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RAC: Range Adaptive Cognitive Radio Networks

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ABSTRACT

In recent years, cognitive radio has received a great attention due to tremendous potential to improve the utilization of the radio spectrum by efficiently reusing and sharing the licensed spectrum bands, as long as the interference power inflicted on the primary users of the band remains below a predefined threshold level. Cognitive radio allows the secondary users in the cognitive radio network to access the licensed spectrum of the primary users opportunistically. In this paper, an autonomous distributed adaptive transmission range control scheme for cognitive radio networks which is called the RAC is proposed. The RAC considers the QoS requirements of both the primary and the secondary users simultaneously. The cognitive user's maximization of its achievable throughput without interfering the primary user by adapting transmission range of the secondary users dynamically is the key feature of the RAC. One of the advantages of using the proposed scheme is its implementation simplicity. The RAC is compared to other cognitive radio schemes in a simulation environment by using ns2. Simulations indicate that, the RAC can well fit into the mobile cognitive radio ad hoc networks and improve the network performance. Having compared to the other schemes utilizing contemporary cognitive radio technology, the RAC provides better adaptability to the environment and maximizes throughput and minimizes data delivery latency.

1. Introduction

It is known that communication frequency spectrum is under-utilized. According to the Federal Communication Commission (FCC) measurements, roughly 90% of the frequency spectrum is not actively in use [1]. On the other hand, the "spectrum shortage" is often complained about in wireless communications arena essentially because of the use of outdated spectrum assignment policies such as allocating spectrum portions statically, which allow little sharing [2]. New promising technologies are required to accomplish a dynamic spectrum usage ruled by the licensing authorities such as FCC [3]. The introduction of cognitive radio (CR) techniques to assign spectrum provide promising approach to overcome the "spectrum shortage" bottleneck. CR, a term first introduced by Mitola [4], is proposed to overcome this bottleneck produced by allocating spectrum portions statically by enabling more efficient distributed decision making algorithms on how spectrum should be shared. Note that, traditionally for wireless communication, a regulator assigns the spectrum by granting licenses to operators, resulting in exclusive access to certain separate frequency allocations.

There are two classes of users in CR networks, primary (licensed) and secondary (unlicensed). Primary users hold the license for the frequency and as their name indicates they own the frequency using rights and they have the priority over the others. Primary users usually do not utilize the frequency continuously and gaps of different lengths become available. Secondary users, which hold no license, would like to share the licensed radio frequency with primary users by exploiting those spectrum gaps intelligently. Consequently, determining the interference impact of the secondary users on primary receivers from a new transmitter activation is vital, especially between systems with diverse transmission ranges. In a CR system, a secondary link is activated along with the primary link in a way that it does not disrupt the primary link. There have been three essential approaches for the cognitive transmission in the literature: the interweave, the underlay and the overlay approaches [5,6]. In the underlay approach, the cognitive radio transmits in a manner that its interference at the primary receivers is negligible. In the overlay approach the cognitive radio imposes non-negligible interference at the primary receiver but it makes up the performance degradation in the primary radio with the help of its non-causal access to the primary users data. The interweave technique is based on the idea of opportunistic communication. There exist temporal spectrum gaps which are also called as spectrum holes that are not in use by the primary owners and consequently can be used for secondary communication.

In this paper, a wireless fading system with a cognitive radio that is concurrently transmitting with a primary user is considered. The primary user operates with a constant power and utilizes an adaptive modulation and coding scheme satisfying a bit error rate requirement. The successful operation of the cognitive radio network will be disturbed, if a primary user detected due to their priority in spectrum access, the operations of primary users should not be affected by unlicensed users. Regardless of the used scheme, frequent interruption in a selected route would degrade

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the performance in terms of the quality of service (QoS) of the communication. Thus, an important concern is to design a communication protocol that provides QoS guarantee which will allow a path to be retained during a data communication session along that path between secondary nodes. RAC: Range Adaptive Cognitive Radio Networks is proposed to achieve this objective by utilizing an adaptive transmission range scheme. Because of active primary user detection, a secondary node involved in the communication process may not be able to continue its transmission, thus disturbing the communication link. The RAC mechanism is based on self-adjusting variable transmission range of secondary users to find an alternative path to keep communication link alive. No negotiation, i.e. no handshaking or messaging, between users is required and the optimization procedure is done at the cognitive radio in the RAC. It may be claimed that a low transmission range will not guarantee proper connectivity among users to ensure effective communication when there is not sufficient number of secondary users in the network. Such a claim is an important issue to be discussed in a system consisting of only primary users. However, providing communication among secondary users in the presence of primary user communication proposes a totally different environment and trying to keep connection even with a reduced range improves the overall network performance for the secondaries. On the other hand, if the transmission range is higher than the optimum value, it will ensure connectivity but will increase the probability of encountering a primary user in the transmission range, cause harmful interference to more primary users, increase collision and congestion of control packets.

There has been an interest in the recent years for determining an optimal transmission range which is also called as optimum power interchangeably for a fixed number of secondary nodes distributed over an operating area [7–10]. To the best of our knowledge, all of these studies tries to find and allocate an optimal range (power) and assigns it statically for a given scenario. Neither of them adjusts the transmission range adaptively during a communication session as the RAC. However, in a CR network environment, the number of both secondary and primary nodes as well as the concentration (density) of nodes in different areas of the operating zone varies. We believe that the RAC, which is a scheme based on adaptive transmission range would be an effective solution in such a changing environment due to varying primary node activities.

The remaining part of the paper is organized as follows. In Section 2, related work in this area is reviewed. Details of the RAC is given in Section 3. The simulation and performance analysis of the RAC is presented in Section 4. Finally, conclusions and future research directions are provided in Section 5.

2. Related work

Cognitive radio is a flexible and intelligent wireless system that is aware of its surrounding environment and changes its transmission or reception parameters to communicate efficiently avoiding interference with the primary or secondary users. The secondary users will benefit from this CR to utilize the licensed band of the primary system as long as the licensee's operation is not compromised [4,11,12]. Based on the CR's interaction with the primary network system, transmission modes are classified into three types: interweave, overlay and underlay modes [5,6]. In the interweave mode, the secondary system can occupy the unused license band, i.e., the spectrum hole, under the assumption that the majority of the spectrum is typically under-utilized. These spectrum holes change with time and geographic location. Therefore, in this mode, the secondary transmitters need to have the real-time functionality for monitoring spectrum and detecting the spectrum holes. A number of spectrum-sensing techniques [12–14] are proposed and spectrum-sharing techniques mainly based on game-theory have been analyzed [15,16]. Overlay mode allows the secondary system to use the license band even if the primary system is using the band. The secondary transmitter is assumed to have knowledge of the primary message [5,6]. In the underlay mode, simultaneous transmissions of primary and secondary systems are also allowed on condition that the secondary system interferes less than a certain threshold with the primary system [5,6]. Accordingly, the concept of interference-temperature [17] has been introduced to determine a tolerable interference level at the primary receiver.

The use of adaptive power in transmission in a CR was initially investigated in the literature in the content of the optimal power allocation problem. Wang and Zhu [7] studied the power control of transmitter in cognitive radio system and employ game theory for modeling. In [8], authors considered the distributed power control problem in a CR network which shares the primary user channel while trying to guarantee the QoS requirements for both the primary and secondary user simultaneously. In [9], the authors proposed an opportunistic power control strategy for the cognitive user, which they proved to be optimal in the sense that it maximizes the achievable rate of cognitive user while guaranteeing the outage probability of the primary user not to be degraded.

As can be seen in these studies, researchers focused on deciding the optimal transmit power of both primary and secondary users in a cognitive radio network. In [18], a mechanism based on self-adjusting variable transmission range of mobile hosts in conventional 802.11 networks is proposed. In this scheme, if two mobile nodes are moving away from each other, both of them have to progressively increase their transmission range in order to protect the link between them to ensure connectivity. In order to protect a path during data communication, all of the node-pairs in the path have to protect their links by increasing their transmission range. They use the adaptive transmission range term only for increasing the transmission range in the proposed protocol. However, to the best of our knowledge, optimization of the network throughput and end-to-end delay as an autonomous distributed adaptive transmission range scheme has never been studied.

There are also a few number of studies concentrated on the performance improvement of cognitive radio networks. Some of these studies focus on the throughput and/or experienced average end-to-end latency. In [19], Cheng et al. proposed an on-demand protocol for routing and spectrum assignment in cognitive radio networks. The authors benefit from on-demand routing and borrow from ad hoc on demand distance vector (AODV) routing protocol and modify route request and route reply packets in their scheme. Their study focuses on constructing a path solely on the basis of delay. In a recent study, Zhu, Akyildiz, and Kuo [20] introduce a spectrum-tree based on-demand routing protocol (STOD-RP) that establishes a “spectrum-tree” in each sensed available spectrum band. Their study is based on taking advantage of combining tree-based proactive routing and on-demand route discovery. Additionally, each spectrum-tree must have a root node which requires a root selection procedure. However constructing all spectrum-trees in the network produces a significant amount of overhead since construction involves message exchange and computation power. Authors assume that all nodes are fixed or move very slowly. This assumption may not be the case for an ad hoc network all the time. Also authors state that overlapping/gateway nodes has equipped with multiple spectrum-agile radios in the network. Since each node in the network has the potential of becoming a gateway node to provide a better performance considering mobility in a realistic scenario, all nodes in the network have to be equipped with multiple radios. Obviously such an approach will increase the network deployment cost.

Like mentioned studies, we believe that on-demand routing is suitable for multi-hop, single transceiver cognitive radio networks, as the topology changes quite often. Some of the studies are chosen to compare to RAC since all of the proposed techniques uses AODV as a starting point and try to improve similar overall performance criteria.

3. RAC

The RAC is a simple yet an efficient approach to utilize throughput and reduce end-to-end delay by dynamically changing transmission range when needed. As soon as primary user communication is detected by the cognitive radio engine, each communicating secondary node that interferes with the detected primary node reduces its transmission range trying to retain the communication path while decreasing the interference on the detected primary user. Range adaptivity is realized in a distributed manner in every node of the secondary network according to the distance metric that is kept in a neighbor table which includes only local data. The use of local data would also provide the scalability of the RAC.

3.1. Network model

In this study, a cognitive radio ad hoc network environment with primary and secondary nodes, where all nodes communicate with each other in their own networks, is considered. There is no communication (i.e., no cooperation) between primary and secondary networks. The network is modeled as a graph $G=(N, L)$ where N is a finite set of nodes, $N=\{x_1,x_2, \ldots, x_n\}$ and L is a finite set of unidirectional links, $L = \{(x_i, x_j)\} : 1 \le j \le n \; for \; x_i \in \Re^d, 1 \le i \le n$. If a node m is within the transmission range of node n, then n and m are assumed to be connected by an unidirectional links $l_{nm} \in L$, such that whenever n transmits a message, it will be received by m via l_{nm} and vice versa. A route or path from node s to node d is an alternating sequence of nodes and links, representing a continuous traversal from node s to node d. Each node n has a wireless optimal transmitter range R_{opt} that is used in normal operation and is allowed to use different transmission ranges R_n independently from other nodes to communicate with other nodes in their neighborhood, $R_{min} < R_n < R_{max}$, to retain the communication path if needed.

3.2. Details of the implementation of the RAC

In the proposed adaptive range scheme, a modified version of AODV adapted to cognitive radio networks [19] is used as routing algorithm. In addition to the inherited characteristics of used AODV protocol, each node n in the network has a neighbor node table, which is constructed using beacon messages to its neighbors once in every time quantum. If the spectrum sensing algorithm uses beacons, there is no need to use additional beacon messages in the proposed scheme. Also if there is an ongoing communication session overhearing nodes uses the information. In the neighbor table, a distance metric is stored for every neighbor locally. Each node receiving the beacon, determines a distance metric to a neighboring node based on measuring the received signal strength indicator (RSSI), Time of Arrival (ToA), and Angle of Arrival (AoA) of the received beacon messages. Calculation of the distance metric is kept out of the scope of this paper [21,22].

Algorithm 1. Range Adaptive Cognitive Radio for node n_i.

```
begin
  if PU detected then
    if PU distance calculated then
      adjust transmission range R_best not causing harmful
      interference to the PU;
    else
      while interference to primary user > T_i do
        reduce the transmission range by ΔR
      end
    end
  else
    adjust transmission range R_opt;
  end
  if PU activity interrupted current communication session then
    multicast RREQ plus the first packet in the queue to
    neighbors that are far from the PU;
  end
end
```

To clarify, the example cognitive radio network shown in Fig. 1 can be considered. In this network, node S has some data to send to node D and therefore needs to find a path to destination D. As stated above, a modified version of AODV adapted to cognitive radio networks [19] is employed. The protocol starts by sending out a broadcast Route Request (RREQ) message seeking destination D. The destination node D knows the spectrum opportunity distribution of all nodes on the path when receiving RREQ message, and assigns a frequency band to its cognitive radio transceiver. It then, sends back a Route Reply (RREP) to the source node, encapsulating the assigned band. Intermediate node assigns frequency band with the help of the band choices extracted from the RREP, and the spectrum hole (spectrum opportunity) information from previous RREQ. Then the node establishes path to the destination via its cognitive radio and generates new RREP message to send back to the source. Once the path is constructed, communication session continues normally. Upon the start of the communication process, every node n in the active path locally broadcasts the active route information in the beacon messages to its neighbors using the neighbor table. Receiving this path information, neighboring nodes control their own neighbor table and decide which nodes in the active path are in their neighbor table. Whenever a primary node activity is sensed by the cognitive radio engine (Fig. 2), every node detecting the primary user activity in the active path, tries to determine the distance of the primary user and according to the determined value, it adapts its transmission range that restricts the interference to the primary user below a certain interference threshold for node i, T_i. As can be seen in Algorithm 1. If the node density is high enough, the best transmission range that enables the retaining the active path without causing any harmful interference to primary node is selected by checking the distance values of the neighbor table. If there is no such value that retains the active path without interfering the primary user, all nodes in the active path adapt their transmission ranges to their maximum range which is not causing any harmful interference to the primary user (Fig. 3). After this adaptation, nodes that detected the primary user activity in the active path, multicast received packets of the ongoing communication session to its available neighbors according to the neighbor table along with a route request message to the destination node D. As a consequence, the new path is constructed with only local update upon the first route reply message received. Algorithm is given in Algorithm 2. If this is not possible, a route error message is sent to the source node. Afterwards, a re-routing from node S to node D is initiated.

Algorithm 2. RAC:Local Repair for node n_i.

```
begin
  if primary user detected then
    use RAC to adapt transmission range;
  end
  if active path information packet received then
    store active path nodes' information;
    decide which nodes on the path are neighbor node;
  end
  if RREQ+packet arrives for a specific destination D then
    check neighbor table and active path information;
    decide which nodes to send;
    multicast RREQ+packet to those;
  end
end
```

4. Simulation and performance analysis

Through simulations implemented in ns2 [23], the performance and functional correctness of RAC and its relative performance

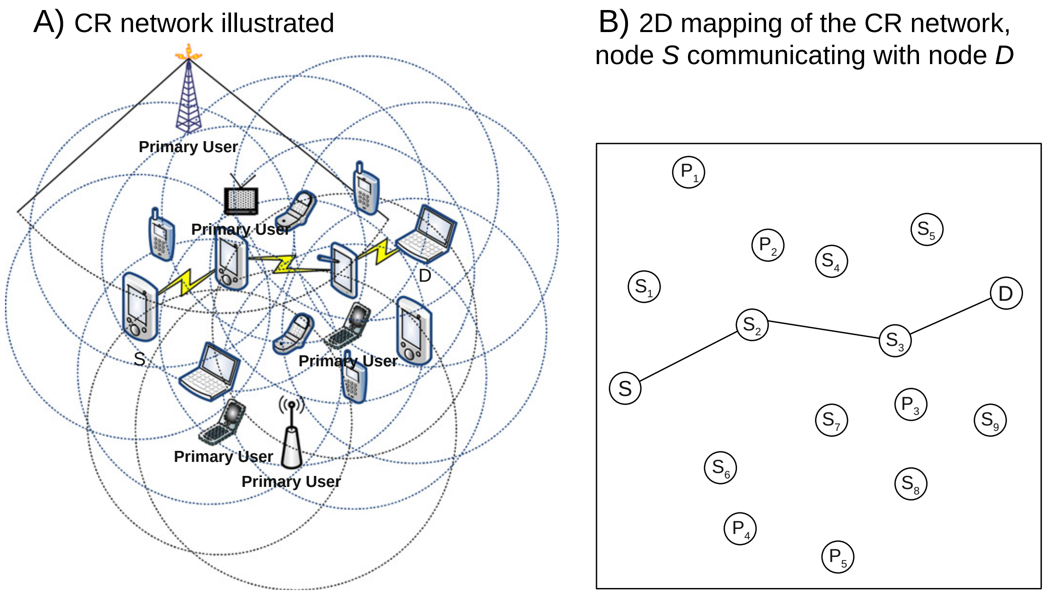

Fig. 1. A mobile CR ad hoc network example.

compared to that of SORP [19] and STOD-RP [20] are evaluated. Unless otherwise noted, simulations are run with the following parameters. Two-ray ground propagation model is used at the radio layer. The bit rate for each channel is 2 Mbps. Variable number of mobile nodes up to 100 moving in a rectangular area 1800 m × 1800 m in dimension is modeled. Each node picks a random spot in the rectangle and moves there with a speed uniformly distributed between 0–20 m/s. Upon reaching this point, the node picks a new destination and repeats the process. The primary users' activities are modeled by using the exponential ON–OFF process. The coverage range of the primary user on its operation channel is 250m. These parameters are set to the given values since they are similar to the default values used in previous study of various protocols. Thus a comparison among the protocols can be done. During the simulation the following default communication pattern is used. Each source node generates and transmits constant bit rate (CBR) traffic and each message is 1 KB in length. The transmission interval for each node is set to 100 ms. 50 experiments are performed in random multihop network topologies, for each different parameter settings.

The characteristics of the RAC are explored under a number of different scenarios. The robustness of the RAC is investigated for various numbers of both primary and secondary nodes, stressing the impact of adaptive transmission range on the throughput performance. The simulations are run for networks of sizes 10 to 100

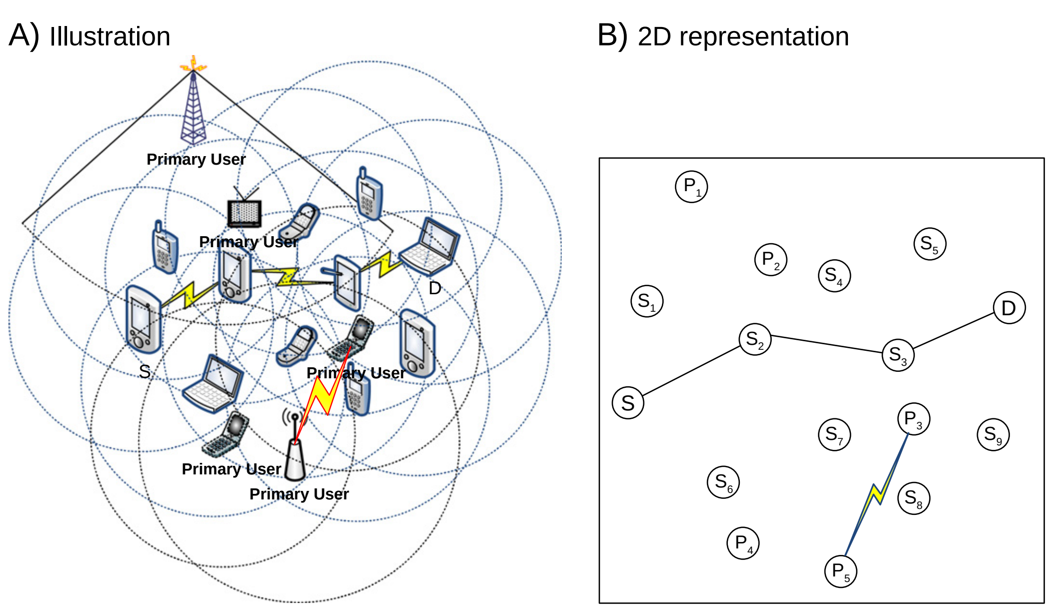

Fig. 2. A primary user starts communication.

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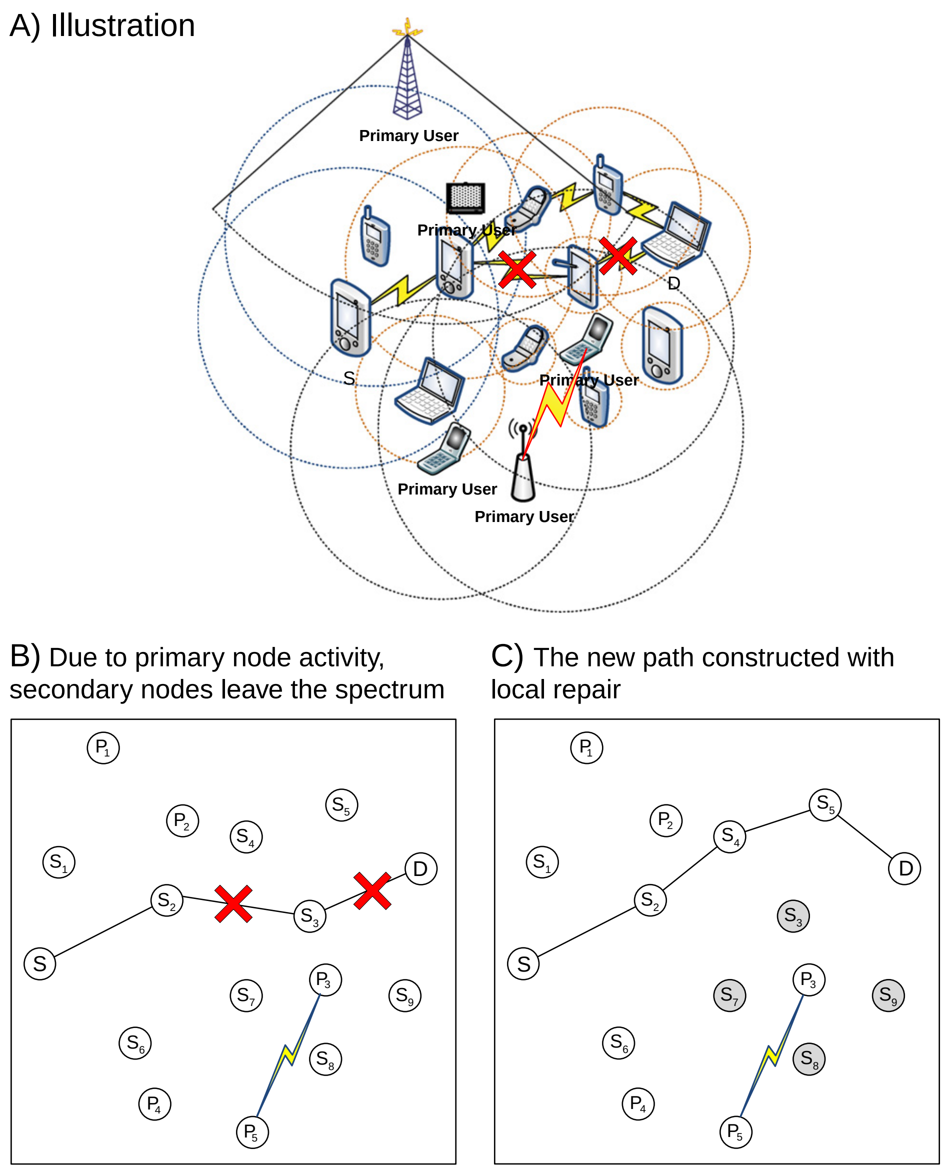

Fig. 3. Re-route with adaptive range and local repair.

secondary nodes and 20 to 100 primary nodes. It is shown that since the node density has a great importance on the performance of the RAC for retaining the path and for the success of the local repair, the RAC performs high throughput for dense networks. However, after a certain threshold throughput starts to decrease due to the congestion. For example the peak average throughput of the RAC with 20 primary node is reached when 60 primary nodes are around. A sharp decrease after 60 nodes indicates the practical limit for the trade of between the number of primary and secondary users. (Fig. 4) As expected, average throughput is inversely dependent on the number of primary nodes as seen in Fig. 5.

As noted earlier, SORP [19]: a modified version of AODV and a recently proposed spectrum-tree based on demand routing STOD-RP [20] are used for comparisons. Throughput and end-to-end delay comparisons have been evaluated between SORP, STOD-RP and RAC to show that RAC can well fit the multi-flow multi-channel environment and effectively exploit the potential large communication capacity in CR networks. In the simulations, the rate of flows is

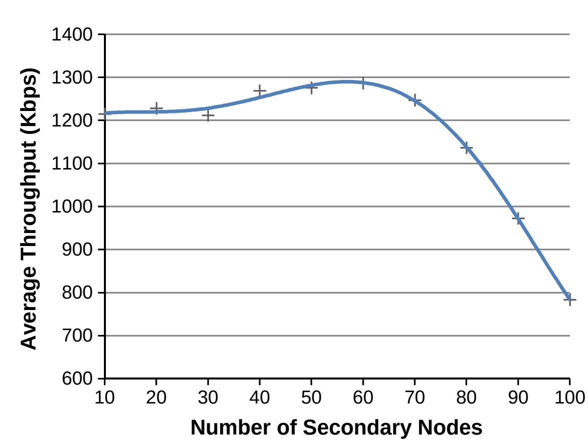

Fig. 4. Average throughput of the RAC with 20 primary nodes in the network.

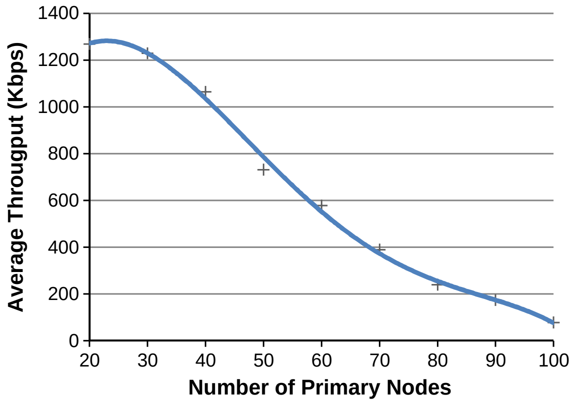

Fig. 5. Average Throughput (Kbps) of the RAC with 50 secondary nodes in the network.

varied from 100 Kbps to 1800 Kbps. The nodes are randomly placed in the area, and 8 flows having the same traffic generation rate are initiated. When the traffic load is low, all three schemes have more or less the same performance. As the flow rate increase, the throughput of SORP increases slowly towards the limit of the established path. Also in SORP, nodes become disconnected due to primary user activity, and no packets are forwarded. STOD-RP performs better than SORP since STOD-RP also employs a route recovery algorithm. As the traffic load becomes higher, the performance improvement of the RAC over the other two schemes becomes more significant due to path retaining and local repair using adaptive transmission range. In a dynamic environment, which means the network topology varies frequently, the RAC adapts nodes transmission range to retain the secondary nodes communication path or performs a local repair when the distance to the destination is not reachable without harmful interference to the primary user. Therefore, the established route in the RAC is better than the route built in the other two schemes in a frequently varying environment. The result is illustrated in Fig. 6.

The end-to-end delay performance of the RAC with other schemes is also compared. We adjust the number of intersecting flows from 1 to 8 to evaluate the performances on intersecting flows. The simulation result is shown in Fig. 7. When the number of flows increases, the RAC seeks a balance between assigning new frequency bands to allow simultaneous transmission and accommodating some nodes on one band to avoid switching delay. Also the re-route

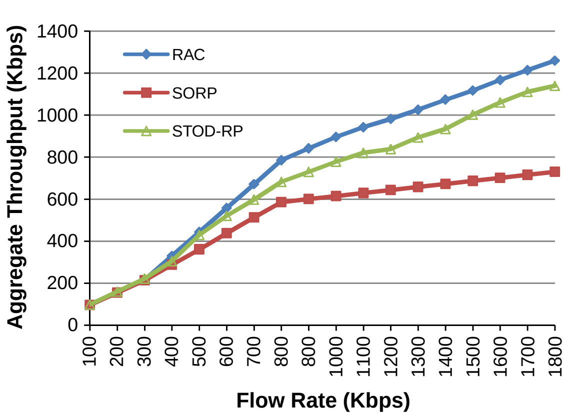

Fig. 6. The RAC performance: throughput observed with different protocols when two hosts, *S* and *D*, communicate.

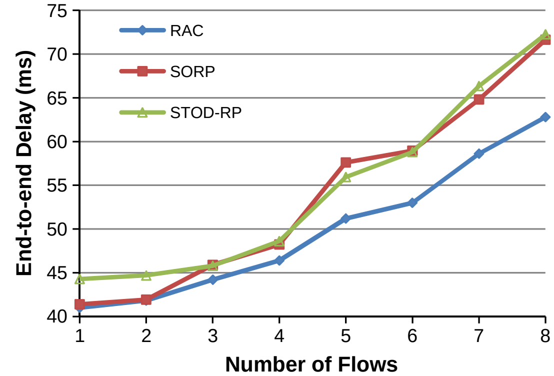

Fig. 7. End-to-end Delay (ms) performance vs. number of flows compared to different protocols.

establishment time is lower in range adaptivity than the others since those techniques have to reconstruct a path from source to destination upon a primary user activity detection. Consequently, the RAC achieves an overall optimal delay, than the other two as the number of intersecting flows grows as shown in Fig. 7.

5. Conclusion

In this paper, Cognitive Radio Ad Hoc Networks are investigated and RAC: Range Adaptive Cognitive Radio Networks is proposed to enhance throughput of these networks. The RAC is an autonomous distributed adaptive transmission range control scheme for cognitive radio networks that simultaneously considers the QoS requirements of primary and secondary users. It is a simple yet an efficient approach to utilize throughput by dynamically changing transmission range when needed. The key feature of the proposed strategy is that, a cognitive user can maximize its achievable throughput and minimize end-to-end delay without interfering any primary user by dynamically changing its transmission range. Through an implementation in the ns2 simulator, it has been shown that RAC scheme achieves significant improvement on the throughput and end-to-end delay. The adaptability and efficiency of the scheme is proved in simulations such that it outperforms the previously proposed approaches.

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