model. It uses the ideal conditions for route construction, which is impractical and unrealistic and only predefined packet error rates are used in NADV. Using a new sublayer is contrary to the well-defined communication architecture.

2.5.2 Drawbacks of the stateful geographical routing protocols

In greedy approaches, there is a possibility that they may not find the route since the search is limited by the local topology knowledge, even if there is a path to destination that can be found with global topology knowledge. On the other hand, beaconing-based greedy approaches consume excessive energy due to beaconing and introduce control traffic overhead. Furthermore, as the topology changes due to mobility, node terminations, link failures, and energy-saving mechanisms that switch between sleeping and active states, providing proactively local topology knowledge reduces the performance and the scalability. Therefore, stateful protocols are not suitable for these types of networks, e.g., ad hoc networks. However, stateless protocols are not affected too much from the topological changes and network dynamics. But, they use broadcasting to find routes as in flooding which wastes resources. Parameter-based schemes can be used to reduce the number of rebroadcasting nodes. Position-based stateless approaches reduce the number of the rebroadcasting nodes by selecting the next rebroadcasting node. However, they use MAC-layer integrated approaches to achieve this and introduce delay. MAC-layer integrated approaches make them dependent to the MAC-layer used.

2.5.3 Stateless geographical routing protocols

An early example of the stateless broadcasting protocols is introduced in [5]. [5] introduces a contention-based forwarding scheme (CBF) that selects the next-hop through a distributed contention process using biased timers. All nodes those receive a packet check if they are closer to the destination than forwarding node and set their timers according to the progression toward the destination. Best suitable nodes respond priorly suppressing the other nodes. Forwarding node selects the best candidate node as the next node from the responding nodes set. In this approach, next node selection phase introduces greater delay and energy consumption on route construction phase with respect to greedy approaches. In greedy approaches, priori topology knowledge produces overhead and energy consumption, but the delay and energy consumption on route construction phase is notable low. On the other hand, in CBF, rebroadcast decision is based on RTF/CTF (Request To Forward/Clear to Forward) packets and timers, which are completely processed in MAC-layer. Used energy models are not defined in [5] and it does not consider the energy-efficiency.

In [6], a beaconless routing algorithm (BLR) is proposed which is very similar to CBF in [5]. [7] proposes another beaconless position based routing protocol by guaranteeing the delivery of the packets. The Guaranteed Delivery Beaconless Forwarding (GDBF) protocol selects appropriate next node by means of RTS/CTS packets. Forwarding node broadcast the RTS packet to its neighbors and the neighbor nodes compete with each other to forward the packet and set a timeout depending on their suitability. After timeout, nodes send CTS back to the forwarding node by using the suppression technique. Forwarding node decides one of the neighbor nodes as the next node and forwards the message to that node. Guaranteed delivery is provided by the recovery mode when the greedy mode fails. When the greedy algorithm reaches to a local minima (no CTS response), the algorithm shifts to the recovery mode. The drawbacks are the same as in [7]. On the other hand, it is a completely MAC-layer integrated solution for routing.

[5], [6] and [7] are very similar to each other in terms of the next node selection. A different approach is proposed in [8], which proposes a Dynamic Delayed Broadcasting Protocol (DDB). DDB allows nodes to make locally optimal rebroadcasting decisions by Dynamic Forwarding Delay (DFD) and make better nodes to rebroadcast first suppressing the transmissions of other nodes. However, it cannot avoid multiple transmissions and introduces delay. On the other hand, at each receive process; nodes have to recalculate/adjust their timers, which is computationally complex. Since packet scheduling is achieved in the MAC layer, on each receive process, a MAC layer – Network layer – MAC layer interoperation is executed, rescheduling the packet transmission each time. Even, a scheduled packet can be canceled after many calculations and scheduling. However, it is stated as a cross-layer approach, it involves MAC layer operations.

2.5.4 Drawbacks of the stateless geographical routing protocols

The proposed stateless algorithms introduce MAC-layer involved solutions for routing, which is contrary to the well-structured communication architecture. They are dependent to the MAC layer they use. As stated explicitly; they use the IEEE 802.11 protocol in the MAC layer. Timing and packet scheduling are the functions of the MAC layer. On the other hand, decision of broadcast, multicast and unicast are the functions of the network layer. In a well-defined communication architecture, routing and node addressing should be independent from the MAC layer functions. Combining the routing function with the MAC layer introduces overhead and makes the routing protocol dependent to the MAC scheme proposed. Moreover, the proposed stateless protocols introduce a computational overhead in MAC/Network layer to schedule the packets and calculate the timers. Their performance is sensitive to the node terminations and nodes' unpredictable come-ups and go-downs.

2.6 Mobility Patterns

Cooperating object networks mostly use sensor and actuator nodes. Therefore, in this section, the mobility patterns in wireless sensor and ad hoc networks are investigated. The definitions are retrieved from [27].

2.6.1 Random walk (memoryless) movement model

"In memoryless, Random Walk Movement Model, the user's next location does not depend on the user's previous location. That is the next location is selected with equal probability. Purely Random walk Model is usually used to model pedestrian traffic, whose movement are usually irregular with frequent stops and directional changes. [27]"

2.6.2 Markovian model

"Unlike the memoryless movement model, the Markovian Movement Model incorporates memory and user's movements are influenced by the user's previous movements. Such memory can include a list of recent directions in the movement (directional history). [27]"

2.6.3 Shortest distance model

"In this model, users are assumed to follow a shortest path from source to destination. At each intersection, a user chooses a path that maintains the shortest distance assumption. The model is particularly suited for vehicular traffic, whereby each user has a source and destination. [27]"

2.6.4 Gauss-Markov model

"This model captures some essential characteristics of real mobile users' behavior, including the correlation of users' velocity in time. In the extreme cases, the Gauss-Markov Model simplifies to the memoryless movement model and constant velocity Fluid-Flow Model. [27]"

2.6.5 Activity-based model

"The central concept of an activity-based model is that of activity. Each activity represents a trip purpose: that is, the activity requires the user to travel to a destination associated with the activity. New activities are then selected/generated based on such factors as the previous activities and time of day. [27]"

2.6.6 Mobility trace

"Actual mobility trace of the users can also be used for simulation. Such trace is certainly more accurate and realistic than other mathematical models. However, such trace is not readily available, especially one of a large size to be useful for network simulations. Furthermore, movement behavior of users in one network may not be the same or valid for other networks, which may depend, among other things, on the size of the network and geography. [27]"

2.6.7 Fluid-flow model

"Although the above models describe an individual user's mobility, there are also models that describe system-wide (macroscopic) movement behavior. The Fluid-Flow Model is one such model. In this model, mobile users' traffic flow is modeled as fluid flow, describing the macroscopic movement pattern of the system. In this model, each user is assumed to move at an average speed v and is uncorrelated with the movement of other users. Further, the direction of each mobile user's movement is uniformly distributed in range $[0, 2\pi]$.

The Fluid-Flow model is suitable for vehicular traffic, where users do not make regular stops and interruptions, as opposed to pedestrian traffic, which can be irregular with frequent stops and directional changes. Pedestrian traffic is usually modeled using a Random Walk Model. Because the Fluid-Flow Model describes macroscopic movement behavior, it is not suitable in cases when individual user's mobility patterns are important. [27]"

2.6.8 Gravity model

"In this model, movement traffic between two sites/regions, i, j is a function of each site's gravity P_i, P_j (e.g., population) and an adjustable parameter $K(i,j)$. As in the case of Fluid-Flow Movement Model, the gravity model describes systemwide, or macroscopic, movement behavior. As such, it cannot be used in simulations involving the individual user's mobility patterns. Gravity models can be used to model traffic in different geographical areas. [27]"

2.7 Motivation to the Thesis Proposal

As described at the beginning of the chapter, sensor and ad hoc network are key components of cooperating objects. In this chapter, challenges and the existing approaches in sensor and ad hoc networks including routing algorithms and mobility patterns are given. It is concluded from the related studies in this area that new routing techniques are required to satisfy the requirements of wireless and mobile environment. These techniques should be adaptive, stateless, reliable, and simple and produce low overhead. In this thesis, a novel stateless routing algorithm is proposed completely executed at the network layer and independent from the MAC layer. To the best of our knowledge, it is the first stateless protocols in the literature that works in the network layer and satisfies the properties mentioned above. The SWR (Stateless Weighted Routing) is a completely distributed stateless algorithm that does not require a priori topology information. The SWR even works with position inaccuracy, while the performance of the geographical routing protocols depends on the knowledge at the nodes. On the other hand, the SWR constructs multiple braided paths for robustness with a minimum delay and provides a basis for the real-time support for time-critical data. The SWR is also the first stateless routing protocol in the literature, to the best of our knowledge that use multiple paths using the greedy approach in WSN and MANET.

3. SWR: STATELESS WEIGHTED ROUTING APPROACH

A novel stateless data flow approach and routing algorithm for wireless ad hoc and sensor networks is proposed, namely Stateless Weighted Routing (SWR), in this thesis. It is also shown that it can also be used in mobile environments. The main objective of the SWR is to enable the data flow toward a sink node. The position of the sink node can be anywhere in the topology.

The SWR is a geographical routing protocol. Standard geographical routing assumptions are valid for the SWR. All nodes are aware of their locations with regard to a sink node. Location information of the nodes is retrieved either by GPS (Global Positioning System) [28] or by applying a localization algorithm [29 - 32]. Using GPS can be costly because of being expensive. To reduce the cost and make the GPS usage economically feasible, all nodes do not have to be equipped with GPS. Nodes can find their locations by a localization technique if they are or not equipped with GPS. There are many localization techniques proposed in the literature [29-32]. Unfortunately, the localization techniques produce communication overhead and introduce additional resource consumption. Therefore, a few nodes can be instrumented with GPS and other nodes can find their locations by using a localization technique which interacts with GPS-mounted nodes to reduce localization communication overhead.

The proposed approach, the SWR, can be considered as a combination of greedy forwarding scheme and gradient broadcast scheme. However, the SWR overcomes the drawbacks of these schemes. The delay encountered in greedy forwarding scheme, the complex calculations in gradient broadcasting, and the communication overhead encountered in both of these schemes are eliminated in the proposed approach. On the other hand, the proposed approach is more flexible than any other routing protocol, since it is able to adapt itself according to the network dynamics.

3.1 Properties of the SWR

The SWR falls into the category of geographical routing protocols. In the SWR, routing is achieved without keeping tables, which provides the stateless property. Since no routing table is kept and no beaconing has to be done, it can be called a reactive stateless protocol. Nodes do not have to be aware of neither local nor global topology information. As in all other geographical routing protocols, geographical positions of nodes would have been sufficient for the routing process. However, the SWR uses weight values instead of geographical positions in routing decisions. Each node has a dynamically changing weight value derived from its current position. The weight value may also include some of the QoS (Quality of Service) parameters such as the energy left at the node. Data should flow to the sink with no external information similar to water flowing to the sink or the melting of snow and flowing down following valleys. To provide this natural flow, nodes away from the sink node have greater weight values with respect to closer ones, as the sink has a weight value *0*. Therefore, the routing algorithm includes a natural data flow toward the sink. Hence, the use of weight metric makes routing process simple and minimizes delay, energy consumption, and processing requirements at nodes in routing decision phase. In the SWR, when a node has data to transmit a packet, it inserts its own and the destination's weight values into a packet, and broadcasts it. When a node receives a packet, it compares its own weight value with the weight values in the packet. If its weight value is between the transmitting node's weight value and the destination's weight value, it rebroadcasts the packet. It drops the packet otherwise.

To limit the number of forwarding nodes, a threshold is set in terms of the weight metric. On a packet receive, a node broadcasts the packet if its weight is between the weights of the transmitting node and the destination node and if also its weight difference is greater than a threshold value. Besides that, decision to transmit a packet includes QoS parameters such as power-left at the node to keep energy-limited nodes out of the route.

On a transmission, multiple nodes may broadcast the packet, yielding to construct multiple paths. Constructing multiple paths provides reliability, eliminates the void problem substantially, and provides robust routes including the shortest path. Using the weight metric instead of geographical positions decreases the total number of calculations at nodes drastically, resulting minimum delay, less resource requirements (such as processor and memory), and minimum energy consumption in processing. Therefore, sensor networks can be established by using cheaper and disposable nodes.

Energy models for the mobile ad hoc networks are investigated and are proposed in [33]. It is emphasized in [33] that receive process consumes almost the same amount of energy as the transmission process. Contrary to this fact only consumed energy during a transmission process has been considered, in previously proposed geographical routing protocols. Ignoring consumed energy during the receive process makes respective simulation results unreliable. On a transmission, all the nodes in range will receive the packet. The overall energy consumption on a transmission is the sum of the energy consumption in one transmission process and total energy consumption in receive processes of all the neighbor nodes. Simulation developed and implemented for this thesis also considers the energy consumption in the receive process to produce realistic results. On the other hand, the energy consumption for the calculations is also considered, and improvements have been achieved for calculations at nodes.

In the SWR, routing is completely achieved at network layer rather than a cross-layered, i.e. MAC-involved, solution.

The SWR has the following properties:

- provides scalability by avoiding the use of routing tables and beaconing.
- simplifies the routing process by using a weight metric, and designing an appropriate algorithm for routing.
- decreases calculations, delay, and resource requirements such as processor and memory at nodes since the weight metric is the only decision parameter.
- decreases energy consumption by avoiding beaconing, by using position-based routing based on a threshold value and considering the energy levels of the nodes.
- provides reliability by producing multipaths.

- executes the routing process completely in the network layer, independent from the MAC layer used below.

3.2 Preliminaries, Abstraction and Methodology

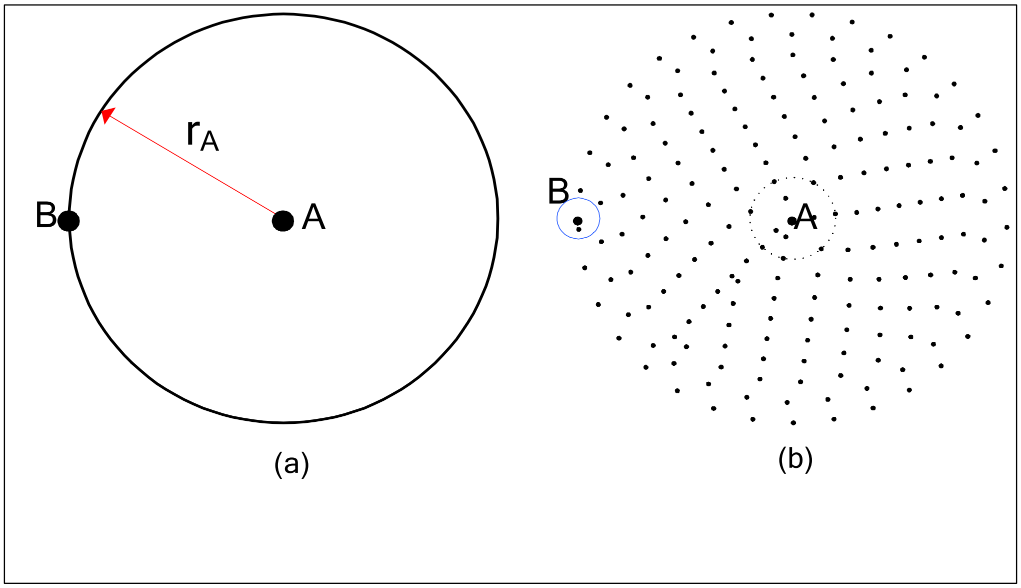


Figure 3.1: Data Flow: (a) B is a node on the circle of which center is A. (b) with additional co-centric circles

Assume that a data packet has to be transmitted from node B to node A. When a circle is drawn of which center is A and radius is r_A=|AB|, all of the nodes on and in the circle may transmit data directly to the node given that their transmission range is r_A (Figure 3.1 (a)). Note that other nodes would use these nodes to transmit their data to the node A. Drawing co-centric circles with the changing values of r_A produces new boundaries for respective transmission ranges (Figure 3.1 (b)).

3.2.1 Data flow without tables

If the transmission range of the nodes is decreased and a number of co-centric circles are drawn, there would be a circle of which center is A intersecting the circle of which center is B and radius is r_B (Figure 3.2).

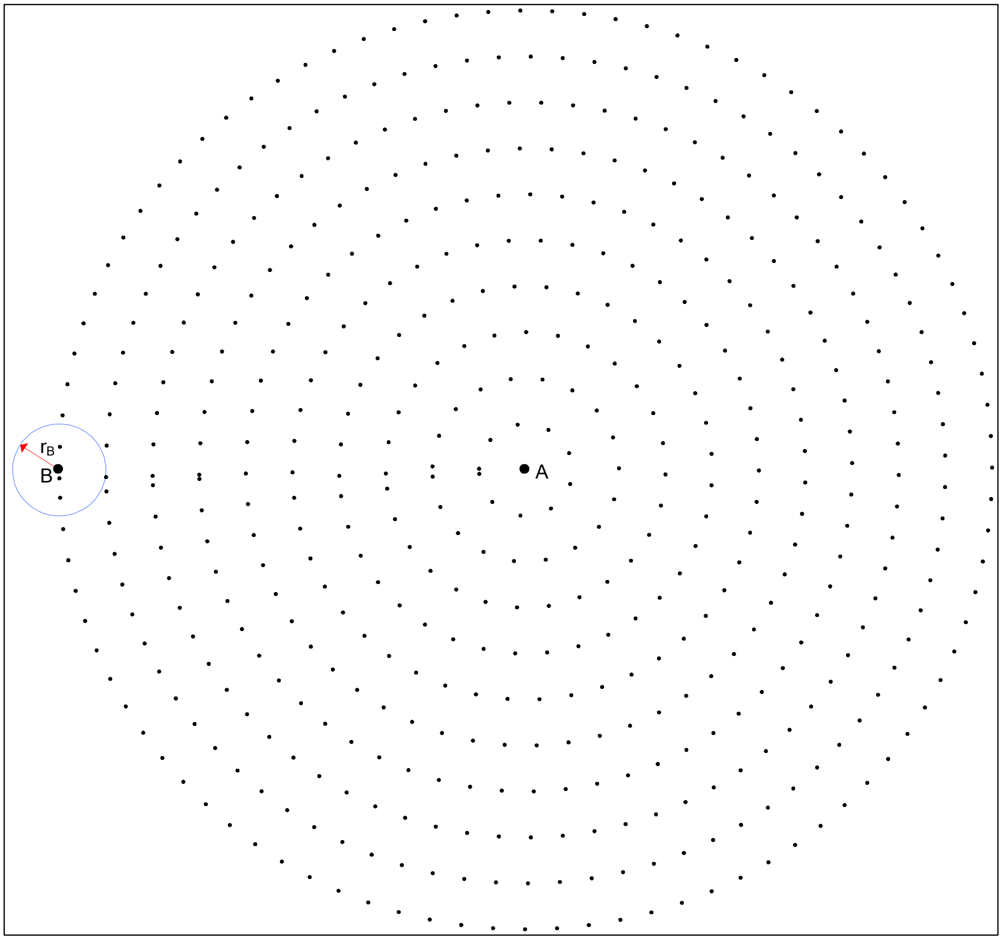


Figure 3.2: Magnification of Figure 3.1 (b).

The shortest route from node *B* to node *A* includes only the intersection points (Figure 3.3). To construct this path, nodes only need to know the circle they are located on. Assume that on a packet received at a node that includes the *r*-value of the transmitting node, if $r_{transmitting\_node} > r_{current\_node}$, it retransmits the packet allowing the packets flow to the central imaginary point 0 (node *A* in Figure 3.3). An x-y coordinate system can be used to provide the nodes with this information. If each node knows its position relative to a reference point such as (*0,0*) point in *x-y coordinate system*, they can find its distance to the destination. To transmit data packets of node *B* to node *A*, node *B* inserts its position information into the data packets. Receiving nodes calculates their distances to node *A* and compares it to the value of the transmitting node to make a decision on retransmissions. If the transmitting nodes put their radius (*r*) values -that is distance to the central point- into the packets instead of the positions, receiving nodes would simply compare their own r-values with the r-value of the packet without any calculation. Then, according to the given definition above and Figure 3.3, only the nodes on the intersection point of the inner circles can forward the packet, constructing a straight line toward the central point, which constitutes the shortest path.

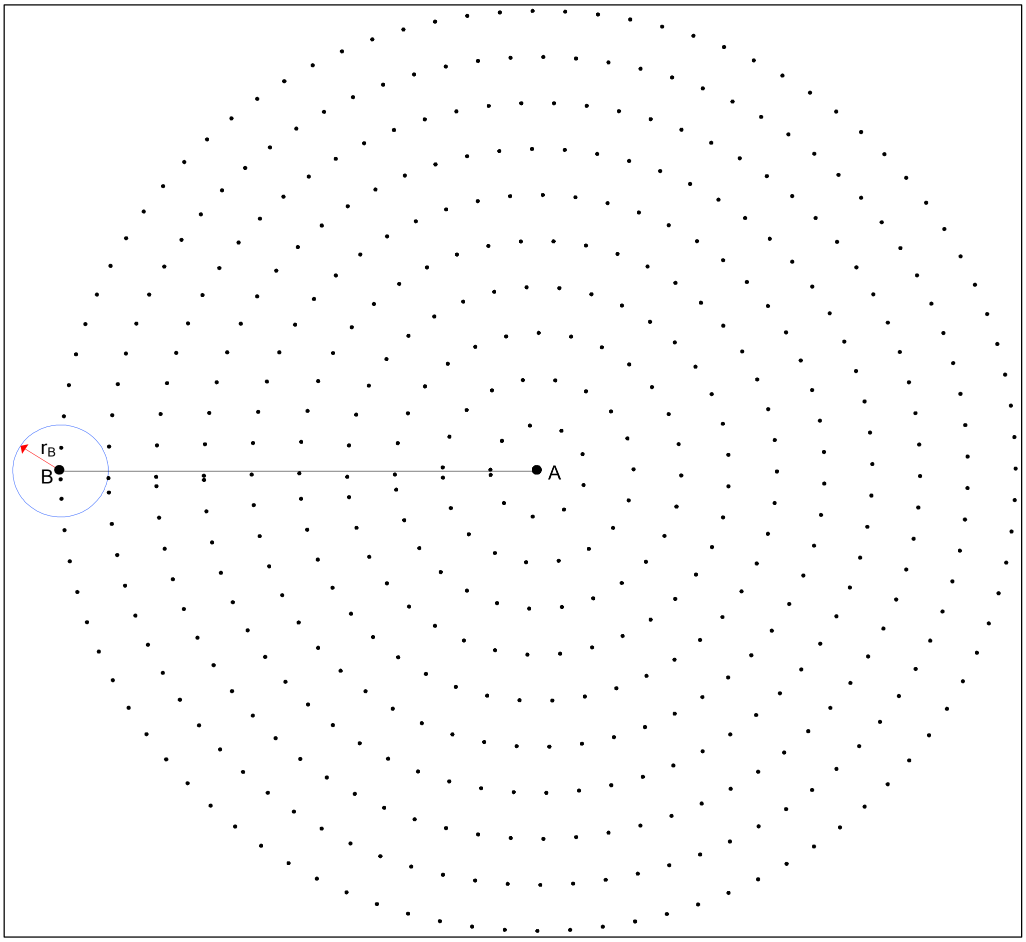


Figure 3.3: Construction of the shortest path.

In this system, a node only compares its r-value with the r-value of a received packet, and decides to retransmit if its own value is smaller. The constructed path which includes only the intersection points composing a straight path will be the shortest path as shown in Figure 3.3. However, if there is no node on the inner circle, route may be constructed by the nodes located on the same circle of the transmitting node. In such a situation, there would be more than one path being constructed. Therefore, there may be more than one shortest path.

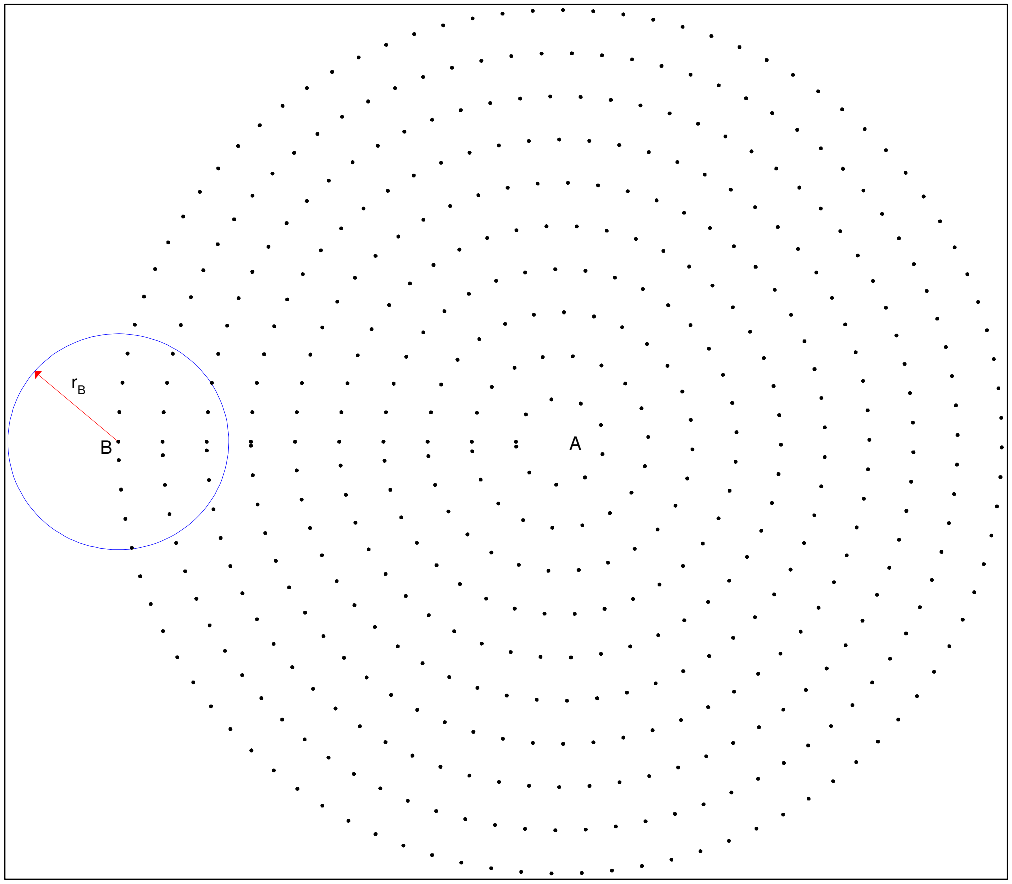


Figure 3.4: Node B with greater transmission range.

If the number of the circles is kept the same and the transmission range is increased, the transmission of the node *B* will be received by many nodes spread over some of the inner circles (Figure 3.4). Hence, there will be many different paths passing through the inner circles and at least one of the paths will be the shortest path. Therefore, data flow is enabled from the outer nodes to the central node.

When the node on point *B* has a greater transmission range, more nodes can forward the packet toward to the node on point *A*. This approach is used in the SWR. Instead of the location information of the nodes, the *weight metric* is used that enables the data flow and makes simple the decisions at nodes. Data will flow toward the destination without any effort, if the nodes know their own weight values and the final destination's weight value. Reference point should not be centered, and can be positioned at any point in the operation area.

3.2.2 Greedy approach

Figure 3.5 is depicted to explain the greedy approach in the proposed routing algorithm. Nodes on point *A* and point *B* are two neighbor nodes with transmission range *r* and distant from each other with *r* (Figure 3.5 (a)). Assume that the circles are filled with regularly distributed points. So that the imaginary points in the intersection will be in the range of both of the nodes. The points on the arc *CAD* are at equal distance to the node on point *B* and points on the arc *CBD* are at equal distance to the node on point *A*.

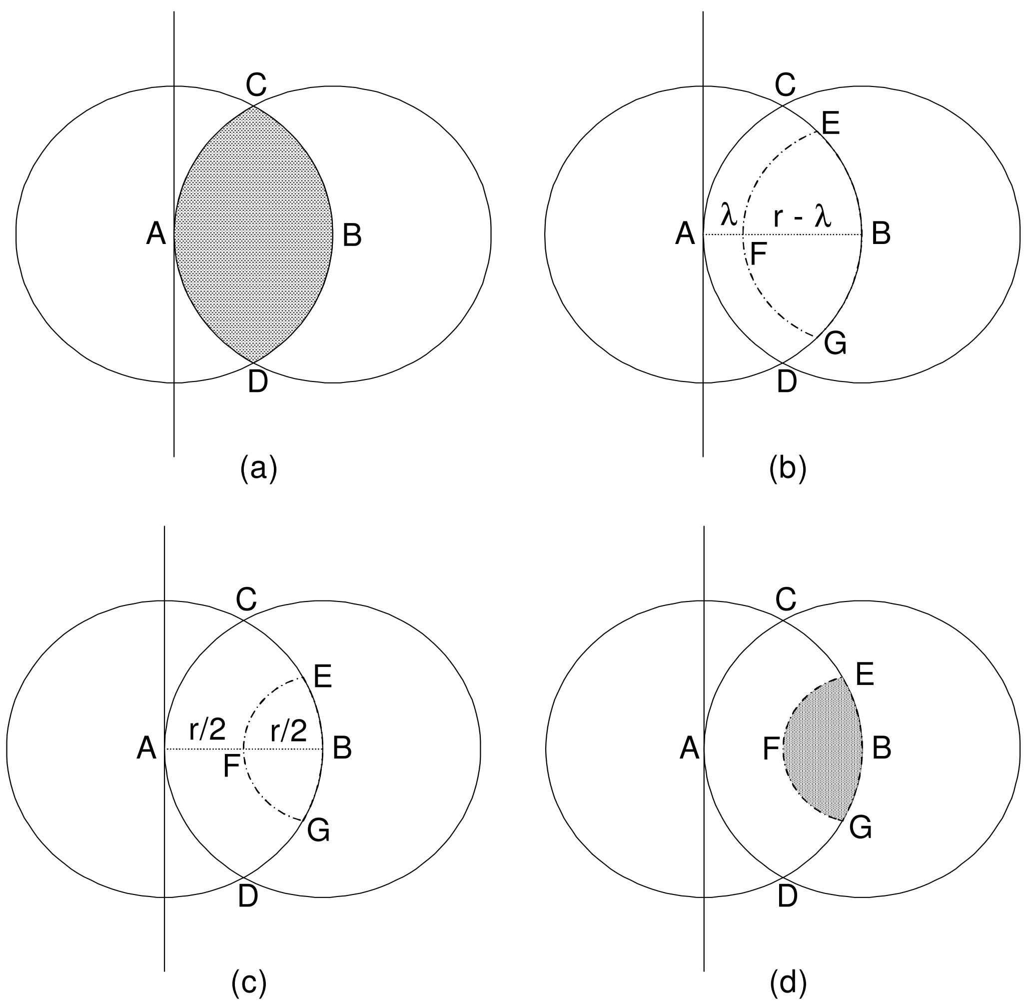


Figure 3.5: Greedy approach in SWR

Assume that a node on point *A* has a packet to transmit to the node on point *B* and the node on point *A* cannot send a packet directly to the node on point *B* due to some constraint such as energy consumption, obstacles, or worse link conditions due to long distance. Therefore, the node on point *A* should forward the packet to another node within the range of *B*. Since any point on arc *CAD* have the same properties as the node on point *A*, they should not be selected as a next node. The node on point *A* should forward the packet to a node that is closer to the node on point *B* than the node on point *A*. As illustrated in Figure 3.5 (b), the distance between the source (i.e. node at A) and retransmission node (i.e. node at F) is λ when the remaining distance to the destination node (i.e. node at B) is r-λ. The points on arc *EFG* are at equal distance to the node on point *B*. If *A* transmits the packet to be relayed to the node on point *B*, nodes in the intersection area surrounded by arcs *EFG* and *EBG* should relay the packet. The transmission of the nodes in the area between the arcs *CE*, *CAD*, *DG*, *EFG* would be inefficient because they are close to the node on point *A* i.e. still away from the node on point *B*. Nodes on the arc *EFG* are λ unit closer than the node on point *A* to the node on point *B*. Nodes in the area between the arcs *EFG* and *EBG* make more progression with distance greater than λ to the node on point *B*. If it is wanted to select only the nodes that make more progression with distance λ to the node on point *B*, *A* should forward the packet to those relay nodes. Increasing the λ value, limits the number of those relay nodes.

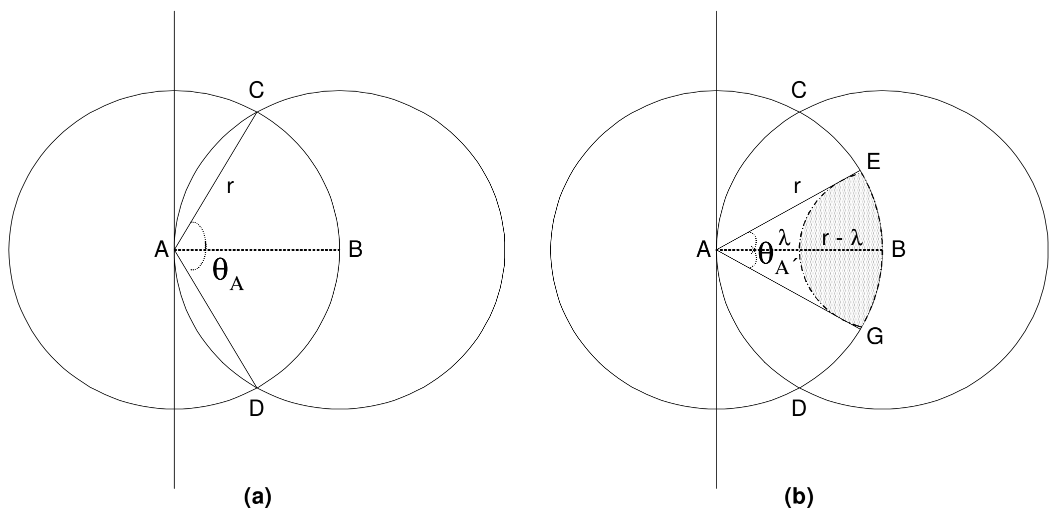


Figure 3.6: θ decreases as the threshold value increases.

The angle between the points *CAD* (θ_A) is 120 and the angle between the points *EAG* ($\theta_{A'}$) is smaller than 120 ($\theta_{A'} < \theta_A$). If λ is taken as $0<\lambda<r$, then θ and intersection area will decrease as the λ increases (Figure 3.6). This means that as λ increases, the number of possible relay nodes will decrease. On the other hand, as λ increases, the angle between the possible relay nodes in the intersection area and the transmitting node will decrease, making intersection points closer to the virtual line between *A*

and B. These results are used in the proposed algorithm, SWR. Let λ has a predetermined value at the beginning of the operation, and be adjustable during the communications, changing dynamically to current conditions. If the distance between A and B are larger than r, a packet transmitted by Node A may follow a path more than two hops to reach to B, depending on the distance between A and B.

3.3 Weight Function

Each node derives its weight value from its current location information and some other parameters (Equation 3.1, w_i defines the weight of node i). These parameters can belong to either the node itself or the network's current situation or the current mission or the goal of the network or a combination of these.

$$w_i = location_i + parameters_i + parameters_{network} \qquad \textbf{(3.1)}$$

Node's own parameters can be the remaining energy (battery power), the closeness to the destination, the density in the node's neighborhood (if available to the node), and the node's willingness to participate in the routing, e.g. it may not participate in the routing if the buffers are full. The network-oriented parameters can be the density of the network, the number of sink nodes (increase in the number sink nodes reduce the possible path-lengths). Other parameters can be related with the current mission, goal, or tasks, such as the silence commitment, the current situation e.g. tracking or attacking to an object. If none of these parameters is included into the weight function, the weight value becomes similar to the pure distance (Euclidian distance) to the sink node (Equation 3.2). Square root of the right hand side of the equation gives the Euclidian distance of the node to the sink node.

In the simplest form, the weight function takes the location information (e.g. geographical position, or relative position such as *(x, y)*) as input and produces the weight value. The weight function can be optimized by considering other parameters and to optimize the network parameters such as the network-lifetime, node lifetime, emergency conditions, silence, as described above. Therefore, while providing the routing, other parameters can be optimized. In the simplest form, the weight function becomes:

$$w_i(x_i, y_i) = x_i^2 + y_i^2 \quad \textbf{(3.2)}$$

The following diagrams identify the evaluation of the weight value. Nodes away from the sink node usually have greater weight values with respect to closer ones, as the sink has a weight value *0*. The weight diagram is shown in Figure 3.7, where only one sink is positioned in the center of the operation area. Therefore, the routing algorithm has a natural data flow toward the sink. Hence, the use of the weight metric makes the routing process simple and minimizes delay, energy consumption, and processing requirements at nodes in the routing decision phase.

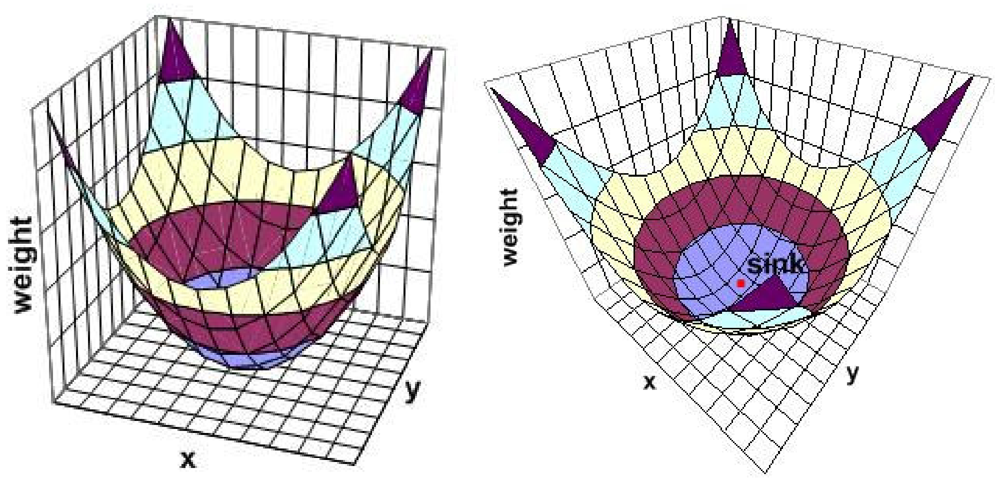


Figure 3.7: Weight metric provides a natural flow toward the sink.

The weight value of a node remains the same as there becomes no change in the parameters of Equation 3.1. Usage of a simpler weight function as in Equation 3.2 reduces the number of evaluations of weight due to reduced number of parameters that affect the weight value. Here, it should be noticed that the weight value mainly depends on the location. The location is a virtual location with respect to the sink node. Therefore, even if the geographical position of a node doesn't change, its virtual location may change depending on the change of the sink node's geographical position. Sink node always has the weight value *0* (zero) and is positioned on the virtual reference point *(0,0)*.

There are many advantages of using the weight metric instead of the location itself. These advantages are:

- The weight usage simplifies routing algorithm and the routing process at nodes.

- The weight usage reduces the number of calculations at nodes. The routing decision is made after only one comparison.
- The weight usage reduces the delay encountered both in the communications and in the routing process. In communications, it enables the nodes always forward the packets toward the destination without any prior negotiation between the nodes. The reduced calculations and the simplified algorithm decreases the delay encountered in the routing process.
- The weight usage reduces the resource requirements (such as processor and memory) at nodes (due to reduced calculations and table-free property).
- Weight usage avoids keeping identities of neighbors and avoids beaconing.
- The weight usage decreases energy consumption avoiding the beaconing and avoiding the negotiations before transmissions.
- Due to item above, weight usage avoids the communication overhead in frequently changing topology and provides support for mobile environment.
- The weight usage decreases energy consumption enabling the usage of a threshold value (the threshold value is described in Section 3.5).
- The weight usage reduces the energy consumption due to reduced calculations at nodes.
- The weight usage provides loop-free multi-hop communications.
- The weight usage indirectly aids to security due to beaconless approach.

Let us describe the case when the pure location information is used instead of the weight value. In fact, most of the geographical routing protocols use the pure location information. In greedy geographic protocols in the literature, nodes select the best neighbor node after receiving all the neighborhood location information. On a transmission need, Euclidian distance to each neighbor node is calculated first and the farthest one that makes more advance to the destination is selected as the best. Then, the packet is forwarded to the selected best node. Therefore, each transmitting node makes *n calculations* + *n comparisons* before the transmission *i* (Equation 3.3). Here, *n* stands for the number of neighbors.

$$Number\ of\ Calculations_i = \ \ n\ calculations + n\ comparisons \qquad \textbf{(3.3)}$$

Each calculation and comparison consumes energy and produces delay. Delay encountered for the calculations on a transmission process at each node in the decision phase is:

$$Delay_i = (n\ calculations + n\ comparisons)\ (delay_{calculation}) \qquad \textbf{(3.4)}$$

However, delay at nodes will be much more than this, because nodes will encounter delay for each massage during the receive process. Each node will check the address part whether the packet is addressed to itself or not. As the density of the network increase, the delay will increase. On the other hand, in the greedy routing algorithms in the literature, the best node selection may cause the *local-minima problem*. Secondly, due to the best node is the farthest node and the quality of the communication links decreases as the distance increases, the communication is executed on less reliable links.

However, in the SWR, a node calculates its own weight value, just one calculation, and only compares its weight value with the weight value in the received packet (Equation 3.5)

$$Number\ of\ Calculations_i = \quad calculation + \quad comparison \qquad \textbf{(3.5)}$$

If the transmitting node already knows its own weight value, that is the expected case, it makes just one comparison (Equation 3.6).

$$Number\ of\ Calculations_i = \quad comparison \qquad \textbf{(3.6)}$$

In SWR, nodes will make only *1 comparison* as given in Equation 3.6. The received packet will be transmitted as fast as possible by not encountering much delay and not consuming much energy. On the other hand, all the process is executed in network layer, without having the complexity as encountered in MAC-layer involved solutions. Making only comparisons rather than complex calculations at nodes minimizes the need of resources such as processor and memory. Therefore, cheaper and disposable nodes can be used.

3.4 Stateless Weight Routing Algorithm

After the definitions and methodologies given in Section 3.1 and Section 3.2, the routing algorithm is given in this subsection. The SWR is a stateless reactive routing protocol which utilizes the geographic location information for routing. The proposed approach is *stateless,* because no routing table is kept. Secondly, it is *reactive,* because no local topology information or table is kept at nodes. Nodes do not need to know the identities of their neighbors. Routes are constructed on-demand. Eliminating the need of the neighborhood information on route construction avoids the beacon messaging and advertising.

Only one table is kept which is analogous to all routing algorithms in the literature. It is used to check the duplicate packets whether a packet is already received or is already transmitted. It used to avoid unnecessary retransmissions. This table can be called as the *History Table*. The format of the table is as (Figure 3.8):

Source Node ID	Seq. No	QoS Parameters
2-4 Bytes	2 Bytes	1 Byte

Figure 3.8: Format of the History Table.

On packet receipt, a node checks its *History Table* whether it received that packet before or not. If it is not received before, it is recorded to table with the parameters given in Figure 3.8. These parameters are copied from the header part of the received packet. Definition and usage of these fields are given in Section 3.4.1. If the packet is received or transmitted before, it is discarded. However, a packet may be received or transmitted with different parameters. Therefore, the applied parameters should be recorded too (Figure 3.8).

3.4.1 Packet types

Source Node ID	Seq. No	Destination ID	Sender ID	Sender Weight	QoS Parameters	
2-4 Byte	2 Byte	2-4 Byte	2-4 Byte	2-4 Byte	1 Byte	

Figure 3.9: Simple packet header.

Nodes do not need to keep routing tables nor neighborhood tables. Routing is accomplished on demand on the transmission time of the data packets. The packet header shown in Figure 3.9 is used in SWR. The description of the fields is given in Appendix A. This packet header is used for all types of packets in the network layer.

QoS Parameters

Threshold	Priority	Silence	Packet Type
3 bits	2 bits	1 bit	2 bits

Figure 3.10: QoS fields of the packet header

In SWR, a couple of performance metrics are enhanced. To be able to achieve this, the *QoS Parameters* field is included into the packet header. In fact, the SWR protocol provides the minimum delay between the source and the sink node, and reduces the energy consumption considerably without integrating such a QoS field. However, some QoS parameter fields are added which affect the QoS metrics directly or indirectly. First, *Priority* field is added to provide priority for real-time traffic. The possible values and their meanings are given in Table 3.1. Usage of this field is described in Section 4.5.

Table 3.1: Values and corresponding meanings of the Priority field in the QoS Parameters field.

Value	In binary	Meaning
0	00	Forced Data
1	01	Urgent Data
2	10	*Reserved*
3	11	Normal

Secondly, for emergency conditions, it may be required to apply *silence* for security, energy saving, reconfiguration of the network, or other possible on demand needs. Therefore, a *silence* field is added. Silence field takes either *0* or *1* value. The usage of this field is described in Section 4.5.

Thirdly, it may be required to limit the number of data traversing nodes according to the current status of the network or according to the current mission or goal. Therefore, a *threshold* field is added. The possible values and their meanings are given in Table 3.2. Usage of this field is described in Section 3.5. Usage of a threshold value provides a couple of advantages besides the advantage given above. It is used to reduce energy consumption by regulating the number of transmitting nodes, is used to increase or decrease the number of possible multiple paths, is used to recover from voids. Usage methods in void recovery are described in Section 4.2. The extension of the *QoS Parameters* field is given Figure 3.10. The *Packet Type* field is not a QoS parameter, but it is put into the *QoS Parameter* field to utilize unused bits in this field. The possible values and their meanings are given in Table 3.3. Usage of this field is described in Section 4.7. A complete documentation is given in Appendix B.

Table 3.2: Values and corresponding meanings of the Threshold field in the QoS Parameters field.

Value	In binary	Meaning
0	000	Threshold set value is 0%
1	001	Threshold set value is 10%
2	010	Threshold set value is 25%
3	011	Threshold set value is 40%
4	100	Threshold set value is 50%
5	101	Threshold set value is 60%
6	110	Threshold set value is 75%
7	111	Threshold set value is 90%

Table 3.3: Values and corresponding meanings of the Packet Type field in the QoS Parameters field.

Value	In binary	Meaning	Abbreviation
0	00	Data packet	DATA
1	01	Acknowledgement	ACK
2	10	Interest Packet	INT
3	11	Position Packet	POS

3.4.2 Data packet transmissions

If a node has a data to send to the sink, it inserts its identification number, current packet sequence number, and the intended destination's identification number into the appropriate fields. Also, it inserts its identification number and the current weight value into the Sender ID and Sender Weight fields, respectively. A node's weight value remains the same as there becomes no change on the position of itself or on the position of the sink. If there is a change in its relative position, it should recalculate the weight value prior to insert the weight value. In QoS Parameters field, *Threshold* field is set to *system-wide default value* which is actually *50%*, but can be changed according to the network dynamics. *Priority* field is set to *Normal*, and the *Silence* field is set to *Normal (0)*. The *Packet Type* field is set to *DATA*. Then the node broadcasts the packet. Actually, the packet is passed to the MAC layer to be sent to the addressed nodes. Above values used in QoS field are according to the normal conditions. For other conditions, e.g. on emergency conditions, appropriate values should be used.

3.4.3 The routing algorithm

The packets are routed according to the information inserted into the packets. The routing algorithm does not use any topological information or routing table. The simplified data flow algorithm is given in Algorithm 3.1. The given algorithm is for the simple case. The complete routing is given in Section 4.8. As shown in Algorithm 3.1, function *Diff(x,y)* returns the weight difference between Node *x* and Node *y*.

Algorithm 3.1 Simplified Data Flow Algorithm

$Diff(x,y) = w_x - w_y$

if $((w_{sender} > w_i > w_{destination})$ **and** $(Diff(sender,i) >= threshold)$ **then**
    rebroadcast;

When node *i* receives a packet, it compares its weight value (w_i) with the weight values in the packet. If its weight value is between the transmitting node's weight value (w_{sender}) and the destination's weight value ($w_{destination}$, here the destination is sink and the sink's weight value is *0*), it rebroadcasts the packet, or drops the packet otherwise. All nodes receiving the data packet executes this simplified algorithm, producing a number of rebroadcasts. The number of rebroadcasting nodes is determined or limited by the threshold value. Usage of the threshold value is given in the following subsection.

GPSR and most of the other geographic protocols selects the farthest node as the best next node because this node makes more advance towards the destination. However, selecting the farthest node causes the transmissions to be made on less reliable links. On the other hand, selection of a very close node to the forwarding node makes no progression towards the destination. Small advances on each hop increases path length and transmissions. Therefore, nodes those make at least λ progression to the destination should be selected as the next node (Figure 3.6). On the other hand, in SWR, the energy levels of the nodes are considered on construction of the routes. On the decision phase, if the node has very low energy, it does not execute Algorithm 3.1. Nodes those are about to deplete their energies do not involve in the routing process, constructing more stable routes.

3.5 Threshold Usage

In order to reduce the number of rebroadcasting nodes, a threshold value is used which is also transmitted within the packet. Only the nodes whose weight difference is greater than the threshold value are allowed to rebroadcast the packet. In other words, such an approach prevents the nodes closer to last transmitting node to rebroadcast. Although the weight metric includes Euclidean distance, the flexibility of the algorithm comes from the other additional values.

The threshold is a value in terms of weight. When a node receives a packet, it calculates the applied threshold value using the *Threshold* field in the *QoS Parameters* field of the received packet. It multiplies the corresponding value of the *Threshold* field value with a constant value which is known by all nodes. This value can be called as *Threshold Constant*. The *Threshold Constant* is calculated once at the beginning of the operation. To avoid the calculation of the *Threshold Constant* at nodes, some other approach can be employed. The sink node may broadcast it to all nodes one at the beginning or all nodes may be loaded with this constant value in the deployment phase. The *Threshold Constant* can be find as:

$$\textit{Threshold Constant} = x^2 + y^2 \qquad \textbf{(3.7)}$$

$$\textit{Threshold Constant} = r^2 \qquad \textbf{(3.8)}$$

where x and y are the points of maximum transmission range in the x-y coordinate system and r is the transmission range known by all nodes. The applied threshold value is the multiplication of *Threshold Constant* and the corresponding value of the *Threshold* field in the *QoS Parameters* field.

Actually, to avoid the calculations at nodes to obtain the threshold value, the applied threshold value can be inserted into the packet by the sender rather than inserting the percentage value. This approach is more practical than the approach described above. The latter one avoids the calculations at nodes. However, putting the threshold value itself into the packet header requires 2 or 4 bytes. It is a tradeoff whether to reduce the packet header or reduce the calculations at nodes. In experiments, the latter one is employed, because it is simpler than the previous one.

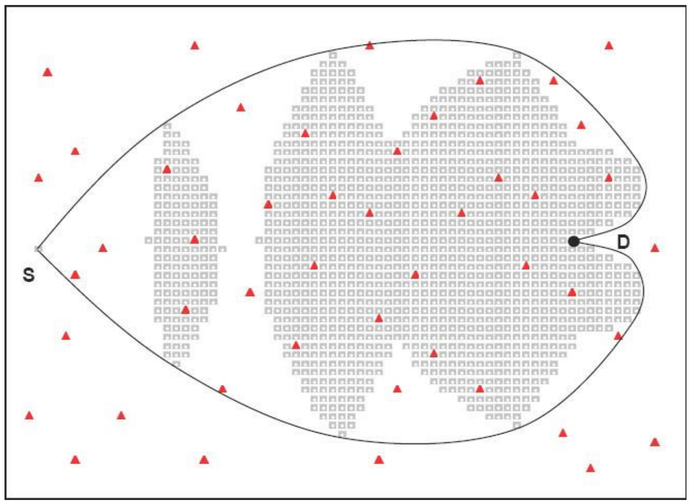


Figure 3.11: Active retransmission area and nodes for a lower threshold value (60%).

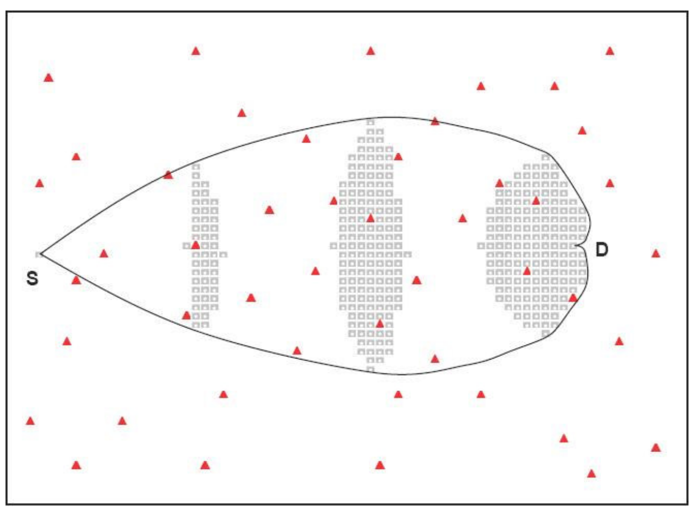


Figure 3.12: Active retransmission area and nodes for a high threshold value (85%) with respect to the one in Figure 3.11.

Threshold is used for several purposes. First of all, the threshold value can be adjusted to save energy by limiting the number of retransmitting nodes since the number of nodes actively contributing to retransmission varies as depicted in Figure 3.11 and Figure 3.12. Figure 3.11 and Figure 3.12 show the covered area after multiple successive transmissions between the source node *S* and the destination node *D*. Egg-like shape represents the borders of the possible coverage area and shaded areas show the covered areas when Algorithm 3.1 is applied with different applied parameters. Only the nodes in these shaded areas can relay the received packets according to Algorithm 3.1. Increasing the threshold value provides fewer nodes in number to relay the data packets and decreasing the threshold value provides more nodes in number to relay the data packets (Figure 3.11).

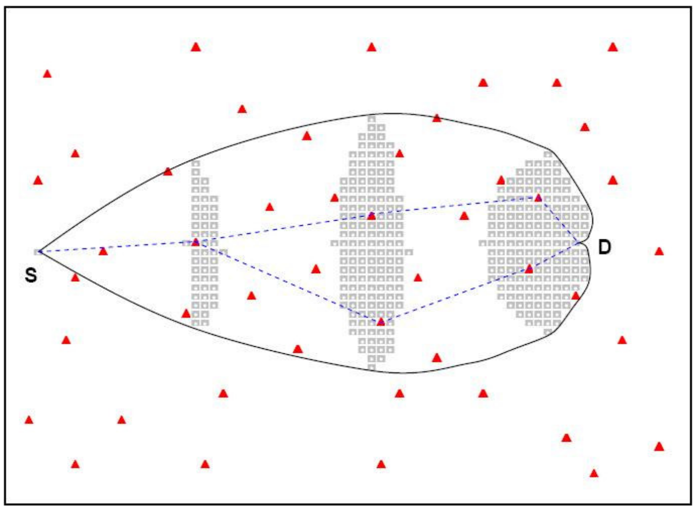


Figure 3.13: Threshold value affects the number of possible paths (threshold is 85%).

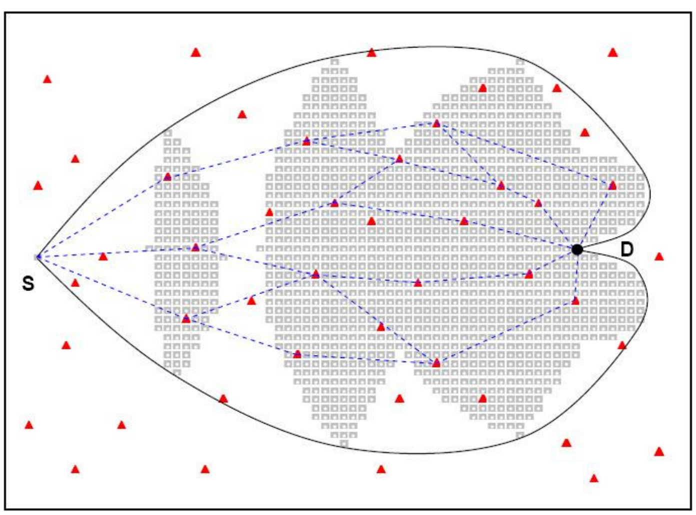


Figure 3.14: Data is carried on multiple paths to the destination (threshold is 60%).

Secondly, the threshold value can be adjusted for reliability (Figure 3.13-3.14). More relaying nodes in number cause the data to flow over multiple paths (Figure 3.14). Data transportation over multiple paths provides reliability. Reliability requirements challenges with the energy saving requirements. Therefore, threshold value can be used to balance these requirements as needed.

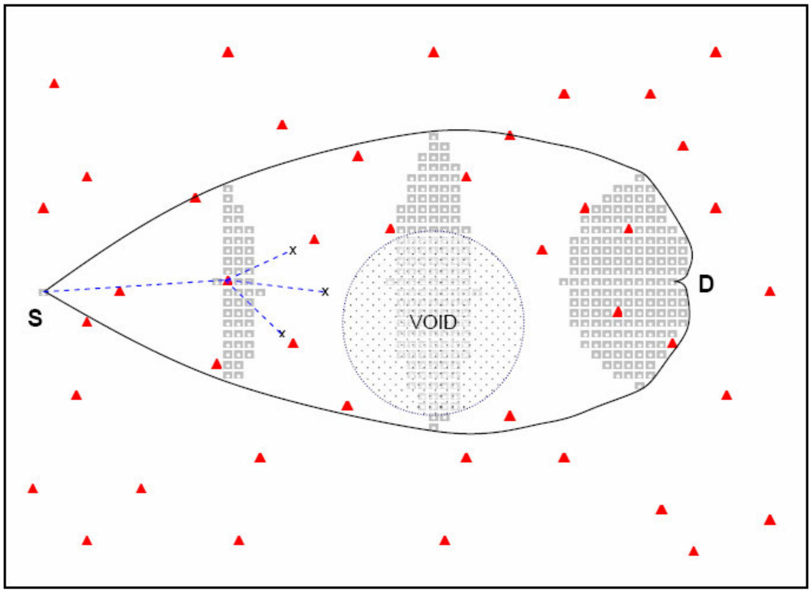


Figure 3.15: Multiple paths help the packets arrive to the destination even if there are voids. But in case of no available path, void avoidance approach should be used (threshold is 85%).

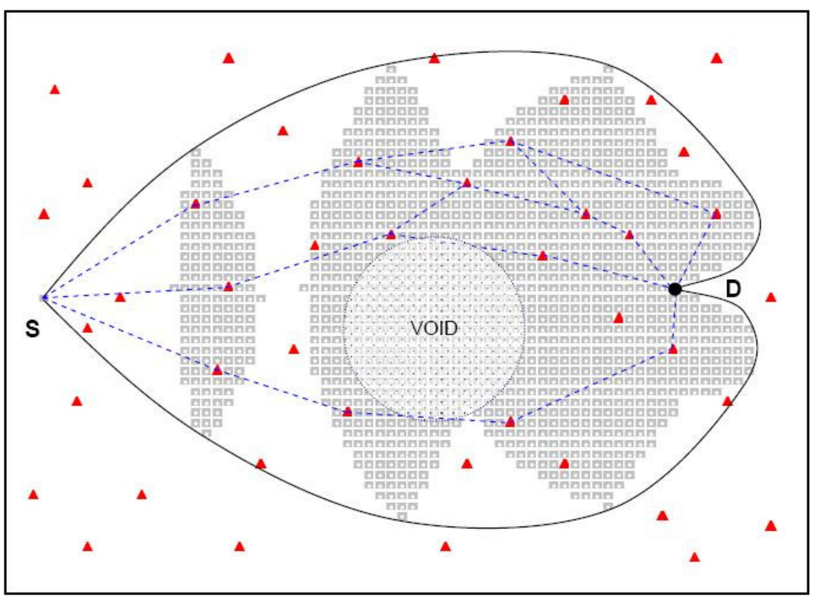


Figure 3.16: A simple approach to eliminate voids, is decreasing the threshold value. By the way, more nodes involve in routing (threshold is 60%).

Thirdly, the threshold value can be adjusted for void avoidance (Figure 3.15-3.16). In case of void detection, the transmitting node decreases the threshold value allowing more nodes to be in data flow algorithm (Figure 3.16). By this way, nodes that may circumvent the void are forced to relay the data packets.

Fourthly, the threshold value should be adjusted according to the node density in the network. In dense networks, the threshold value can be set to be high by default to limit the retransmitting nodes. In non-dense networks, the threshold value can be set to be low to allow enough nodes to participate in data flow.

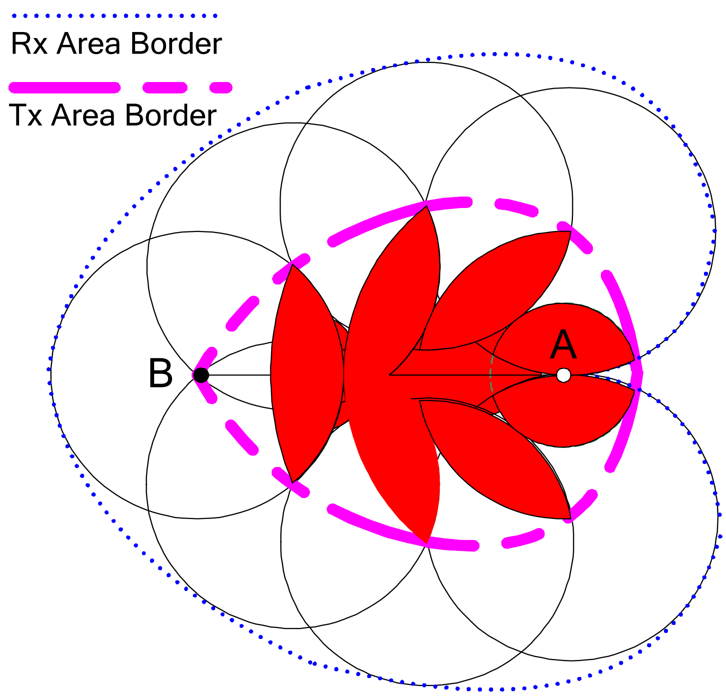


Figure 3.17: Possible transmission and receive areas between the source node B and destination node A.

The multi-paths constructed by Algorithm 3.1 cover the shaded area sampled in Figure 3.17. Possible rebroadcasting nodes remain in the symmetric pedal curve shaped transmission area as shown in Figure 3.15 and Figure 3.16. Such an area between the source and the destination is constructed but when the distance between the source and the sink is far enough. Maximum number of transmissions will be close to the number of nodes in this area, since nodes can transmit only once. If the nodes are uniformly distributed in the operation area, a close approximation of the number of possible transmitting nodes can be found by calculating the shaded area remaining in egg-shape. Calculation of this area is given in Section 4.1.3. Ratio of this area to total operation area gives the ratio of the nodes in this area to total nodes. However, in real condition, number of transmitting nodes will be smaller than this value, due to propagation and transmission delays. Instead of this approach, if the periodic-beaconing scheme were used, all the operation area would be covered at every beaconing time.

3.6 Multiple-Paths

Number of rebroadcasting nodes can be determined by adjusting the threshold value as required. If there were one or more rebroadcasting nodes, the destination can receive multiple copies of the same packet. A source-generated packet may follow different routes on the way to the destination. The number of the paths and the number of the copies at the destination node depend on the number of the rebroadcasting nodes determined by the threshold value. SWR uses Algorithm 3.1 to make the broadcast decision. Constructed multiple paths are disjoint braided paths which are shorter and more robust than other possible paths between the source and the destination. Using multiple paths provides robustness and reduces the bad effects of mobility, link failures, node terminations, node state transitions and works at uncertainty.

3.7 Improvements on Performance Metrics and Parameters

There are many routing protocols in the literature proposed to enhance some performance metrics or parameters. They can be considered as successful if they are evaluated with given objectives. However, when the conditions change, most of these protocols become inefficient and unreliable, failing to be successful. Therefore, dynamic and multi-objective approaches are needed to satisfy all conditions. The approach proposed in this thesis is a multi-objective and dynamic one which can be used in every environment. On the other hand, the proposed approach, SWR, does not require any adaptation to the current environment. Some approaches used in and beneficial of SWR are summarized in Table 3.4;

Table 3.4: Enhancement methods proposed in SWR.

Enhancements	Used Method / Approach
Reduction on Energy Consumption	▪ reducing the number of transmissions ▪ reducing the number of calculations drastically ▪ concerning the energy consumption in calculations
Reliability	▪ using multiple paths ▪ recovering from voids ▪ guaranteeing the delivery ▪ providing multicasting in case of multiple-sink usage
Real-Time Support	▪ minimizing the end-to-end delay ▪ providing priority usage. ▪ using multi-paths ▪ providing multicasting in case of multiple-sink usage
Recovery From Voids	▪ implicitly by multiple paths and threshold usage ▪ explicitly by void recovery algorithm
Easy Implementation	▪ simplifying the routing algorithm ▪ reducing the calculations at nodes ▪ by distributed algorithm without any coordination ▪ by reactive stateless approach
Prolonging the Network Lifetime	▪ reducing the transmissions ▪ eliminating topology learning overhead
Low Resource Requirements (CPU, Memory, etc.)	▪ simplifying the routing algorithm ▪ reducing the calculations at nodes
Large-scale Network Implementation	▪ using multiple sinks without any modification in the routing algorithm
Mobility Support	▪ naturally with routing algorithm and weight usage
MAC-Layer Independence	▪ independent from the MAC-layer used. ▪ no dependency to the IEEE 802.11

4. ENHANCED PERFORMANCE METRICS AND SOLUTIONS TO KNOWN PROBLEMS

The proposed routing algorithm, SWR, is very simple to implement. On the other hand, a number of performance metrics are enhanced and solutions are proposed to some known problems existing in wireless ad hoc and sensor networks. In this section, the methods and algorithms used in SWR are described and their effects on the performance metrics are given.

4.1 Energy

Energy becomes the most valuable resource in wireless sensor networks, as the sensor nodes become disposable and become smaller tiny objects. Energy related studies are carried on multiple branches. There are studies to enhance the battery power while minimizing the size of the battery. However, in communications, studies are related with the reduction of the consumed energy by enhancing the existing protocols or by designing new energy-aware protocols. Studies cover the layers from the physical layer to transport layer. A great amount of energy can be saved by a carefully designed network layer and *MAC*-layer protocols. However, some studies in this object, proposes cross-layer solutions, which interact between the *MAC*-layer and the network layer. This approach avoids the modularity in the communications protocol stack. On the other hand, all these proposed solutions use the *IEEE 802.11* protocol as *MAC*-layer coordination function. *IEEE 802.11* is a poor protocol in the consideration of energy efficiency. Dependency to the *IEEE 802.11* protocol and energy inefficiency of it, make these proposed protocols energy inefficient or to remain valuable for a short time-scale.

Other energy-efficient protocols generally attempt to reduce energy consumption either at network layer or at MAC layer. At MAC layer, protocols are proposed to reduce the energy consumption in the coordination phase of transmissions to access the transmission media. In the network layer, problem is more sophisticated. To route the data to a destination, routing function may require topology information and some kind of network parameters. Provision of such information and routing function itself introduces extra overhead. Therefore, design of routing protocols which are energy efficient and reducing the overhead are required. On the other hand, such protocols should provide some *Quality of Service (QoS*) parameters such as delay, real-time support, reliability, guaranteed delivery, lifetime of the network, scalability. However, proposed protocols handle only one or a few of these objectives. On the other hand, performance of the proposed protocols in the literature is worse in mobile environments while some are just for immobile environments. They can also be affected from the network's unstable conditions such node terminations, link failures, nodes' sleep schedules, and coverage area problems.

The energy-efficient algorithms can be classified according to the methods used to decrease the energy consumption. A well known method is to use *multi-hop* communication instead of *single-hop* communication. Due to the attenuation characteristics of the wireless channels, multi-hop communication provides a significant energy saving over a single-hop communication for the same distance. Attenuation causes *loss* during the propagation. The *loss* can be given as:

$$Loss = 10\log\left(\frac{4\pi d}{\lambda}\right)^{\alpha} dB \qquad \textbf{(4.1)}$$

where d is the distance, λ is the wavelength, and α is the path loss exponent (Equation 4.1). In wireless applications, it is assumed that α value changes between 2 and 4, according to the environment, antenna length, obstacles in the environment, and other energy sources in the environment. Loss changes with respect to the power α of distance. As the distance increases, the loss increases with the power α of distance. Multi-hop usage decreases the energy consumption due to path loss formula given above.

One approach that uses multi-hop communication is finding the shortest paths to the sink from each node. To do so, the *minimum energy tree (MET)* of the network graph is found, and the nodes use the shortest paths provisioned before. However, there are many drawbacks of these approaches. First, finding the MET consumes excessive energy. On the other hand when a node on the tree toward the root (here the root is the sink) terminates, all the leaf nodes or child nodes on that tree loose their paths toward the sink. De facto is that nodes closer to the sink exhaust their energy earlier than the distant nodes. On the other hand, sensor nodes are very prone to failures. Therefore, keeping a MET is not applicable in sensor networks. In a frequently changing topology, it is impractical to use such a technique.

Finding the shortest path on-demand which is very similar to MET approach is another approach and considers the transmission ranges and tries to find the shortest path toward the destination. As defined above, multi-hop communication reduces the energy consumption. In a network in which the nodes have a fixed transmission range, reducing the transmission to the minimum reduces the energy consumption. Actually, in MET approach, the tree is found to do so. Finding the shortest path with the current information at nodes is more flexible than MET approach, but there are some drawbacks. Provision of the topology information introduces communication overhead. Finding the shortest path may cause local-minima problem. Finding the shortest path objective challenges the objective of prolonging the network lifetime. Involvement of low-battery nodes will cause them to deplete their batteries, leaving holes in their locations. Another drawback is that in shortest path objective, the far-end nodes may be selected to relay the messages. However, the quality of the transmission links decrease as the distance increases. There are impairments that affect the communication. Selecting the farthest nodes may cause link breakages.

An admirable solution is to use adaptive antennas. The transmitting node adjusts the power of transmitter according to the distance of the receiver node, if the distance is known. An appropriate routing algorithm can be used with this approach. Therefore, excessive energy consumption is reduced for short distances transmissions. However, distances to the neighbors should be known and the nodes should have neighborhood information.

Another approach is clustering. In this approach, in addition to use of identical sensor nodes, more functional and powerful nodes are used. Sensor nodes closer to these more powerful nodes are organized to form a cluster or a group. Sensor nodes communicate via these more powerful nodes. These more powerful nodes are used to relay the messages between the source and the destination nodes. Therefore, possible path lengths over the existing topology are shortened to a lesser one. In these approaches, cluster-head selection introduces overhead. However, the partitioning the topology by these cluster-heads provides scalability in large scale networks.

There are some other approaches to minimize the energy consumption or to prolong the network lifetime. *Agent-based* approaches, *statistical relaying node selection* approaches, *randomly relaying node selection* approaches are some of these approaches.

4.1.1 Energy model

There are, however, too many approaches to minimize the energy consumption in routing algorithms; most of these approaches consider only the energy consumption in transmissions process. Energy consumptions on receptions, calculations and sensing are not involved or modeled in the simulation environment. Regretting these energy consumptions, especially energy consumption in receive process, outcomes unrealistic performance results.

In most of the existing geographical routing protocols, used energy models are not defined. Besides that, [25, 26] explicitly dictate that they are only concerned with the energy consumption in the transmissions. Related studies in energy consumption [33] emphasizes that *receive process consumes as much power as the transmission process*. Neglecting the energy consumption in receive process, causes to retrieve *unrealistic* and *untreatable* simulation results. Therefore, this study considers the energy consumption in receive process for realistic results.

Depending on the performed operation, a node consumes one or more of; *sensing energy*, *transmitting energy*, *receive energy*, and *computation energy* [34]. During the life of a node, it monitors the environment or performs the expected behavior, performs calculations, derives results, transmits the results as data packets to other nodes, and receives the packets transmitted by other nodes. Then the total energy, E_{total}, consumed by a node at an arbitrary time is the sum of these energy requirements [34]. However, many of the existing protocols only concerned with the transmission energy. All these energy consumptions are concerned due to energy savings in the proposed approach, SWR. The *energy model* defined in [34] is used in this thesis.

$$E_{Total} = E_{transmit} + E_{receive} + E_{computation} + E_{sensing} \tag{4.2}$$

It is also defined in [34] that efficient sensing circuitries and computation algorithms reduce $E_{sensing}$ and $E_{computation}$ substantially. Therefore, they are considered as constant values in [34]. However, SWR makes a non-negligible energy saving at calculations at nodes. Therefore, the energy consumption at calculations are also considered in SWR

4.1.2 Energy savings

In this subsection, the energy consumptions of a node and the system during a transmission process are investigated. On a transmission, transmitting node consumes the energy, $E_{transmit}$, and a receiving node consumes the energy, $E_{receive}$. If the transmitting node has n amount of neighbors, the overall system consumes the energy, E_{system}, for one transmission;

$$E_{system} = (n.E_{receive}) + (1.E_{transmit}) \qquad \textbf{(4.3)}$$

If it is assumed that $E_{transmit} = E_{receive}$, the overall system consumes $n+1$ times greater energy than the transmitter at a transmission. Neglecting such an amount of energy consumption causes unreliable system performance results. According to Equation 4.3, *beacon-based geographical routing protocols* consume most of their energies in the beaconing processes. Nevertheless, protocols in the literature do not consider the energy in the receive process, failing to be unrealistic.

On the other hand, beacon-based protocols make a great amount of computation to update their tables. Every node in the network periodically broadcast beacon packets. Neighbor nodes receive these beacon packets and update their tables with the location information in the received packet. On a packet to transmit, a node calculates the Euclidian distances to each of its neighbors and selects the best one, and sends the packet addressed to it. If there is n number of neighbors, this process requires n times Euclidian distance calculation and n times comparison. Therefore, the total energy consumed in decision phase, $E_{computation}$, will be as shown in Equation 4.4. If it is assumed that $E_{calculation} = \beta.E_{comparison}$, where β is a constant defining the energy consumption relationship and is equal or greater than one ($\beta \geq 1$), these values can be summed as in Equation 4.5. Equation 4.4 will change with the addition of these new energy consumptions during the decision phase (Equation 4.5-4.6).

$$E_{computation} = (n.E_{calculation}) + (n.E_{comparison}) \quad \textbf{(4.4)}$$

$$E_{computation} = (\beta.n.E_{comparison})(n.E_{comparison}) \quad \textbf{(4.5)}$$

$$E_{computation} = (n.E_{comparison})(\beta + 1) \quad \textbf{(4.6)}$$

Since ($\beta \geq 1$), ($\beta + 1$) can be adjusted as (β), where ($\beta > 1$). Then, the Equation 4.6 becomes;

$$E_{computation} = n.\beta.E_{comparison} \quad \textbf{(4.7)}$$

$$E_{system} = (n.E_{receive}) + E_{computation} + (1.E_{transmit}) \quad \textbf{(4.8)}$$

$$E_{system} = (n.E_{receive}) + (n.\beta.E_{comparison}) + (1.E_{transmit}) \quad \textbf{(4.9)}$$

There is a great amount of energy saving both on transmission and in calculations at node. The energy saving can be explained as below:

The energy model, used in this thesis, is rewritten (Equation 4.2);

$$E_{\text{total}} = E_{\text{transmit}} + E_{receive} + E_{computation} + E_{sensing}$$

The energy consumption in a system, during a simulation time, t_{sim};

$$E_{SIMULATION}(t_{sim}) = E_{beaconing} + E_{events} \quad \textbf{(4.10)}$$

Note that $E_{beaconing}$ is only consumed in beaconing protocols.

4.1.2.1 Energy consumption in beaconing protocols

Energy consumption on a single transmission is;

$$E_{system} = (n.E_{receive}) + E_{computation} + (1.E_{transmit}) \quad \textbf{(4.11)}$$

The receiving nodes make calculations, and the system consumes $E_{computation}$;

$$E_{computation} = (n.E_{calculation}) + (n.E_{comparison}) \quad \textbf{(4.12)}$$

If the sensing energy in Equation 4.2 is neglected, then, E_{system}, for one beaconing;

$$E_{system} = (n.E_{receive}) + (1.E_{transmit}) + (n.E_{calculation}) + (n.E_{comparison}) \quad \textbf{(4.13)}$$

During the simulation time, t_{sim}, and beaconing period t_{per}, and with $\boldsymbol{N}$ nodes in the network, total energy consumption for beaconing is;

$$E_{beaconing} = \left(\frac{t_{sim}}{t_{per}}\right).N.E_{system} \quad \textbf{(4.14)}$$

On data packet transmissions, the system consumes, E_{DATA} (for one data packet transmission);

$$E_{DATA} = \{(n.E_{receive}) + (1.E_{transmit}) + (n.E_{calculation}) + (n.E_{comparison})\}.hop\_count \quad \textbf{(4.15)}$$

Then, the Equation 4.10 becomes;

$$E_{SIMULATION}(t_{sim}) = \left[\left(\frac{t_{sim}}{t_{per}}\right).N.E_{system}\right] + [(\#of\_data\_packets).E_{DATA}] \quad \textbf{(4.16)}$$

According to Equation 4.10, and Equation 4.13-4.16, $E_{SIMULATION}$ becomes;

$$\begin{aligned} E_{SIMULATION} = & \left[\left(\frac{t_{sim}}{t_{per}}\right).N.\{(n.E_{rx}) + (1.E_{tx}) + (n.E_{calculation}) + (n.E_{comparison})\}\right] + \\ & \left[\begin{aligned} & (\#of\_data\_packets).(hop\_count). \\ & \{(n.E_{rx}) + (1.E_{tx}) + (n.E_{calculation}) + (n.E_{comparison})\}\end{aligned}\right] \end{aligned} \quad \textbf{(4.17)}$$

The equation above can be simplified as;

$$E_{SIMULATION} = \left\{ \left[\left(\frac{t_{sim}}{t_{per}} \right) .N. \right] + \left[(\# of\_data\_packets).(hop\_count) \right] \right\}$$
$$\left\{ (n.E_{rx}) + (1.E_{tx}) + (n.E_{calculation}) + (n.E_{comparison}) \right\} \quad \textbf{(4.18)}$$

4.1.2.2 Energy consumption in SWR

SWR protocol consumes energy only on data transmissions (no beaconing energy consumption). Therefore, the energy consumption will be a result of transmissions on data forwarding. The applied algorithm (Algorithm 3.1) causes multiple nodes to retransmit the received packet. When the algorithm is applied, a region similar to Figure 3.17 is covered by the transmitting nodes. In other words, the nodes which remain in the shaded area retransmit the received packet for only once. The figure is not a real situation but illustrated to emphasize the multiple retransmissions. The real situations are shown in Section 3.5.

Thus, the energy consumed in data transmissions for SWR can be found by, E_{DATA} (for one data transmission);

$$\begin{aligned} E_{DATA} = & \left[(less\ than\ the\ number\ of\ nodes\ in\ shaded\ area).E_{transmit} \right] + \\ & \left[(less\ than\ the\ number\ of\ nodes\ in\ shaded\ area).n.E_{receive} \right] + \\ & \left[(less\ than\ the\ number\ of\ nodes\ in\ shaded\ area).n.E_{comparison} \right] \end{aligned} \quad \textbf{(4.19)}$$

For SWR, Equation 4.10 becomes;

$$E_{SIMULATION} = \left[(\#\ of\ data\ packets).E_{DATA} \right] \quad \textbf{(4.20)}$$

For SWR protocols, energy *is not consumed* for beaconing and energy *is not consumed* for calculations. Therefore, Equation 4.20 becomes;

$$\begin{aligned} E_{SIMULATION} = & (\#\ of\ data\ packets).(less\ than\ \#\ of\ nodes\ in\ shaded\ area). \\ & \left[E_{transmit} + n.E_{receive} + n.E_{comparison} \right] \end{aligned} \quad \textbf{(4.21)}$$

The number of nodes in the shaded area can be calculated as in the following part. However, the transmissions will be less than the nodes in this area.

4.1.3 Possible transmissions area

In this section, formulation is given to obtain the number of nodes residing in the possible transmission area in data forwarding scheme used in SWR protocol. Figure 4.1 is used to describe the formulation. The shaded area in Figure 3.17 remains between the two *symmetric pedal curves*. This area can be found by equally dividing it and calculating each area. The area can be divided as *two symmetric shapes* with a line crossing the source and the destination node. Then, the shaded area is the sum of these two symmetric areas.

$$Shaded\_Area = 2xSymmetric\_Area \quad \textbf{(4.22)}$$

Calculation of the symmetric area is a little complex. Therefore, Figure 4.1 – Figure 4.4 are given to find the formulation of this area.

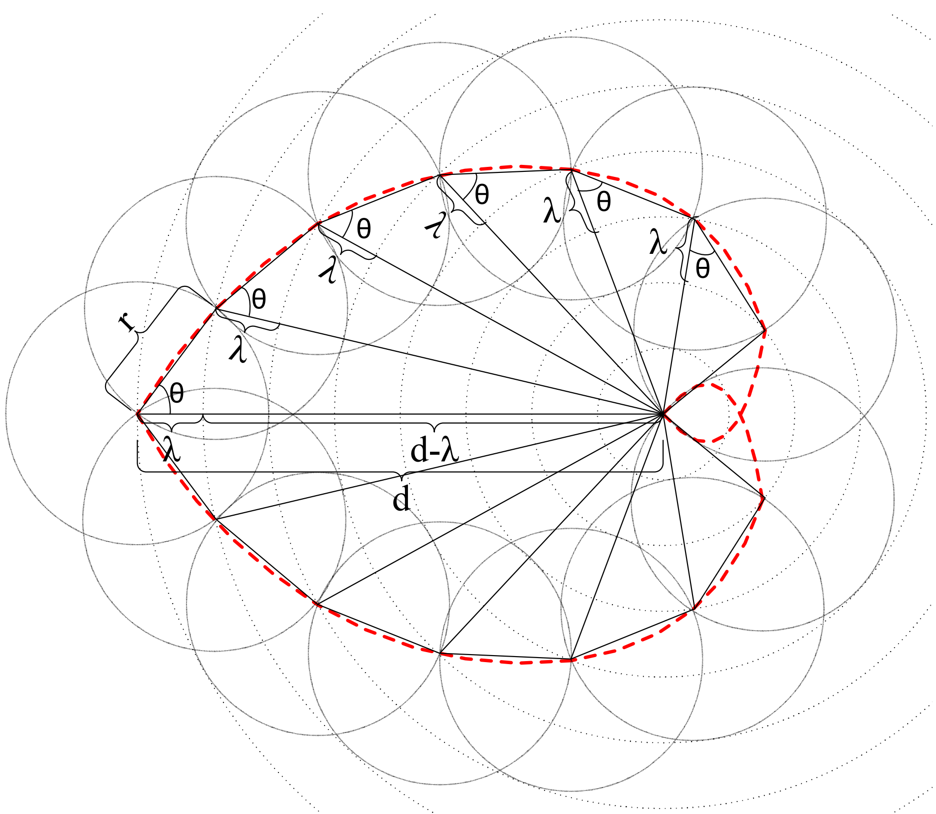


Figure 4.1: Possible transmission area calculation for SWR.

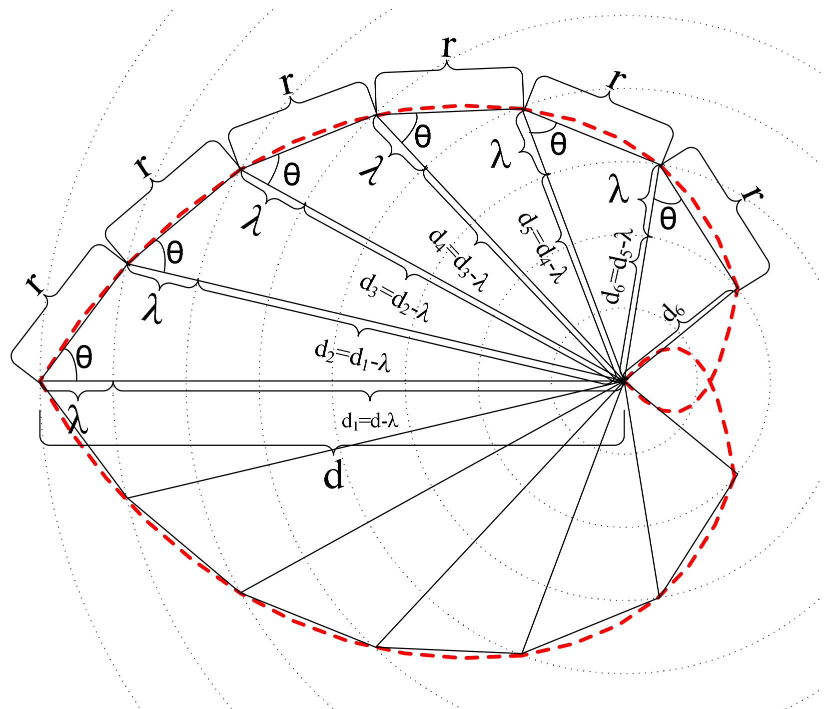


Figure 4.2: Possible transmission area calculation for SWR. Transmission range ring is removed from Figure 4.1.

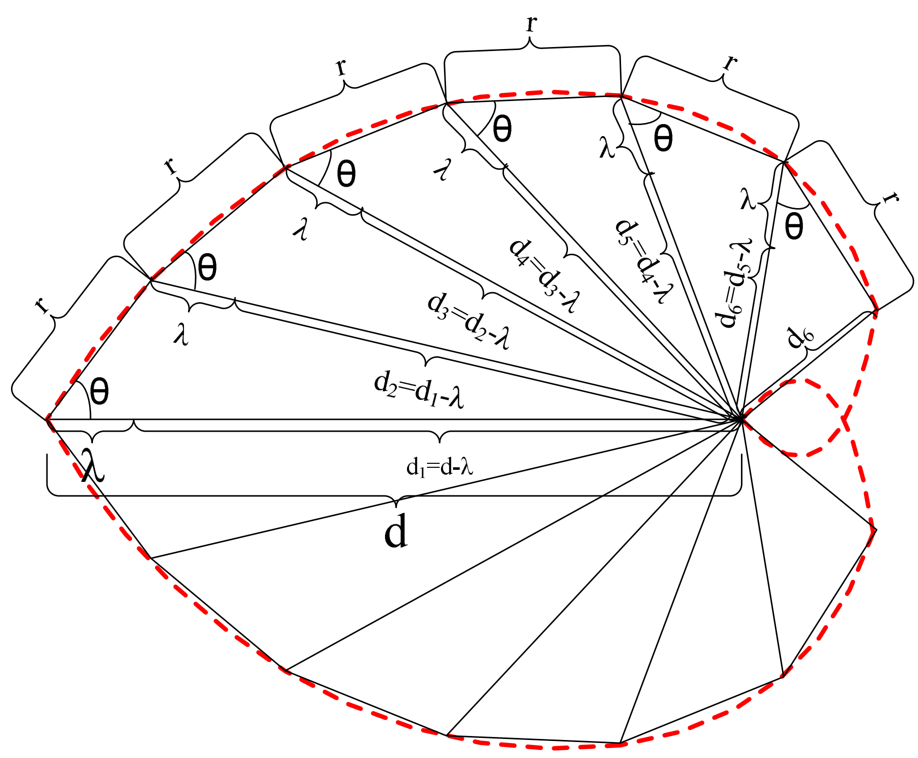


Figure 4.3: Possible transmission area calculation for SWR

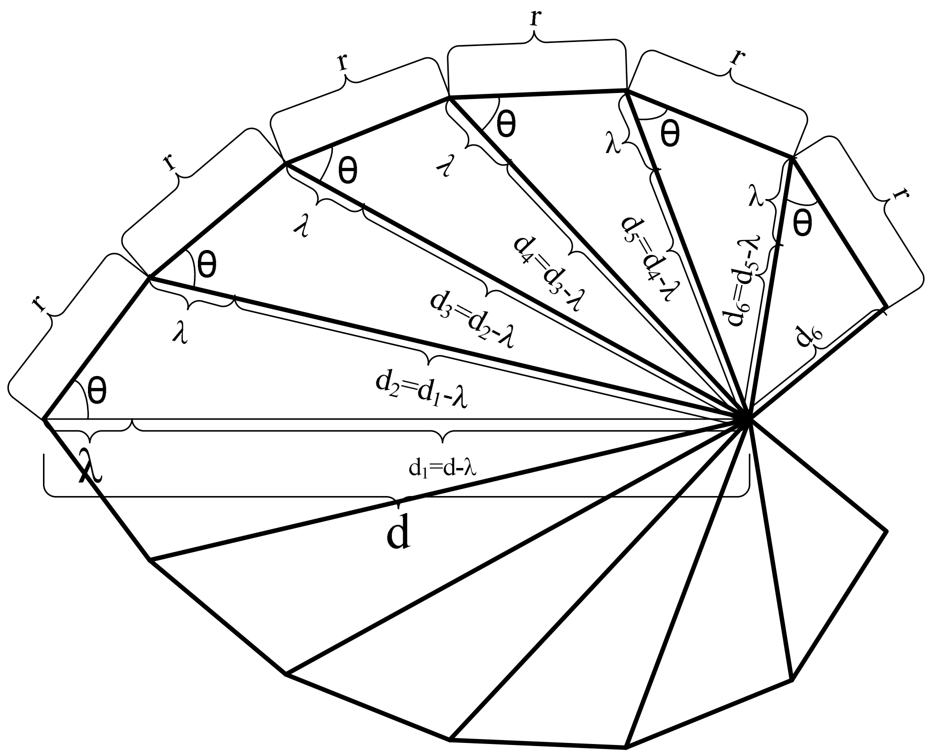


Figure 4.4: Possible transmission area calculation for SWR. Only the necessary information for calculation is kept with respect to Figure 4.1.

Then, the symmetric area can be found by summation of a series of decreasing triangle areas. The number of the triangles is determined by $\lceil {}^{d-r}/_{\lambda} \rceil$, where d is the distance between the source and the destination, r is the transmission range and λ is the applied threshold value.

$$Symmetric\_Area < \sum_{i=1}^{\lceil {}^{d-r}/_{\lambda} \rceil} Area_i \tag{4.23}$$

The *area of a triangle* can be found by [35]:

$$Area\_of\_a\_triangle = \frac{1}{4}\sqrt{(a+b+c)(b+c-a)(c+a-b)(a+b-c)} \tag{4.24}$$

In Formula 4.24, $a = r$, $b = d_i$, $c = d_{i+1}$, and $d_{i+1} = d_i - \lambda$. Then, the area of a triangle in step i is;

$$Area_i = \frac{1}{4}\sqrt{(r + d_i + d_{i+1})(d_i + d_{i+1} - r)(d_{i+1} + r - d_i)(r + d_i - d_{i+1})} \qquad \textbf{(4.25)}$$

Then the symmetric area can be found as;

$$Symmetric\_Area = \sum_{i=1}^{\lceil (d-r)/\lambda \rceil} \frac{1}{4}\sqrt{(r + d_i + d_{i+1})(d_i + d_{i+1} - r)(d_{i+1} + r - d_i)(r + d_i - d_{i+1})} \qquad \textbf{(4.26)}$$

And the shaded area can be found as;

$$Shaded\_Area = \frac{1}{2}\sum_{i=1}^{\lceil (d-r)/\lambda \rceil} \sqrt{(r + d_i + d_{i+1})(d_i + d_{i+1} - r)(d_{i+1} + r - d_i)(r + d_i - d_{i+1})} \qquad \textbf{(4.27)}$$

Equation 4.27 is simplified as;

$$Shaded\_Area = \frac{1}{2}\sum_{i=1}^{\lceil (d-r)/\lambda \rceil} \sqrt{(r + 2d_i - \lambda)(2d_i - \lambda - r)(r - \lambda)(r + \lambda)} \qquad \textbf{(4.28)}$$

$$Shaded\_Area = \frac{1}{2}\sum_{i=1}^{\lceil (d-r)/\lambda \rceil} \sqrt{\left((2d_i - \lambda)^2 - r^2\right)\left(r^2 - \lambda^2\right)} \qquad \textbf{(4.29)}$$

The maximum number of transmissions is equal to the maximum number of nodes in the shaded area. This value is the maximum possible value. However, transmissions will be less than this value, because the area is not covered completely ever. On the other hand, shaded area may decrease according to the applied threshold value. Increase in threshold value reduces the number of retransmitting nodes.

An approximate value of the number of transmitting nodes can be found by multiplying the shaded area with the *node density* in the overall operation area. The node density in the operation area can be found as;

$$Node\_dencity, \sigma = \frac{\#\_of\_nodes}{operation\_area} \tag{4.30}$$

Then, the number of the nodes in the possible transmissions area which is also equal to the number of transmissions is;

$$Number\_of\_nodes = \sigma \times Shaded\_Area \tag{4.31}$$

Thus, Equation 4.21 becomes as follows;

$$E_{SIMULATION} = (\#\ of\ data\ packets).(\sigma \times Shaded\_Area). \\ \left[E_{transmit} + n.E_{receive} + n.E_{comparison}\right] \tag{4.32}$$

Equation 4.29 and Equation 4.32 can be merged as;

$$E_{SIMULATION} = (\#\ of\ data\ packets).\left(\sigma \times \left[\frac{1}{2}\sum_{i=1}^{\lceil d-r/\lambda \rceil} \sqrt{\left((2d_i - \lambda)^2 - r^2\right)\left(r^2 - \lambda^2\right)}\right]\right). \\ \left[E_{transmit} + n.E_{receive} + n.E_{comparison}\right] \tag{4.33}$$

Equation 4.33 gives the energy consumption for SWR protocol during the simulation.

It is assumed that the threshold value λ has a predetermined default value, Equation 4.33 can be simplified. For λ=r/2, the Equation 4.29 becomes;

$$Shaded\_Area = \frac{1}{2}\sum_{i=1}^{\lceil d-r/\lambda \rceil} \sqrt{\left(\left(2d_i - \frac{r}{2}\right)^2 - r^2\right)\left(r^2 - \left(\frac{r}{2}\right)^2\right)} \tag{4.34}$$

$$Shaded\_Area = \frac{1}{2}\sum_{i=1}^{\lceil d-r/\lambda \rceil} \sqrt{3r^2\left(d_i^2 - \frac{d_i r}{2} - \frac{3r^2}{16}\right)} \tag{4.35}$$

Equation 4.35 only gives the shaded area when the threshold value λ has a predetermined default value r/2. This is simpler than Equation 4.29. Assumption of the threshold value λ as a predetermined default value *r/2* can be considered as a realistic condition. Decreasing the threshold value to *r/2* reduces the number of next forwarding nodes to an acceptable small number. It can be seen in Figure 3.5.d.

4.2 Voids

The system comprised of the sensor nodes may not sustain its expected functionality due to some impairments subject to sensor nodes. There can be some kind of *holes* [36] effecting the performance of the system. The coverage area may not be covered as required, causing coverage holes or -in other words– *voids* in the topology due to random deployment or geographical area obstructions. On the other hand, node failures and nodes' power depletions introduce voids in the previously covered topology. Existence of voids impairs the communications of sensor nodes. The network may not perform the promised functionality. On the other hand, opponents in the effort of avoiding the functionality of the constructed network may attempt hazardous countermeasures. Jamming may cause the *jamming holes* which affect the availability of the system. Denial of service attacks may cause the *worm holes* which affect the reliability of the communications.

Holes can be classified as *coverage holes*, *routing holes*, *jamming holes*, and *Sink/Black Holes/Worm Holes* as defined in [36]. This thesis deals with the coverage holes and the routing holes which is also known as *void*.

4.2.1 Voids – coverage holes and routing holes

As defined above, there may remain some uncovered regions after the deployment of the nodes over the operation area. And some nodes get death due to energy consumptions leaving a hole in their positions. These uncovered regions are named as *coverage holes*.

Routing holes can be defined from an extended view, in addition to the inclusion of the coverage holes. Routing is accomplished for transferring the data to the destination. However, the transfer may fail due to coverage holes on the route or due to some nodes' uncooperative reactions for the transfer. Some nodes may fail to respond to the routing process due to the routing algorithm (routing algorithm avoids that node to participate in the routing process), or due to some resource limitations such as very limited remaining energy (e.g. just for emergency cases), buffer fill-up, processing overhead. In the *first case*, a robust and adaptive routing algorithm should be developed to overcome this kind of failures. *Local-minima problem* is an example to this kind of failures and explained as follows. "Local minimum phenomenon often faced in geographic greedy forwarding. Forwarding here is based on the destination location. In Figure 4.5, a node *x* tries to forward the traffic to one of its *1-hop neighbor* that is geographically closer to the destination than the node itself. This forwarding process stop when *x* cannot find any *1-hop neighbor* closer to the destination than itself and the only route to destination requires that packet moves temporarily farther from the destination to *b* or *y*. This special case is referred to as local minimum phenomenon and is more likely to occur whenever a routing hole is encountered. [36]"

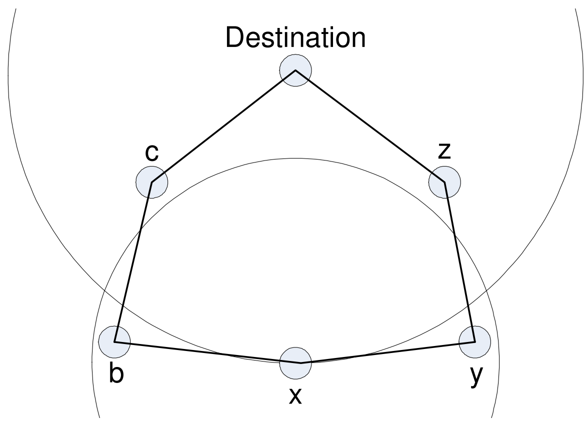


Figure 4.5: Local minimum phenomenon in greedy forwarding [36].

Another case is the more reliable one. If there are some other nodes that establish the route toward the destination, routing algorithm should be adaptive to include them in case of such situations. But, this approach may consume excessive energy. In *the latter case*, the routing algorithm should be efficient and effective. To do so, routing algorithm may avoid unnecessary transmissions, may use priority queues, or some kind of QoS (Quality of Service) parameters. There is a tradeoff between solution approaches of the first and second cases. The routing algorithm should balance this tradeoff.

4.2.2 Jamming holes

A node may not communicate with its neighbors due to interference even if there is direct communication links. Interference may be casual or unintentional. If the interference avoids the communication continuously, it is considered as jamming. Jamming can be either consciously made by opponents to avoid communication of the nodes, or due to failure of a friendly node that continuously transmits and occupies the wireless channel denying the facility to other neighboring nodes [36]. The area or zone of the nodes affected from these jamming is considered as *jamming holes*.

4.2.3 Sink/black holes/worm holes

A *malicious node* may disrupt the communication between the nodes and the sink node. Message passing through the malicious node may be dropped, may be altered, or may be sent to another node selected intentionally. Therefore, the data flow toward the sink node gets influenced. The area or zone of affected nodes centered with the malicious node is considered as *sink holes* or *black holes*. On the other hand, malicious nodes in the network may cause the packets to be routed on paths worse than the optimal paths. Deviation from the optimal paths may affect the limited resources such as bandwidth, energy, processors, memory and may cause congestion. "Worm hole is another kind of denial of service attack. Here the malicious nodes, located in different part of the sensor network, create a tunnel among themselves. They start forwarding packets received at one part of the sensor network to the other end of the tunnel using a separate communication radio channel. The receiving malicious node then replays the message in other parts of the network. This causes nodes located in different parts of networks to believe that they are neighbors, resulting in incorrect routing convergence. [36]"

4.2.4 Void avoidance methods

Since the security related issues are not primarily of concern of this thesis, only approaches for void avoidance and recovery are proposed. There are many proposed solutions for void avoidance and recovery. The void avoidance and recovery methods in the literature can be classified according to the capabilities of the nodes with respect to their mobility [36]. In mobility enabled nodes, sensor nodes have ability to make movements for maximally covering the operation area. In static networks, coverage problem is investigated according to the density of the network and according to the desired degree of the coverage. In the hybrid networks that have some mobility enabled nodes, coverage problem is tried to be solved by the help of or using the mobile nodes. The coverage hole problem and proposed solution in the literature are summarized in [36]. The methods include either one or combination of the methods of using multiple-paths and alternating paths, retransmissions, broadcasting, flooding or localized flooding, and discovery of the voids and boundary of voids.

However, frequent topology changes affect the performance of the proposed solutions. Effectiveness and responsiveness of these methods depend on the frequency and reliability of the retrieved topology information. Therefore a tradeoff exists between the provisions of the topological information and the accuracy of this information. Frequently exchange of information consumes energy and introduces communication overhead. On the other hand, infrequent information exchange causes the nodes have unreliable topology knowledge. Geographical routing has an advantage with respect to other type of routing protocols by means routing overhead. They are table-free by keeping only the location information of itself, its neighbors and the sink. Most of the geographic routing protocols use greedy forwarding relying on the local information to route the packets toward the sink. The void avoidance methods proposed in geographical routing algorithms are given in [36].

4.2.5 Void avoidance in SWR

Geographical routing protocols use local topology information and have not any overhead because of continuous process of update [1 - 8]. Therefore, they provide scalability in mobile networks with respect to conventional routing protocols. On the other hand, energy resource limitations require energy-efficient approaches. Stateless geographical protocols can be used to provide energy efficiency. They do not require local topology information. However, the stateless geographical routing protocols in the literature propose solutions to be implemented at the MAC layer and generally have local minima problem. On the other hand, only a few ones propose solutions for the void problem, while the solutions are too complex to implement and costly. A void avoidance algorithm for SWR protocol is proposed in this subsection. The proposed algorithm is peculiar to the SWR and guarantees the delivery of data to the destination. The usage of threshold value to shape the data flow toward the sink is also described in this subsection. Threshold usage aids the void avoidance algorithm implicitly and explicitly.

4.2.5.1 Implicit void avoidance approach

In SWR, nodes implement the Algorithm 3.1 to route the packets. When a node has data to transmit, inserts its own and the destination's weight into the packet, and broadcasts the packet. As soon as a node receives a packet, it compares its weight with the ones in the packet. If its weight is between the sender node's weight and the destination's weight, it rebroadcasts the packet after replacing the sender's weight with its own. If node's weight is not between the weights of the sender and the destination, node simply drops the packet.

In order to reduce the number of rebroadcasting nodes, a threshold value is used which is also transmitted with the packet. Only the nodes which weight difference is greater than the threshold value is allowed to rebroadcast the packet. As defined in Section 3.5, threshold value can be used for several purposes. One is to use for void avoidance. Increasing the threshold value provides fewer nodes in number to relay the data packets and decreasing the threshold value provides more nodes in number to relay the data packets (Figure 3.11). More relaying in number causes the data to flow over multiple paths (Figure 3.14). In case of void detection, the transmitting node decreases the threshold value allowing more nodes to be in data flow algorithm (Figure 3.16).

Nodes can understand the existence of a void by the non-retransmission of the packet with the same parameters by the nodes those have lower weight values. The interference of the void is gotten rid of implicitly by multipath usage. By adjusting the threshold value, data can be carried over multiple paths. By this way, nodes that may circumvent the void are forced to relay the data packets. Without any effort, the void problem is eliminated substantially due to multiple route construction in SWR. Even if one of the paths encounters a void that it cannot pass around, the other paths remain toward to the destination. For the case of large gaps in the topology, a void elimination algorithm is proposed to solve the void problem.

4.2.5.2 Explicit void avoidance algorithm

Algorithm 4.1 Simple Void Avoidance Algorithm

```
if (threshold > 0) then
    set threshold to 0 (zero);
    rebroadcast;
if (the packet cannot be relayed) then
    set the w_sender to w_sender+w' in header;
      rebroadcast;
```

The threshold value variations determine the range of the area that data disseminates. However, due to the size of the void, nodes still may encounter a void. In this case, an explicit void elimination approach is used. On encountering a void, the node executes the void elimination algorithm given in Algorithm 4.1. The algorithm consists of two steps. In the first step, the algorithm tries to transcend the void by decreasing the threshold value to *0* (zero). Therefore, more area can be covered to forward the packet. If the packet still cannot be forwarded due to void, the second step is implemented. Transmitting node, retransmits the packet with a weight value greater than its weight (e.g., $w+w'$) embedded into the sender's weight field in the packet and the threshold value set to *0* (zero). Here, w is the weight of the transmitting node and w' is the additional weight to be added where $w' > 0$. By changing its weight value to a fake weight value, the transmitting node enforces the rearward nodes to participate into the routing with these new parameters. Therefore, a void can be passed by without any complex calculations. The Detailed void Recovery Algorithm is given in Section 4.9.

4.3 Reliability

Among the performance metrics and design objectives described in this section, reliability is the most challenging one with the energy-efficiency. Attainment of both the reliability and the energy-efficiency is an open research area while there are many studies on this subject.

In addition to the transmission impairments observed in wireless networks, the properties of sensor networks make the reliability a key design issue.

Communication is carried on wireless medium. Due to the short transmission ranges in wireless sensor networks, the data is routed through a sequence of multiple hops. Each hop reduces the successful delivery of the data at the destination. The issues that affect a successful transmission can be summarized as follows [59].

Unpredictability of the environment: nodes can be deployed in unknown terrains, even hostile environments, where the destruction of nodes may occur. Also, nodes may fail to work or work with low performance depending on the environment.

Unreliability of wireless medium: as depicted above, communication in wireless medium is unreliable and prone to errors. Impairments in wireless medium disrupt the signal on transmissions. On the other hand, unpredictable and varying link quality may cause fluctuations in the network.

Resource-constraint nodes: nodes are resource limited in terms of power, storage, and processing capabilities. On the other, the available bandwidth is limited.

Dynamic topology: in addition to the mobility of the nodes, links may come and go depending on the environment and wireless medium.

Route breakages: due to link and node failures, used paths may change frequently. Therefore, data packets may be dropped, may be delayed, and may follow a very-long circumventing path that reduces the possibility of successful arrival at the destination.

Congested nodes: depending on the topology of the network and depending on the applied routing protocol, some nodes may become over-utilized.

Routing protocols have to cope with these issues to provide reliability. One way of provision of reliability is allowing multiple copies of the data to be delivered to the destination over different paths. This mechanism is called as multiple-path construction. Flooding is the well-known and the most reliable protocol carrying the data over all possible paths toward the destination. However, flooding is not energy-efficient due to the same reasons. Some protocols carry the data over only a single path and take care of the issues described above by the repair mechanisms. Such approach seems to reduce energy-consumption but does not guarantee the reliability. Provision of reliability introduces energy cost. Therefore, reliability challenges with the efficient-energy consumption.

Comparing the multiple-path routing, single-path routing is simpler and consumes less energy. However, single-path routing is more prone to failure of delivery of the data at the destination. If P_n denotes the failure rate of the nodes, P_t denotes the channel error rate on transmissions, and L denoted the path length in number of hops, then the probability of successful delivery, $P_{success}$, at the destination provided by single-path is [70];

$$P_{success} = \left(1 - P_n \cup P_t\right)^L \tag{4.36}$$

The equation above summarizes that as the hop number increases the possibility of successful delivery of the data reduces. It is a trade-off to provide reliability and energy-efficiency. A common approach to provide reliability in single-path routing is to use path-repair techniques in case of route breakages. However, these techniques do not provide high reliability and introduce delay. Moreover, these path-repair techniques generally require local or global topology information and are complicated.

The most reliable technique for successful delivery is allowing data to be transmitted on multiple-paths, which is also used for load balancing, higher aggregate bandwidth [54, 59, 71 - 73]. Another approach is using multi-casting. Data is sent to more than one destination to make sure the data is received reliably. Actually, multicasting is used to realize group communications [74 - 77]. In the following subsections, the multiple-path (Section 4.3.1) and multicasting (Section 4.3.2) approaches in the literature and in SWR (Section 4.3.3) are described.

4.3.1 Multiple-paths

The reliability of the system can be improved by constructing several paths from source node to destination and traversing the same data packet through each of the path. This routing approach is known as multiple paths. Multiple-path routing provides dynamic and fast route reconfiguration [78]. In case of route failures, the data is carried over other remaining paths. Its effectiveness is determined by the redundancy of the multiple-paths [78]. However, pre-established redundant paths are also affected from the dynamics of WSN and MANET. Therefore, on-demand multiple-path construction is required to provide higher reliability.

In addition to reliability, multiple paths are used for load balancing and to provide higher aggregate bandwidth [59]. By spreading the traffic over multiple paths toward the destination, load may be reduced in over-loaded nodes. Data packets flow toward the destination over the paths other than over-loaded node consisting paths. By the way, possible congestion and bottlenecks can be reduced.

The bandwidth in WSN and MANET is limited. Usage of a single path for routing may not provide the required bandwidth for the current communication. In case of transmission of packets over multiple paths, the aggregate bandwidth of multiple-paths may satisfy the bandwidth requirement of the current communication [59]. Therefore, a smaller end-to-end delay may be achieved [59].

Multiple-path constructing techniques try to find either *disjoint multiple-paths* or *braided multiple-paths* (Figure 4.23). Disjoint multiple paths are also known as *node disjoint paths*. They have no nodes in common. *Link disjoint paths* can use the same nodes or links on the route. Therefore, they are called as *braided multiple-paths*.

There are advantages and disadvantages of both of these multiple-path constructing schemes. In disjoint multiple-paths, one of them becomes a primary path due to its advantage on one or more of the terms of delay, energy, cost, etc. with respect to other paths. The other paths remain as alternate paths. In case of failure on primary path, the alternate paths are not affected from the failure. On the other hand, the advantage of the primary path is lost due to complete node disjointedness, causing a less optimal path to be used. However, braided paths that partially overlay with primary path may still preserve the advantages of primary paths, due to partial overlay [54].

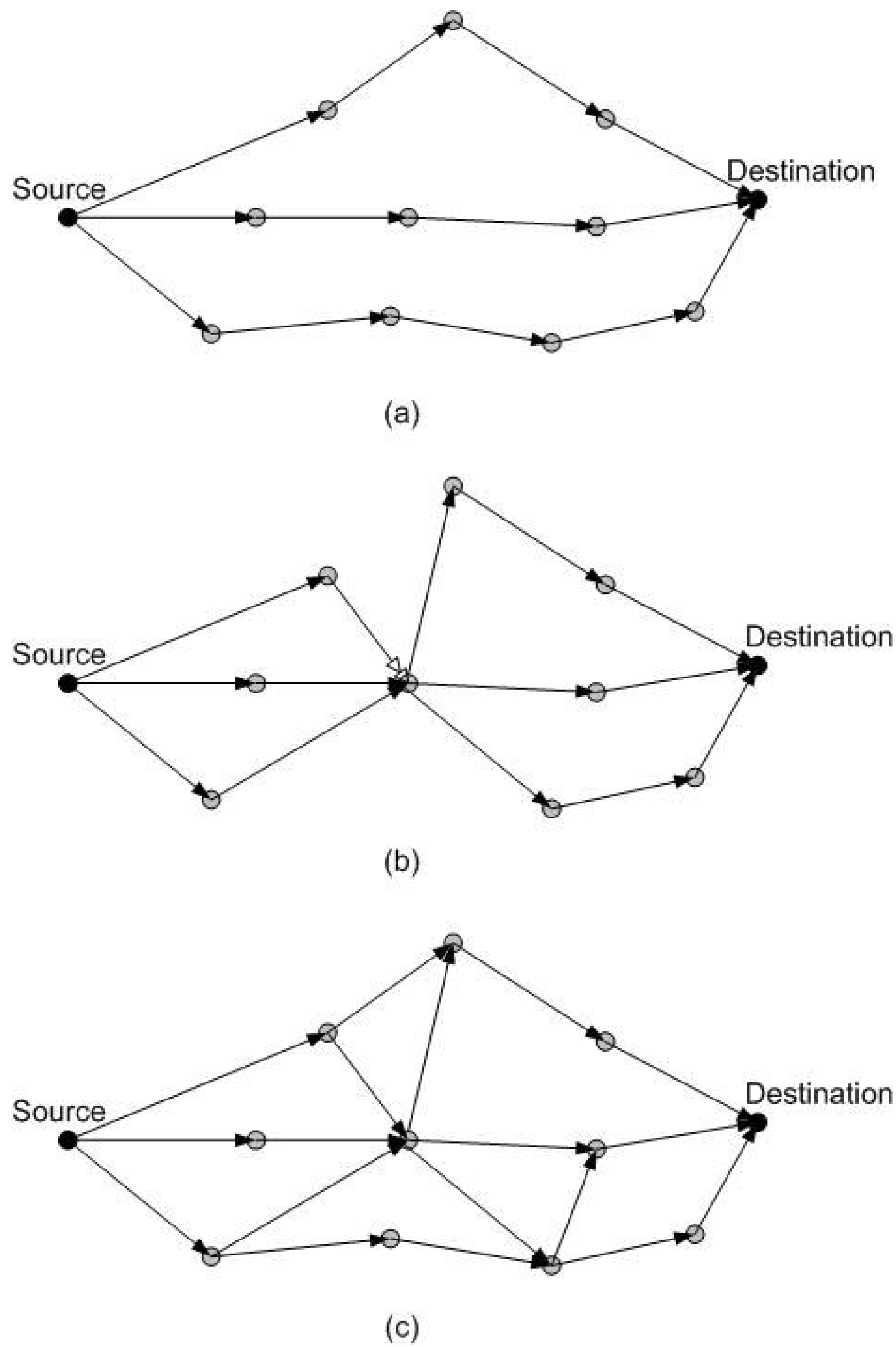


Figure 4.6: Multiple path types. (a) node-disjoint paths. (b) link-disjoint paths (c) non-disjoint paths.

The main advantage of braided paths is that they can be more easily discovered [59]. Node disjointedness in disjoint paths makes it hard to find such paths. Number of the disjoint-paths is very low between two arbitrarily nodes in a moderate dense network. Finding these paths are hard.

Sending the same data over *k* number disjoint paths (*k>2*), increases the delivery ratio proportional to value *k* [70]. However, finding such paths is hard and due to reasons described above, they may reduce the performance on path failures. Moreover, it is experimentally shown that braided paths have a higher performance results with respect to disjoint paths [65]. “It was found in [65] that energy-efficient multiple-path routing using the braided multiple-path approach expends only 33% of the energy of disjoint paths for alternate path maintenance in some cases, and has a 50% higher resilience to isolated failures [59]”. Moreover, construction of low coupling or correlated paths increases the performance of the network [59].

The end-to-end reliability for multiple-paths is calculated by the reliabilities of all paths used for routing. The single-path reliability can be defined as in Equation 4.36. Then, end-to-end reliability for multiple-paths, $MP_{success}$, can be found as [59];

$$MP_{success} = \left(1 - \prod\nolimits_{k \in K} (1-k)\right) \tag{4.37}$$

where k is the path reliability of a path and K is the set of all paths [59]. Exploring from the equation, it can be easily realized that multiple paths increase the reliability. A survey on multiple-paths is presented in [59], which includes all related issues and challenges in multiple-path routing and multiple-path usage.

4.3.2 Multicasting

Conventional multicasting is used for group communications. Data packet is sent to all group members who desire to receive those packets. Therefore, such multicasting protocols are composed of group membership management, creation and maintenance of multicasting tree. However, there is one other important usage area for multicasting. It is used to increase the reliability. The latter one is under scope of this thesis.

In mission critical applications both in *military* (e.g. command and control in battlefield areas) and *civilian* (e.g. disaster relief and recovery) environments, reliable group communication (one-to-many and many-to-many) is required. On the other hand, robustness, QoS, and real-time communications are the major concerns of these type critical applications [16, 74]. Therefore, multicasting appears a fundamental requirement for collaborative study of network components. Group coordination requires reliable and real-time multicast and anycast communication [16].

There are two main categorizations of the multicast protocols, *tree-based* and *mesh based*. "The tree-based protocols construct a tree structure for the multicast delivery, and the tree is known for its efficiency in utilizing the network resource optimally [77]". The two major methods to construct the multicast tree are the *shortest path* and the *Steiner tree* [76]. In shortest path tree, packets are sent over the shortest known paths between the source and all destinations. "However, Steiner tree minimizes the cost of the multicast tree. It is proven that construction of Steiner tree in arbitrary graphs is NP-complete [76]". Also, it is shown in [79] that minimum-energy multicast tree construction is also NP-complete by reducing the Steiner tree to it. The main drawback of tree-based approaches is that the tree connections are easily broken, so maintenance becomes difficult.

The mesh-based protocols are proposed to enhance the robustness by providing redundant paths between the source and destination pairs. However, this type of multicasting techniques is also affected from overhead of provision of multicasting and from the dynamic topology structure of WSN and MANET [77].

One option to reduce the overhead of multicasting is usage of location information for routing packets toward the group members. Insertion of address and location information of group members into the header of the packet is a simple and easy way to provide multicasting. Application of multicasting within a stateless geographic routing protocol will reduce the overhead observed in other multicasting protocols.

A very common and another simple way of providing multicasting is usage of flooding. Actually, flooding is the most reliable protocol that utilizes every path in the network. Transmitted packets are received by each node. In this view, it is a multicasting protocol where all nodes in the network are the members of the same one group. Therefore, there are protocols in the literature that utilize the properties of flooding [74 - 76]. They present a method to reduce the overhead of flooding.

Flooding uses broadcasting. At first glance, it may be thought that flooding and broadcasting causes more overhead than tree-based multicasting approaches. In tree-based approaches, one copy of the data packet is addressed to each member of the group. However, in flooding, one transmission is enough. When this property is aggregated with location-based flooding approaches or geographical routing approaches, multicasting becomes feasible. It is also shown in [75] that flooding-based approaches presents better delivery ratios with respect to other compared protocols.

A variant of multicasting and anycasting is stated in [16] which can be convenient for WSN. It is stated in [16] that real-time multicasting and anycasting may be based on geographic areas. "Area multicasting delivers the same message to every node in a specified region for registration of nodes for an event or to send a query to all nodes in that region or for coordination among nodes in local group [16]".

"Area anycasting delivers the message to at least one node in a specified region. Area anycast can also be used for sending a query to a node in an area. The node can initiate group formation and coordination in that area [16]". These approaches are very convenient for WSN. In WSN, data is more important than the Id of the sender. Therefore, location information becomes more useful parameter for data gathering in a specified region rather than the usage of ID of the nodes.

4.3.3 Multiple-paths and multicasting in SWR

Reliability in SWR is increased by multiple paths. On the other hand, in case of multiple-sink usage, multicasting and anycasting is also possible in SWR to provide reliability and to respond the requirements in emergency conditions which also require real-time support. Moreover, SWR is more reliable than any other protocol in the literature due to its behaviors described below in this section.

The routing algorithm of SWR presented in Algorithm 3.1 constructs multiple paths toward the destination node. Paths are constructed on-demand. Data packet is carried over every constructed path. The number of the paths depends on the distance (length in hops) and the applied threshold value. As the distance increase, the number of the constructed paths increases. Threshold value is determined as defined in Section 3.5. Constructed multiple paths in SWR are the *braided multiple paths*.

It is indicated in Section 4.3.1 that paths should be constructed on-demand for frequently changing environments. However, almost all of the proposed protocols in the literature construct the multiple paths prior to send the data packet. In these approaches, generally the packet is sent over the primary one. In case of route failure, the packet is sent over the other one. Switching from the failed path to a new one introduces delay. If all paths known in-advance are failed, switching between these paths and experiencing the data delivery on these failed paths increase the delay more. Besides that, after switching one after all these paths, a new route recovery is required, which increase the delay longer. However, in SWR, at each data packet transmission, new multiple paths are constructed while the copies of the same packet traverse toward the destination. In SWR, information about paths is not kept at nodes for future use. Keeping such information is needless in frequently changing topology and introduces overhead and delay as depicted above. However, most of the other protocols in the literature do not have this property. Protocols that construct multiple paths in similar approach with SWR are a few in numbers. And these protocols do not have the flexibilities that SWR has. The differences are presented in the following paragraphs. Comparing with multiple-path using protocols in the literature, SWR provides the minimum delay. Multiple path construction in SWR is described in Section 3.5 and Section 3.6. The results about the multiple paths are presented in Section 5.

Considering the construction and usage of multiple-paths, SWR is more reliable than any other protocol in the literature (except flooding). On the other hand, SWR does not introduce the overhead and reduction on performance metrics observed in other protocols. To provide the guaranteed delivery of the packet, SWR includes mechanisms. As defined above, data packets are flowed over multiple paths at the same time in SWR. Data packets flow over braided paths. This means that paths overlay with each other and these paths have the advantages of the best path. It is intended in SWR to provide *guaranteed delivery* of the packet. Guaranteed delivery in SWR is described in Section 4.6. If one of the data flow fails, void recovery algorithm presented in Section 4.7 is invoked. According to this algorithm, if a node experiences void, threshold value is lowered and a fake weight value is used in the next step of on-going of void experience. These approaches increases the covered area of the data packet is sent, building more paths on-demand. The delay encountered in these steps should be accepted as negligible due to very small time differences. These methods are triggered and the paths are constructed on demand. On the other hand, while the void recovery is invoked for one of the data flows which encounters the void, data continues to flow over other paths. Therefore, it will not be false saying that delay does not increase in path failures. Figure 4.7 shows the constructed multiple paths in SWR. Actually, multiple paths in SWR are braided paths. To illustrate the subpath construction, these braided paths are shown as separate paths. The figures are illustrated to explain the path recovery and redundancy in SWR. Depending on the distance between the source and the destination, multiple braided paths are constructed. If a node which should be on a path encounters fail to send the data (void existence), new subpaths are constructed. These subpaths may be part of other paths or overlay a portion of the other paths. New path construction is not a separate process of the routing algorithm. Actually, there is not new sub path construction. All these processes are executed on the time of packet forwarding.

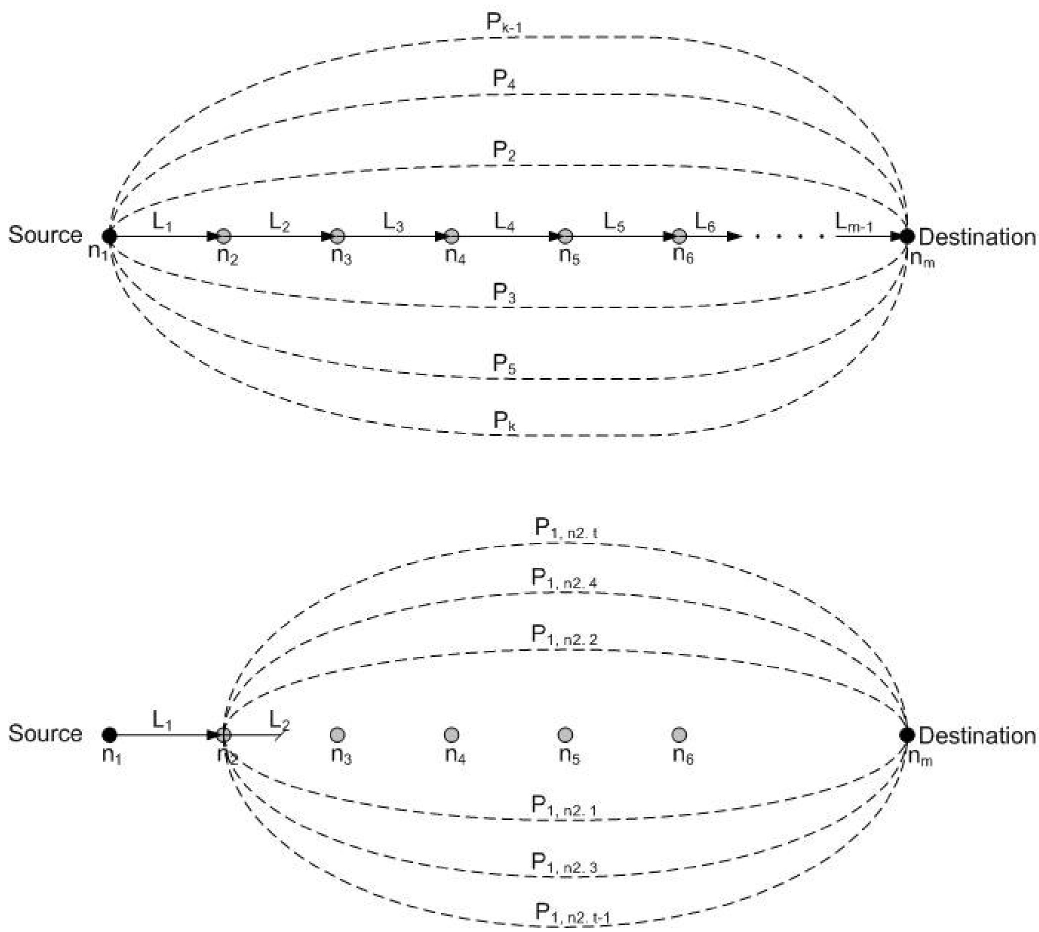


Figure 4.7: In SWR, constructed multiple paths are braided paths. The figures are illustrated to explain the path recovery and redundancy in SWR.

While providing the reliability, SWR use the energy efficiently and consumes much less energy than other protocols in the literature. Results are presented in Section 5. Excessive energy consumption, increased delay, and routing overhead observed in other protocols to provide reliability by multiple-paths are not observed in SWR. SWR provides the reliability without excessive energy consumption.

To increase the reliability and support real-time boundaries, multicasting can be used in SWR. Application of multicasting in SWR in mission critical applications provides more reliability than other protocols, because the data is carried on multiple-paths toward the addressed destinations. In this respect, SWR is the first multicasting protocol that utilizes multiple paths for data transmissions. Meanwhile, SWR provides energy efficiency.

Multiple sink usage to provide scalability is described in Section 4.4. Each node addresses the data packet to a convenient sink node, generally the closest one. Then the data is carried on multiple paths toward the addressed sink node. It is expected that the sink node receive multiple copies of the data. However, in critical applications or emergency conditions, it may be desirable to send the data to multiple destinations (sink nodes). Demand comes from the possibility of absence of the sink node, e.g. destroy or termination of the sink node in battle field area. In such a scenario, addressing the data packet to multiple sink nodes increases the possibility of the delivery of the packet at least one sink. On the other hand, the packet arrives with minimum delay on the reception of the first of the sink nodes. Another demand may be the requirement of emergency data delivery to all or some of sink nodes. Also, for coordination of the sink nodes, the packet may be addressed to multiple sinks.

To deliver the packet to multiple sinks, the same routing algorithm (Algorithm 3.1) is used. To provide the multicasting, only the header part of the packet is changed. Instead of a single Destination ID and Sender Weight, multiple Destination ID and Sender Weight fields are used. The number of these fields is equal to the number of sink nodes. On a packet reception, the node calculates its weight value with respect to the sink nodes indicated in the header of the packet. If there are multiple sink IDs in the header of the packet, the node finds multiple weight values. The Algorithm 3.1 is applied for each weight values and destination pairs. If any of them satisfies the transmission condition, the packet is retransmitted again.

Multicasting can also be used for sink-to-nodes communications to provide the area multicast and area anycast described above. Weight usage in SWR provides a basis to apply multicasting for this purpose. Sink node can send the packet to the nodes in an area by using the weight value. And only the nodes those are in that area respond.

Implementation of multicasting by multiple paths in a multiple sink network is also the first study in the literature. SWR provides this property without degrading the other performance metrics. In this respect, SWR is the unique one.

4.4 Scalability

One of the main challenges in wireless ad hoc and sensor networks is the *scalability*. There are many influencing parameters and conditions that affect the system failing to be scalable. In routing algorithms, scalability of the system is affected mainly from;

- node density,
- number of the nodes in the system,
- communication load,
- mobility,
- overhead produced in provision of system wide information.

Approaches and methods proposed to solve the deficiencies challenge with each others. Especially, mobility and large number of nodes in the system generate the most challenging effects.

In wireless sensor networks, as the network size increases, energy becomes the most valuable resource. There are energy aware protocols in the literature generally using multi-hop paths to use the energy more efficiently. However, increase in the hop number between the source and the destination nodes bears some issues that must be considered [9, 37]. First, nodes close to the sink deplete their energies quickly; leaving the sink unreachable and the system into off-state [10]. Secondly, increase in the hop-number cause more nodes to buffer the packet on-the-route, causing a processing overhead and delay at nodes. Processing overhead and buffer fill-up may cause the packets to be dropped. On the other hand, delay at nodes challenges with the real-time requirements of the system [9].

As the network size grows, the length of the constructed paths increases, causing the problem described above more challenging. On the other hand, the energy consumption will not be efficient anymore. The delay will increase, and the packets will be dropped. Packet drops will cause retransmissions, which increase the delay excessively.

When the network size or the mobility increases, *flat and proactive (table-based) routing algorithms* introduce overhead and become infeasible. One approach is to use a hierarchical structure for routing. Partitioning the network reduces the overhead in communications. However, using a *hierarchy* alone does not solve the problem at all. Networks with heterogeneous nodes introduce cost for this hierarchical structure. In a network consisted of homogenous elements, there should be a distributed partitioning and leader election mechanism (e.g. clustering and cluster-head selection). These mechanisms are also introduces communication overhead and affected from mobility or frequently changing topology.

Reactive (on-demand) routing algorithm is a solution for frequently changing topology networks. However, they are not scalable for large-scale networks. *Hybrid approaches* make an advance to become feasible, but remain as partial and application dependent solutions.

As the GPS and GPS mounted devices becomes available in the markets with low costs, location aware approaches assisted the routing schemes defined above to be feasible in frequently changing topologies. Availability of the geographical locations reduces the topology information provisioning overhead. On the other hand, they provide the table-free property. Routing can be achieved without tables *(table-free property)* by using location information of the nodes retrieved from GPS or by applying a localization algorithm. In geographic routing protocols, nodes know their actual or relative positions, and share this information with immediate neighbor nodes for routing process. Geographic routing protocols use only local topology information and have not any update overhead. Therefore, they provide scalability in mobile networks with respect to conventional routing protocols.

To be scalable for large-scale networks, the network can be partitioned to *subnetworks*. Thus, a geographical and reactive approach can be used with large-scale and frequently changing topology networks. Partitioning the network reduces the path length and reduces the communication overhead. However, appropriate algorithms are needed for partitioning and providing communication. In sensor networks, one approach to provide scalability is to use *multiple sink* nodes.

4.4.1 Multiple sink usage in large scale networks

Multiple sinks (multi-sink) usage appears as a solution for large scale networks [9, 37]. However, deploying more sink nodes does not solve the problem directly and evenly. Energy-efficient protocols should be adapted for the multi-sink networks. However, the protocol in use may not be energy-efficient anymore in large scale networks due to increase in the number of nodes. Table-based protocols fall into this category. Due to topological changes, keeping up-to-date local/global routing tables at nodes makes them inefficient in routing process. Table-free protocols should be used to provide energy-efficiency and scalability. Routing without tables can be achieved by using geographic routing protocols.

Related studies in multi-sink sensor networks [9, 10, 34, 37 - 41] do not propose a novel routing algorithm. Studies using mobile sink node generally attempt to prolong the lifetime of the network. Reference [42] proposes mobility patterns for the sink and takes the advantage of sink's mobility to prolong the lifetime of the network. In [15] and [43], it is proven that that mobile sink node improves the lifetime of the network. In order to maximize the network lifetime in [44] and [45], the sink is moved with an adaptive strategy, which is hard to apply. In [39], repositioning of the sink node to enhance the performance metrics is investigated. There is a little work done on the multiple-sink wireless sensor networks. In [34], multiple sink location problems to manage the energy efficiently and solutions to these problems are presented. In [40], the formulation to find optimal locations of multiple sinks is proposed. Reference [10] proposes a solution for correlated data gathering to minimize the system-wide energy consumption. In [9], the worst case analysis of sensor networks with multiple sinks, namely, network calculus is presented. Reference [38] presents a methodology for optimally designing the topology to optimize the communication cost for wireless sensor networks with multiple sinks. Reference [37] proposes a model to adopt existing single-sink algorithms to multi-sink networks. Reference [41] proposes a two-tier data dissemination approach for large-scale sensor networks, which is completely proactive and energy-inefficient.

The proposed routing algorithm, SWR, can work with multiple sinks. Multiple sink version of the SWR is called as *MS-SWR*. In addition to the properties of SWR, MS-SWR is scalable in large-scale ad hoc and sensor networks.

To the best of our knowledge, MS-SWR is the first stateless routing protocol in the literature that constructs multiple paths in a multi-sink sensor network using the greedy approach in WSN and MANET.

4.4.2 Multiple sink deployment

As the network size grows, it is essential to use multiple sinks for partitioning the operation area. The question arises whether the used routing algorithm can be applied when the network size grows and/or number of sinks increases. The MS-SWR can be implemented in a network with any number of sinks. Increasing the number of sink nodes causes the network to perform better results in MS-SWR. Deployment of additional sinks does not require any modification in the routing protocol, SWR. Sinks can be positioned anywhere in the network. It is assumed that each sink informs the neighborhood nodes about its position. In a static network, this information can be diffused only once, e.g. on the node deployment phase.

In Figure 4.8 (a), a single sink is positioned in the center of the operation area. Two nodes have data to send to the sink. The possible relaying nodes are those that are located in the two symmetric logarithmic spiral curve shaped area (Figure 4.8 (b)). More than one path will be constructed toward the sink from each node. Distance of the nodes to the sink affects the size of the symmetric logarithmic spiral curve shaped area, which therefore affects the number of transmissions in SWR.

To reduce the distances of the sensor nodes to the sink, multiple sinks can be used. As shown in Figure 4.8 (c), two sinks are located in the same topology used in Figure 4.8 (a) and Figure 4.8 (b). If the sinks are positioned optimally, the operation area can be partitioned optimally. Using two sinks instead of one reduces the distances to the closer sink. As the distances to the sink get closer, the number of transmissions decreases.

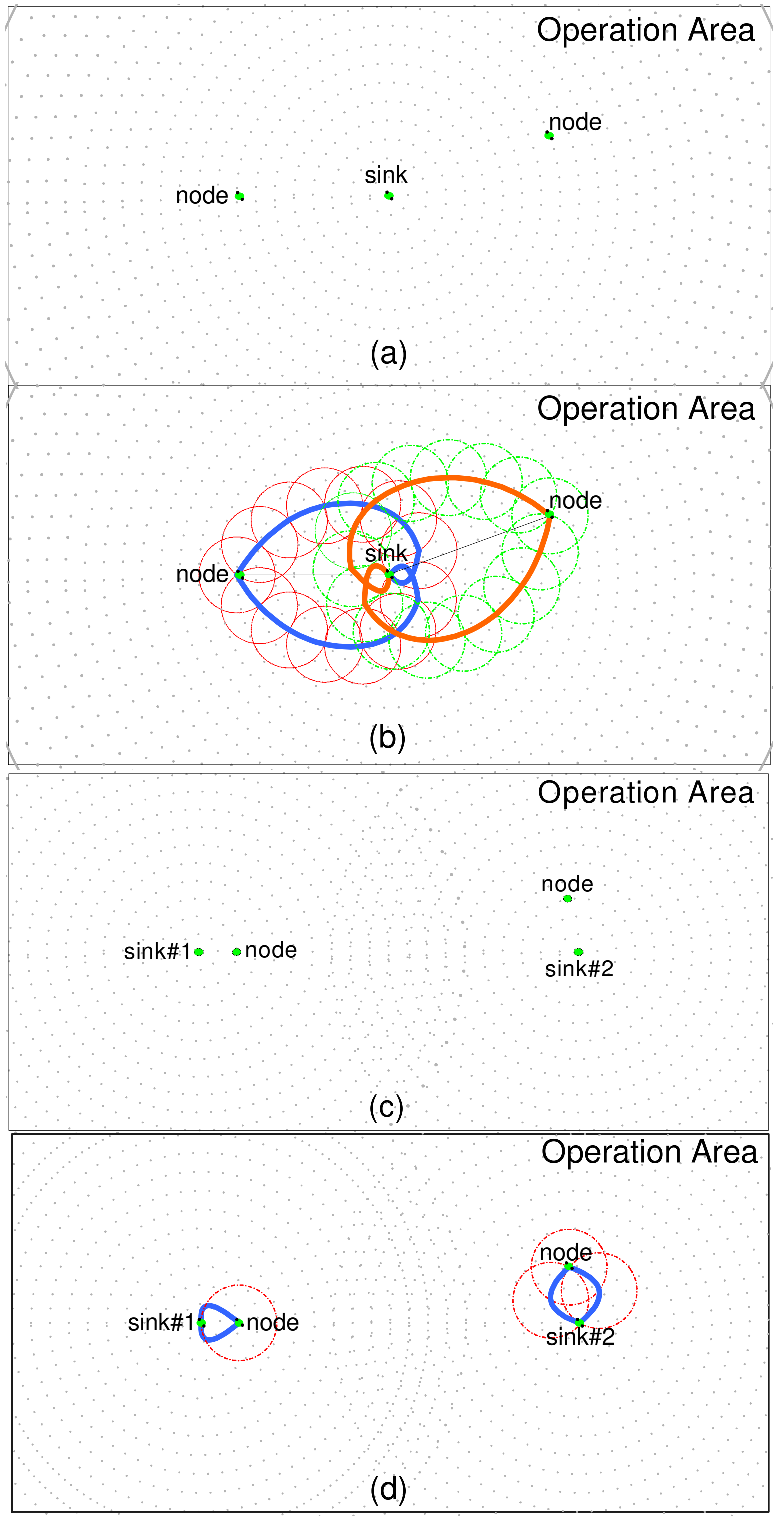


Figure 4.8: Multi-sink usage reduces the path lengths with respect to the single sink usage.

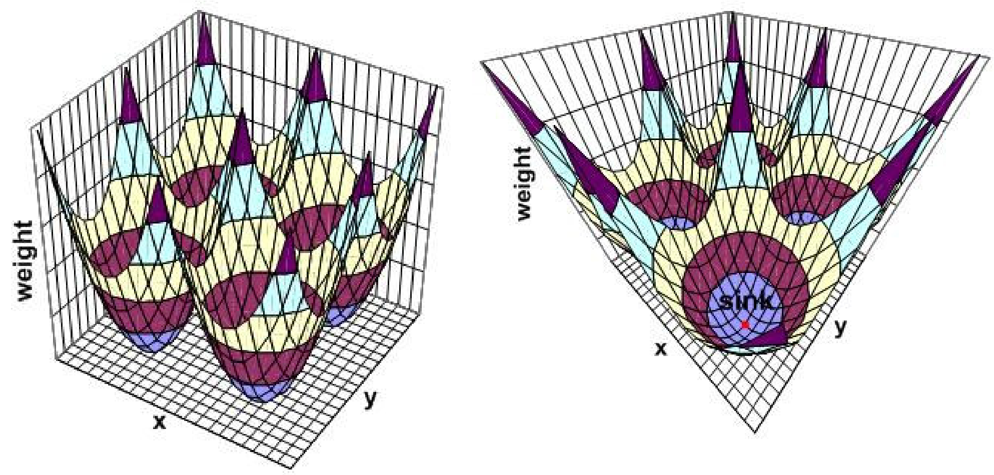


Figure 4.9: Multiple sink usage. Nodes choose the closest sink and calculate their own weights with respect to the selected sink.

In SWR, sink nodes inform the other nodes in the network about their own positions. Therefore, nodes choose the closest sink as destination. Then, nodes calculate their weight values with respect to the selected sink node. Situation is depicted in Figure 4.9, which is the multiple sink case of Figure 3.7.

It is shown in Section 5 that when the SWR protocol is applied, multiple sink usage decreases the energy consumption in routing processes and contributes to prolong the lifetime of the network. However, it is also shown that other compared protocols (GPSR and flooding) do not exhibit enhancement to their previous performance without modification. After the modification in these protocols, performance of the flooding remains the same and a negligible enhancement occurs in GPSR. Performance enhancement in the MS-SWR with respect to multiple-sink usage is related with the data flow approach presented in Section 3. As the distance between the source node and the sink node becomes shorter, the number of retransmitting nodes (relay nodes) decreases. Therefore, energy consumption is reduced as the number of sinks increases.

4.4.3 Sinks' mobility

MS-SWR can also be applied in mobile sensor networks. In this subsection, mobile sink nodes are used to improve the performance. More energy can even be saved by introducing mobile sinks to the system. The essential approach is again to decrease the distance between source nodes and the sink nodes.

As known in wireless sensor network applications, sensor nodes acquire environmental data and send it to the sink by either a periodic acquisition or an event triggered acquisition process. Some surveillance and detection systems are considered as event triggered acquisition process in which a group of nodes in the event area, which are close to each other may encounter the same event and report that event to the sink. These nodes are called as EAR (Event ARea) nodes. Upon an event, EAR nodes start sending data to sink. For the same event, multiple transmissions occur simultaneously causing multiple copies of the data from different sources to flow toward the sink. The number of transmissions can be decreased by shortening the paths if the sink moves toward the EAR nodes. The movement of the sink should be limited to make only a few steps toward EAR nodes in order not to break the original deployment strategy.

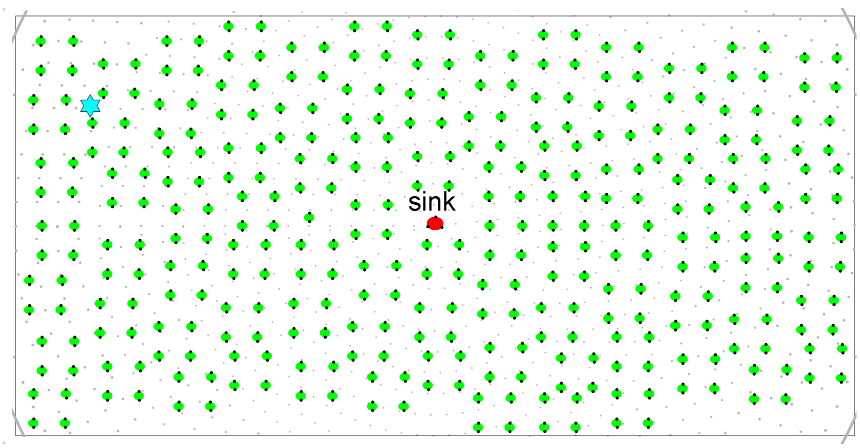


Figure 4.10: An event occurs in the operation area, such as target detection.

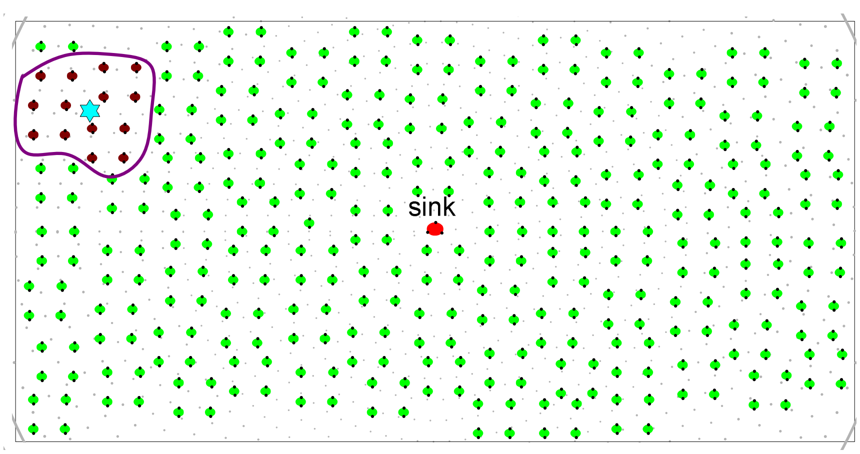


Figure 4.11: Multiple nodes detects the target (object) and gathers information. These nodes are called as EAR nodes.

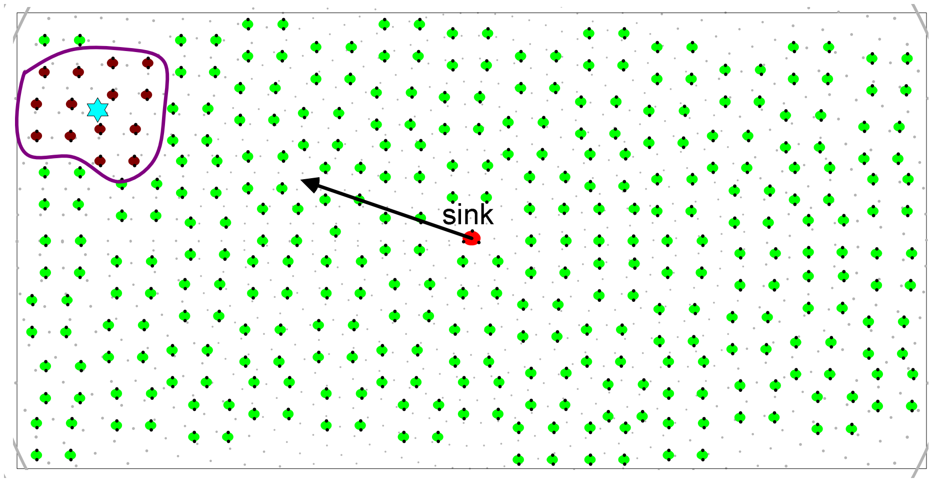


Figure 4.12: To reduce the path length, sink node moves toward the EAR nodes.

Besides that, if there is a void on the path toward the sink and if the sink finds out the existence of such a void by the aid of the received packets, a movement to eliminate the void problem may be considered. However, this is an optimization problem that is out of the scope of this research.

The number of hops for the sink's movement depends on the number of total sinks in the network (i.e., the number of sensor nodes per sink) and the average distance between source nodes and the sink node. When a sink realize that received data is related to the same event, it moves toward the direction of the source nodes. Sink nodes are able to compute the distance of the source node by using the weight value in the header of the packet. It is also assumed that upon an event, the location information of the sensor node is inserted in the first event packet in order to inform the sink about the direction. Note that location information will not be transmitted in the further stages of the communication. Distance can be computed with the help of the weight. Regarding to the weight value, movement of the sink may vary from a small step to a large one. The sink informs the nodes about its new position by a broadcast message if it moves significantly, i.e. more than the length of a hop. If the movement is not significant, less than a hop, there is no need to inform the nodes. Furthermore, sinks may move to new locations to optimize the coverage area and performance metrics.

4.4.4 Nodes' mobility

SWR can be used in mobile environment where the nodes and sink are mobile. As defined in Section 3.6, SWR protocol adapts itself to the current conditions without communication overhead. Nodes' mobility does not affect SWR, due to forwarding node selection criteria defined in Section 3. As there are existing nodes in the possible transmission area, the packet is forwarded. If there is not found any, the void recovery algorithm is invoked. Actually, the void recovery algorithm enables more nodes to be involved in routing. Therefore, in case of none-existence of any forwarding node, the scope of the possible transmission area is extended to involve more nodes. This extension is local and instant for that transmitting node. In the next transmissions, the regular routing strategy is employed. By this way, the data packet is always transmitted by at least one node (if there is any) which satisfies the packet forwarding conditions given in Algorithm 3.1.

Therefore, weight usage and flexible structure of the routing algorithm in SWR enables to find routes even in case of mobile nodes.

4.5 Real-Time Support and Delay

Another important requirement in WSN is reducing the delay encountered on data traverse between the source node and the destination. It is called as end-to-end delay. In many routing protocols in the literature, delay is considered as one of the main performance metrics. Delay is measured as the elapsed time between the generation of the data packet and arrival at the destination. If there is not priorly known path to the destination, path construction time is added to the delay. Therefore, path-setup techniques increase the delay.

Priorly known paths can be provided by proactive routing techniques. Data can traverse on known paths. However, such routing techniques are not convenient for WSN, as described previously. Due to resource limitations and some properties of WSN, it is better to use on-demand route construction techniques. There are many on-demand routing techniques to enhance some performance metric and to find route toward the destination. However, minimum delay requirement may challenge with other performance metrics. Hence, end-to-end delay becomes a dominating metric for WSN.

Techniques to reduce the end-to-end delay include MAC-layer, network layer, and the transport layer issues. However, only the network layer issues are considered in this thesis not to deviate from the main subject.

One way of reducing the end-to-end delay is reducing the hop number between the source and the destination. Data traverses on the shortest path. However, shortest path may not provide the minimum delay; indeed it may increase the delay due to congestion at nodes on the shortest path.

The convenient way of reduction of end-to-end delay requires two step integrated approach. First, the delay encountered at nodes should be reduced. Delay at nodes is called as the processing delay. Processing delay includes the delay in buffers and time elapsed for routing decision. Time elapsed in routing decision can be reduced by using simple routing algorithms. Time elapsed in buffers can only be reduced by reducing the transmissions. Secondly, an appropriate next-node should be selected to forward the packet. Selection of an overloaded node increases the end-to-end delay.

As stated above, one more action should be taken to reduce the end-to-end delay; *reduction of the transmissions*. Unnecessary transmissions introduce overhead at nodes. Nodes' buffers may be filled up which increases the delay and may introduce packet drops. The received packets use the CPU time to be processed. Packet drops cause retransmissions. Therefore, in addition to requirement for a simple routing algorithm which reduces the decision time, the routing algorithm should reduce the transmissions to avoid overhead at nodes.

Table 4.1: Events that increase the end-to-end delay by the vision of routing protocol

Event/problem	Affects on delay	Counter-measure
Transmissions	▪ Buffer fill-up. Waiting in buffers increases the delay. ▪ Buffer fill-up. Causes packet drops. ▪ Packet drops. Causes retransmissions. .	Reduce the transmissions.
Routing Algorithm	▪ Complex routing algorithm introduces delay. ▪ Worst next node selection introduces delay. ▪ Long-path construction increases the delay.	▪ Simple routing algorithm ▪ Efficient routing algorithm ▪ Short(est) path constructing algorithm.
Link Failures	Requires retransmissions (see above)	Reliable or Multi-path routing
Node terminations	Causes retransmissions (see above)	▪ Reliable or Multi-path routing ▪ Energy-efficient routing

Voids	▪ Void increases the delay. ▪ Void recovery algorithms may increase the delay.	▪ Routing algorithm. must recover from voids. ▪ Time-efficient void recovery algorithm.
Local-minima problem	Local minima increases the delay	Routing algorithm should avoid local-minima.

Summary of the delay introducing events is given in Table 4.1. Link failures, node terminations, voids in the topology and local minima problem also increase the end-to-end delay. Therefore, the routing algorithm must cope with all these problems to be able to reduce the delay.

A well known routing algorithm, *flooding*, provides the minimum delay coping with most of the problems given in Table 4.1. However, it requires many transmissions and does not use the energy and bandwidth efficiently. To use the energy and bandwidth efficiently, *gossiping* and *negotiation-based* techniques are proposed. However, these techniques introduce delay.

As defined in the third column of the table, the routing algorithm should be simple, energy-efficient, should reduce the transmissions, should be reliable, should recover from voids and should avoid the local minima problem. Provision of these intentions challenges with each other. Especially, *delay-energy efficiency-reliability triple* is the most challenging combination of performance metrics in WSN.

In addition to the *low delay requirements*, some applications require *real-time support*. A *real time system* can be defined as “one in which the correctness of the computations not only depends on their logical correctness, but also on the time at which the result is produced [46]”. This definition points out the triple challenge described above and enforces for the on-time data delivery requirement. Reliable data should be on-time at the destination. For the applications of WSN, it will useful to clarify the real-time system requirements. Real-time systems can be categorized into two as *hard real-time systems* and *soft real-time systems*. In *hard real-time systems*, it is required that one or more activities must never miss a deadline or timing constraints, otherwise the system fails or results in catastrophe [46]. This requirement generally challenge with the requirements for and expectations from WSN. WSN generally is used to aid or assist the predefined goal of a complete system. The system can be completely built from the WSN objects, hence it carries the properties of WSN objects. However, these properties entail WSN to be used for soft real-time systems. A *soft real-time system* also has timing constraints, but occasionally missing them does not cause serious effects and these effects can be considered as negligible for the application requirements when these requirements for the main goal are considered as a whole. Therefore, only the soft real-time requirements are aimed to be satisfied in the proposed approaches in the literature for WSN.

The proposed approaches for real-time systems or aimed to satisfy real-time requirements are limited in the literature. These are [47 -49, 51]. "SWAN [47] uses feedback information from the MAC layer to regulate the transmission rate of non-real-time TCP traffic in order to sustain real-time UDP traffic. RAP [48] uses velocity monotonic scheduling to prioritize real-time traffic and enforces such prioritization through a differentiated MAC Layer [49]. "The RAP provides a suite of high-level query and event services, as well as a location-addressed transport layer. RAP provides a multi-layer communication protocol stack that cooperates on prioritizing packets at not only the network layer, but also at the MAC layer. Their architecture allows the flexibility of incorporating any location-aware routing protocol desired. The authors introduce a novel approach to scheduling packets at the network level with VMS (Velocity Monotonic Scheduling) based on a packets requested velocity. It was surprising that DVM (Dynamic Velocity Monotonic) didn't perform as well as expected [50]". "In [51], an adaptive MAC layer rate control to achieve fairness among nodes with different distances to the base station is proposed [49]"

These algorithms including the MAC layer by locally degrading a certain portion of the traffic. "Local MAC layer adaptations cannot handle long-term congestion where routing assistance is necessary to divert traffic away from any hotspot [49]". To deal with these issues, SPEED is proposed in [49]. "SPEED provides a combination of MAC layer and network layer adaptation [49]". However, "it does not work on the premise of packet deadlines, but by guaranteeing a minimal packet speed across the sensor network. The application is then required to make a decision on how to proceed. The authors' claim of operation in with an existing underlying MAC protocol is misleading. They do not indicate how SNGF (Stateless Non-deterministic

Geographic Forwarding algorithm in SPEED) and NFL (Neighborhood Feedback Loop) receive feedback from the underlying MAC layer. It seems that something must be added to the MAC layer in order for SPEED to operate. It is unclear how the network can recover from backpressure messages, once a node has received one from a downstream node. Once the congestion in the area has subsided, how does an upstream node know that it is safe to send packets downstream again. One problem with SPEED is that it does not guarantee packet delivery. Their void avoidance algorithm may result in dropped packets, but their experiments show this has been minimized. It is unclear of the authors' intent, but seems that if the avoidance scheme gets to a point where it drops a packet, the packet probably wasn't going to meet its "deadline" anyway. Finally, it appears the value of $S_{setpoint}$ is fixed which does not allow for different classes of packets. The protocol guaranteed a fixed speed across the network for all application packets [50]". All those protocols described above require local or global topology knowledge to provide real-time requirement.

WSN are generally expected to be used in emergency conditions, in detection systems, and for surveillance in battlefield areas. Routing algorithms are one of the key design areas to support and to satisfy the real-time requirements, together with the transport layer and the MAC-layer. There are also MAC-layer solutions or MAC-layer integrated routing approaches to support real-time systems, as described above. Only the network layer issues, however, are considered in this thesis.

Commonly intended and endeavored satisfaction of real-time requirements in the approaches described above is the delivery of time-constraint data. Whole or a portion of sensed data is stamped as time-critical data. It is expected from the routing algorithm to carry the time-critical data to the destination on-time. A *mechanism* to provide this requirement is expected to be part of the routing algorithm which also monitors the results whether the real-time requirement is satisfied or not. To provide the monitoring capability, a *feed back control* may be needed and involved in the *mechanism* described above.

4.5.1 Delay and real-time support in SWR

Due to the reactive stateless property of SWR, it *inherits the benefits of flooding*. SWR eliminates the delay producing events/problems presented in Table 4.1 while providing the energy-efficiency. The methods for these events are described in this chapter. SWR constructs multiple paths including the shortest one toward the destination to provide reliability. Due to the stateless property, negotiation delay encountered on other protocols is not observed in SWR. Due to the less number of transmissions (in Table 5.8 presented in Section 5.2.4), waiting time in buffers is considerably low in SWR. On the other hand, the algorithm in SWR is very simple. There are only comparisons in the routing algorithm of SWR. Time spent in CPU is lower than any other protocols. Reduced number of transmissions in SWR avoids the probability of congestion. Multi-path usage avoids the data packet to interfere with voids. On the other hand, there is an explicit void recovery algorithm in SWR, which does not require many transmissions and does not produce delay. Therefore, packets arrive to the destination with a minimum possible delay. Besides that, SWR guarantees the packets to arrive to the destination as described in Section 4.6. Analytical analyze of calculations at nodes are given in Section 3.3. Simulation results for reduced number of transmissions are given Section 5.2.4.

In addition to provision of minimum delay for data delivery, SWR introduces a real-time support for real-time traffic. This support is for the soft real-time traffic similarly with other proposed approaches in the literature. SWR tries to deliver data in the minimum delivery time. On the other hand, a priority scheme is proposed to be implied in SWR to provide real-time requirements. For time-critical traffic, data packets are stamped with the priority levels presented in Table 3.1 in Section 3.4. Nodes process the received packets according to these priority levels. Therefore, prioritized packets are enforced to be delivered prior than others with minimum possible delay. On the other hand, there is mechanism to commit *silence* in the network. In case of congestions or in case of long delay encountered for time-critical data at the destination (sink node) due to heavy traffics in the network other than real-time traffic, *silence* can be committed. In case of commitment of silence, nodes drop the packets which have priority level *normal* from their buffers to reduce the traffic overhead and delay. *Silence* can also be committed for emergency conditions and to provide actual silence in the network by suppressing the transmissions of the nodes.

4.6 Guaranteed Delivery

There can be many objectives in the approaches one can propose. The performance of the proposed approaches is evaluated by measuring whether these objectives are obtained or not. However, in addition to these objectives, some performance metrics are also evaluated. One of the performance metrics is the delivery ratio (or rate). The delivery ratio is the ratio of the number of the received packets by the destination nodes to the number of the packets sent by sender nodes. There are some protocols that promises high delivery ratio but not exceed percentages of 90-95 %. However, a new objective appears as a concept in the literature: *the guaranteed delivery*. Some protocols have this goal in addition to the routing. In this goal, all the packets are delivered successfully to the destinations. The affects of the other layers, however, are not considered anyway. The ability of the routing algorithm is measured. There is already a routing protocol that provides this objective: *flooding*. Flooding guarantees the delivery of the packets if there are paths to the destination, since the packets follow every path in the topology. However, flooding protocol introduces overheads which are well known. In other protocols, as in flooding, extra energy is consumed to provide the guaranteed delivery. Thus, guaranteed delivery challenges with low energy consumption.

There are some proposed routing approaches in the literature that provide the guaranteed delivery. The general approach for successful delivery is to use multi-path routing. Route breakages on a single path routing approach degrade the delivery ratio. Route remedying approaches on route breakages are also used to increase the delivery ratio. However, only the multi-path approaches provide the guaranteed delivery property. In these approaches, the most important point is the determination of the number of multiple paths. The protocol should limit the width of the paths or the number of the paths to reduce energy consumption. On the other hand, selection of the optimal paths reduces the energy consumption too.

4.6.1 Guaranteed delivery in SWR

SWR uses the multi-paths for packet delivery. The width and the number of the paths are determined by the threshold value. The applied approach is very dynamic by adapting itself to the current conditions.

The guaranteed delivery property is the natural result of the routing algorithm given in Algorithm 3.1. This algorithm provides the packet to be delivered on multi-paths. In case of gaps in the topology (voids), the void recovery algorithm given in Algorithm 4.1 is used. Therefore, the packets always routed over the available paths toward the destination (sink). The number of the paths is determined by the threshold value. The threshold value can be a default value for all packets, determined before deploying the nodes. However, due to the node terminations and other reasons, voids may appear in the topology. On the other hand, finding the optimal paths may fail due to local minima problem. SWR protocol avoids the local minima problem without any attempt and it generally recovers from the voids naturally. But, in case of voids that could not recover naturally, void avoidance method given in Algorithm 4.1 is applied. In this algorithm, first the threshold value is reduced. In case of fail, the sending node inserts a fake weight value into the packet header that is greater than its own weight to recover from the void. By this way, adaptation of threshold value according to the network condition is possible. After the void recovery, nodes apply the default threshold value.

4.7 Detailed Void Recovery Algorithm

The detailed void recovery algorithm is given in Algorithm 4.2. The *Packet Type* field of the *QoS Parameters* field of the *History Table* (Figure 3.8-Figure 3.10) is used as *void_recovery_iterator* field.

Algorithm 4.2 Void Recovery Algorithm

Void Experiencing Node:

```
If (the packet previously not transmitted)
{
  if((w_sender> w_i > w_destination) and (Diff(sender,i) >= threshold) then
  {
    rebroadcast;
    If (not transmitted again)
    {// void existence
        void_recovery_iterator =1; // set the void_recovery_iterator to 1
        set the threshold to 0 (zero);
        rebroadcast;
          If (not transmitted again)
          {
            void_recovery_iterator =2; // set the void_recovery_iterator to 2
            set the w_sender to w_sender+w' in header;
            set the threshold to 0 (zero);
            rebroadcast;
          }
```

}// end_of void existence code
  }
}

Intermediate Node:

If ((the packet previously transmitted) and (*threshold* == 0))
{//head of recovery algorithm
  If (*void_recovery_iterator* == 0)
  {
     void_recovery_iterator =1; // set the void_recovery_iterator to 1
     if((w_{sender}> w_i > $w_{destination}$) **and** (Diff(sender,i) >= *threshold*) **then**
     {
        set the *threshold* to 0 (zero);
        rebroadcast;
     }
  }
  else if (*void_recovery_iterator* == 1)
  {
     void_recovery_iterator =2; // set the void_recovery_iterator to 2
     if((w_{sender}> w_i > $w_{destination}$) **and** (*Diff(sender,i) >= threshold)* **then**
     {
        set the *threshold* to 0 (zero);
        rebroadcast;
     }
  else if (*void_recovery_iterator* == 2)
  {
        set the w_{sender} *to* w_{sender}+*w'* in header;
        set the *threshold* to 0 (zero);
        rebroadcast;
  }
} // end of recovery algorithm

Source Node:

If ((the packet belongs to itself) and (*threshold* == 0))
{
  change the *seq_no* of the packet;
  set the *threshold* to 0 (zero);
  set the w_{sender} to w_{sender}+*w'* in header;
  rebroadcast;
}

5. PERFORMANCE EVALUATION OF THE PROPOSED SYSTEM

In order to evaluate the performance of the proposed system, a simulation system is designed and implemented in C++ on a Windows based operating system. The simulation system is designed as illustrated in Figure 5.1. First, the simulation system is supplied with a text file which has initialization parameters for the simulations and the parameters for the routing algorithms implemented. The proposed routing algorithm (SWR) and the compared routing algorithms are implemented. Implementation includes the main modules illustrated in the block diagram simulation system (Figure 5.1).

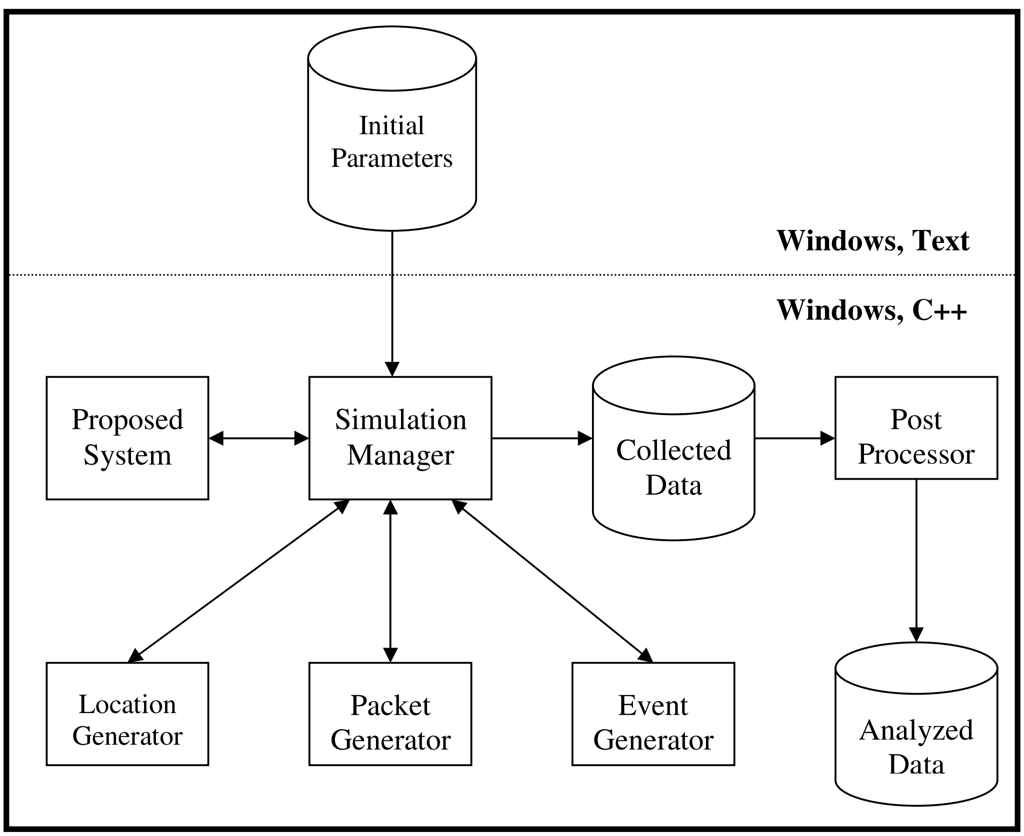


Figure 5.1: The layout of the developed simulation system.

After the startup of the simulation, the simulation manager is triggered to control and to process the events. It advances the simulation time second by second. At each second, *Packet Generator* and *Event Generator* modules are invoked. Each node executes its own internal processes. Data related with the events and/or generated after the processes are written into text files. *Location Manager* is used only in simulations when there are mobile nodes. Location manager calculates the location of a node for the next second and carry forward to that location in the next second. Initially, all nodes in the simulation are deployed in the operation area randomly. Sink nodes are positioned optimally, e.g. single sink is centered in the operation area.

The packet generation probabilities are taken from [17]. Those were a result of a statistical study described in [17]. However, some exceptions to regular packet generation are needed to provide a set of neighbor nodes to generate packets at the same time (or closer times). This exception will be explained in Section 5.6.1. At each generation, the source node produces a data packet and addresses it to the sink. It is assumed in [17] that the packet generations are Poisson. The exponential distribution for the packet generation interval times is the suitable one in an operation area such as battlefield.

5.1 Performance of the Proposed System

The proposed approach, SWR, is a stateless geographical routing protocol which also does not require any neighborhood information. There are many geographical routing algorithms in the literature as discussed in Section 2. One of the benchmark of all geographical routing protocols is the *Greedy Perimeter Stateless Routing* (GPSR) protocol. GPSR is a stateless geographical routing protocol which does not require any routing table and uses location information for routing. However, it uses neighborhood topology information for packet forwarding in greedy manner. GPSR collects the local topology (neighborhood) information by periodic beaconing messages. In need of a packet transmission, transmitting node calculates the distances to all neighbor nodes and selects the next best node (generally, farthest node in the direction of the destination). The transmitting node addresses the packet with the next best node. Therefore, there is a great possibility to construct shortest path or close to the shortest path. Due to the short path construction, the latency is short in GPSR. The latency is primarily affected on the calculations at nodes. However, GPSR protocol suffers from the local minima problem that GPSR may not find the path even there exists. Local-minima problem is described in Section 4.2.1. To avoid the local minima problem and to recover from voids, GPSR uses the

Perimeter Approach. Periodic beaconing and Perimeter Approach causes too much energy consumption which constitutes the secondary drawback after the local minima problem for GPSR. GPSR is well known and commonly used in research studies. Almost all of the geographical routing protocols are compared with GPSR.

The most well-known routing algorithm is the flooding. It has many properties and superiorities to other protocols, but also has some drawbacks. Actually most of the routing protocols for WSN and ad hoc networks are the variants of flooding with some modifications and optimizations. Flooding is a simple routing protocol. The received packet is rebroadcasted again. To avoid the repetitive transmissions of the same packet, a simple table is kept at nodes about the transmitted packets. With these approaches, flooding is the *simplest stateless routing protocol* in the literature. It does not require any routing table. Rebroadcast of every received packet travels all over the network if there is not any hop limit. The original data packet traverses on every path in the network including the shortest one. Therefore, *flooding is the most reliable routing protocol*. It is very convenient to use flooding in emergency conditions due to its reliability property. Main drawback of flooding is its huge resource consumption. Dissemination of every packet throughout the network consumes energy and CPU time, overflows buffers, and consumes bandwidth inefficiently. SWR is compared with GPSR and flooding. Reasons for this selection is described as follows. The proposed approach SWR is compared with GPSR, because they are both stateless geographical routing protocols. They both use the geographical information (location) for routing. Moreover, GPSR is a benchmark protocol commonly used for comparisons in WSN. Comparing a new proposed geographical approach with GPSR makes the relative comparison possible with other proposed geographical routing protocols in the literature. Same reasons are valid for flooding also. The proposed approach SWR and the GPSR both use a similar greedy approach for routing. In GPSR, only the best next node is selected (allowed) to forward the packet, while many next nodes are allowed in SWR. Therefore, multiple paths are constructed in SWR with respect to only one path in GPSR. There are some other differences between the GPSR and SWR, these differences are defined in simulation results.

The proposed approach, SWR, is compared with the flooding because there are many similarities between these two algorithms. Flooding requires no routing table and no topology information. Therefore, it is the simplest stateless routing protocol. In this respect, SWR is very similar to flooding. Actually, SWR can be considered as *flooding with constraints*. Both protocols use broadcasting for packet forwarding. However, in SWR, only a portion of the receiving nodes relay the received packet while most of the nodes in flooding relay the received packet. Both SWR and flooding carry the data on multiple paths. In flooding, at least one of them is the shortest path. However, in SWR it is not always true that one of the paths is the shortest one. In flooding packet is forwarded over every possible path. Therefore, if there is an existing path to the destination, it is found in flooding. Secondly, the latency between the source and the destination is the minimum in flooding. In SWR, in spite of the data is carried on multiple paths, due to greedy approach to decrease retransmissions in packet forwarding, the ordinary routing approach may fail to find a circumventing path. Then, in SWR, such problematic paths can be found by changing the parameters such as the threshold value or the weight value (pushing a fake weight value into the packet). In such situations, applied recovery approaches in SWR may cause extra delay with respect to the delay in flooding. Flooding is reliable routing protocol and guarantees the delivery of the packets. However, it consumes excessive amount of energy to do so. The motivation in SWR is to provide reliability and guarantee the data delivery to the destination similar to flooding but also provide energy efficiency. One other similarity between the SWR and flooding is that in both protocols, routing approach is very simple to implement and requires simple processors and reduced amount of memory at nodes.

The results are also compared with an imaginary routing protocol which is called as *virtual optimal routing protocol*. It is assumed in this protocol that it has not any routing overhead and the data packets are carried over optimal path towards the destination. Therefore, the transmissions and the energy consumption will remain minimal. Such a protocol provides a good comparison about effectiveness of the proposed protocols by also comparing other performance metrics. Performance degrades of the proposed protocols with respect to virtual optimal routing protocol presents the tradeoff to achieve the goal of the system in real conditions. In this virtual protocol, the following assumptions are made;

- Nodes do not consume energy for topology learning,
- Energy is only consumed in data packets transmissions and receptions,

- All nodes always know the optimal path to the destination.

In simulations, protocols are experimented with 10 different scenarios presented in Table 5.1. Parameters for the scenarios are subject to observe the performance of the system in different conditions. On the other hand, scenarios are designed to observe different performance metrics such as scalability, to observe the behavior of the system in multiple-sink usage, to observe the enhancements in mobile sink usage, and effects of the mobile environment. Succeeding scenarios are hardened to observe some deficiencies if there are any.

In scenarios from 1-2, and 7-10, nodes are regularly distributed and in scenarios from 3 to 6, nodes are randomly distributed in a well-defined topology [52]. Network is designed with the methodology defined in [20]. Randomly generated, UDP based Constant Bit Rate (CBR) traffic is used for evaluations. Nodes randomly generate 128 Byte payloaded packets with a probability of 0.05 packet/min. Parameters for simulations are selected to be very commonly used ones. Aim of the parameter selection is to make the obtained results of simulations to be comparable with the other proposed protocols in the literature. There is no packet loss due to transmission collisions in the simulation environment.

In scenarios 4 and 5, mobile nodes are used. Nodes' individual movement is based on the Random Walk Mobility Pattern. For group mobility, Reference Point Group Mobility Model is used. In Scenario 4, nodes move with a low speed to resemble the movement on sea surface. The speed of nodes varies randomly between 0-5 meters per minute. Group mobility is 2 meters per minute toward the general east direction. Sink node always move to the center of the group where the optimal place is. Direction of the nodes varies randomly within the 30 degree sector centered with the group's general direction. Speed and direction of the nodes and group are determined to simulate the movement of sensor nodes over the sea surface. It is assumed that nodes movement is affected only from the current and wind, but not significantly. According to the given parameters, a node moves on the sea surface with a speed of 0-0.13 knots (miles per hour).

In Scenario 5, highly mobile nodes are used. The speed of nodes varies randomly between 0-60 meters per minute. Group mobility is 30 meters per minute toward the general east direction. Sink node always move to the center of the group where the optimal place is. Direction of the nodes varies randomly within the 180 degree sector centered with the group's general direction. Speed and direction of the nodes and group are determined to simulate the movement of sensor nodes over the sea surface when the effect of current and wind is very high. According to the given parameters, a node moves on the sea surface with a speed of 0-2 knots (miles per hour).

Scenario 10 is used to observe the results in special topology which has voids and dense sub areas. In a natural environment, such as terrains, there are hills and holes. When nodes are randomly distributed over such an operation area from an aircraft, nodes falling over the hills will roll down to the foot of hills, and nodes falling into the holes will gather near the center of the holes. To simulate such a topology, Scenario 10 is used.

To provide the double range property, nodes have a *sensing range* (R_s) 50 meters and a *transmission range* (R_c) 100 meters ($R_c/R_s = 2$). The parameters for GPSR are obtained from the results of [20] with 1 second periodic beaconing (Table 5.4). Default threshold value for SWR protocol is set to $R_c/2$. The proposed results are the averages of 10 runs of 900 seconds simulation periods. Energy consumption values for receiving and transmitting states are *1.05 joules* and *1.4 joules*, respectively. At the startup of the simulation, 2000 joules is given to each node. Most of the simulations are evaluated with these values. However, to be able to observe some performance metrics in some simulations, it is assumed that nodes have unlimited energy capacity.

Mainly focused performance metric is the energy consumption. The total energy consumption of the system is observed with the changing parameters of the system, such as node density and the threshold value. Detailed results are retrieved as energy consumption in transmission and receive processes for the routing, measurement of the network lifetime, comparison of the remaining energies of the nodes and the system.

Different factors are considered and used to see the effects on the performance of the system. In performance evaluations, the following metrics are used;

- Energy consumption in routing,
- Network lifetime,
- Routing overhead (in bytes and in number of packets)

- Route acquisition latency (in milliseconds)
- Reliability,
- Guaranteed delivery,
- Route robustness (in number of hops)
- Load of components

Table 5.1: Scenarios used in simulations.

Sce. No.	# of Nodes/ Distribution	# of Sinks	Mobility	Area	Rx/Tx Energy Consumption (Joule)	Energy Capacity (Joule /Node)
1	50 Regular	1	None	300m x 500m	1.05/1.4	1000
2	100 Regular	1	None	500m x 500m	1.05/1.4	2000
3	100 Random	1	None	500m x 500m	1.05/1.4	2000
4	100 Random	1	Low	500m x 500m	1.05/1.4	2000
5	100 Random	1	High	500m x 500m	1.05/1.4	2000
6	100 Random Specially	1	None	500m x 500m	1.05/1.4	2000
7	0.0005xarea, 0.001 x area, 0.01 x area, Regular	1	None	1000mx1000m	Identical (1.4)	Unlimited
8	100 Regular	1/2/3/4	None	500m x 500m	1.05/1.4	2000
9	1600 Regular	16/32	None	2000mx2000m	1.05/1.4	2000
10	1600 Regular	16	Sinks are Mobile	2000mx2000m	Identical (1.4)	2000

Table 5.2: Parameters belong the nodes and used in all simulations.

Parameter	Value
tx range	100m
sensing range	50m
initial power	1000 joule
packet generation probability	0.05 packet/min
simulation time	900 sec

Table 5.3: Parameters for SWR used in all simulations.

Parameter	Value
Default Threshold Value	50%

Table 5.4: Parameters for GPSR used in all simulations.

Parameter	Value
Beacon Period	1 sec.

5.1.1 Default threshold value for SWR

Before testing, it would be convenient to give the reasons of selecting the threshold value as 50%. It is proven in the following sections that as the threshold value increases (limiting the number of relaying nodes), energy consumption decreases. Threshold value also affects the number of possible paths. Increasing the threshold value also decreases the number of possible multiple paths. Energy consumption and the reliability are two main performance metrics which also challenges with each other. Determination of the threshold value requires a trade off between these two performance metrics. In experiments, the default threshold value is selected as 50%. The reasons are;

- The proposed approach has the energy efficiency property. Increasing the threshold value would be unfair to other compared protocols.
- 50% threshold value provides a considerable amount of energy saving with respect to other protocols.

- Identifying the proposed approach and obtained result will be clearer with default 50% threshold value.

5.2 Energy Related Performance Metrics

In this section, energy related performance metrics are measured. The major performance metric in Wireless Sensor Networks is the energy consumption. Another important metric is the lifetime of the system. These two metrics are related with each other, but do not give the same information. Nodes may consume excessive amount of energy, however the system may continue to live by load balancing and selecting more powered nodes as transmitting nodes. In other words, the lifetime of the system may be prolonged by avoiding the transmissions of energy-limited nodes. The opposite is the other case. In spite of most of the nodes still keep a great portion of their energies; the system may fail due to very quickly energy depletion at some nodes. Therefore, these two metrics should be investigated in conjunction to understand the behavior of the system according to the energy metric.

Another energy related performance conclusion can be made by investigating the remaining energy levels at nodes. This information gives clues on node redeployment strategies. Strategies on node redeployment can be about the number of nodes to redeploy, places, frequency of redeployment, etc.

To make it clear, the following definitions are made:

- **System Energy:** Cumulative energy of the nodes in the system. At the beginning of the system, all nodes are full powered and the system has 100% of energy.
- **System Lifetime:** The lifetime of the system. It is measured from the beginning of the system until the first failure on path construction from source to the sink.
- **Remaining Energy Level:** The ratio of the energy at current time to the energy at the beginning.

5.2.1 Lifetime and energy consumption

Lifetime and energy consumption of the protocols with scenarios given in Table 5.1 is measured.

5.2.1.1 Network composed of regularly distributed stationary nodes

First simulations are carried on Scenario 1 and Scenario 2. The differences between these scenarios are the number of nodes and the size and the shape of the simulation area. In Scenario 1, 50 nodes are regularly deployed over a 300m x 500m area. In Scenario 2, 100 nodes are regularly deployed over a 500m x 500m area. It is desired to observe the effect of the shape of the operation area to the energy related metrics.

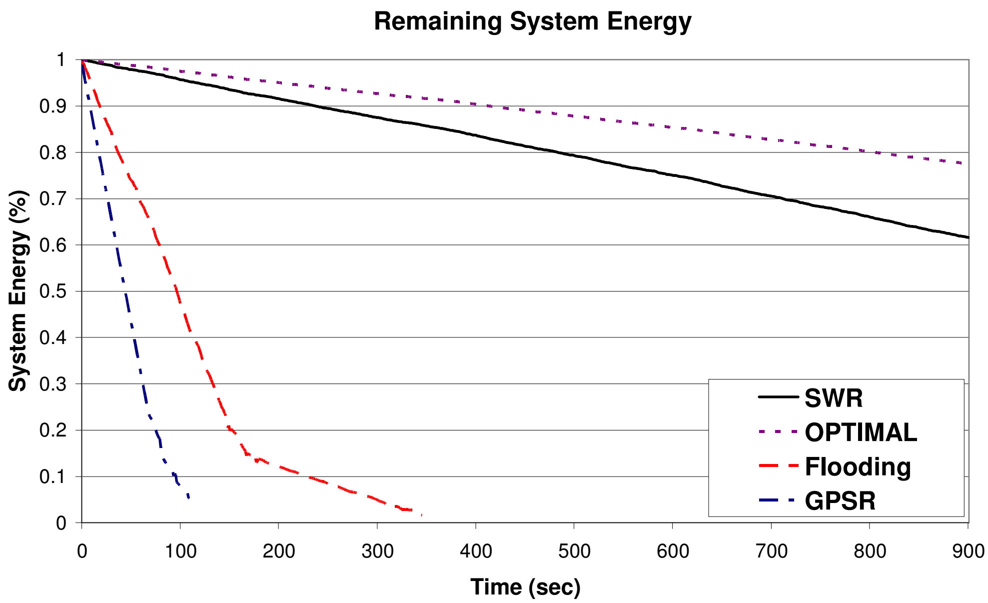


Figure 5.2: Remaining energy levels of the protocols in Scenario 1 with a single sink.

Figure 5.2 shows the remaining system-wide energy percentages according to the applied routing algorithms in Scenario 1. The *x-axis* shows the elapsed simulation time in seconds. The *y-axis* shows the remaining energy levels of the system. Only the energy consumption related with routing processes (transmissions and receptions) are considered. Other energy consumptions such as energy consumptions in MAC layer are not included. Therefore, Figure 5.2 only gives information about the energy consumptions related with the routing processes.

As seen in Figure 5.2, the *System Energy* is depleted very quickly when the *GPSR* protocol and *Flooding* is used. In GPSR, the simulation ends after 110 seconds failing to find routes (Table 5.5).

Table 5.5: Comparison of the protocol for Scenario 1.

	Flooding	GPSR	SWR
Average System Lifetime	345 sec	110sec	>900sec
Time of the First Node Termination	311 sec	80 sec	*NONE in 900sec*
Average Number of Terminated Nodes on Destination Unreachable	29	9	*NONE in 900sec*

The overall system energy of the flooding is a little better than GPSR protocol, causing the system to live longer than GPSR. GPSR depletes most of its energy at the beaconing, while the flooding depletes its energy just on routing processes. The observed system energy in GPSR protocol is according to the beaconing period with 1 second. The system will live longer in GPSR protocol when the beaconing interval is extended. SWR protocol continues to live when the simulation ends after 900 sec. The remaining system energy in SWR is higher than GPSR and flooding for each second. In SWR, the energy is consumed only in routing processes. The energy consumption decreases linearly in SWR. However, the energy consumptions in GPSR and flooding seems to decrease slowly after a sharp decrease when the system about to deplete its overall energy. The reason is that nodes begin to terminate at the break points and exhausted nodes` energy is not included to the system energy. In SWR, none of the nodes terminates at the end of the simulation and remaining system energy is 62%. When compared with the virtual Optimal Routing, energy consumption in SWR is close to the energy consumption in Optimal Routing. Beaconing period of 1 second in GPSR protocol is a commonly used one. Beaconing protocols always consumes extra energy with respect to reactive stateless protocols for the provision of neighborhood information. Flooding should be the most energy consuming protocol. Indeed it is. However, in Scenario 1, the results show that flooding lives longer than GPSR. One reason of such controversial results is the number of nodes in the system. When the number of the nodes increased in the system, flooding will perform worse than GPSR. Supporting results are observed in other scenarios.

It is concluded from Table 5.5 that nodes fail to find routes when some nodes terminate due to energy depletion. Node terminations compose gaps in the topology. However, paths are constructed when the gaps are small or when there are available paths. In GPSR, the paths are constructed until second 110 and the number of terminated nodes less than 9. When the number of terminated nodes reaches to 9, GPSR fails to find routes to the sink. These terminated nodes are located close to the sink node. Although there are more terminated nodes in flooding (29 terminated nodes), paths are constructed until 345th second. The reason is that, every possible path is tried in flooding. Another reason is that GPSR consumes most of its energy in beaconing. Nodes consume almost equal energy for beaconing in GPSR. Besides that nodes closer to the sink deplete energy more quickly because paths toward the sink involve these nodes. Thus, nodes close to the sink depletes earlier than other nodes, composing a gap surrounding the sink. However, in flooding, nodes deplete their energy almost equally, because every node equally involves in routing. Supporting results are observed in Figure 5.3-Figure 5.5.

Figure 5.3 and Table 5.5 should be investigated together. It is seen in Figure 5.3 that when the GPSR fails to find any route at 110th second, the other nodes almost have depleted their energies. This means that energy consumption has been diffused allover the system. If the lifetime of the system has been prolonged a few more seconds, almost all of the nodes would terminate. If a redeployment mechanism exists, all of the nodes must be replaced with the new ones. Although the nodes in flooding have higher energy levels than GPSR (Figure 5.4) at this moment, similar results to GPSR are observed in flooding. Due to flooding, all nodes participate equally to the routing process. This makes the nodes have almost equal energy levels. On the contrary, in SWR, all nodes have higher energy levels with 90% (Figure 5.5). The reason is that only a portion of the nodes are involved in routing in SWR.

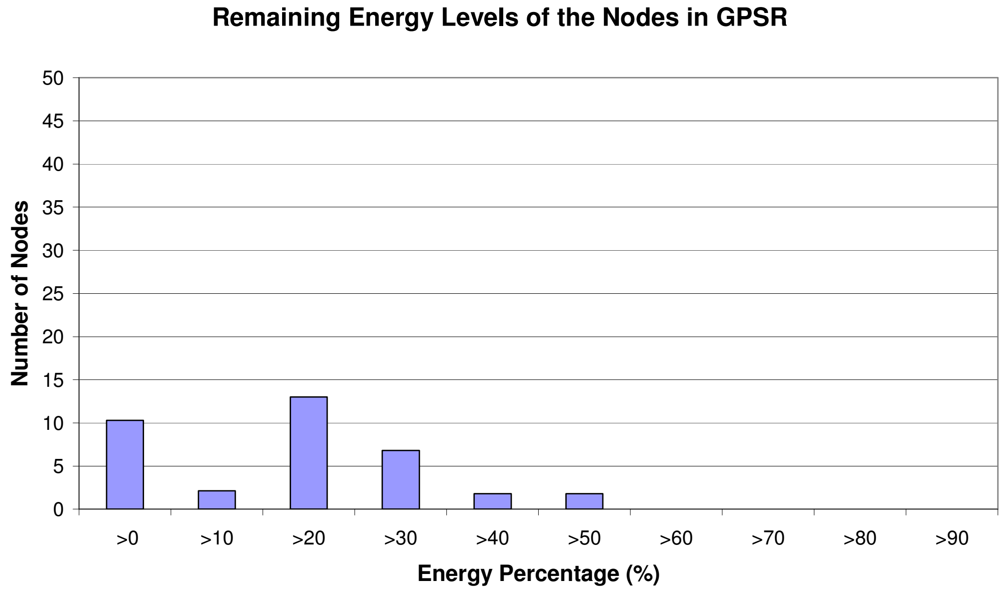


Figure 5.3: Remaining Energy levels of the nodes in GPSR when the GPSR protocol fails to find a route at time 110 sec.

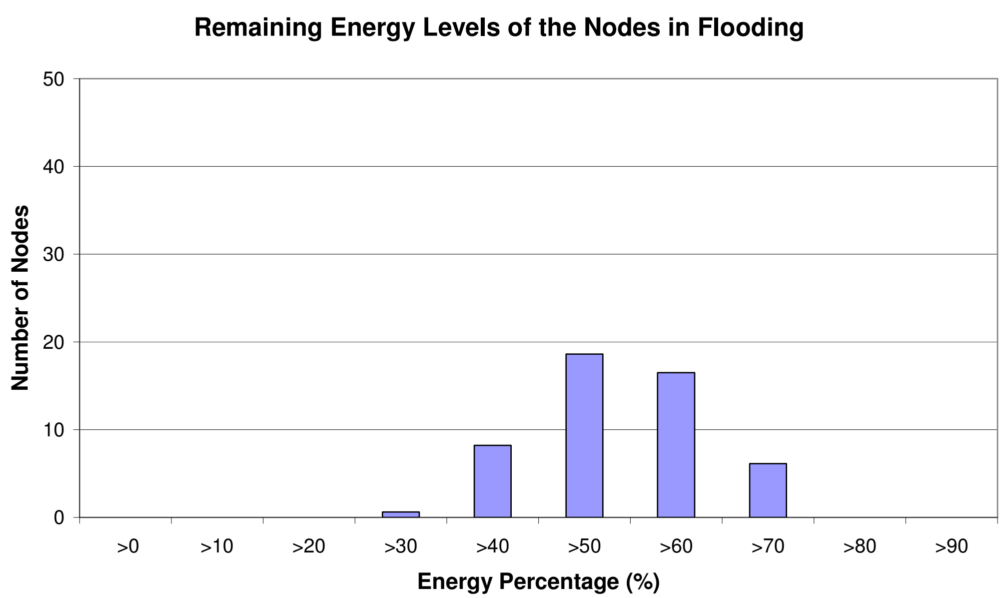


Figure 5.4: Remaining Energy levels of the nodes in flooding when the GPSR protocol fails to find a route at time 110 sec.

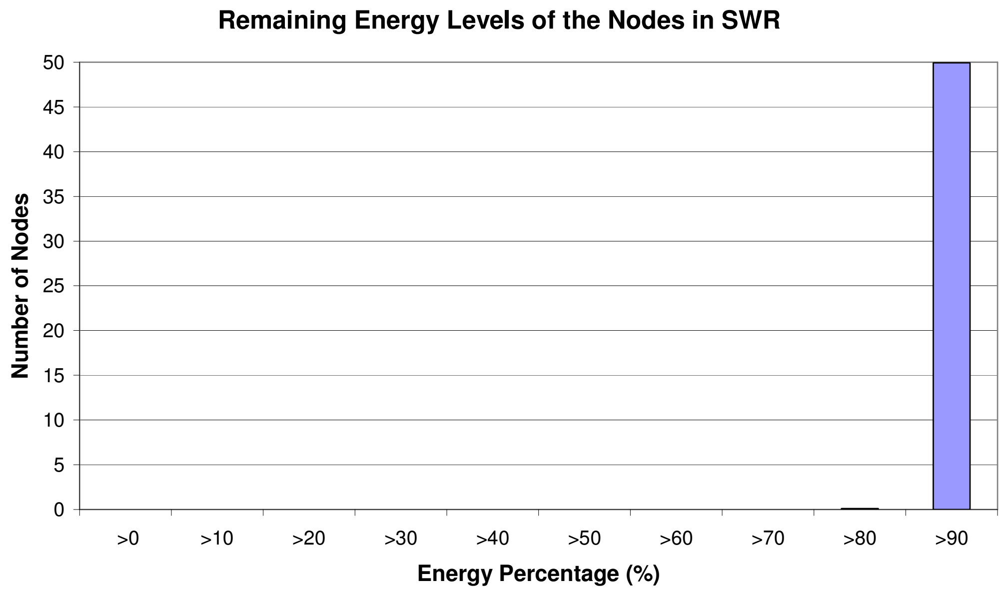


Figure 5.5: Remaining Energy levels of the nodes in SWR when the GPSR protocol fails to find a route at time 110 sec.

The same results can be observed in the Figure 5.6-Figure 5.7, when the flooding fails to find a route at 310 sec. It is seen in Figure 5.6 that almost all nodes deplete their energy in flooding. However, in SWR, 98% of the nodes have energy level higher than 80% (Figure 5.7).

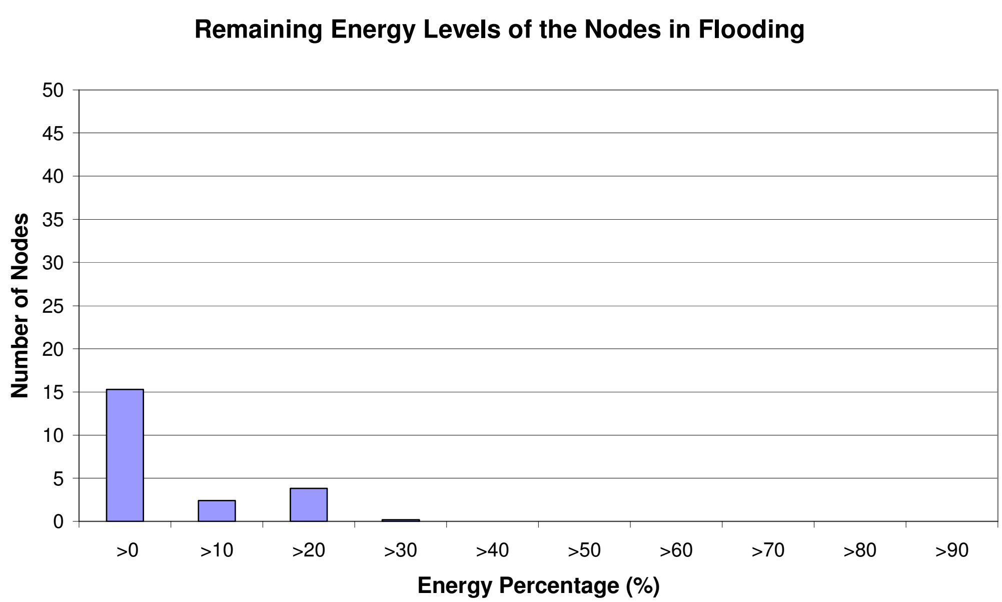


Figure 5.6: Remaining Energy levels of the nodes in flooding when the flooding protocol fails to find a route at time 310 sec.

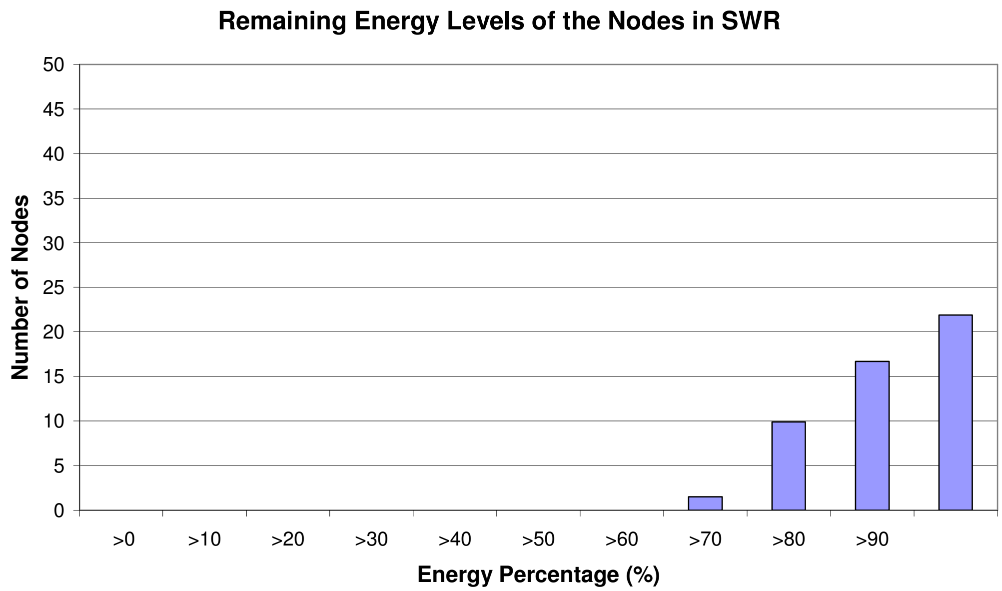


Figure 5.7: Remaining Energy levels of the nodes in SWR when the flooding protocol fails to find a route at time 310 sec.

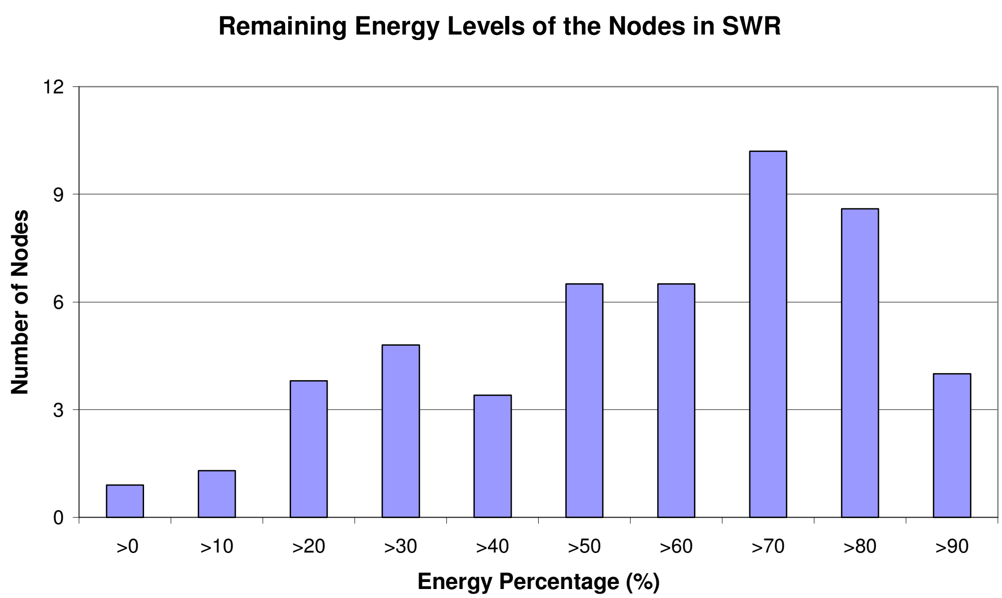


Figure 5.8: Remaining Energy levels of the nodes in SWR when the simulation ends at time 900 sec.

In Scenario 2, the number of sensor nodes in the system is increased. 100 nodes are deployed in the operation area. The results are presented in Figure 5.9 and Table 5.6.

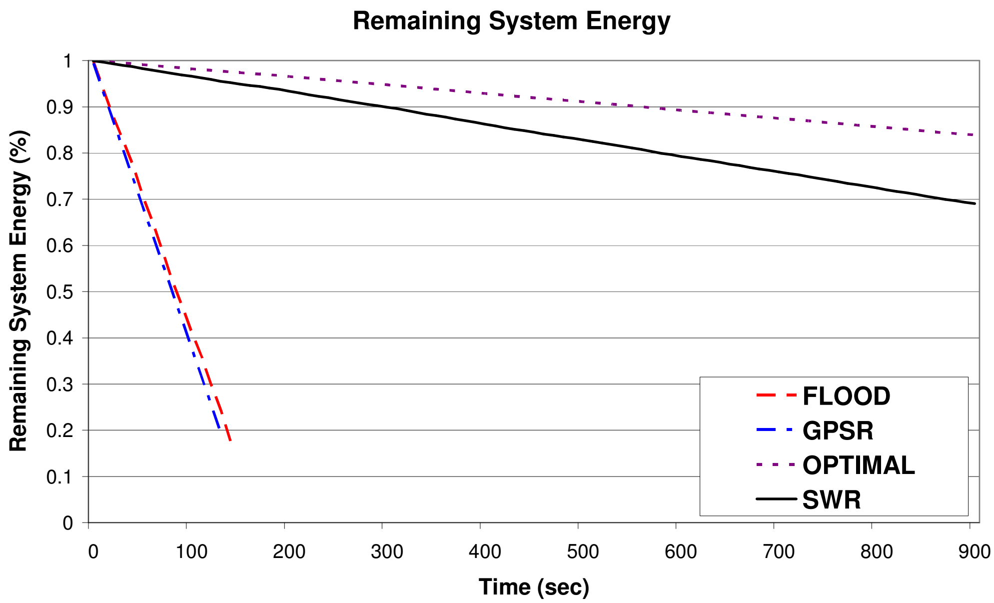


Figure 5.9: Remaining energy levels of the protocols in Scenario 2.

Table 5.6: Comparison of the protocols for Scenario 2.

	Flooding	*GPSR*	*SWR*
Average System Lifetime	*141 sec*	*139 sec*	*> 900 sec*
Time of the First Node Termination	*136 sec*	*132 sec*	*NONE in 900 sec*
Average Number of Terminated Nodes on Destination Unreachable	*35*	*9*	*NONE in 900 sec*

As stated before, increase in the number of nodes in the network in flooding causes the system depletes the energy more quickly. In Figure 5.9, it is seen that remaining system energy in flooding and GPSR are almost equal. The lifetime of the system is very close at both protocols as given in Table 5.6. A conclusion similar to the given one according to the results of Table 5.5 can be given in Table 5.6. Average System Lifetime in GSPR remains almost the same while Average System Lifetime in flooding reduces with respect to Scenario 1. Increase in the number of nodes in the network affects the performance of flooding. However, no performance degradation is observed in SWR. In fact, there is an increase from 62% to 69% in Scenario 2 with respect to Scenario 1. The reason of the increase is related with the shape of the area.

Due to the rectangular shaped area, less number of nodes are disseminated away from the sink in Scenario 1 with respect to Scenario 2. In Scenario 2, the area is square-shaped so number of close and distant nodes is more balanced in Scenario 2. Probability of transmission of a far-end node is the same as the probability of transmission of a closer node to the sink. Therefore, it is better to use square-shaped area in SWR. As seen in Figure 5.2 and Table 5.9, SWR protocol overflows the others. SWR protocol has not any node termination within the simulation time. Paths are constructed until the end of the simulation. When the simulation ends at 900th second, the system preserves its energy at 69%. It is very high for a 900 second period. On the other hand, energy consumption in SWR is very close to the Optimal Routing. When the other protocols (GPSR and flooding) deplete their energies and fail to find any route at second about 140, they have the system energy of 17.5%. However, at that time, SWR has the system energy of 95%, and Optimal Routing has 97.5%.

5.2.1.2 Network composed of randomly distributed stationary nodes

Furthermore, Scenarios from 3 to 5 is used to observe the performance in different environmental conditions. In these scenarios 100 nodes are randomly deployed over a 500m x 500m area. In Scenario 3, nodes are stationary; in Scenario 4, nodes have low mobility; in Scenario 5, nodes have high mobility.

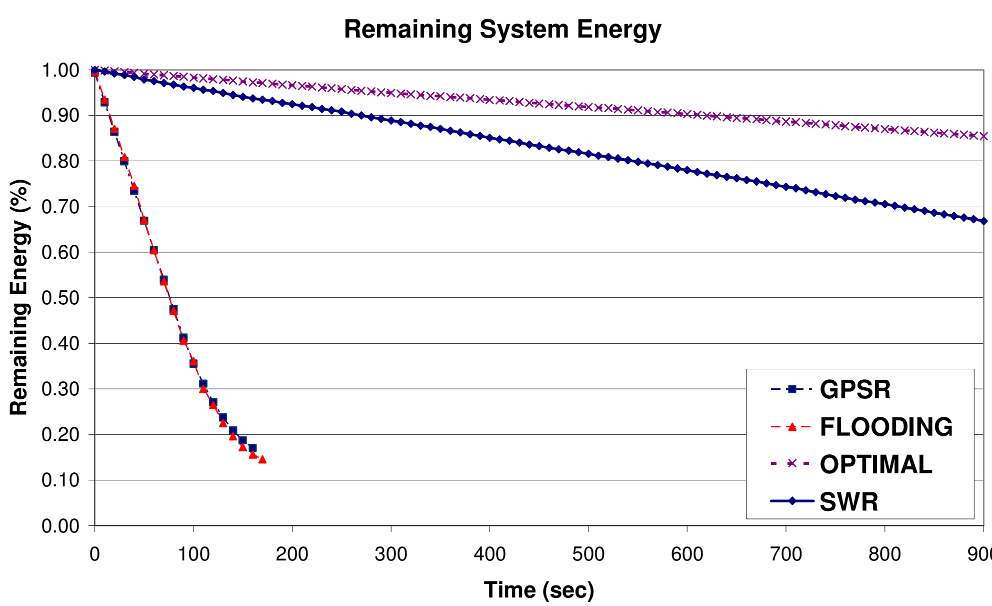


Figure 5.10: Remaining energy levels of the protocols in Scenario 3.

Table 5.7: Comparison of the protocols for Scenario 3.

	Flooding	*GPSR*	*SWR*
Average System Lifetime	*181 sec*	*150 sec*	*> 900 sec*
Time of the First Node Termination	*109 sec*	*106 sec*	*891 sec*
Average Number of Terminated Nodes on Destination Unreachable	*34*	*21*	*NONE in 900sec*

Figure 5.10 shows the remaining energy levels of the protocols in Scenario 3. It is seen that the results are similar to the results in Scenario 2. Other results are presented in Table 5.7. There is only a small lifetime improvement in GPSR and flooding with respect to Scenario 2. However, node terminations occur earlier than Scenario 2 for all protocols. Reasons can be explained as follows. In Scenario 2, nodes are regularly distributed over the operation area. Each node except the boundary nodes has 12 neighbor nodes. Therefore, in flooding and GPSR, neighbor nodes consume the receiving energy at each transmission. Nodes consume the energy as similar amounts. Only the nodes on the route toward the destination and their neighbors in GPSR consume some extra energy on data packet transmissions. As a result nodes close to the sink terminate at first in GPSR. Node terminations in Scenario 1 (is an example to regularly distributed topology) are shown in Section 5.4. After the termination of 9 nodes in GPSR for Scenario 2, the paths are not constructed. Due to the regularly deployed nodes with equal distances between each other, these 9 terminated nodes which were located around the sink node, avoids the path construction making a hole around the sink.

On the other hand, in Scenario 3, nodes are distributed randomly. Distances between nodes are not regular. Therefore, energy consumption at each node is not regular. Nodes which have more neighbors will consume more energy than the ones which have fewer neighbors. On the other hand, nodes close to sink are not regularly deployed around the sink. Nodes on the way toward the sink are used more frequently, that they terminate earlier than the regularly distributed nodes. Therefore, node termination is Scenario 3 is earlier than Scenario 2. However, the lifetime is extended. The reason is related with the number of terminated nodes before the simulation ends. Due to the regular distribution in Scenario 2, terminated nodes avoids the packet to be relayed to the sink causing the simulation end. In Simulation 3, unequally energy consumed nodes causes some nodes live longer than others. On the other hand, irregular distribution enables to select new nodes close to the terminated nodes. Therefore, gaps around the sink node are formed after more node terminations in Scenario 3 with respect to Scenario 2. In Scenario 3, 21 nodes terminate when the path is not found while there are only 9 node terminations in Scenario 2. These results extend the lifetime in Scenario 3 with respect to Scenario 2.

Random distribution affects SWR similar to GPSR and flooding. In some experiments of SWR in Scenario 3, node terminations are observed. Node termination happens about to completion of simulation. The reason is the effects of random distribution described above.

5.2.1.3 network composed of randomly distributed low mobile nodes

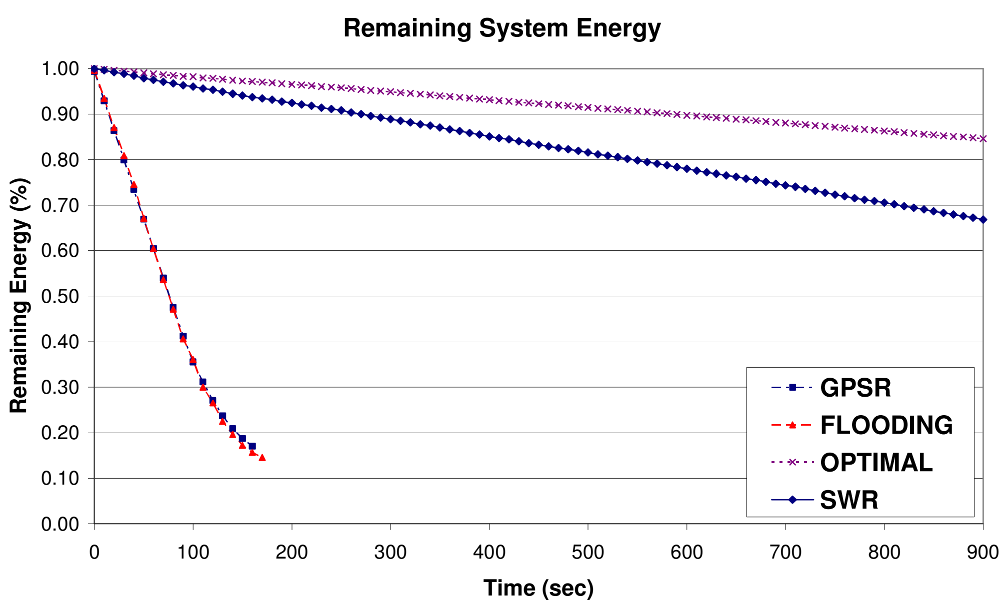


Figure 5.11: Remaining energy levels of the protocols in Scenario 4.

Table 5.8: Comparison of the protocols for Scenario 4.

	Flooding	*GPSR*	*SWR*
Average System Lifetime	*177 sec*	*149 sec*	*> 900 sec*
Time of the First Node Termination	*106 sec*	*104 sec*	*836 sec*
Average Number of Terminated Nodes on Destination Unreachable	*33*	*20*	*NONE in 900sec*

As seen in Figure 5.11 and Table 5.8 that there is not much difference between the results of Scenario 3 and Scenario 4. The only difference is the small amount of lifetime shortening in GPSR and flooding. The reason is about the mobility of nodes. In Scenario 4, nodes have low mobility. The distance between the previous and current positions at each time unit is very short. However, there is a difference with respect to the stationary nodes. Therefore, low mobility effects the lifetime a poor amount in GPSR and flooding. First node terminations and number of the terminated nodes are almost the same. On the other hand, SWR presents the same performance in Scenario 4. It is not affected from low mobility.

5.2.1.4 Network composed of randomly distributed high mobile nodes

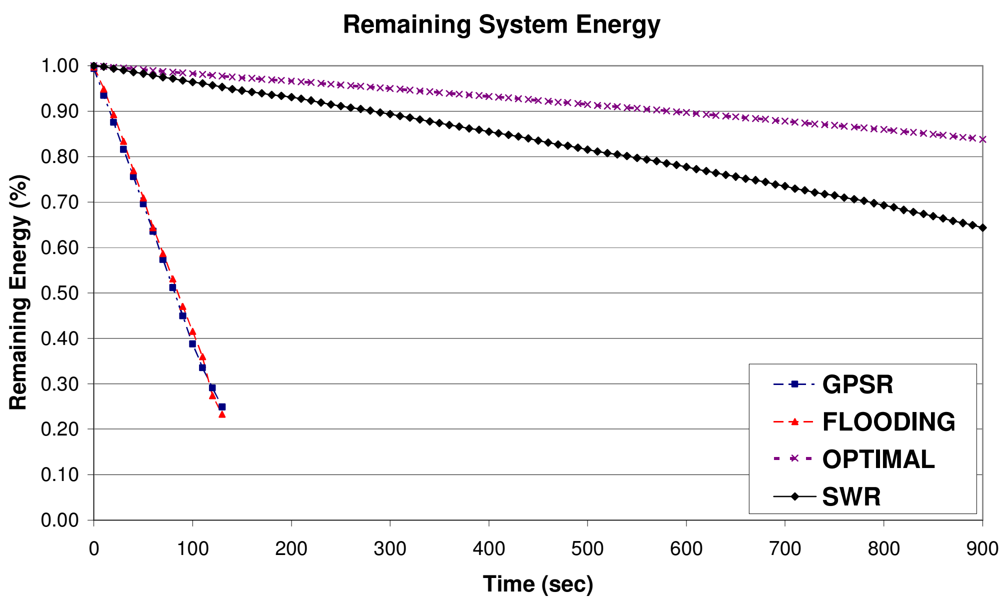


Figure 5.12: Remaining energy levels of the protocols in Scenario 5.

Table 5.9: Comparison of the protocols for Scenario 5.

	Flooding	*GPSR*	*SWR*
Average System Lifetime	*148 sec*	*145 sec*	*> 900 sec*
Time of the First Node Termination	*102 sec*	*101 sec*	*865 sec*
Average Number of Terminated Nodes on Destination Unreachable	*28*	*18*	*NONE in 900sec*

The effects of high mobility to the performance of the protocols is seen in Scenario 5 (Figure 5.12 and Table 5.9). Lifetimes of both the GPSR and flooding decrease. The main reason is related with the high mobility. Due to high mobility, nodes introduce gaps in the topology. When the node terminations begin, these gaps enlarge and path construction becomes impossible. It is seen in the results of flooding. In flooding, all paths are tried to reach the destination. However, it is seen that after 28 node terminations and due to high mobility, flooding fails to find any path toward the destination. Therefore, lifetime decreases even fever nodes terminate with respect to Scenario 3 and 4. SWR continues to find paths until the completion of the simulation. It is not affected from the mobile environment. The main reason is the similarity of SWR to flooding on path construction.

5.2.1.5 Specially distributed network with stationary nodes

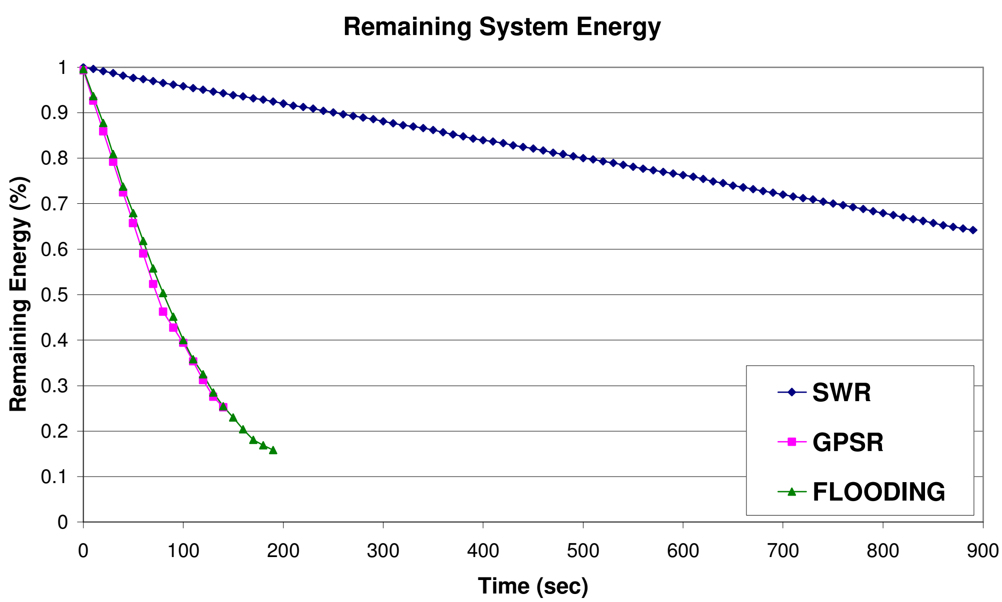


Figure 5.13: Remaining energy levels of the protocols in Scenario 6.

Table 5.10: Comparison of the protocols for Scenario 6.

	Flooding	*GPSR*	*SWR*
Average System Lifetime	*201 sec*	*146 sec*	*> 900 sec*
Time of the First Node Termination	*84 sec*	*80 sec*	*753 sec*
Average Number of Terminated Nodes on Destination Unreachable	*42*	*25*	*NONE in 900sec*

Figure 5.13 and Table 5.10 shows the results for specially designed topology which has a void and a densely deployed node consisting sub-area. It seen that results are very different than other results. First, nodes begin to terminate earlier in Scenario 6. The reason is about the densely deployment of nodes in the sub-area in addition to the effects of random distribution. In densely deployed area, nodes deplete their energies earlier than others. Therefore, these nodes terminate earlier than other nodes in the network. It is seen in Table 5.10 that there is an increase in the number of terminated nodes for GPSR and flooding when the destination is not reachable. Terminated nodes in the densely deployed sub-area do not affect the route construction. Paths are constructed until the occurrence of a void around the sink node. The effects of dense deployment of nodes in sub-area also affects the SWR protocol. Node terminations occur in some experiments in SWR. During the simulation, in few experiments, one node is terminated due to the reasons given above. However, SWR continues to live until the completion of simulations.

5.2.2 Effects of node density

Many routing protocols suffer from the density of the network; because increase in density introduces more overhead and nodes consume more energy. Therefore, it is expected from routing protocols not to suffer from node density. Some protocols in the literature fail or collapse the system due to introduced overhead in dense environment. Therefore, some protocols are especially designed for dense environment. However, some of such protocols also suffer from the non-dense environment. Hence, there is always a need for a routing protocol that works at both dense and non-dense environments.

Therefore, SWR and other protocols are tested in varying density environments. Scenario 7 is used for this purpose. Number of the nodes in the unit area is increased to observe the effects of node density. As stated previously, it is expected from flooding to present worse performance in dense environments. Secondly, routing algorithm of SWR causes more nodes to relay the received packets. The transmitting nodes remain in a symmetric pedal curve shape given in Figure 3.17. Increase in the node density increases the number of the nodes remaining in that shape, which may affect the energy consumption negatively. Therefore, the behavior of SWR is observed in dense environments.

In Scenario 7, to be able to observe and compare the effects of node density, unlimited energy is given to each node. Other parameters are as given in Table 5.1-4. Results of energy consumption with different node densities are presented in Figure 5.14 to Figure 5.17. The *x-axis* shows the elapsed simulation time in seconds. The *y-axis* shows the system-wide energy consumption in joules. Only the energy consumption related with the routing processes (transmissions and receptions) are considered. Note that the *y-axis* is in logarithmic scale. It could not be comparable if logarithmic scale would not be used. Figure 5.14 shows the energy consumption for GPSR. It is clear that as the node density increases, energy consumption increases.

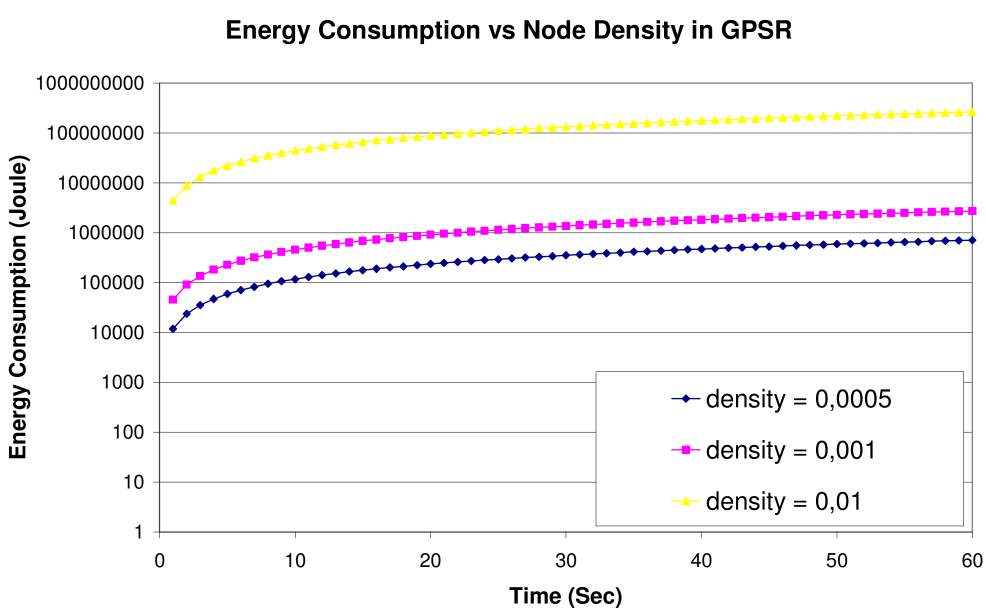


Figure 5.14: Energy consumption for GPSR protocol with different node densities. It is used to observe the effect of node density to energy consumption.

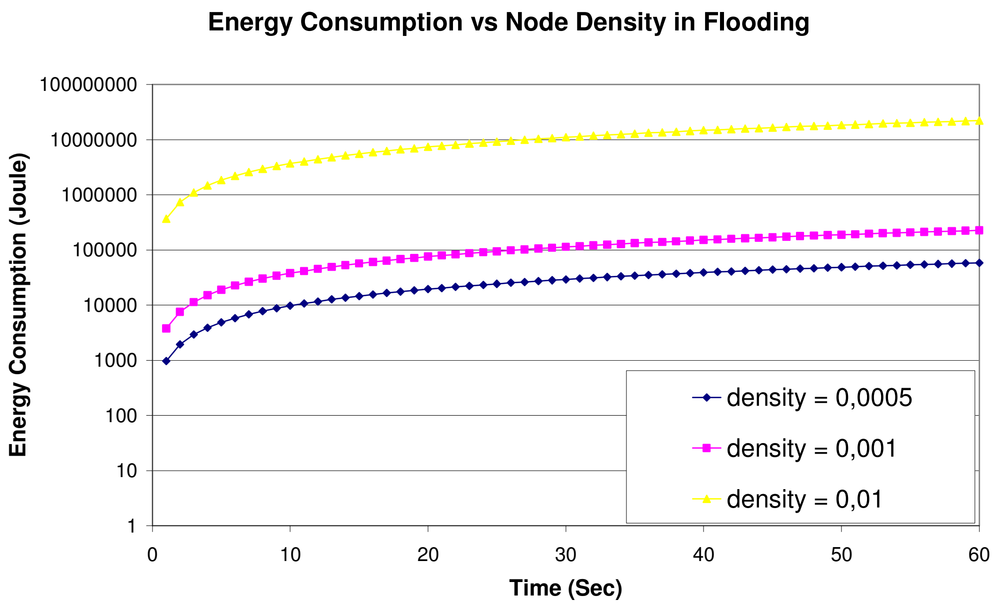


Figure 5.15: Energy consumption for flooding with different node densities.

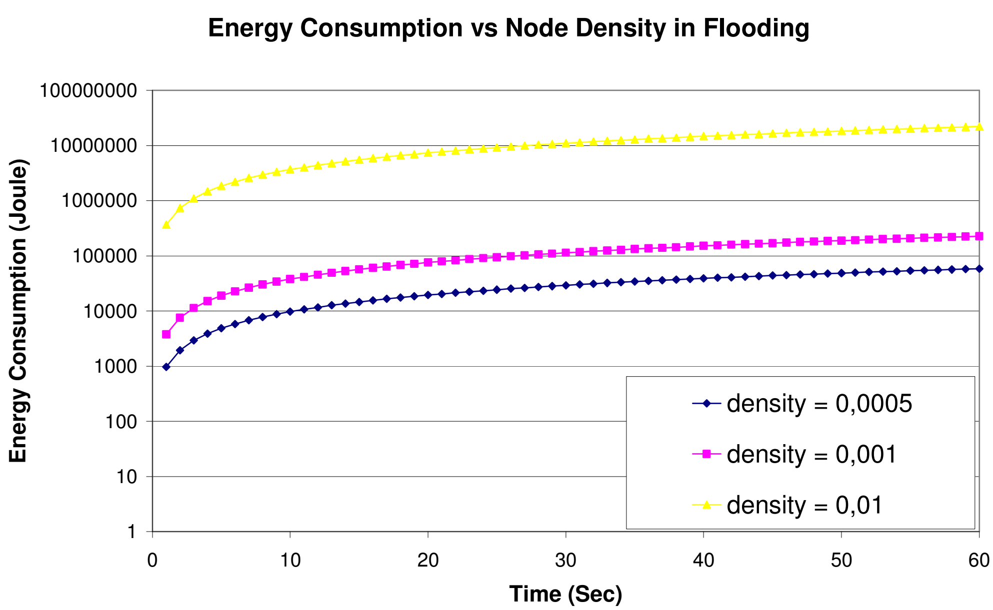


Figure 5.16: Energy consumption for SWR protocol with different node densities.

Similar results are observed for flooding and SWR (Figure 5.15 and Figure 5.16). The difference between all these figures is the amount of consumed energy that is shown in *y-axis*. For the node density 0.0005, GPSR consumes 11701 joules during the first second, flooding consumes 974 joules during the first second, and SWR consumes 111 joules during the first second. When the simulation proceeds, the total energy consumption for GPSR becomes 702085 joules, for flooding 58477 joules, and for SWR 6712 joules until the sixtieth second. There are a great amount of energy consumption difference between the SWR and the other protocols. The difference is as high as that GPSR consumes 100 times more energy than SWR.

Effects of node density to SWR protocol is not more than other protocols. In fact, the effect remains at a moderate level with respect to other protocols. On the other hand, the amount of consumed energy can be decreased by changing the threshold value.

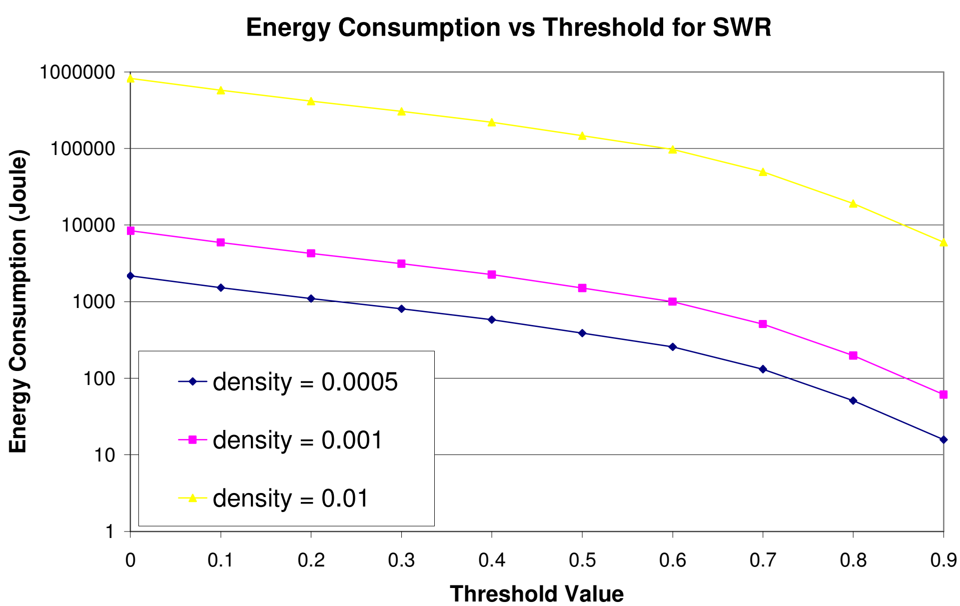


Figure 5.17: Effects of the threshold value and the node densities to the energy consumption in SWR.

Increasing the threshold value reduces the number of retransmissions, as described in Section 3. Therefore, SWR protocol enables a great flexibility to be adapted according to the environment whether the environment is dense or non-dense. Figure 5.17 shows the energy consumption with different threshold values for SWR. The x-axis shows threshold values applied in routing algorithm for SWR. The y-axis shows the system-wide energy consumption in joules. Only the energy consumption related with the routing processes (transmissions and receptions) are considered. Note that the y-axis is logarithmic scale. It is seen in the figure that increasing the threshold value decreases the energy consumption. The amount of energy saving is very high when a higher threshold value is used. For the density 0.005, the amount of energy consumed with threshold value 0.5 is 388 joules, and with threshold value 0.9 is 16. There is a 95% energy saving with these values.

When the density of the network increases, it becomes more noticeable. For the density 0.001, the amount of energy consumed with threshold value 0.5 is 1509 joules, and with threshold value 0.9 is 61 joules. For the density 0.01, the amount of energy consumed with threshold value 0.5 is 146706 joules, and with threshold value 0.9 is 5956 joules. The amount of energy saving is 96% with these values.

5.2.3 Effects of range and threshold values to energy consumption

In SWR, is a great amount of energy can be saved by adjusting the threshold value. Therefore, the threshold value can be changed according to the current needs. In cases of void recovery, higher reliability and guaranteed delivery requirement, urgent or real-time data requirement etc., the threshold value can be reduced for that event. After the completion of the event, the threshold value can be adapted again to save energy. These adaptations do not require any central authority or do not need any approve from somewhere else. Adaptations occur in a distributed manner. Each node itself decides to increase or decrease the threshold according to the current conditions. However, in case of preknown information about the topology or in case of required satisfaction for some metrics such as reliability, the threshold value can be set to a default value. It can be set again to the predefined threshold value after the adaptations as needs according to the current environment as described above.

One another parameter which affects the energy consumption is the range of the transmissions. This effect is different than path loss effect described in Section 4.1. As range increases, more nodes receive the transmissions which increase the system-wide energy consumption. On the other hand, increase in range may cause shorter paths to be constructed, which reduces the energy consumptions in transmissions and receptions. Therefore, the effect of range to the energy consumption is investigated. SWR protocol uses the threshold value that affects the reliability and energy consumption. Thus, it is better to investigate these two parameters together. One important fact should be pointed out that nodes cannot change their transmission range. Transmission range is related with the hardware of the transmitter of the nodes and assumed as fixed. What a node can change is only the threshold value in SWR. There are some techniques to adjust the transmission range of the transmitter according to the known distance of the receiver. However, in SWR, nodes do not have any information about the topology nor neighbor nodes. Therefore, usage of adaptive transmitter is useless for SWR.

First, the effects of range and threshold value are shown on separate figures. Figure 5.18 - Figure 5.23 show the Relay Nodes Coverage relation with range and threshold value. The *x-axis* in these figures shows the *applied threshold value* and the *y-axis* shows the *relay node coverage reduction*. SWR protocol uses other nodes which has lower weight values to relay the data. Number of these nodes is dependent to the applied threshold value. These relay nodes remain or are located in an area shaped similar to in Figure 3.11 – Figure 3.17. Therefore, change in threshold value changes the covered area, in other words, changes the number of relay nodes.

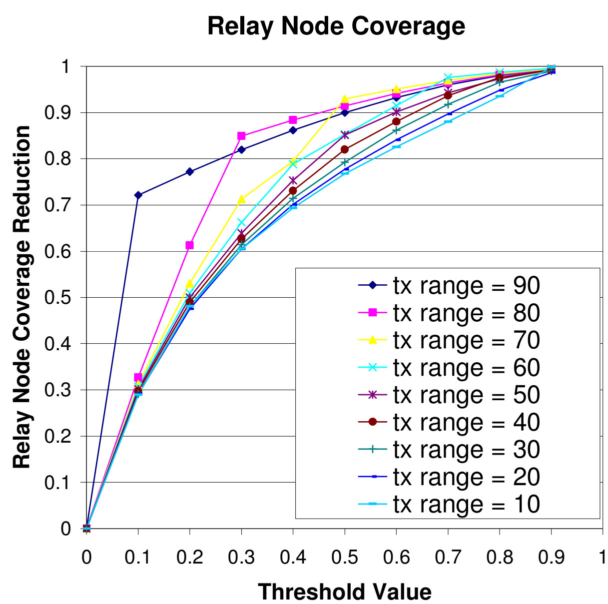


Figure 5.18: Relay node coverage area relation with different threshold and transmission range values. Distance between the source and the destination is 100 meters.

Figure 5.18 shows the Relay Node Coverage relationship for a source-destination pair 100 meters away from each other. For transmission range 90 meters (tx range = 90), data is relayed by 2 hops. With a threshold value 10%, the covered area is reduced 72% with respect to the area covered with threshold value 0%. For transmission range 80 meters (tx range = 80), data is again relayed by 2 hops. With a threshold value 10%, the covered area is reduced 33% with respect to the area covered with threshold value 0%. Other transmission ranges (tx range = 70, 60, 50, 40, 30, 20, 10) show similar results with respect to the transmission range 80 meters (tx range =80) for threshold value 10%. Secondly, transmission ranges between 70 meters and 10 meters present close reduction values for the same threshold values. However, transmission ranges 90 meters and 80 meters present a better reduction in area coverage. The reason is that with high transmission ranges in close distances between the source and the destination, some unnecessary part of the topology is covered. In other words, the data is relayed to some far way nodes from the sinks. Applying a threshold value avoids the far way nodes from the sink to be a relay node. When a smaller transmission range is used, the distance between the source and the destination is divided more equally. Therefore, when the threshold is applied, the covered area for short transmission ranges is larger than the covered area for long transmission ranges. This is similar to occupy a square shape area with smaller square shape areas. To occupy the whole area, some outer parts of the main square is also covered when a large square is used. As the occupying square gets smaller, the outer covered area reduces to minimum.

It is clear that increasing the threshold value reduces the covered area by relay nodes. It should be pointed out that there is great coverage area reduction (between 77% - 93%) even with a 50% threshold value. However, in simulations, it is found out that 50% threshold value provides a high reliability. On the other hand, increasing the threshold value makes smaller reduction in the coverage area. Therefore, 50% threshold value can be selected as default parameter.

Similar results are observed in Figure 5.19 and Figure 5.20. Figure 5.19 is for distance 80 meters between the source and the destination and Figure 5.20 is for distance 60 meters. It is deduced from these figures that applying the threshold value is more required in long transmission ranges with respect to short transmission ranges. Reducing the coverage area reduces the number of relay nodes which are located in this area. These relay nodes make transmissions; therefore there is an energy consumption reduction due to reduction in transmissions.

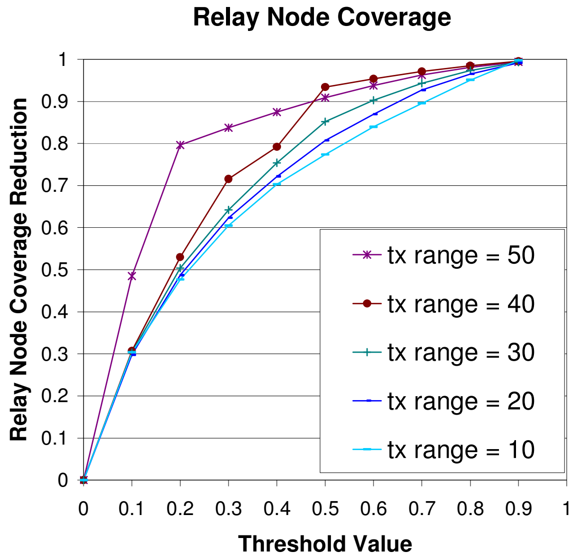
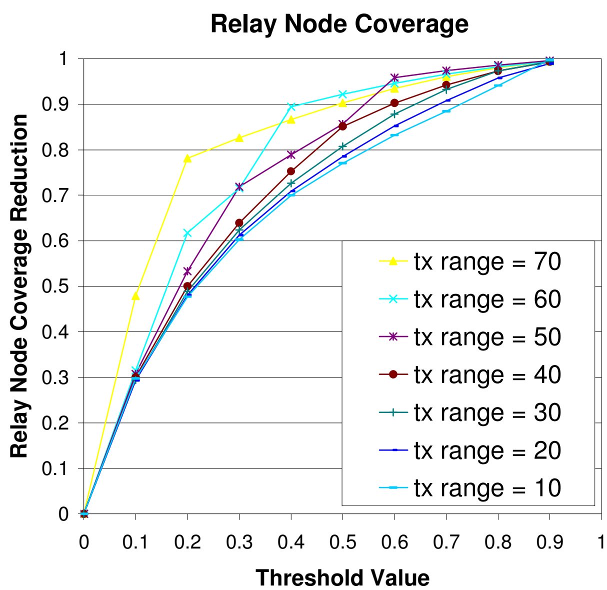


Figure 5.19: Relay node coverage area relation with different threshold and transmission range values. Distance between the source and the destination is 80



meters.

Figure 5.20: Relay node coverage area relation with different threshold and transmission range values. Distance between the source and the destination is 60 meters.

The inference related with range and threshold value given above is seen more clearly in Figure 5.21. In this figure, the effect of range and threshold value is shown together. These are the results for 100 meters distance between the source and the destination. As seen in the figure, as the threshold value increases, the energy gain increases. However, energy gain gets higher as the transmission range increases. The reason of the erratic part for ranges 90 and 80 is described above.

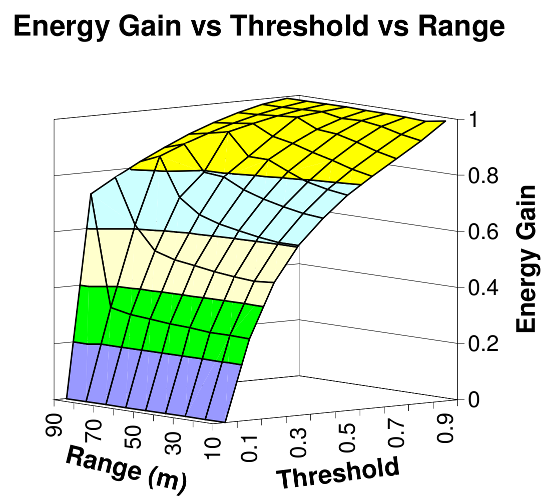


Figure 5.21: Effects of the applied threshold and transmission range to the energy gain.

5.2.4 Energy consumption per data delivery

The energy consumption on transportation from source node to destination for one data packet is also measured. Multiple receptions at the destination for the same data packet are counted as one data delivery. Table 5.11 shows the comparative energy consumptions for different path lengths for Scenario 1. In flooding, the same amount of energy is consumed for each path length. For each packet, all nodes receive the packet for several times and all nodes make transmissions. However, for GPSR and SWR, number of transmissions and receptions vary according to the path length. Therefore, energy consumptions vary for different path length for these protocols.

Energy consumption for beaconing is considered and added to the energy consumption of GPSR protocol. Otherwise, it would not be fair to compare it with SWR protocol. GPSR protocol uses periodic beaconing to construct and update the neighborhood topology. Without this proactively obtained knowledge, it is impossible to construct a path in GPSR. Therefore, energy consumption for local topology learning should be involved in the energy consumption in routing process.

Table 5.11: Comparison of the energy consumption of the protocols for Scenario 1.

Routing Protocol	Energy Consumption (Joule)					
	1 hop	2 hop	3 hop	4 hop	Arithmetic Average	Average during Simulation
Flooding	546.7	546.7	546.7	546.7	546.7	398.37
GPSR *with 1 sec. beaconing*	560.7	574.7	588.7	602.7	581.7	981.19
SWR *with 50% threshold*	14	49	84	126	68.25	41.10

As expected, GPSR and flooding exhibit the higher energy consumptions. In GPSR, beaconing consume excessive energy. On the other hand, packet forwarding consumes much less energy with respect to other protocols because shortest paths are constructed in GPSR due to priori known topology. Thus, increase in the number of hops makes small amount of additions of energy consumption with respect to the energy consumption with shorter paths.

SWR protocol consumes very much less energy for routing. The reason as stated many times is that routes are constructed on demand without any beaconing or messaging needs. The amount of consumed energy is considerably very low with respect to GPSR and flooding. However, the amount of changes in energy consumption when the path length is increased is more than the GPSR. The reason is the multiple transmissions on route constructions in SWR while there is only one path in GPSR.

Table 5.12: Comparison of the number of the transmissions of the protocols for Scenario 1.

Routing Protocol	Number of Transmissions and Receptions					
	1 hop	**2 hop**	**3 hop**	**4 hop**	**Arithmetic Average**	**Average during Simulation**
Flooding	50 tx 454 rx	50 tx 454 rx	50 tx 454 rx	50 tx 454 rx	50 tx 454 rx	41 tx 324 rx
GPSR *with 1 sec. beaconing*	51 tx 466 rx	52 tx 478 rx	53 tx 490 rx	54 tx 502 rx	53 tx 484 rx	97 tx 805 rx
SWR *with 50% threshold*	1 tx 12 rx	4 tx 42 rx	6 tx 72 rx	9 tx 108 rx	5 tx 59 rx	3 tx 35 rx

The *Arithmetic Average* values are the averages of previous columns. However, *Average during Simulation* values are the averages of the results obtained in Scenario 1. Therefore, the latter one presents the actual energy consumption during the simulations. The decrease in *Average during Simulation* with respect to the *Arithmetic Average* for flooding is caused by the terminated nodes. Flooding has the ability to find routes if there is any. Node terminations do not avoid the route construction. In Scenario 1, as shown previously in Table 5.5, flooding continues to find routes even there are many node terminations.

Supporting results are observed in Table 5.12. Flooding always makes the same amount of transmissions and receptions if there are not any node terminations. However, node terminations during the simulation reduce the number of transmissions and receptions in flooding. For GPSR, the difference between the *Arithmetic Average* and the *Average during Simulation* is result of the assumption described above. Energy consumptions on beaconing is added to the energy consumption on route construction. Depending on the beaconing period these results may change. If the beaconing frequency is decreased, GPSR will consume less energy. On the other hand, if the event generation probability is increased, the energy consumption per data delivery will decrease for GPSR. In Table 5.11 and Table 5.12, the *Arithmetic Average* values are the results of a single event after beaconing.

However, the *Average during Simulation* values are the results of events observed during Simulation 1.

Table 5.13: Comparison of the number of constructed paths per data delivery for Scenario 1.

Routing Protocol	Number of Constructed Paths per Data Delivery			
	1 hop distant	**2 hop distant**	**3 hop distant**	**4 hop distant**
Flooding	2-13	2-13	2-13	2-13
GPSR *with 1 sec. beaconing*	1	1	1	1
SWR *with 50% threshold*	1	2	2-3	3-4

Table 5.13 shows the number of paths constructed between the source and the destination. Multiple paths provide reliability. As seen in table, GPSR always finds only one path which is the shortest one. Flooding constructs 13 paths during a long portion of the simulation but when the nodes begin to terminate, number of the paths reduces. When the sink node is hardly reachable due to node terminations around sink, only two paths are constructed in flooding. In SWR, the number of the paths depends the distance between the source and the destination. If the distance is short e.g. one hop away, only one path is constructed. As the distance increases, the number of the paths constructed by multi-hopping increases. It is emphasized here that as seen in Table 5.11-Table 5.13, the number of transmissions and the energy consumption is very low in SWR with respect to others, while providing the reliability by multiple paths. Another important feature of SWR which is not shown here is that SWR has an adaptive nature. In SWR, the number of the paths depends to the requirements for reliability. Distributed and adaptive property of SWR makes itself to be adaptive for dynamic environments or unexpectable conditions such as topology changes. SWR has this property behind the properties described above.

5.3 Routing Overhead

One of the main performance metrics of the routing protocols is the overhead produced on routing. Generally, the routing overhead is considered as the ratio of the number of the control packets to the number of all packets sent. In some applications routing overhead is considered as the ratio of control packet to data packets. In some applications, it is used as the ratio of the control packets per data packet. The first definition is used for routing overhead which is commonly used in simulations. However, considering only the number of packets can be found as unfairly. For example, the number of transmitted packets is measured as given in Table 5.14. Each hop-wise transmission of a control packet is counted as one packet transmission.

Table 5.14: Comparison of the routing overhead of the protocols in number of control packets.

Routing Protocol	**Routing Overhead (%)** **(metric is number of packets)**
Flooding	0
GPSR *with 1 sec. beaconing*	97.6
SWR *with any threshold*	0

Flooding does not use any control packet for routing. Data packets are disseminated all over the network without any control. SWR has a controlled routing mechanism but it also does not use any control packet for routing. Thus, routing overhead is 0% for flooding and SWR when the number of control packets is considered as routing overhead. On the other hand, GPSR has a routing overhead 97.6% with 1 second periodic beaconing. However, the data is transmitted by all nodes in flooding while there does occur only a few data packets transmissions in GPSR. It is unfair to say that flooding has no routing overhead. Actually, each packet has a header part. Each received packet is serviced to upper network layer, header part changes, and is rebroadcasted again in flooding. To be fair in comparison, the header part of the data packets is considered as control information for routing in the following comparisons. This approach is not a new one, but most of the proposed protocols in the literature are compared with the number of control packets for routing overhead to overflow the others rather than the number of bytes used for control information. When the same approach is used, SWR is the superior one as shown in Table 5.14. Similarly, neglecting the header part of the data packets which use source routing is unfair. Therefore, the header part of the data packets is considered to be fair. Two similar methods are used. In the first one, ratio of sum of the number of bytes in the header part of the data packets and the number of the bytes in control packets to the total number bytes of the packets is considered. In the second one, ratio of the sum of number of the bytes in the header part of the data packets and the number of bytes in control packets per data is considered. The latter one is called as *Normalized Routing Load*.

Table 5.15: Comparison of the routing overhead of the protocols in number of byte.

Routing Protocol	**Routing Overhead (%) (metric is number of byte)**
Flooding	7.3
GPSR *with 1 sec. beaconing*	79.6
SWR *with 50% threshold*	12.9

Table 5.15 presents comparison according to the first method. Any byte used for controlling is considered. These are the bytes in control messages, e.g. beaconing, and the bytes included the header part of the data packet. It is seen that using the byte as metric, routing overhead of GPSR decreases with respect to Table 5.15. On the other hand, overhead of flooding and SWR increases. However, Table 5.15 does not show the exact overhead for flooding and SWR. Overhead of flooding should be much more than the SWR protocol but the contrary happens in this comparison. The reason is that the control bits are just summed and later divided with the total bits transmitted. It gives the same result when the size of header part of the packet is divided with the total size of the packet with an exception for GPSR since there are beaconing messages in GPSR. Moreover, the overhead caused by the multiple

transmissions of the same data packet in flooding and SWR is not observed in this comparison. The results are reanalyzed to provide the exact normalized routing load and are shown at Table 5.16 and Table 5.17. In Table 5.16, ratio of the total transmitted bytes to total number of successful deliveries is given. Multiple receptions at the destination for the same data are counted as one. By this way, the average transmitted bytes for a successful delivery is found. In Table 5.17, ratio of the number of control bytes including the beaconing and data packet's header part to the total number of successful deliveries is given. By this way, the average transmitted control bytes for a successful delivery is found. The difference is clarified by examining the tables.

Table 5.16: Comparison of the Normalized Routing Overhead of the protocols.

Routing Protocol	**Normalized Routing Load (in number of bytes, all packets)**
Flooding	5708
GPSR *with 1 sec. beaconing*	1467
SWR *with 50% threshold*	499

As seen in the Table 5.16, GPSR protocol transmits much more bits than other protocols for a successful delivery. This table shows that due to redundancy of the same data packets conveyed to the destination node, flooding has a routing overhead in number of bytes with respect to others. GPSR's overhead is less than flooding and greater than SWR. It is less than flooding because the whole data packet is transmitted in every transmission in flooding. However, most of the transmissions in GPSR are the beacon messages. Beacon messages only contain the *ID* of the sender and its *position*. Therefore, totally send bytes in GPSR are less than the transmitted bytes in flooding. The amount is 1/3 for GPSR to flooding. GPSR's total transmitted bytes are less than the flooding but the number of the transmitted packets is higher than flooding (Table 5.14). Therefore, GPSR consumes more energy than flooding. Flooding accomplish routing without keeping tables and without beaconing.

Therefore, it floods the data packet making many redundancies of the same packet and increasing the possibility of congestion in the network.

SWR protocol transmits much less bytes than both GPSR and flooding. SWR accomplishes this performance without keeping tables and without beaconing. On the other hand, SWR provides reliability similar to the case in flooding, but not suffer too much from redundancies. It still has a better performance than GPSR and flooding. The ratios of the values are 1/11 of flooding and 1/3 of GPSR in addition to the reliability property in SWR.

Table 5.17: Comparison of the Normalized Routing Overhead of the protocols in number of control bytes.

Routing Protocol	**Normalized Routing Load (in number of bytes, only control bytes)**
Flooding	414
GPSR *with 1 sec. beaconing*	1168
SWR *with any threshold*	65

Table 5.17 shows the average transmitted control bytes for a successful delivery. These values are measured because this table supplements the comparison given in Table 5.17. Contrary to the Table 5.17, flooding has a better performance than GPSR. The value for flooding is very low than GPSR. It is due to the beacon packets used in GPSR. SWR has the lowest overhead and outperforms the others. It has very low overhead with respect to flooding and GPSR. Especially for GPSR, SWR has transcendent. In addition to the better performance, SWR has the reliability property by providing multiple-paths.

To consider the routing overhead, in addition to the tables given above (Table 5.14-Table 5.17), Table 5.12 also should be investigated. As seen in these tables that, GPSR protocol makes many transmissions to route the data. A great portion of these packets are the beaconing messages. Beacon messages are short in length with respect to the data packet. Therefore, GPSR consumes less bandwidth with respect to the flooding. SWR protocol outperforms the other protocols at each comparison. The differences are very high in favor of SWR. In addition to the high performance of SWR, it also provides reliability by multiple paths. Data is carried on multiple paths in SWR.

On the other hand, SWR protocol has the QoS parameters to provide QoS. In these evaluations, the field used for QoS is also considered. SWR can provide priority in need for routing e.g. congestion.

SWR protocol has transcendent properties with respect to other protocols. The transmission of both the number of the packets and the number of the bytes are very low. Therefore, buffer requirement for SWR is very low. However, flooding and GPSR protocols require higher buffer sizes.

Number of the transmitted packets also affects the CPU usage and processing requirements. In SWR, the CPU requirement will be very low with respect to flooding and GPSR. Buffer size and the CPU requirements together affect the congestion in the network. Therefore, it can be concluded that, probability of congestion in SWR is lower than GPSR and flooding due to low routing overhead in SWR. Nodes have lower load values in SWR with respect to other protocols. The load of nodes is investigated in Section 5.5.

5.4 Network Lifetime

One of the metrics related with the energy consumption is the lifetime of the network. It is one of the goals to achieve for wireless sensor networks. Proposed protocols can be energy efficient, may not prolong the lifetime of the network. Lifetime prolonging requires other methods to extend the continuity of the network by means of some methods including the reduction of energy consumption. Lifetime of the network is measured as the time of the first node termination or the time of the first path which is not found toward the destination. Some energy efficient protocols calculate the best energy-efficient path to reduce the energy consumption. Energy-efficient path term is deviated according to needs to prolong the lifetime of the network. Lifetime of the network can be prolonged by disseminating the energy consumption through the network. This can be done by not selecting the same nodes to relay the data. Selection of the same nodes due to being part of the shortest path to the destination causes to deplete these nodes' energy very quickly. Therefore, selection of different nodes or alternative nodes rather than the previously selected one may pervade the energy consumption through the network. On the other hand, low-energy-remained nodes should not be selected in the path construction.

GPSR protocol does not have any criteria on path construction to prolong the lifetime of the network. GPSR selects the best node in greedy manner. Best node selection criterion is advance in distance toward the destination. Nodes keep the positions of the neighbor (one-hop distant) nodes in their tables. These tables are updated by the beaconing messages. Therefore, the only criterion for best node selection is the distance in GPSR. If the remaining energy levels are included in the beacon messages and the nodes keep this information in their tables, GPSR protocol may adopt itself to select the best next node according to the remaining energy level criterion. As a result, GPSR protocol does not propose any method to prolong the lifetime of the network.

Flooding also does not have any method to prolong the lifetime of the network. Construction of every possible path is the main property of flooding. Therefore, every node involves in routing. Thus, flooding has not any favor thing on energy consumption and network lifetime prolonging.

The proposed routing algorithm, SWR, has a natural mechanism to prolong the lifetime of the network and is adaptive to the current conditions considering the remaining energy levels of the nodes. In SWR, data is relayed on multiple paths toward the destination. Path selection is not the choice of the destination. Paths are constructed on demand in a distributed manner. Nodes involvement in routing depend their current conditions and the information in the received data packets. Last transmitting node's weight value and the applied threshold value is inserted into the data packets. According to the simple routing algorithm given in Algorithm 3.1, only the nodes that has the weight values less than the sender node's weight values and below the threshold value can retransmit the packet to construct the path in real-time. Therefore, only a portion of the nodes which are suitable to the criteria involve in routing. On different paths, different nodes are selected. Node's involvement in routing process is disseminated throughout the network. The difference from other protocols can be explained with the shortest path rule. In most of the protocols, construction of the shortest path with minimum hop-count is the main purpose. In energy-limited networks, this objective changes to the best energy-efficient route.

According to the shortest path rule, a sub-path in the shortest path is also a shortest path. Most of the other protocols generally use the shortest path construction to reduce the energy consumption. Therefore, constructed shortest path toward the destination involve the previously used shortest sub-paths. In such conditions, the same nodes are selected to forward the packet, which causes these frequently selected nodes to terminate very early than others. However, in SWR, each path may be different than the others and previously used ones. The criteria given above provide distinct path construction. A shortest sub-path may not be used in path construction if it does not obey the criteria defined above and in Algorithm 3.1.

On the other hand, as described in Section 3.2, weight value includes information about the remaining energy level of the node in addition to the position information and some possible other parameters. Each node derives its own weight. Weight values are not shared between the nodes, but these values are used to flow the data packets by inserting these values into the packets. Therefore, each node compares its weight value with the weight value of the received packet. Retransmission conditions are described above. For the retransmission of the packet, weight value of node-in-process should be less than the weight value of the sender of the received packet. However, if the remaining energy level of the node-in-process is very low, it can avoid itself to be in path even it satisfies the conditions given above. To do so, it increases the weight ratio of the energy-parameter in the weight formula given in Equation 3.1. By this way, its weight value increases and it may not satisfy one of the conditions given above. Therefore, energy-critical node does not involve in the path construction. In reverse condition of which an energy-critical node wants to relay its own data, it should increase its own weight similar to the previous situation. It increases the weight ratio of the energy parameter of the weight formula given in Equation 3.1. Therefore, more nodes are involved in path construction in next step. This approach is similar to the void recovery approach, but is executed at the originator of the data. Therefore, the data of the one-shot energy-remaining nodes can be relayed in a more reliable way (due to increased number of the multiple paths). This approach does not challenge with the void recovery method, indeed it aids the recovery method due to the behavior described above.

Table 5.18 shows the results about the lifetime of the system. As seen in the table, lifetime of the system when the SWR protocol is used is longer than other protocols.

Its main reason is the on-demand route construction without any prior information in SWR protocol. Also, SWR protocol limits the number of transmissions by using the weight and threshold values. As a result, it reduces the number of transmissions with respect to flooding and GPSR. System continues to live even after 900 seconds simulation time without any node termination in SWR. However, a great number of node terminations occur both in flooding and GPSR protocol in a short time.

Termination order and termination period (lifetime of each individual node) of the nodes give hints for redeployment strategy. A redeployment strategy for SWR is given in Section 5.8. To be able to do that, these lifetime concerned values (termination order and node's lifetime) are also investigated in the simulations (Figure 5.22 – Figure 5.27).

Table 5.18: Lifetime comparison of the protocols for Scenario 1 and 2.

	Scenario -1			**Scenario-2**		
	Average System Lifetime	Time of the First Node Termination	Average Number of Terminated Nodes on Destination Unreachable	Average System Lifetime	Time of the First Node Termination	Average Number of Terminated Nodes on Destination Unreachable
Flooding	345 sec	311 sec	29	141 sec	136 sec	35
GPSR	110 sec	80 sec	9	139 sec	132 sec	9
SWR	>900 sec	*NONE in 900sec*	*NONE in 900sec*	>900 sec	*NONE in 900sec*	*NONE in 900sec*

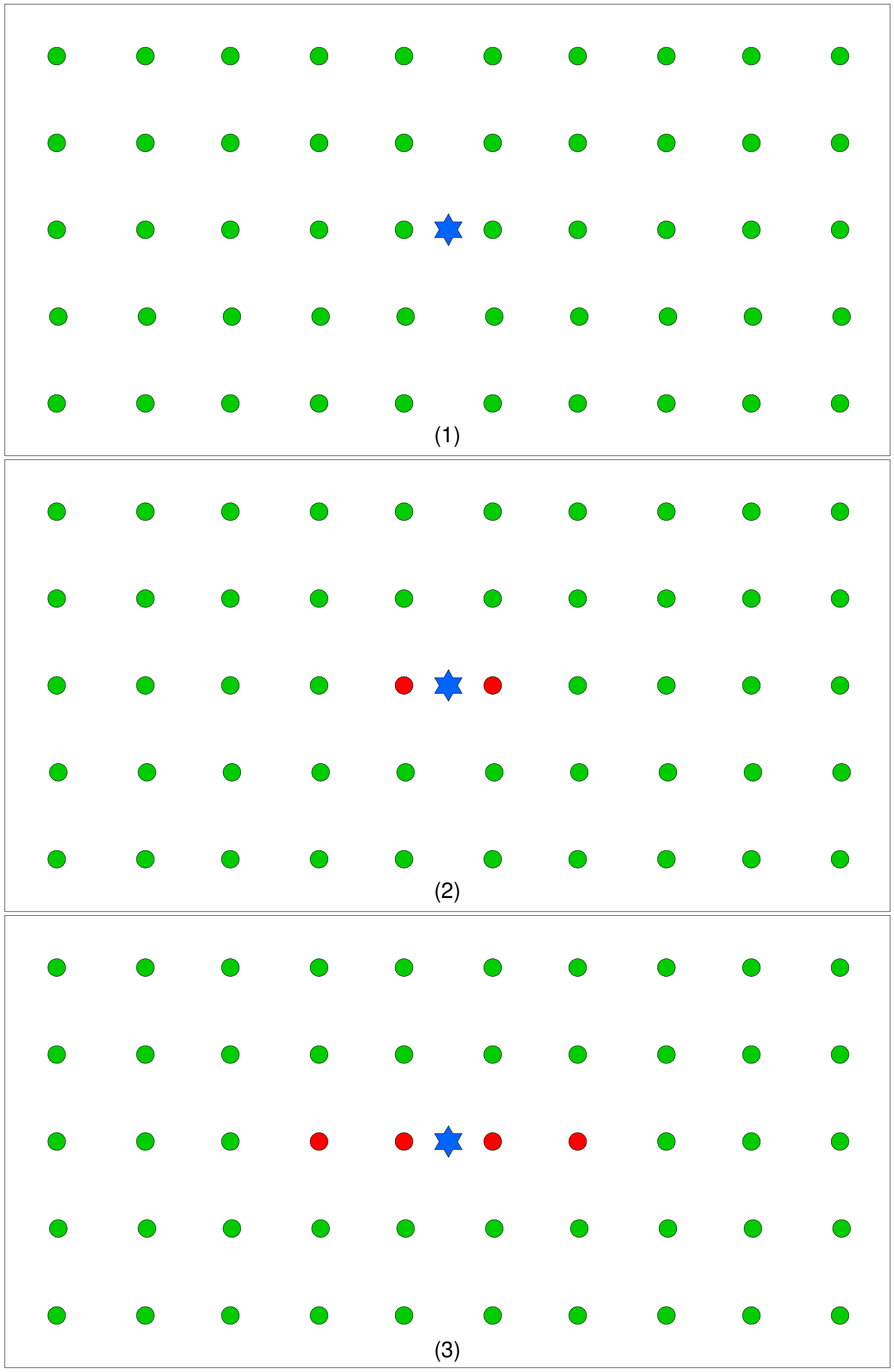


Figure 5.22: Node termination order in GPSR for Scenario 1. (1) is the network with no terminations. (2) is the first node termination phase. (3) is the second node termination phase. Node terminations occur in the direction of the longest border, similar to the shape.

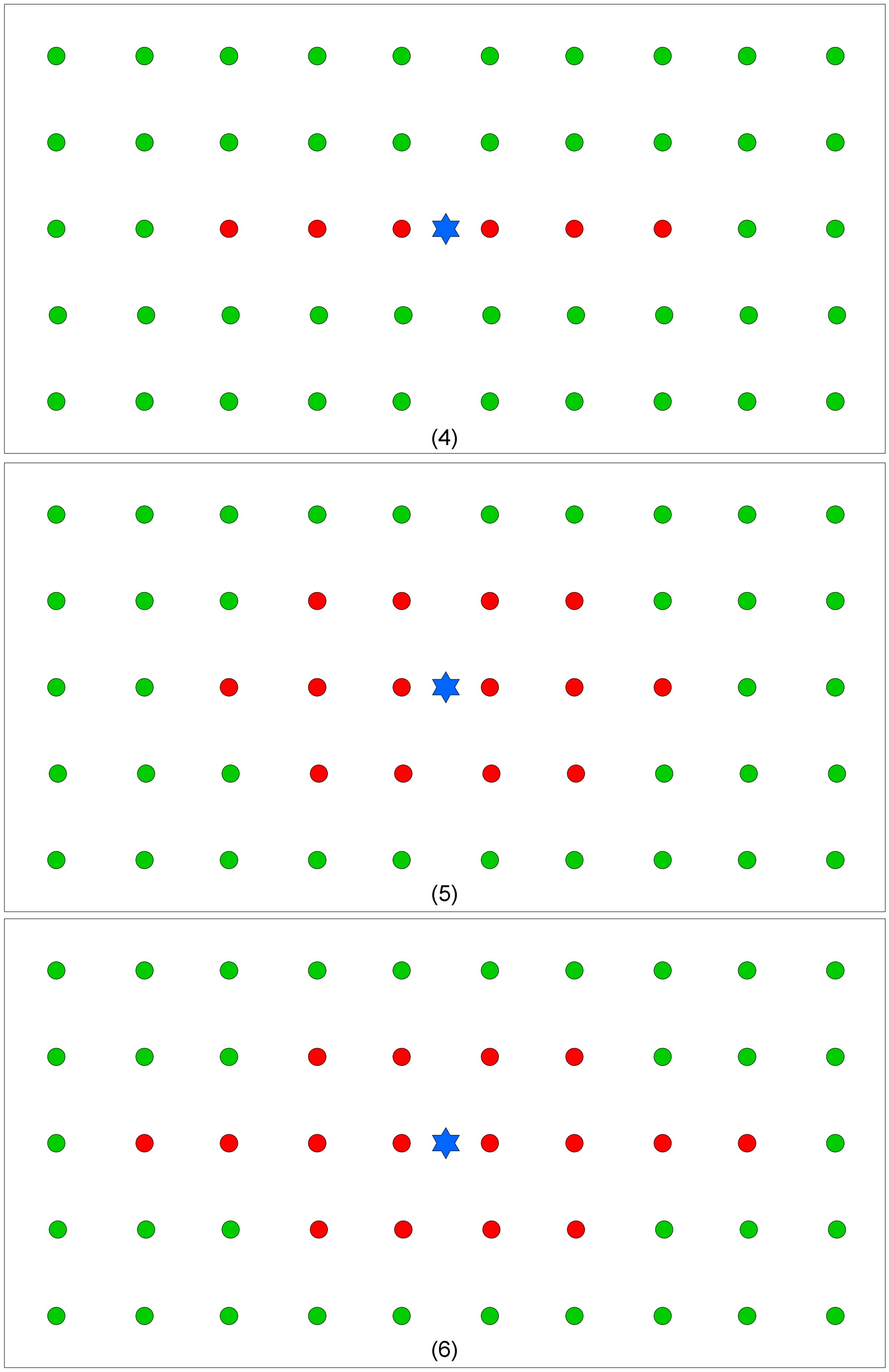


Figure 5.23: Node termination order in GPSR for Scenario 1, continued from Figure 5.22. (4) is the third node termination phase.. (5) is the fourth node termination phase. (6) is the fifth node termination phase. Order of the termination are similar to Figure 5.22.

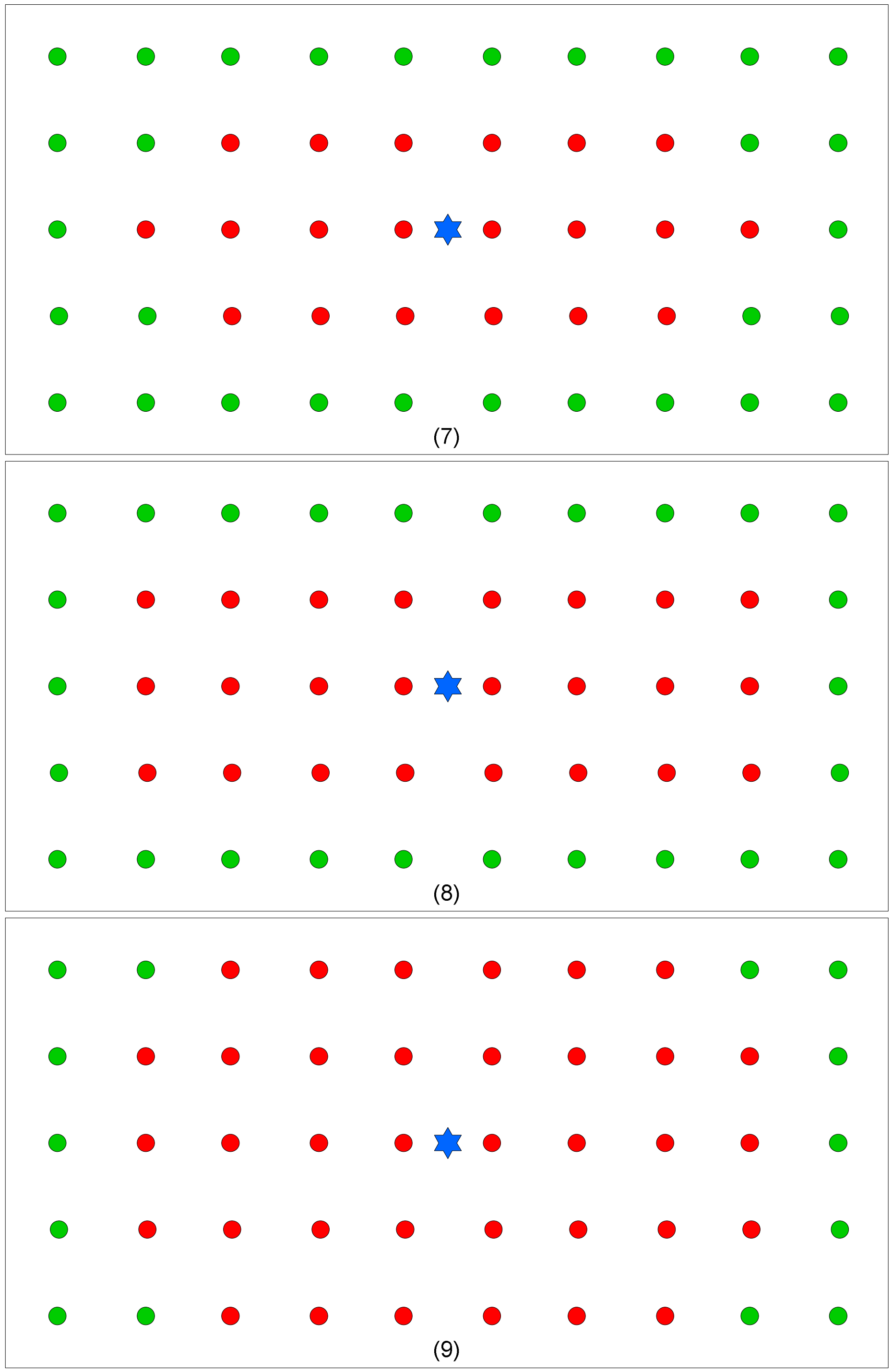


Figure 5.24: Node termination order in GPSR for Scenario 1, continued from Figure 5.23. (7) is the sixth node termination phase.. (8) is the seventh node termination phase. (9) is the eighth node termination phase.

In a square shaped area, termination order of the nodes is expected to be in circular order with respect to the sink node. Nodes close to the sink node and at equal distances should terminate at first phase. Then the other nodes at equal distances to the sink which may construct a circular shape with sink in the center point are expected to terminate at second phase. Terminations continue until the sink node becomes unreachable by the applied routing algorithm.

However, when the nodes are distributed over an area other than square shape, the order of the terminations will differ. To observe this difference and the effect of routing protocol, node terminations are observed with Scenario 1 which uses rectangular shaped operation area.

The order of the node terminations for GPSR is shown in Figure 5.22-Figure 5.24. Node terminations begin close to the sink node and continue on the direction to the both narrow ends of the area (Figure 5.22). Following node terminations form an area (void) similar to the shape of the operation area. In GPSR, almost all nodes consume equal energy on beaconing. However, nodes on the route toward the destination consume more energy than others. In GPSR protocol, always the shortest path is constructed. Therefore, in rectangular shaped area, nodes on the line toward the sink involve in the shortest path. That's why, node terminations in GPSR follow the order given in Figure 5.22-Figure 5.24.

Order of the node terminations in flooding differs slightly than GPSR. The reason is related with the routing approach. The number of the transmissions for one beaconing in GPSR is equal to the number of transmissions for one data packet delivery in flooding. Therefore, energy consumption diffused uniformly all over the operation area in both of the protocols. However, GPSR protocol makes some additional transmissions. If there is data packet to send, shortest path is constructed. In a rectangular shaped area, some nodes are involved in routes more than some others. Therefore, these nodes consume their energy early than others as shown in Figure 5.22 and Figure 5.23.

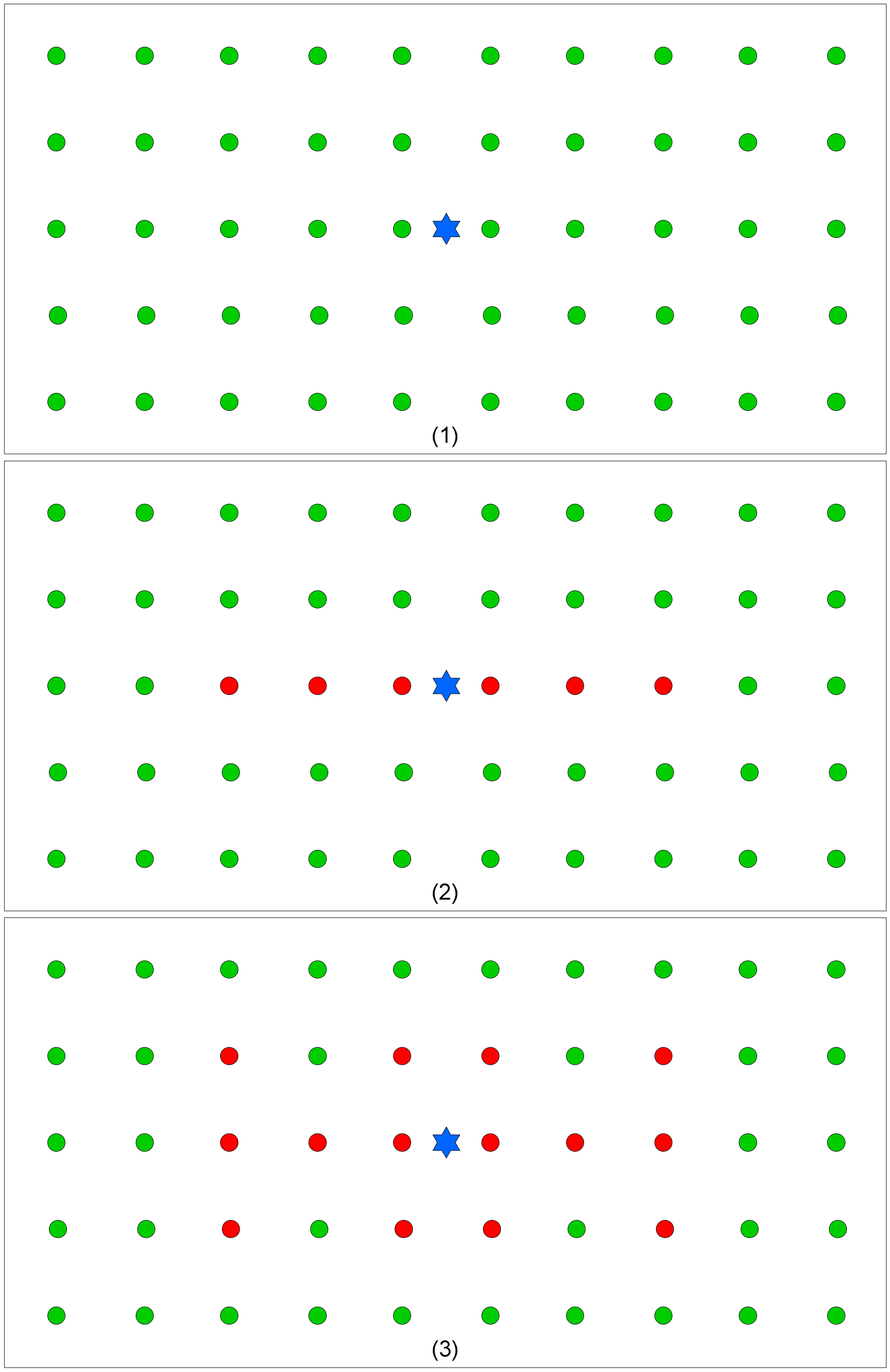


Figure 5.25: Node termination order in flooding for Scenario 1. (1) is the network with no terminations. (2) is the first node termination phase. (3) is the second node termination phase. Nodes close to sink node terminates first. However, order of the termination differs slightly from the node terminations in GPSR.

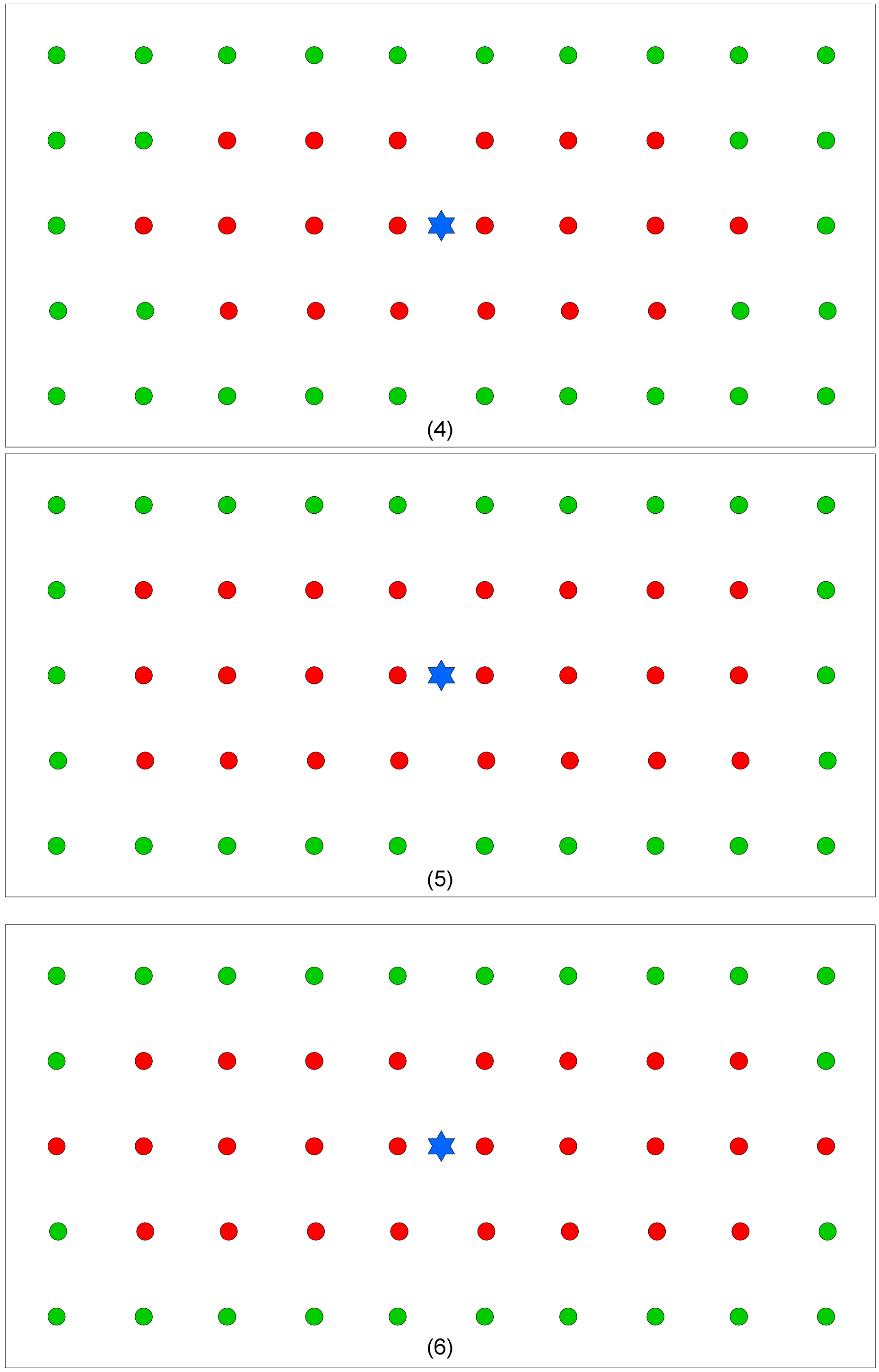


Figure 5.26: Node termination order in flooding for Scenario 1, continued from Figure 5.25. (4) is the third node termination phase.. (5) is the fourth node termination phase. (6) is the fifth node termination phase. Order of the terminations is similar to GPSR.

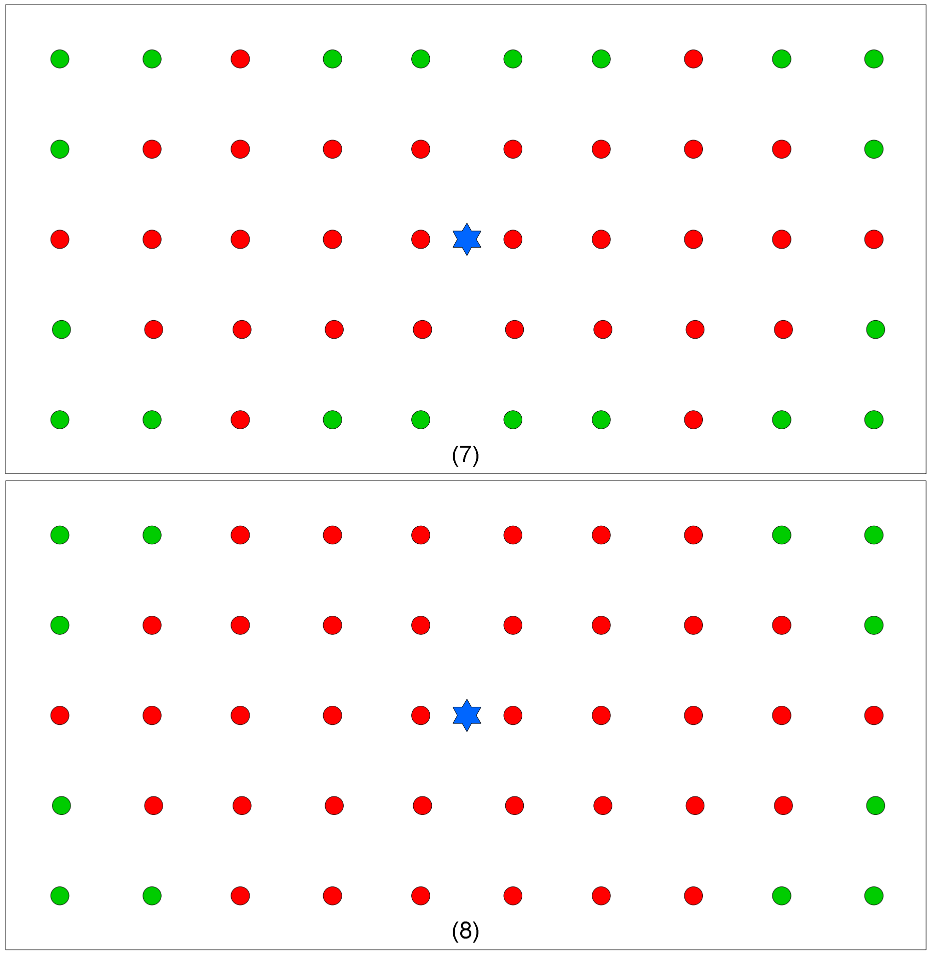


Figure 5.27: Node termination order in flooding for Scenario 1, continued from Figure 5.25. (7) is the sixth node termination phase.. (8) is the seventh node termination phase. The important conclusion is that node terminations form a void similar to the shape of the operation area.

5.5 Load of Components

The other important metric that also affects the scalability, routing overhead and the lifetime of the network is the load at nodes. The network is composed of homogenous type of sensor nodes and more powerful sink nodes. The load of these component should be investigated to be able analyze the behavior of the routing algorithm.

The load of a component is investigated by the number of the packets it received, processed and transmitted. Load of transmissions is given previously in Table 5.12. Load occurred in receptions is given in Table 5.19.

Table 5.19: Comparison of the protocols with respect to load at nodes for Scenario 1

	Flooding	**GPSR**	**SWR**
Average Number of Packets Received Per Node	252	744	55
Average Number of Packets Received Per Minute	6880	20292	1510
Average Number of Packets Received Per Data Delivery	324	805	34

Average number of packets received per node is very low in SWR with respect to flooding and GPSR. The ratio of the average number of packets received per node in SWR to the average number of packets received per node in GPSR is 7.4%. On the other hand, the ratio of flooding to GPSR is 33.9%. In other words, nodes at SWR and flooding challenge with the 7.4% and 33.9% load of the nodes of GPSR according to the received packets. The results are similar for the average number of packets received per minute.

The load sustained at data delivery is another important comparison for the load at nodes. As seen in Table 5.19, the load per data delivery is very low in SWR with respect to other protocols. The ratio of the average number of packets received per data delivery in SWR to the average number of packets received per data delivery in GPSR is 4.2%. On the other hand, the ratio of flooding to GPSR is 40.2%. In other words, there is 4.2% of packet reception load in SWR and 40.2% packet reception load in flooding with respect to the load in GPSR by means of successful data delivery. Note that the load in SWR involves the load generated at multiple path construction.

Load at nodes affects the requirements of buffer size, number of CPUs and CPU processing speed. According to Table 5.12 and Table 5.19, these requirements will be very low for SWR with respect to flooding and GPSR. Application of SWR in a network composed of disposable nodes is more convenient than other protocols. Indeed it is mandatory.

Load at nodes introduces delay at nodes. As the number of the packets in queues waiting to be processed increases, the processing delay increases. As known, buffer extension does not reduce the delay, indeed, increases. Packets begin to drop due to packet lifetime termination. Contrarily, usage of short buffers to reduce delay in queues causes packet drops due to buffer fill-up. Increasing the quantity of CPU and speed increases the cost and does not solve the problem completely. The only and unique solution is to decrease the loads at nodes. This can be accomplished by only reducing the transmissions, hence reducing the receptions. Comparing the other protocols, SWR is the best technique in this respect.

5.6 Scalability and Multiple Sinks

SWR protocol performs better results than others compared protocols. It is also shown in Section 5.2.2 that SWR does not affected negatively from the node density. SWR shows similar performance results as the density increases. However, obtained results in Section 5.2.2 are for the energy consumption.

Increase in node density provides higher data accuracy since the phenomena is reported by more nodes in that location. On the other hand, transmissions of more nodes may cause extra overhead. Therefore, higher node density may require larger buffer requirements at nodes. More nodes need to share the same medium which increases the possibility of the collisions in the medium. The processing capability gets more importance to reduce the processing delay. In case of any abatement or scale-down of one or more of these resources may cause congestion in the network. The length of the buffers and the medium access method are the concerns of the MAC layer. Due to the effects to the congestion, they should be considered in the routing protocol design.

In Section 5.2.2, it is also shown that SWR has less number of transmissions in total than other protocols. In case of an event, SWR makes more transmissions with respect to GPSR (beacon messages are not included since they are periodically sent). However, the amount of these additional transmissions is very low. On the other, SWR does not use beaconing. Thus, SWR protocol gets rid of the buffer fill-up of beacon messages. This property makes it to reduce processing requirement and delay at nodes. Therefore, node density does not reduce the performance of SWR protocol.

Scalability of protocols is measured with effects of the number of the nodes in the network to the performance metrics. It can be considered as the node density but it is not the only one. In addition to the density, the size of the operation area should also be considered in measuring scalability metric. One example can be given as follows.

A well-performed protocol in a dense topology may perform worse in a topology with the same number of nodes distributed over a larger operation area. Main reason of this downgrade can be explained with the effects of increase in path length. Extending the size of the operation area without changing the number of the nodes in the network may reduce the connectivity of the network. In addition, possible distance between the source and the destination pairs gets increase. Increase in path-length increases the number of hops toward the destination. Increase in hop length reduces the possibility of successful delivery of the packets. Secondly, increase in hop length increases the number of transmissions which affects the size of buffers, energy consumption, and processing requirements at nodes.

The reverse is also possible. The well-performed protocol may perform worse when the size of the network lessened, in other words when the density increased. Thus, for scalability, in addition to the node density, size of the network should also be considered. Therefore, in these simulations, the size of the network and the number of the nodes in that network are also considered in measuring the scalability metric.

As defined above, increase in path length may reduce the performance of the protocols. To reduce the effects of large-scale networks, network partitioning can be used (Section 4.4.2). Partitioning the network reduces the path length and its bad-effects to the performance. As described in Section 4.4.2, one way of partitioning is using multiple sinks.

To provide scalability for large-scale networks, multiple sinks are used in SWR and named as MS-SWR. The details of MS-SWR are described in Section 4.4.2.

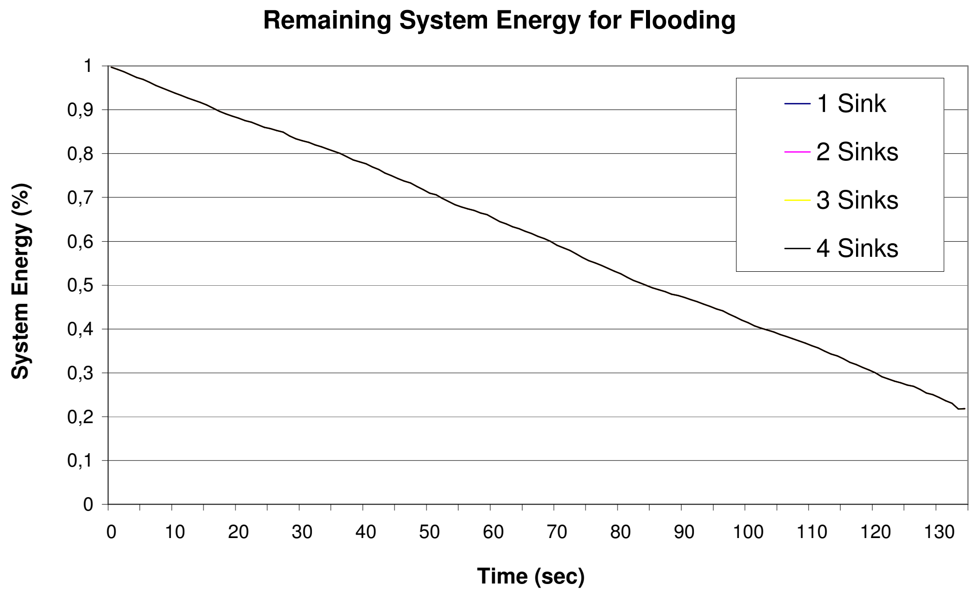


Figure 5.28: Remaining system energy when the flooding is applied as routing protocol with varying number of sink nodes in Scenario 4. Remaining system energy percentage is the same for all number of sink nodes.

The remaining energy level of the system with a single sink is shown in Figure 5.2 and Figure 5.9 for Simulation 1 and Simulation 2, respectively. Different number of sink nodes is deployed in Scenario 8 to observe how the routing protocols are affected from multiple-sink deployment. Both the remaining energy level of the system and the remaining energy levels of the nodes are observed. It is found out that increasing the number of the sinks does not affect the performance of the flooding protocol and the GPSR protocol. Figure 5.28 and Figure 5.29 shows the effects of multiple-sink usage to energy consumption in flooding and GPSR, respectively.

Adding more sinks does not avoid the transmissions in flooding. Therefore, the flooding presents the same performance in multiple-sink networks. Since the obtained results of different multiple-sink networks are the same, their corresponding plotting form the same results and plotted on each other in Figure 5.28.

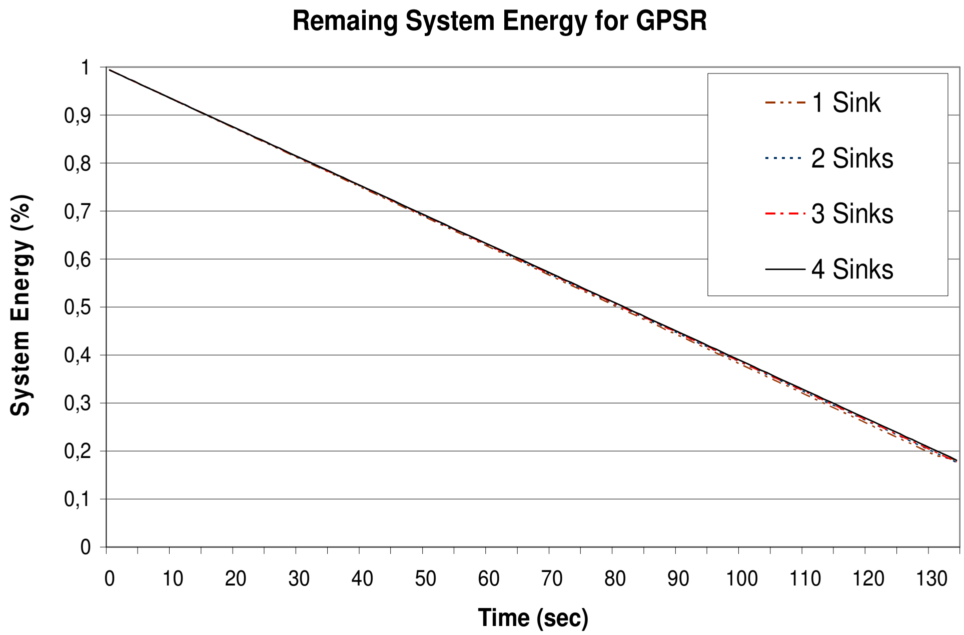


Figure 5.29: Remaining system energy when the GPSR is applied as routing protocol with varying number of sink nodes in Scenario 4. The remaining system energy percentage increases slightly as the number of sinks increase.

On the other hand, in GPSR, increase in the number of the sinks only affects the transmissions in data packets. In GPSR, the energy is mainly consumed in beaconing. Decreasing the shortest path in GPSR only avoids a few transmissions. Therefore, reduction on path length due to multiple-sink usage makes small enhancement for energy consumption in GPSR protocol. Figure 5.29 shows the enhancement in system lifetime for GPSR with multiple-sinks. Note that time scale both for Figure 5.28 and Figure 5.29 is for 135 seconds.

Figure 5.30 shows the effects of multiple sink usage to energy consumption for MS-SWR protocol. It is clearly seen in this figure that adding more sinks to the network decreases the energy consumption and increases the lifetime of the network. As stated previously, adding more sinks decreases the distance and path-length between the source and destination. In addition to this feature, in MS-SWR, shortening the distance between the source node and the sink node decreases the possible retransmission area described in Section 4.1.3. Reduction of the possible transmission area is explained in Section 4.4.2 and shown in Figure 4.6. Reduction of the possible retransmission are reduces the transmissions. Therefore, using multiple sinks decrease the energy consumption in MS-SWR.

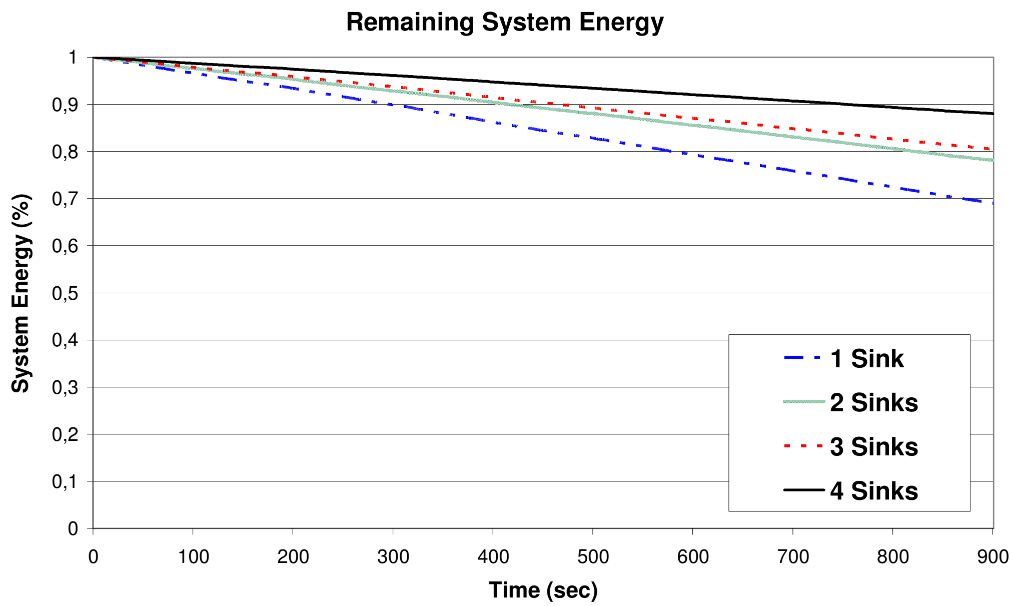


Figure 5.30: Remaining system energy when the SWR is applied as routing protocol with varying number of sink nodes in Scenario 4. There is a considerable amount of increase in the remaining system energy percentage as the number of sinks increase.

There is a considerable amount of system-wide energy saving when the number of sinks increases (Figure 5.30). Note that the time scale is for 900 seconds. The simulation ends after 900 seconds. However, for GPSR and flooding, the simulation ends after 135 seconds due to node terminations and unreachable destinations.

System-wide remaining energy increases from 69% for one sink to 88% for 4 sinks in MS-SWR. The amount of remaining energy increase is not equal as the number of sinks increases. The reason is about the shape of the operation area and the number of the sinks. In Scenario 8, a square shaped operation area is used. When only one sink is used, it is positioned at the center of the operation area. That is the optimal placement for one sink. However, placement of multiple sinks is not so easy. It requires optimization. A square shaped area can be partition in many ways for two sinks. For three sinks the problem is more complicated. There is not a fairly placement of three sins for each node. Some nodes will always be closer to one of the sinks while some nodes will always be away from every sink. Therefore, placing three sinks reduces some of the path-lengths may not reduce some. As a result, there is a small increase in system-wide remaining energy for 3 sinks with respect to 2 sinks. However, 4 sinks can be easily placed optimally to a square shaped area. Therefore, the increase in system-wide remaining energy is very high for four sinks with respect to three sinks. Placement of multiple sinks to enhance the performance metrics is an optimization problem. It is not involved in this thesis, but is planned as a future work.

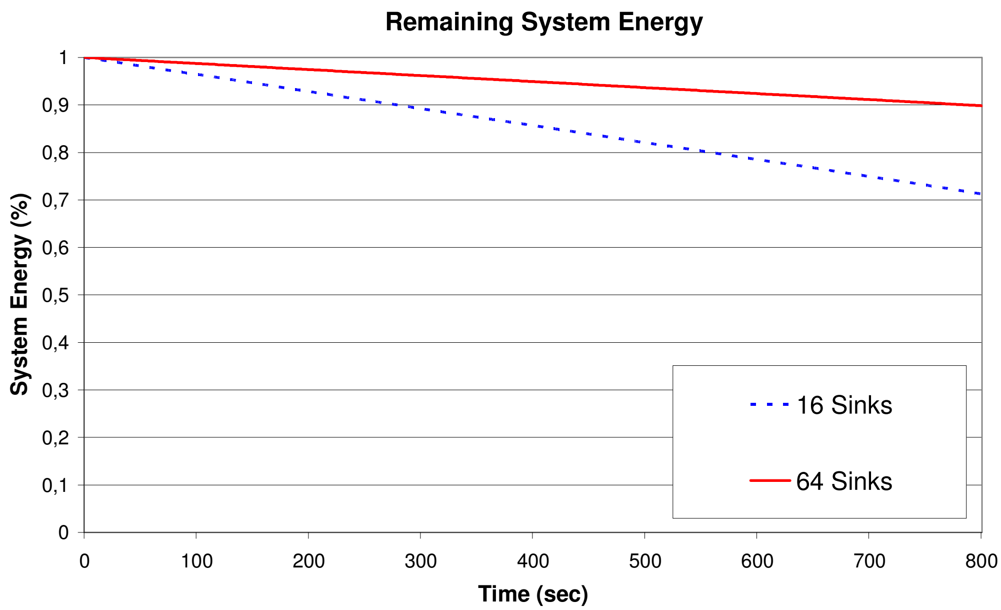


Figure 5.31: Remaining system energy when the SWR is applied as routing protocol in Scenario 5 which composed of large scale network. The number of sinks is 1% (16 sinks) and 4% (64 sinks) of total number of nodes in the network.

As seen above, multiple sink usage reduces the energy consumption and prolongs the lifetime of the network. To observe the performance of MS-SWR in large-scale networks, Scenario 9 is used. 1600 nodes are distributed over a square shaped 4000000 m^2 area (2000m x2000m). As stated above, 4 sinks can be placed optimally very easily. Also, 16 sinks can be placed optimally very easily. Number of easily optimally placed sinks can be found as 2^{2n} where n is the natural numbers (0, 1, 2, 3, …). Therefore, Scenario 9 is tested with 16 sinks and 64 sinks to place the sinks optimally. 1600 nodes is huge number compared to the proposed simulations in sensor networks. Most of the large-scale networks are composed of nodes not more than 500 nodes. In related studies in the literature, it is very common to use 5% and more sink nodes of overall nodes. It is stated in [53] that 5% sink nodes is a good acceptation for large-large scale sensor networks. 16 sink nodes and 64 sink nodes have the percentages of 1% and 4% to overall nodes (1600 nodes). It can be seen in Figure 5.31 that MS-SWR protocol has low system-wide energy consumption in large-scale networks even with these percentages. Obviously seen in Figure 5.31 that increase in sink number increases the system-wide remaining energy. Scenario 9 is tested for GPSR and flooding also. Similar results are observed as in the Scenario 8. Flooding and GPSR protocols are depleted their energies very quickly and adding more sinks did not effect the energy consumption in these protocols. On the other hand, the flooding protocol consumed all the system energy in a few seconds due to large-scale.

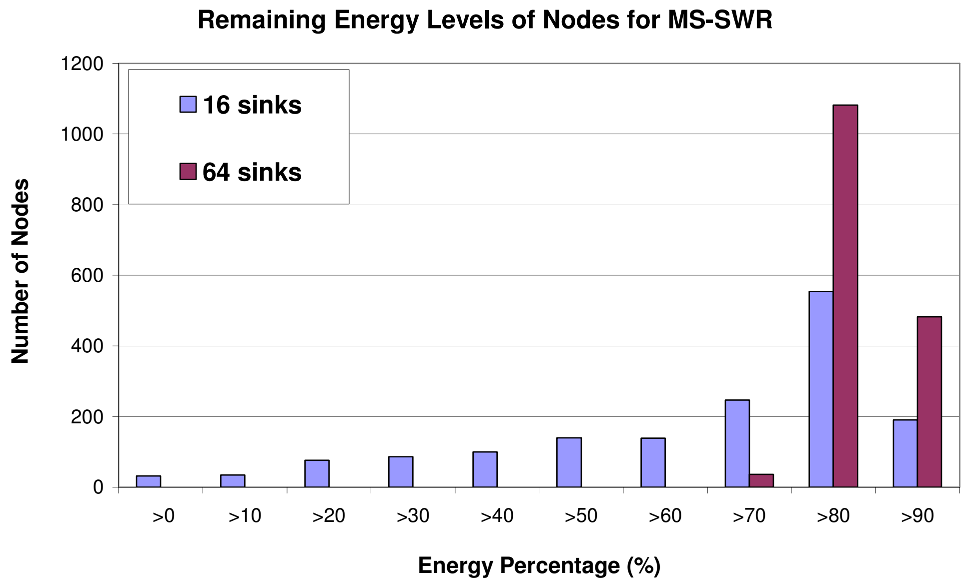


Figure 5.32: Remaining energy levels of the nodes when the SWR is applied as routing protocol with varying number of sink nodes in Scenario 5. Nodes live longer as the number of sinks increases.

Remaining energy levels of the nodes for Simulation 9 is given in Figure 5.32. Increasing the number of sinks reduces the energy consumption at nodes. When 16 sink is used in Scenario 9, some of the nodes are about deplete their energies. The amount of these nodes is not much, but as the sink increase nodes preserve their energies. Almost all of the 1600 nodes have remaining energy levels higher than 80%, when the simulation ends at 900 second in MS-SWR. All nodes have energy levels higher than 70%. As states before, number of the sinks in network should be 5% of the total nodes. However, with 16 sinks, it is 1%. That is the reason of the nodes-about-to-deplete energies in 16-sink network. Using 64-sink in such a large scale network is more suitable. It can be concluded that MS-SWR protocol performs well in large-scale networks. On the other hand, implementation of SWR for multiple-sink networks does not require any adaptation in the algorithm. The same algorithm for SWR can be used in multiple-sink networks. Implementation of SWR in large-scale networks introduces no complexity in the network.

5.6.1 Mobility of sinks

As stated in Section 4.4.3, mobile sinks can be used to enhance the performance metrics. SWR and MS-SWR can be used in mobile environment. However, in this section, only the mobile sinks are used.

As defined in Section 4.4.3, sink nodes move toward the EAR nodes to reduce the distance. The motivation is the same as described above. Reduction of distance between the source and destination pair reduces the possible transmission area. Therefore, movements of sink nodes are limited to make a few hops toward the EAR nodes.

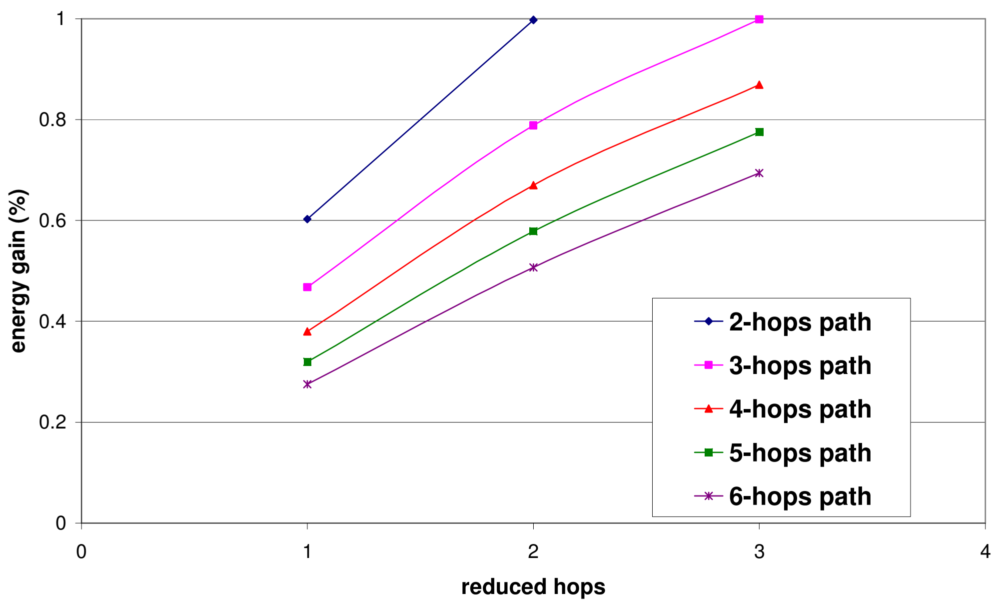


Figure 5.33: Reduction of path length decreases the energy consumption in SWR like in other protocols. However, the amount of reduction is higher in SWR due to multiple-path construction.

Scenario 10 is used to for this test. To limit the number of sink nodes to 1% of the total sensor nodes, 16 mobile sinks are deployed. Destination (sink) nodes are positioned uniformly in the operation area. Sensor nodes are stationary while the sink nodes can move in their regions. Sink nodes make their movements to shorten the distance between themselves and the EAR nodes. On a source node's transmission, the EAR nodes are forced to make new transmissions for the same data toward the same destination to provide the situation described in Section 4.4.3. In scenario 10, the effects of sink nodes' mobility to energy consumption in routing process is observed.

Performance of the system with mobile sinks is presented in Figure 5.33 and Figure 5.34. In Figure 5.33, the effect of shortening the path to energy consumption in routing process is investigated. Path length is measured as the hop count from the sink node to the center of the EAR nodes. It is seen Figure 5.33 that as the sink node gets closer to the EAR nodes, energy gain in routing process increases. In 2-hops path, decreasing the path one hop causes a 60% energy gain in routing process with respect to the 2-hop path. And, in 6-hops path, decreasing the path one hop causes a 27.5% energy gain in routing process.

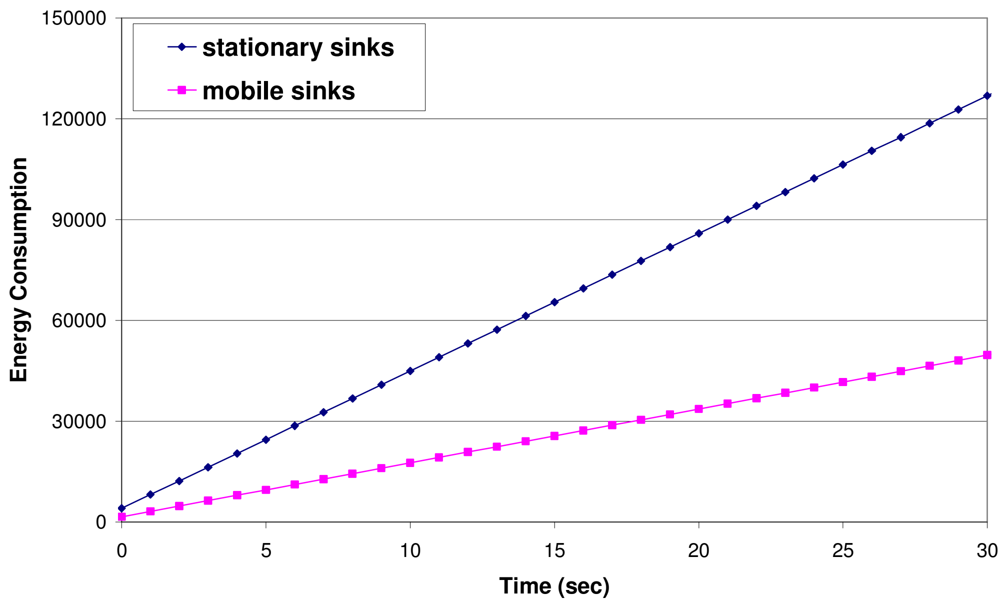


Figure 5.34: Energy consumption in SWR can be reduced if the mobile sinks move toward the EAR nodes.

Energy consumption comparison between the stationary sink nodes and mobile sink nodes in routing process is shown in Figure 5.34. It seen that using mobile sinks reduces the energy consumption in a considerable amount.

5.7 Mobile Environment

SWR protocol and MS-SWR protocol can be easily used in mobile environment. Supporting simulation results are not shown this thesis, but simulation is planned to be a future work. SWR protocol has ability to be used without any adaptation to mobile environment. First of all, in SWR, sensor nodes in the network are not affected from their own mobility and other nodes' mobility. Its reason is due to the usage of weight metric. A node's weight metric is derived from the relative location of the node, but routing is not dependent to the locations. Weight derivation is made independently at each node and routing is accomplished according to the weight metric inserted into the packets. Nodes do not share their weight values. Only shared data is on-the-route data packet.

In mobile environments, positions of the nodes and the sink may change. Mobility pattern becomes the most dominating factor in performance results. Routing protocols for mobile environments in the literature exchange positions or routing tables of nodes to adapt to the mobile environment. That is the difference between the SWR protocol and the others. In SWR, no adaptation is required for the system. As stated above, nodes' derive their weights when there is a change. Secondly, to reduce the occurrences of weight derivations at nodes, the routing algorithm can be enhanced to derive weight values only when there is a received data packet.

5.7.1 Effects of mobility to performance metrics

Routing Overhead: It is expected not to affect negatively the routing overhead. There will not be any other messaging other than data packets as usual. Routing overhead is caused by the control packets sent to route the data. However, as defined in Section 5.3, control bits in header can be considered as the routing overhead. In that case, there can be a small increase due to some reasons. First, due to mobility, possibility of void occurrence can be high in mobile environment. Second, path lengths may increase. These may cause unsuccessful transmissions which require retransmissions and therefore may increase the routing overhead and energy consumption. However, the amount of increase is not expected to be high.

Energy Consumption: Due to similar reasons in *Routing Overhead* described above, it is not expected to be very high in mobile environment, but only a small fraction.

Reliability: Reliability can be affected positively and negatively in mobile environment. As described Routing overhead, path lengths may increase. Increased path length reduces the possibility of successful delivery for single-path routes.

However, as given in Section 5.3, increase in path-length increases the number of multiple-paths in SWR, which affects the reliability positively.

Void occurrences may require additional transmissions with difference parameters. It increases the energy consumption and overhead but also may increase the reliability. Retransmissions with different parameters increase the number of multiple-paths.

Accuracy of the routing is dependent to the accuracy of the location information at nodes. Fast moving objects reduce the accuracy of the routing protocol, which affects the reliability. Anyway, a high reliability is expected in mobile environment.

Guaranteed Delivery: Similar to the Reliability, Guaranteed Delivery is expected to be high for the same reasons.

Delay: The delay may increase due to applied reactions on void occurrences. However, similar to the other metrics above, for the same reasons, it is not expected to be high in mobile environment.

Load of Components: It is expected to be higher in mobile environment. Nodes will derive their own weight values as there occurs any change in their own positions. Weight derivations will introduce processing overhead. On the other hand, the retransmissions due to reasons given at above metrics will introduce load at nodes. Transmissions and receptions will increase, which increase the load at nodes.

5.8 Delay and Real-time Support

As defined in Section 4.5, SWR reduces the end-to-end delay to minimum and takes care of the time-consuming events in the network. Besides that, SWR has a real-time support for time-critical and mission-important traffic. However, the performance of the system for these metrics could not be evaluated in the proposed simulations. Evaluation of these metrics would be unrealistic with the current simulation environment. Therefore, the results related with delay and real-time traffic are not presented in this thesis.

5.9 Node Deployment Strategy

Results of energy consumption help us to design redeployment strategy. In most of the WSN routing algorithms, nodes closer to the sink depletes their energies earlier than other nodes, as expected. The first redeployment strategy that comes to one's mind may be to redeploy the nodes those are close to sink. But, in periodic beaconing schemes, the nodes those are not close to the sink also deplete most of their energy due to periodic beaconing (Fig. 10). On the other hand, in flooding, almost all nodes consume their energy equally, giving rise to redeploy all nodes. As seen in Table 5.5, Figure 5.3, Figure 5.22 – Figure 5.24, when the nodes close to the sink deplete their energy in GPSR, the sink becomes unreachable. In flooding, routes can be constructed even if there are more terminated nodes. The reason is that, in flooding, all nodes equally participate in routing, making a uniform distributed node termination over the operation area. However, in SWR, most of the nodes preserve their energy (Figure 5. 5, Figure 5.7, and Figure 5.8). Therefore, the redeployment strategy should involve only the nodes close to the sink. Another strategy can be to deploy more energy loaded nodes close to the sink to extend the lifetime of the system without any redeployment.

5.10 Effects of Periodic Beaconing to the Energy Consumption in GPSR

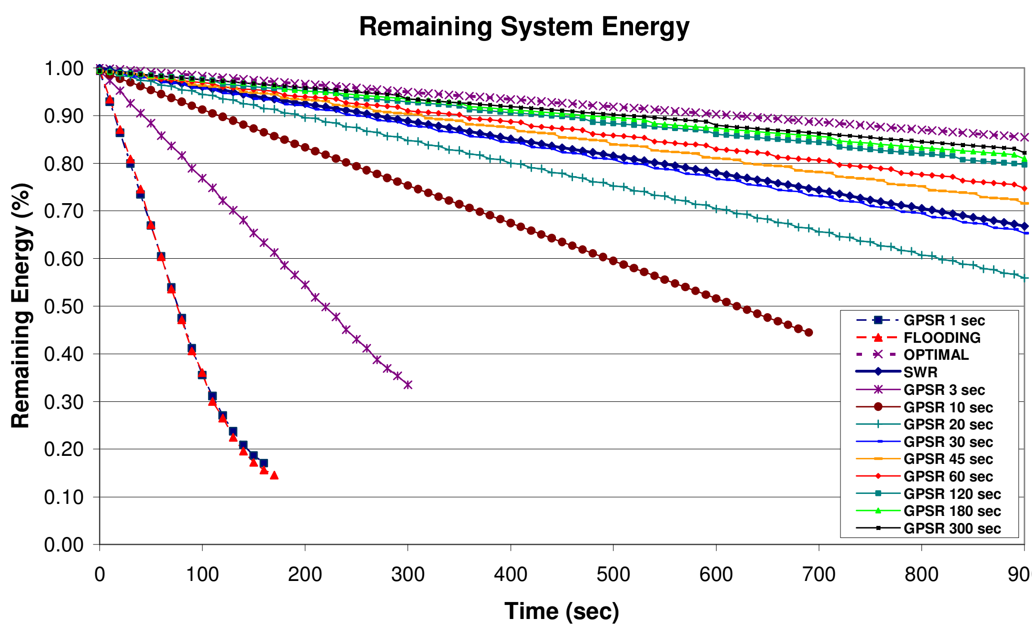


Figure 5.35: Remaining energy levels of protocols with varying beaconing periods in GPSR.

GPSR uses the periodic beaconing to obtain the topology knowledge. The accuracy and reliability of this information depend on the applied beaconing period. On the other hand, beaconing produces energy consumption on transmissions and receptions. Higher frequencies of beacon messaging introduce higher energy consumptions. Therefore, there is trade-off between the energy consumption and accuracy of the knowledge according to beaconing period.

In GPSR, nodes keep local topology tables to establish routes on demand. Nodes broadcast beacon messages periodically which are independent of data packets to provide this information. Receiving neighbor nodes update their neighborhood tables accordingly. Route establishment is achieved by selection of the best next node from the neighbor nodes. However, such an approach may fail or corrupt if the tables are not kept fresh. Wireless links are very unreliable and nodes' status may change during the operation. Furthermore, as the topology changes due to mobility, node terminations, link failures, and energy-saving mechanisms that switch between sleeping and active states, pre-obtained local topology information becomes useless and inaccurate. In this case, route establishment fails. To be able to establish routes, these local topology tables should always be kept fresh. Table refreshing can only be made by frequent beacon messaging. In the literature, the period is 1 second for GPSR protocol. In some studies, the period is set as 3 seconds, but it is noticed about the possible drawbacks due to inaccuracy of the information.

On the other hand, beaconing introduces communication overhead and consumes energy. Continuous table updating introduces processing overhead and buffers overflow due to periodic beaconing.

In Figure 5.35, the remaining system energy during the simulation is presented. 100 nodes are randomly deployed over a 500m x 500m area. As seen, GPSR consumes almost the same amount of energy with flooding when the 1 second periodic beaconing is used. As the period increases, the remaining system energy increases also. However, the increase is not linear as the beaconing period. It is seen in Figure 5.35 that increasing the beaconing period reduces the energy consumption and extends the lifetime of the system. With a 30 seconds periodic beaconing, GPSR consumes almost the same amount of system-wide energy with SWR. However, such a periodic beaconing is not acceptable for routing due to the reasons described above. In GPSR, to be able to establish routes on demand, tables should be kept as fresh as possible. During the 30 seconds, nodes may terminate, links status may change, and nodes may move far away from the previous locations. According to the scenario given in the thesis that has fast mobile nodes, nodes move a 0-60 meters per minute. In this case, within 30 second period, each node may get away 30 meters from the previous location. Therefore, usage of 30 seconds periodic beaconing is unrealistic and unacceptable approach. Besides that, it is dictated in the literature that beaconing period should not be longer than 3 seconds.

Although GPSR consumes the same amount of system-wide energy with SWR when 30 seconds periodic beaconing is used, only a single path is constructed in GPSR while multiple paths are constructed in SWR. Besides that, in periodic beaconing tables still need to be updated which introduces computation overhead.

It is also seen in Figure 5.35 that, increasing the period longer than 30 seconds does not affect the energy consumption so much.

6. CONCLUSION AND FUTURE WORK

6.1 Conclusion

In recent years, routing in sensor networks has gained great important due to its effects on the system-wide performance. Sensor networks introduce unique challenges peculiar to it, in addition to the challenges in wireless and ad hoc networks. The most challenging performance metric is the energy while its efficient usage challenges with other performance metrics. Geographical routing protocols appears to be a promising solution for energy-efficiency, scalability and prolonging the lifetime of sensor based systems primarily depending on techniques used in the MAC-layer and the network layer. Geographical routing protocols in the literature generally utilize local or global topology information to route the data. In this thesis, a novel geographic routing protocol for wireless sensor networks is proposed. The proposed routing algorithm is Stateless Weight Routing (SWR).

First the definition of reactive stateless routing approach and distinction of stateless routing algorithms are clearly given. SWR is a reactive stateless geographical routing protocol which does not require any local or global topology information for routing. It completely works in a distributed manner without any coordination between other nodes.

It is analytically and experimentally shown that geographic routing protocols which use periodic beacon messages to provide local topology information reduce the performance of the system. Beaconing introduces communication overhead and consumes energy.

On the other hand, other stateless geographical routing approaches proposed to reduce the energy consumption and overhead introduce MAC-layer integrated solutions. MAC-layer integrated approaches make them dependent to the MAC-layer used. SWR protocol provides the modularity in the communication hierarchy and can be used with any MAC-layer, independent from the services provided in MAC-layer. Routing is achieved completely in the network layer according to the ISO OSI Reference model. Being independent of the MAC-layer makes SWR applicable with any MAC-layer underneath, and makes it unique as providing this property while the other protocols in the literature propose MAC-layer involved routing solutions.

In SWR, a simple data flow approach and a weight metric is proposed, which decreases the energy consumption, and resource requirements such as processor and memory at nodes. SWR enhances multiple performance metrics. These metrics are energy consumption, network lifetime, reliability, routing overhead, and delay.

Performance results show that the SWR prolongs the network lifetime longer than other compared routing protocols and has lower energy consumption. Comparing the remaining energy levels at the nodes, the SWR over performs the other protocols. SWR appears as a simple and effective technique. Routing overhead is compared with other protocols and it is seen that SWR has very low routing overhead

It is shown that without any topology information, SWR forwards the packet to the destination over multiple-paths to provide reliability. Number of the paths is determined by a threshold value. The threshold value which is in metric of weight is also used to shape the data flow toward the destination. Therefore, SWR is applicable in both dense and non-dense networks. All parameters are dynamically determined by the nodes without any coordination. Generally, providing reliability with multiple paths challenges with the energy constraint. However, it is observed that SWR has low energy consumption while providing the reliability.

Another method proposed in thesis is multicasting. Multicasting is used to distribute the data to more than one selected sink as required. As known, SWR is the first routing algorithm that uses multicasting with multiple paths.

A void recovery algorithm peculiar to SWR is also proposed in the thesis. Void recovery algorithm uses the weight and threshold values to circumvent voids.

SWR algorithm can be used in large scale networks. SWR is evaluated with a large-scale network composed of multiple sinks. It is called as MS-SWR (SWR with Multiple Sinks). It is demonstrated that MS-SWR works with any number of sink nodes without any modification in the protocol

One approach to decrease the energy consumption is to use mobile sink nodes to collect data. However, related studies are limited to small scale networks with a single sink node. For large scale wireless sensor networks, it is demonstrated that mobile sinks with MS-SWR protocol reduces the energy consumption in routing and extends the lifetime of the network.

On the other hand, SWR provides a basis for real-time traffic by means of delay and reliability. Methodology and behavior of the algorithms for real-time traffic is described in the thesis, but supporting results are not presented. Real-time evaluation is postponed as a future work.

SWR is simple to implement and works distributedly at nodes. Usage of the weight metric and the stateless property enable it to have natural adaptation to frequently changing topology. Hence, SWR can be used in mobile networks.

Collaborated the features of SWR, it can be seen that SWR is a unique approach by having all these features. It's simplicity, low resource requirements, adaptive nature, independency from other services in the communication architecture, enhancements on performance metrics, real-time support, ability to be implemented in mobile networks make it a unique one. On the other hand, providing reliability by using multiple paths and multicasting with a stateless geographical routing algorithm in a large scale immobile/mobile network with multiple sinks is the first one in the literature.

6.2 Future Work

Real-time use of SWR is kept out of the scope of this thesis. Although, the approach includes some features *priority* and *silence* the future work real-time use of SWR is considered the next step that will follow this study.

Moreover, SWR is a good candidate for routing in mobile networks. Since the SWR is essentially based on the relative geographical position of the sensor node to the sink, it can be used in mobile environments. It is reserved for future work to evaluate the SWR in mobile environment.

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APPENDIX A: A Packet Header

SIMPLE PACKET HEADER

Source Node ID	Seq. No	Destination ID	Sender ID	Sender Weight	QoS Parameters	
2-4 Byte	2 Byte	2-4 Byte	2-4 Byte	2-4 Byte	1 Byte	

Source Node ID : Identification of the source node.

Seq. No : Sequence number of the packet originated from the sender with identification “Source Node ID”.

Destination ID : Identification of the destination node. Generally, it is the identification of the sink node, and known priorly to all nodes. However, in the case of multiple sink usage, identification of the intended destination sink may be given.

Sender ID : Identification of the sender node. “Sender” is the last transmitting node.

Sender Weight : Weight of the sender node. “Sender” is the last transmitting node.

QoS Parameters : Quality of Service (QoS) parameters are inserted into this field. These parameters are: 1. Threshold 2. Prioriy 3. Silence 4. Packet Type. Packet type actually is not a QoS parameters but to save the bits transmitted, we use the available bits in this field.

APPENDIX B: Quality of Service Parameters in a Packet Header

THRESHOLD FIELD		
Value	**In binary**	**Meaning**
0	000	Threshold set value is 0%
1	001	Threshold set value is 10%
2	010	Threshold set value is 25%
3	011	Threshold set value is 40%
4	100	Threshold set value is 50%
5	101	Threshold set value is 60%
6	110	Threshold set value is 75%
7	111	Threshold set value is 90%

PRIORITY FIELD		
Value	**In binary**	**Meaning**
0	00	Forced Data
1	01	Urgent Data
2	10	*Reserved*
3	11	Normal

SILENCE FIELD		
Value	**In binary**	**Meaning**
0	0	SILENCE is set
1	1	Normal

PACKET TYPE FIELD			
Value	**In binary**	**Meaning**	**Abbreviation**
0	00	Data packet	DATA
1	01	Acknowledgement	ACK
2	10	Interest Packet	INT
3	11	Position Packet	POS

APPENDIX C: Generated Map Samples for Various Application Scenarios

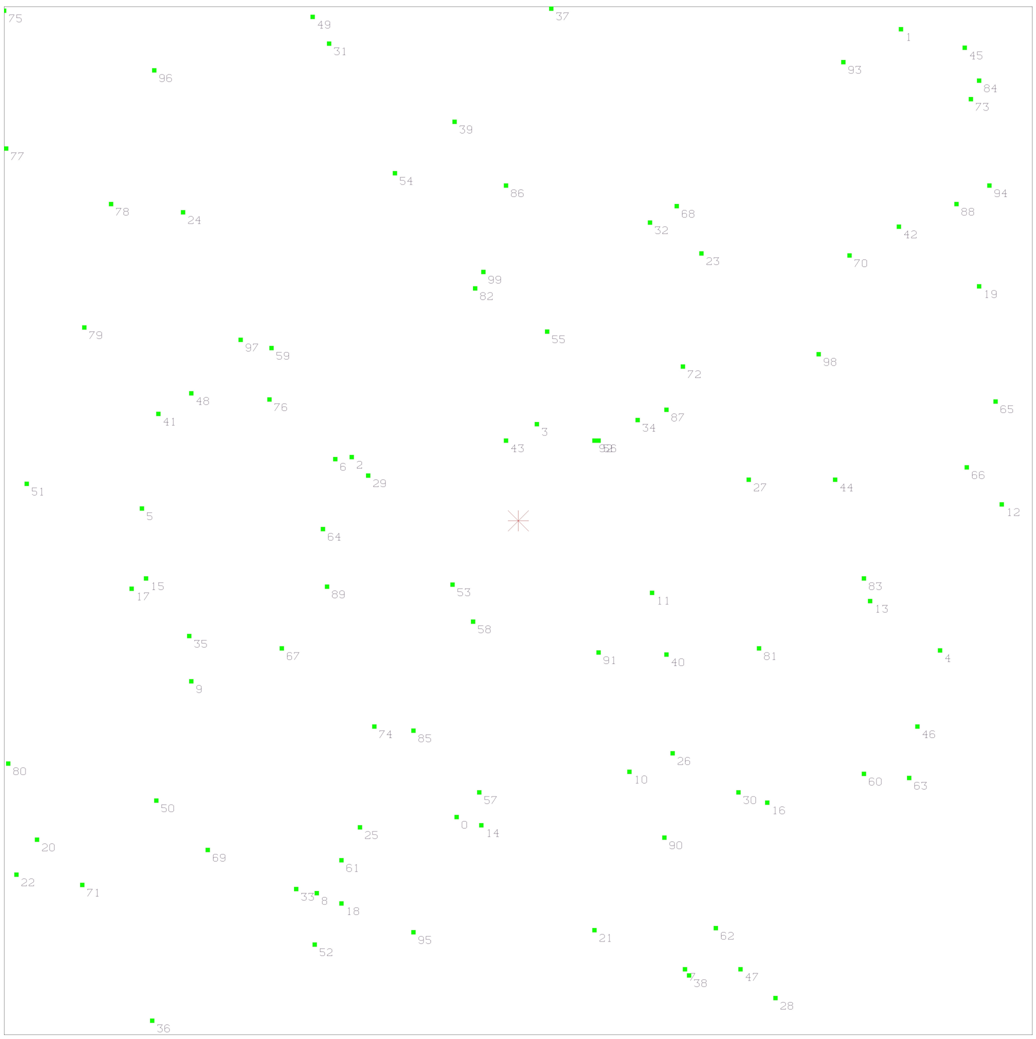

Figure C.1: A random distribution of sensor nodes (Scenario 3).

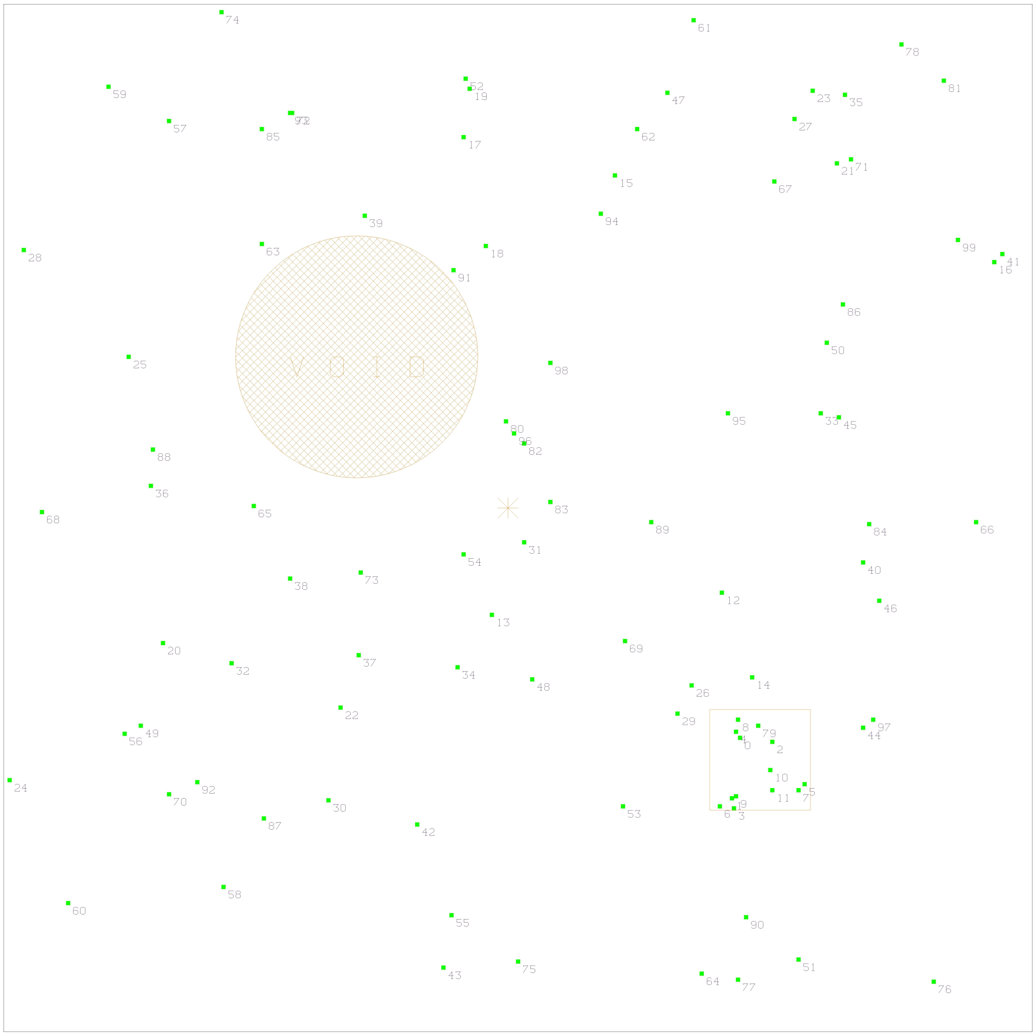

Figure C.2: A random distribution of sensor nodes with a single void and a dense area (Scenario 6)

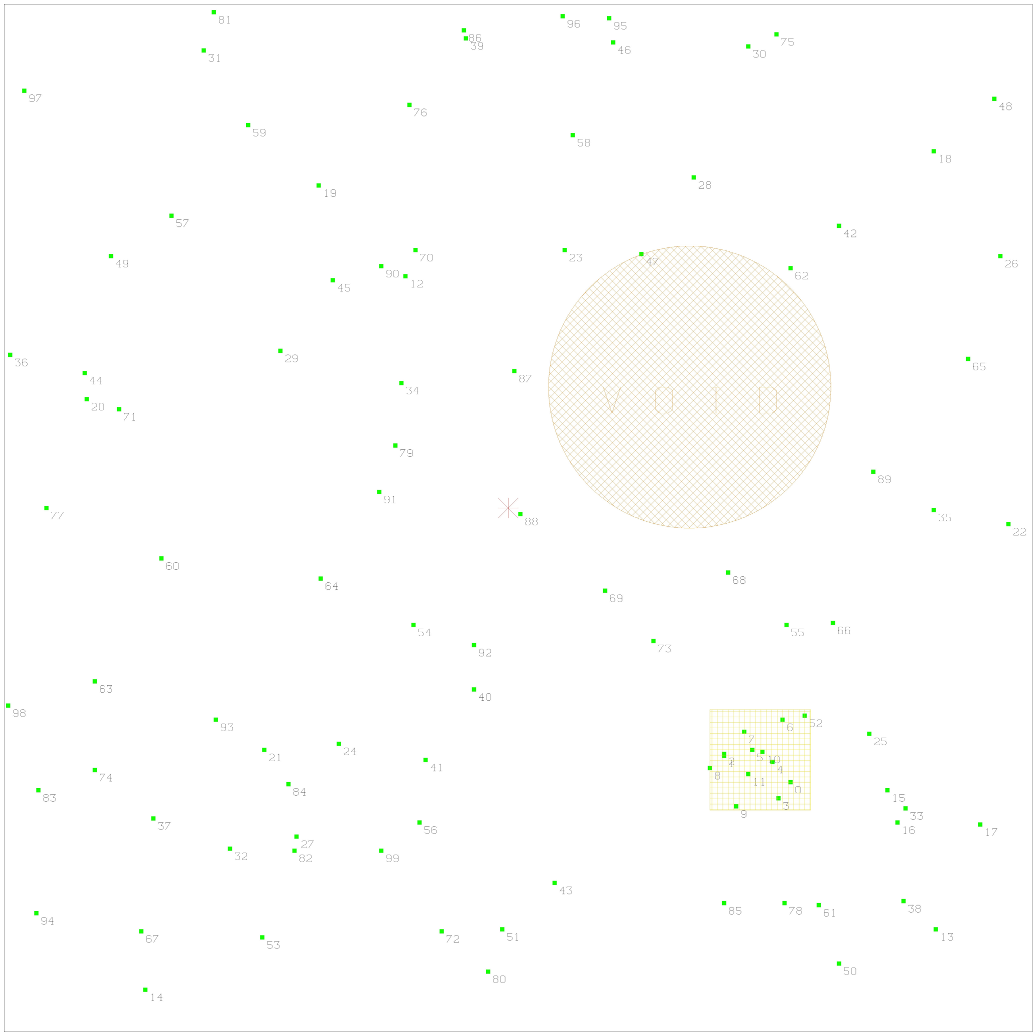

Figure C.3: Another random distribution of sensor nodes with a single void and a dense area (Scenario 6)

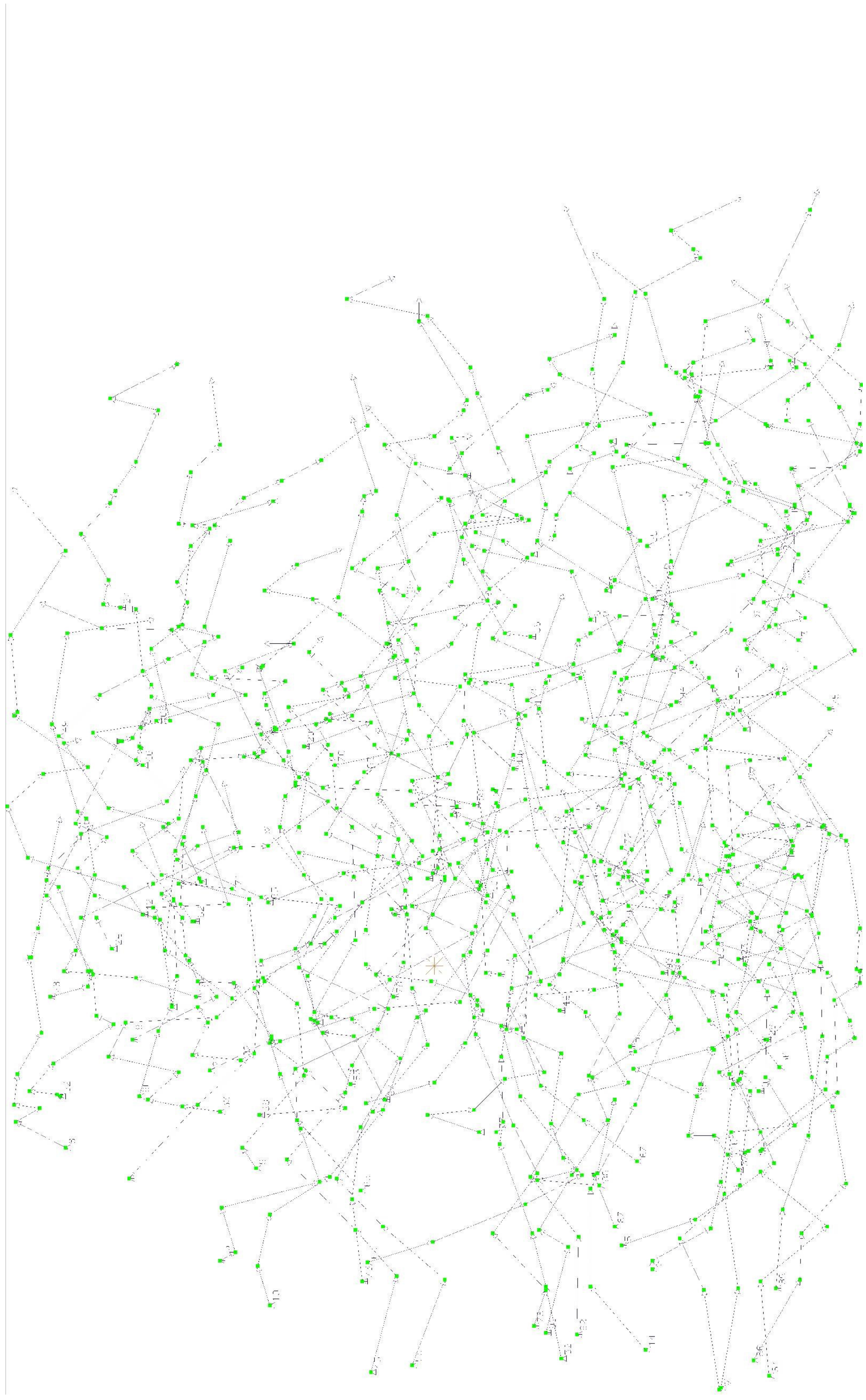

Figure C.4: A randomly generated mobility pattern for a randomly distributed sensor network.

BIBLIOGRAPHY

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