Tree-based Multicast Routing and Channel Assignment for Enhanced Throughout in Emerging Cognitive Radio Networks

Haythem Bany Salameh
Department of Network and Communications Engineering,
Al Ain University, Al Ain,
United Arab Emirates
haythem.banysalameh@aau.ac.ae
Department of Telecommunications Engineering,
Yarmouk University, Jordan
haythem@yu.edu.jo

Mustafa Ali
Electrical Engineering Department,
Mustansiriyah University, Iraq
mustafa_mahdi@uomustansiriyah.edu.iq
Department of Telecommunications Engineering,
Yarmouk University, Jordan
mustafa_mahdi@yu.edu.jo

Abstract: *In future multi-hop wireless networks like 5G and B5G, efficient large-scale video sharing and data dissemination are expected to rely heavily on multicast routing and Cognitive Radio (CR) technology. While multicast routing is efficient when the network always has access to the spectrum, the dynamic nature of Primary User (PU) activities, heterogeneous spectrum across the CR Network (CRN), and PU access priority make it challenging to implement efficient multicast routing protocols in CRNs. This paper proposes a hierarchical multicast routing mechanism for multi-hop CRNs that exploits the Shortest Path Tree (SPT) and Minimum Spanning Tree (MST) concepts. The proposed multicast routing mechanism consists of tree construction and channel assignment algorithms. The tree-construction algorithm models the network topology as a multicast tree rooted at the CR source and spanning all the CR nodes. Based on the constructed tree, the channel assignment algorithm employs the Probability Of Success (POS) metric to assign channels to the various layers defined by the constructed SPT or MST, ensuring that the most reliable channel is used for the multi-hop multicast transmissions. Simulation experiments are conducted to evaluate the mechanism's effectiveness, revealing significant improvements in throughput and Packet Delivery Rate (PDR) compared to state-of-the-art protocols under different network conditions. The simulations also show that the SPT-based mechanism outperforms the MST-based mechanism in terms of throughput but has a higher tree construction complexity.*

Keywords: *Cognitive radio, multicast routing, minimum spanning tree, shortest path tree, licensed spectrum.*

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1. Introduction

Cognitive Radio (CR) has been utilized as a key technology to address the problem of licensed spectrum underutilization. CR opportunistically exploits the underutilized licensed spectrum owned by the legacy Primary Radio Networks (PRNs) to enhance network throughput, spectrum efficiency, system security, spectrum management, and network connectivity [3, 12, 15, 35]. CR Networks (CRNs) are intelligent wireless systems that can adapt their transmission parameters per the dynamically changing operating RF environment to enhance spectrum utilization without impacting the PRNs' performance. Such dynamic spectrum utilization can be achieved by implementing software-defined radios [17, 30].

Multicast routing is one of the most critical processes for enabling effective data transmission and multimedia sharing in next-generation wireless networks (including B5G, IoT, and 6G). Multicast allows a source user to send data packets to multiple destinations in the network simultaneously (i.e., the source sends the same packets to multiple nodes in the network) [8, 26, 27, 29]. The source user can deliver the data packets to the different destinations using single-hop or multi-hop paths. The multicast reduces communication cost, improves channel efficiency, provides effective use of energy and bandwidth, minimizes the sender and router processing, and minimizes delivery delay [1, 25]. Several multicast routing algorithms were proposed for traditional wireless networks (e.g., [5, 18, 22, 24, 33]), but none are directly applicable to CRNs due to their uncertainty and the dynamic nature of their operating environment. Specifically, unlike traditional wireless networks in which the successful packet delivery over a given channel depends only on the link quality conditions between the communicating nodes over that channel, the successful packet delivery in CRNs heavily depends on both the quality and availability (PU activity) of the operating channels. This makes designing the multicast routing a challenging issue in multi-hop CRNs. Worse yet, in multi-hop CRNs, the availability of the different channels varies across the network (spectrum heterogeneity) due to the PU activities (i.e., non-neighboring CR devices may have different views of spectrum availability). We note that a number of multi-cast routing protocols were proposed for CRNs (e.g., [1, 8, 21, 25, 29]). However, most of them needed to account for the multi-hop nature of CRNs and partially account for the unique features of the CRN operating environment. Therefore, in this paper, we develop an efficient multi-layer multicast routing algorithm for CRNs that considers the peculiar requirements of the multihop CRN operating environment while being spectrum heterogeneity aware. The proposed algorithm utilizes the concepts of the Shortest Path Tree (SPT) and Minimum Spanning Tree (MST) to convert the network topology to a multi-layer tree. Based on the constructed tree, our algorithm assigns operating channels to the different layers in the tree based on the Probability Of Success (POS) metric, such that the most reliable channel is assigned to each layer. The POS accounts for the CRN operating environment regarding channel quality and availability due to PU activities over the different layers in the CRNs. The organization of this paper is as follows: Section 2 highlights the related works regarding multi-cast transmissions in CRNs. Section 3 describes the system model, POS analysis, SPT, and MST concepts. Section 4 describes our proposed tree-based POS-aware multicast routing and channel assignment protocol. In Section 5, we demonstrate the effectiveness of our proposed protocol through simulations. Finally, Section 6 concludes this paper.

2. Related Work

Several routing protocols have been proposed to support multi-hop cognitive radio networks (CRNs) transmissions [1, 6, 9, 8, 10, 11, 21, 25, 29, 31, 34]. However, these protocols either did not enable data multicasting or did not consider the unique features of CRNs. In [6], the authors developed a multi-cast routing algorithm with the objective of minimizing the overall energy consumption in the CRN. This was done by minimizing the number of needed relay nodes and operating channels for each multicast session while considering the Primary radio Users (PUs) channel availability conditions. The works in [16, 21] have proposed optimization problems for video multicasting in CRNs while considering the various network parameters such as retransmission, modulation, scheduling, power control, and the introduced interference to the PUs. The work in [21] developed a multicast routing protocol based on a combined expected transmission count metric and Steiner Minimal Tree (SMT). In [4], the authors proposed energy-efficient multicasting protocols for CRNs. They formulated the problem as a MILP and solved it using a sub-optimal heuristic algorithm. Jin *et al*. [20] proposed a multicast scheduling protocol considering fairness, power control, and router assignment for infrastructure CRNs. In [26], the authors provided a detailed review of protocols designed for multicasting in CRNs. Jayaram and Anjaneyulu [19] proposed an Opportunistic cooperative CR multicast routing protocol (OCCMRP). OCCMRP consists of four steps: spectrum sensing, capacity-aware channel assignment, optimized path selection, and optimized relay selection. The work in [28] transformed the multicast problem into a directed Steiner tree problem to construct minimum energy multicast trees based on the PU traffic load. The simultaneous transmission was more efficient when PU activity was low, while the sequential transmission was more suitable when PU activity was high. In addition, a jointly distributed algorithm was proposed in [13] to improve network throughput by dynamically performing channel assignments while guaranteeing a bit error rate. Chen *et al*. [10] investigated the packet multicast problem in CRNs based on a random network coding method. However, their solution was limited to single-hop wireless multicast CRNs and cannot be generalized to multi-hop CRNs. A network coding-based scheme was proposed in [14] to enhance network throughput by formulating a minimum energy multicast problem, in which a polynomial-time linear solution was provided.

We note that, in this paper, we extended our previous work by proposing a new MST-based multicast routing protocol and conducting extensive simulation experiments to investigate the performance of both protocols under different network conditions[1].

3. System Model and Analysis

3.1. Network Model

We consider a multi-hop multi-channel ad hoc CRN that consists of a CR source attempting to send multicast packets to N_r CR destinations. The CR users geographically coexist with several PRNs, as shown in Figure 1. The CR users opportunistically utilize the idle PU channels. Let M denote the set of all PU channels, and $M=|M|$ denote the total number of PU channels. Each PU channel's status is modeled as a two-state Markov model, with ON and OFF states. An ON state indicates that the channel is currently being used by a PU user and thus cannot be utilized by the SUs. The OFF state indicates that the channel is not occupied by the PUs, allowing the SUs to utilize them opportunistically. The list of idle available channels for SUs to utilize can be identified through spectrum sensing. A dedicated Common Control Channel (CCC) is reserved to coordinate the multi-cast

[1]A limited subset of initial results for only the SPT-based multicast routing was presented in the 2022 ACIT Conference, 2022, UAE.

communications in the CRN. Given the aforementioned network model, we aim to design a multicast routing algorithm for video multicasting to improve the overall PDR and network throughput.

3.2. Probability of Success Analysis

A Rayleigh fading propagation model is considered to model the channel quality conditions in the CRN. According to the PUs activities' stochastic model and Rayleigh fading model, the POS of a packet transmission between any two communicating CR users *i* and *k* over channel *j* is computed as:

$$P^{i\text{-}k}_{suc(j)} = \exp(-T_{r(j)}^{(i\text{-}k)}/\mu_j) \quad (1)$$

where μ_j is the average spectrum availability duration associated with channel $j \in M$, and $T_{r(j)}^{(i\text{-}k)} = D/R_j^{(i\text{-}k)}$ is the needed packet transmission time for nodes *i* and *k* transmission over channel *j*, *D* is the packet length, and $R_j^{(i\text{-}k)}$ denotes the achieved data rate over channel *j* for the transmission between node *i* and node *k*.

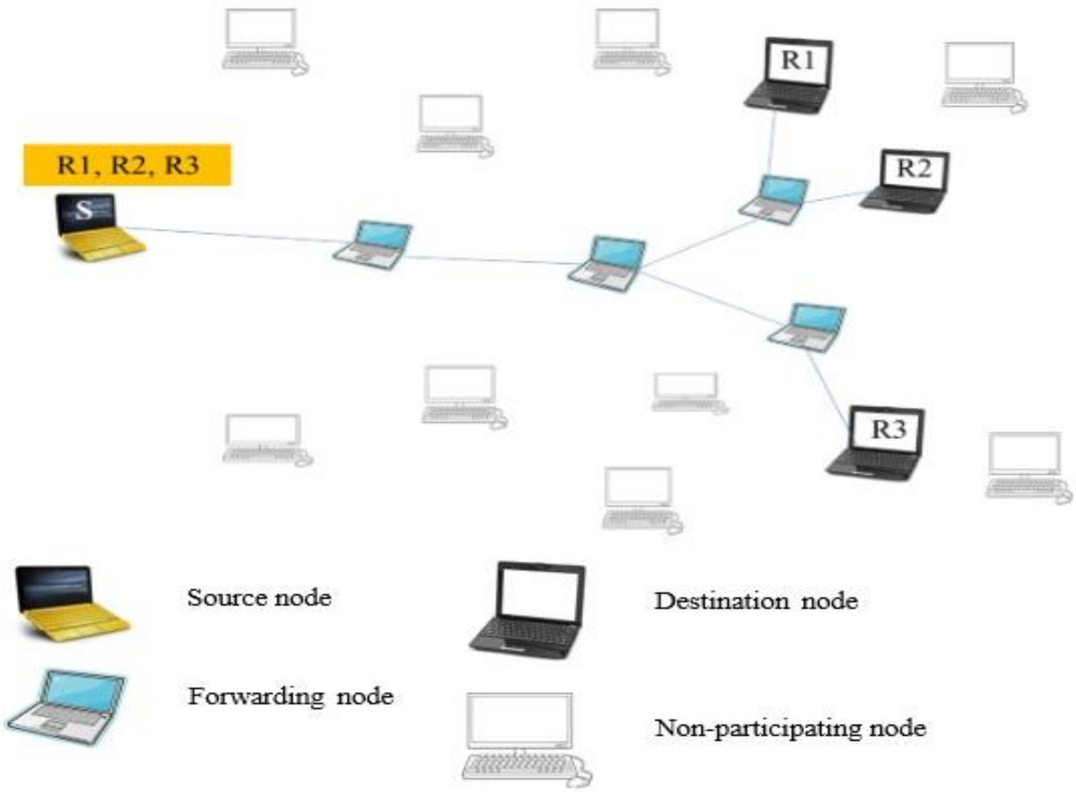


Figure 1. Network model with a CR source and three multi-cast destinations (R1, R2, and R3).

3.3. SPT Analysis

The SPT finds the shortest distance (cost) path from the CR source to each vertex (CR receiver) in the network topology. To construct the tree, SPT assumes the existence of a source (root) node, so if the CR source is changed, the entire SPT must also be changed [32]. The SPT is constructed using Dijkstra's algorithm for any connected and undirected graph with a given CR source (e.g., node "a" in Figure 2).

The SPT can be used to convert a multi-hop network topology into a multicast tree with several layers, in which each layer may have multiple sub-trees. The end nodes of the tree are the multicast destinations. Each sub-tree has its source. Let the set of all layers in the SPT is defined as *L*, which depends on the original network topology and the location of the intended destinations. In each layer *l*, a node can be a source for a sub-tree s if-and-only if this node is connected to other nodes in layer $l + 1$. Let S_l denote the set of all sub-trees belonging to layer *l*. We denote the source of a sub-tree $s \in S_l$ in layer *l* as $S_{l,s}$. For the CRN topology in Figure 2, with nodes c, h, f, and e as destinations, the resulting SPT is given in Figure 3. It is clear that there are four layers: layer *1* with only one sub-tree and a source node $S_{1,1}$=a, layer *2* with two sub-trees and two sources $S_{2,1}$=g and $S_{2,2}$=b, layer *3* with only one sub-tree and one source node $S_{3,1}$ =d, and layer *4* with no sub-trees (all nodes in this layer are end nodes in the SPT).

3.4. MST Analysis

MST is a tree constructed from a subset of edges that includes every vertex in a network topology, such that the total distance (cost) of all the edges is minimized (see Figure 4). The algorithm used to find the MST is Kruskal's algorithm, which has a total running time of ($m\log(m)$), where *m* is the number of edges in the topology [7, 32]. The MST is applicable to any node in the topology as the source and does not need to be rebuilt when the source changes. The MST for the network topology in Figure 2 is shown in Figure 4.

The MST has the same number of edges as the SPT. For a topology with v vertices and m edges, both the SPT and MST have $v-1$ edges. However, the source node in the MST always requires more hops to reach all other nodes than in the SPT for the same topology. For example, in the topology with eight nodes and eleven edges in Figure 2, the source node in the MST requires five hops to reach the last node, as shown in Figure 4, while the source node in the SPT requires only three hops as shown in Figure 3.

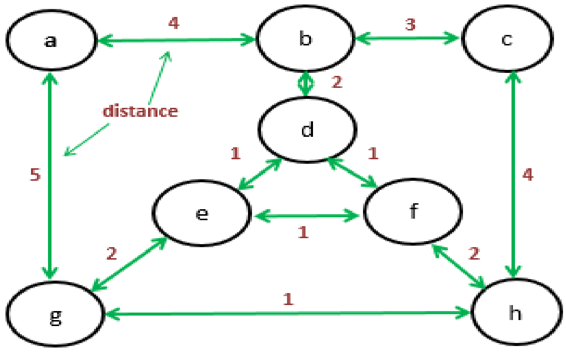


Figure 2. An example of a CRN topology with 8 CR nodes, from which one CR source and 4 multi-cast destinations.

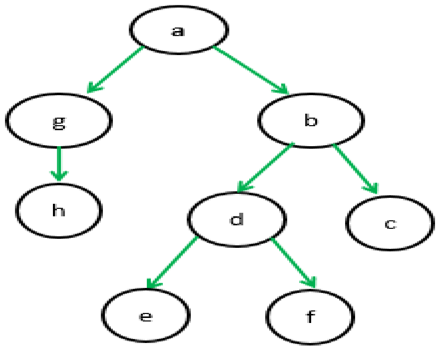


Figure 3. The constructed SPT associated with the CRN topology in Figure 2.

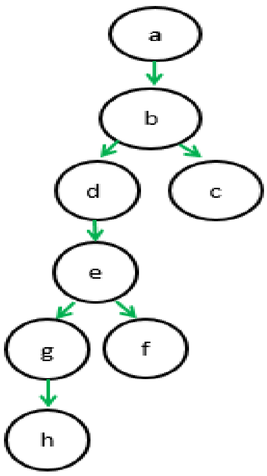


Figure 4. The constructed MST associated with the CRN topology in Figure 2.

4. Tree-based POS-aware Multi-cast Routing Problem

We develop a joint multi-layer on-demand SPT-based multicast routing and POS-based channel assignment algorithm for multi-hop CRNs. The proposed algorithm addresses the critical issue of determining the operating common idle PU channels that can be used to successfully deliver, with high probability, the multicast video packets to all intended CR destinations.

4.1. Problem Definition

Given a multi-hop CRN topology, a limited number of idle PU channels, channel quality, and availability conditions, a single CR multicast source, and several CR destinations, our main objective is to determine the appropriate multicast paths from the CR source to all destinations along with the channel assignment to enhance the overall network performance (throughput and PDR of the multicast video packets). The problem can be solved by converting the network topology into a multicast SPT "spanning tree" to determine the loop-free routes to all CR destinations from the source.

4.2. The Proposed Multicast Algorithm

The fundamental goal of our proposed algorithm is to improve network performance by sending multicast video packets from a single source to multiple multi-hop CR destinations by exploiting the concepts of POS and SPT. The proposed algorithm is executed in two phases:

- **Phase 1: Constructing the Multicast Tree**

The main idea of our proposed protocol is to transmit several multicast packets from a given source to multiple destinations in a multi-hop CRN using SPT or MST such that the network throughput is improved. Initially, the proposed algorithm models the CRN topology (undirected graph) as a multicast SPT or MST rooted at the CR source spanning the CR destinations. We note that the nodes at the SPT branches' ends are the intended destinations. Because of the multi-hop nature of the CRN, multi-layer (hierarchical) transmissions are required to deliver the multicast packets to the intended multicast destinations. The multicast packets travel from the CR source down the SPT or MST through several layers toward the CR destinations. Based on the constructed SPT or MST, the proposed algorithm identifies the set of all layers L in the constructed tree. Each layer l may consist of one or multiple sub-trees with a sub-tree source. For each layer $l \in L$, our algorithms identify the set of all sub-trees S_l, and the source of each sub-tree s_l, denoted by $(S_{s,l})$.

For each layer, the most reliable channel that maximizes the packet delivery to the destinations in that layer is selected based on the POS metric as follows:

- **Phase 2: POS-based Multi-Cast Channel Assignment**

After identifying all layers and sub-trees, the proposed algorithm attempts to assign the most reliable channel for each sub-tree transmission in each layer such that the packet delivery to all connected nodes in that sub-tree is maximized. Precisely, for each sub-tree $s \in S_l$ and $\forall l \in L$, the proposed routing is executed as follows:

1. The CR source $S_{s,l}$, associated with the sub-tree s of layer l, disseminates a Message Announcement (MA) to all nodes belonging to sub-tree s of layer l, including the sub-tree source ID, sub-tree ID, layer ID, and the idle channel list for $S_{s,l}$'s transmission ($\boldsymbol{C_{s,l}}$).
2. Once a CR user, say k, belonging to the sub-tree s of layer l receives the MA packet, it calculates the achieved POS over each idle channel $j \in \boldsymbol{C_{s,l}}$, denoted as $POS_k^{(j)}(s,l)$. The node k then replies with an acknowledgment (ACK) message to the CR sub-tree source $S_{s,l}$ with the computed $POS_k^{(j)}(s,l)$.
3. The CR source $S_{s,l}$ pauses for a predefined time until receiving all ACK messages from all CR nodes belonging to its sub-tree.
4. Following the time-out, the node $S_{s,l}$ calculates the minimum achieved POS over each idle channel $j \in \boldsymbol{C_{s,l}}$ as:

$$POS_{s,l}^{(j),\min} = \min_k \left\{ POS_k^{(j)}(s,l) \right\} \quad (2)$$

The CR node $S_{s,l}$ chooses the idle PU channel with the highest POS for its sub-tree transmission as follows:

$$c^*_{s,l} = \operatorname{argmax}_{j \in C_{s,l}} \left\{ POS_{s,l}^{(j),\min} \right\} \quad (3)$$

5. The above process is repeated for every layer and every sub-tree in the constructed multicast SPT (MST).

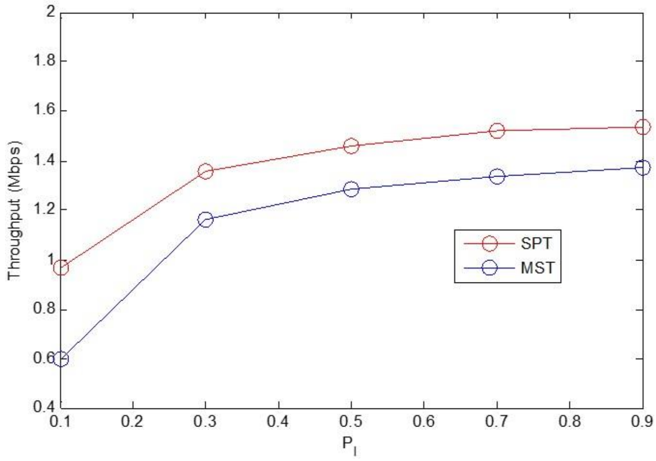
5. Performance Evaluation

Simulation experiments based on MATLAB programs are conducted to examine the performance of the proposed MST- and SPT-based multi-cast routing algorithms. Then, the performance of the proposed multicast SPT-based routing algorithm is compared with that of the Maximum Average Spectrum Availability time (MASA), Maximum Data Rate (MDR), and Random Selection (RS) algorithms [2]. The simulation results reported in this paper are the average of 100 experiments, each consisting of *10000* random CRN topologies.

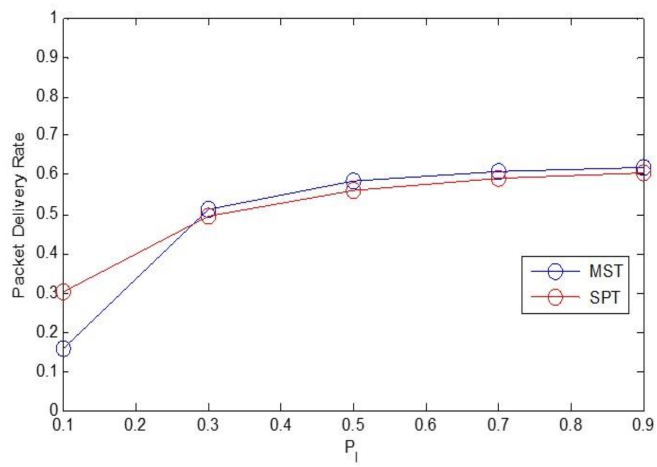
5.1. Simulation Setup

A uniformly distributed multi-hop network topology consisting of a single CR source, N CR users, and N_r CR multicast destinations are generated in a 200 m × 200 m field. The CR users geographically coexist with several PRNs. A Rayleigh fading propagation model with a path-loss exponent of 4 (i.e., indoor propagation environment) is considered to estimate the received power at any CR receiver [2, 23]. For all PU channels, the thermal-noise power spectral density (PSD) and the bandwidth are fixed to $N_0=10^{-18}$ W/Hz and $BW=1$ MHz, respectively. The data packet length, CR transmission power (Pt), and the number of PU channels are fixed to *4* KB, *0.1* Watt, and $M=20$, respectively. The ON/OFF Markov two-state model with average OFF (Idle) and ON (Busy) time periods of μ_j and λ_j is considered to describe the status of each PU channel $j \in M$. Each channel's average spectrum availability duration for each PU channel j (i.e., μ_j) ranges between *2* to *70* ms.

Accordingly, the idle probability of channel j can be computed as $P_I=\mu_j/(\mu_j+\lambda_j)$, where λ_j represents the average busy period for channel j. We consider in our simulations three PU activity levels (low PU activity with $P_I= 0.9$), (Moderate PU activity with $P_I=0.5$), and (high PU activity with $P_I=0.1$). According to the SPT approach, Dijkstra's algorithm can find the minimum cost (i.e., distance) paths from the source to each CR destination in the multicast group.



a) Throughput.



b) PDR.

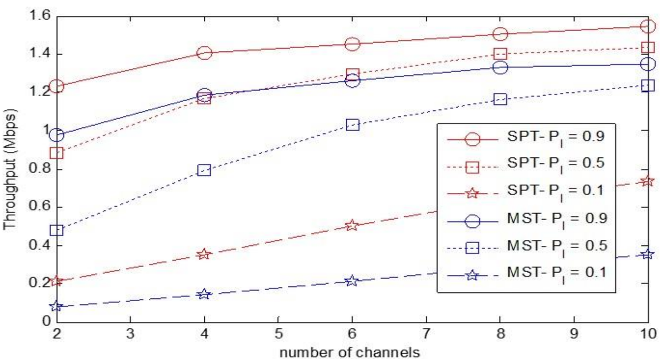
Figure 5. Network performance vs. idle probability for $N=40$, $N_r=16$, $M=20$, $Pt=0.1$ W, $BW=1$ MHz, and $D=4$ KB.

5.2. Simulation Results

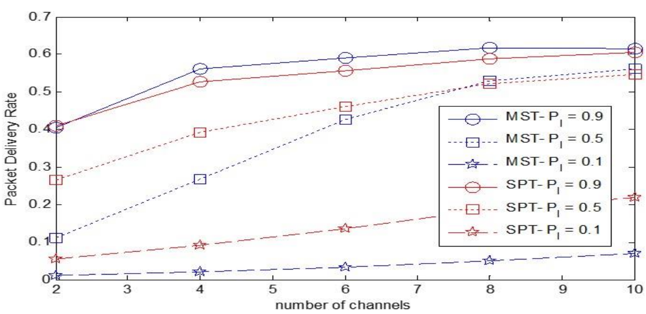
5.2.1. Performance Comparison of SPT and MST Multicast Routing

We first investigate the performance of the proposed SPT- and MST-based routing algorithms. Both algorithms assign channels to the different layers in the constructed tree based on the POS metric. We set the total number of nodes N to 40 and the total number of destinations N_r to 16. Figure 5 investigates the throughput and PDR Performance versus the idle probability P_I. Specifically, Figure 5-a) indicates that the SPT-based algorithm outperforms the MST-based algorithm in terms of throughput (up to 40%), irrespective of P_I. Figure 5-b) shows that both algorithms achieve a comparable performance in terms of PDR (the SPT-based algorithm slightly outperforms the MST when $P_I \leq 0.3$. Figure 5 reveals that even though both algorithms depict comparable PDR performance, the SPT-based algorithm provides higher throughput because the SPT-based algorithm attempts to utilize the shortest path, resulting in higher end-to-end throughput.

Figure 6 investigates the overall throughput and PDR performance versus the number of available primary channels M for different values of P_I. This figure shows that increasing M enhances the network performance as more channels become available for the SUs. This figure shows that the SPT-based algorithm outperforms the MST-based algorithm in terms of throughput by up to 26%, 85.6%, and 162% under P_I=0.9, 0.5, and 0.1, respectively. Regarding the PDR performance, both the SPT- and MST-based multicast routing protocols depict comparable performance.



a) Throughput.



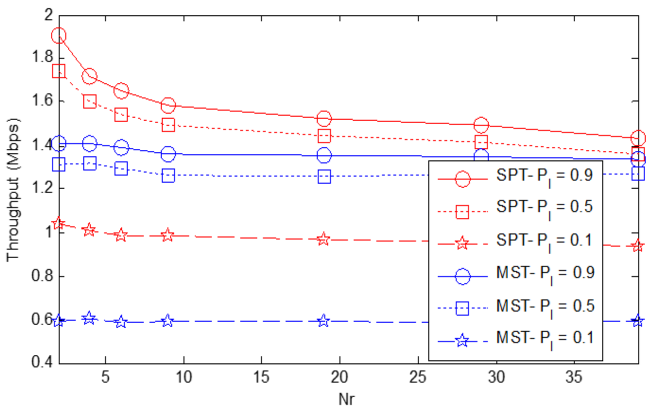
b) PDR.

Figure 6. Network performance vs. the number of primary channels for N=40, N_r=16, Pt=0.1 W, BW=1 MHz, and D=4 KB.

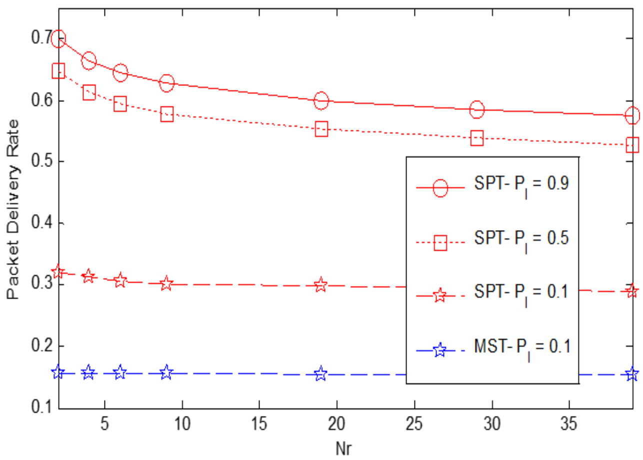
Figure 7 investigates the network performance as a function of the number of destinations N_r. This figure indicates that increasing the number of destinations negatively affects the performance of the SPT-based multicast routing algorithm because of the increased number of needed hops to reach the destinations, which negatively affects the channel assignment decisions. In contrast, increasing the number of destinations in the MST-based multicast routing algorithm does not affect the overall network performance because the source CR node already needs a longer path to reach each destination compared to the SPT-based multicast routing algorithm.

Figure 7 also reveals that the SPT-based algorithm outperforms the MST-based algorithm in terms of throughput, irrespective of the value of N_r.

In summary, the SPT-based routing algorithm outperforms the MST-based algorithm regarding throughput with comparable PDR but requires a higher tree construction complexity. Therefore, we consider only the SPT-based routing algorithm in the next set of experiments. The proposed multicast SPT-based routing algorithm's performance (i.e., POS) is compared with that of the reference algorithms (i.e., MASA, MDR, and RS).



a) Throughput.

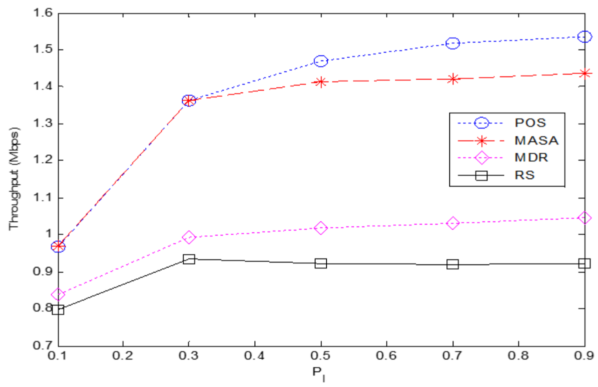


b) PDR.

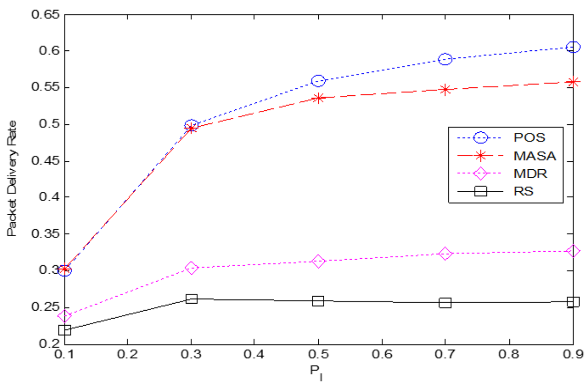
Figure 7. Network performance vs. N_r for N = 40, M=20, Pt=0.1 W, BW=1 MHz, and D=4 KB, with P_I=0.1, 0.5 and 0.9. For the PDR, SPT and MST depict the same performance.

5.2.2. Performance Evaluation of SPT-based Routing

Figures 8-a) and Figures 8-b) investigate the throughput and PDR performance as a function of the idle probability P_I for *N=40* and N_r*=16* CR destinations. These figures indicate that the network throughput and PDR increase as P_I increases. This is because more channels become available for CR transmissions when the idle probability is high. This results in more choices for the channel assignment process, resulting in enhanced network performance. It can be noticed that our algorithm performs better than the other algorithms under low and moderate PU activity.



a) Throughput.



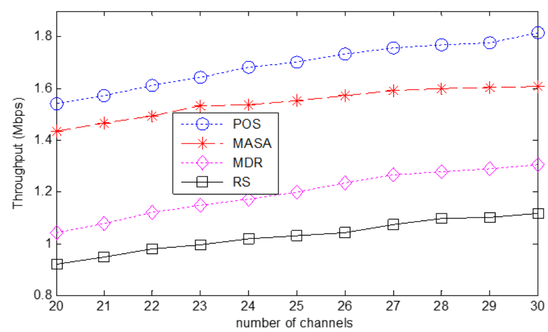
b) PDR.

Figure 8. Network performance vs. P_I for *N=40*, N_r*=16*, *M=20*, *Pt=0.1 W*, *BW=1* MHz, and *D=4* KB.

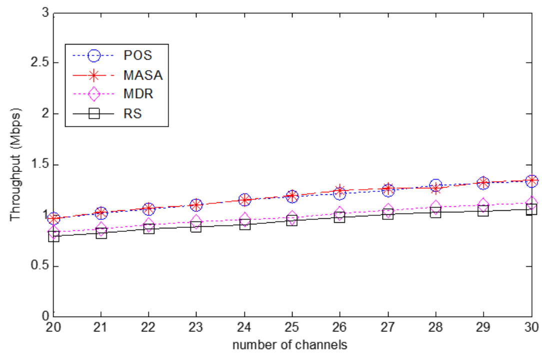
On the contrary, the performance of the proposed algorithm is comparable to that of the MASA algorithm under high PU activity. In contrast, it still performs better than the MDR and RS algorithms. Specifically, the proposed algorithm outperforms MASA, MDR, and RS algorithms in terms of throughput by up to 10%, 47%, and 66%, respectively. In addition, the proposed algorithm outperforms the other algorithms in terms of PDR by up to 9%, 86%, and 135%, respectively.

Figure 9 investigates the overall network throughput versus the number of available PU channels *M* for high and moderate PU activity conditions. This figure shows that increasing *M* improves network throughput. This is because increasing *M* provides CR users with more spectrum opportunities, resulting in improved network throughput.

Under low PU activity level, Figure 9-a) reveals that our algorithm performs the best (i.e., compared to MASA, MDR, and RS algorithms, the reported throughput improvement is up to *13%*, *48%*, and *68%*, respectively). Under high PU traffic activity, Figure 9-(b reveals that the channels are usually busy and cannot be used by SUs. Specifically, in such scenarios, the number of available PU channels for the CRN becomes very limited, resulting in reduced system performance. As a result, the performance improvement of our algorithm compared to the other algorithms is very limited.



a) P_I=0.9.

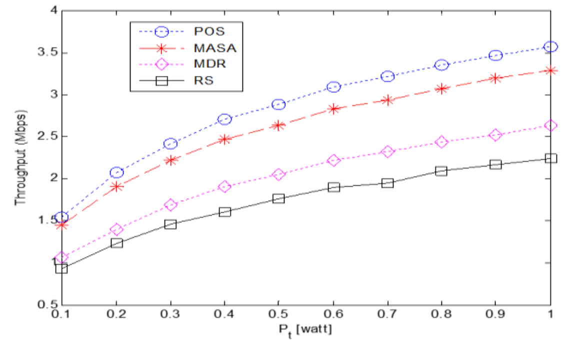


b) P_I=0.9.

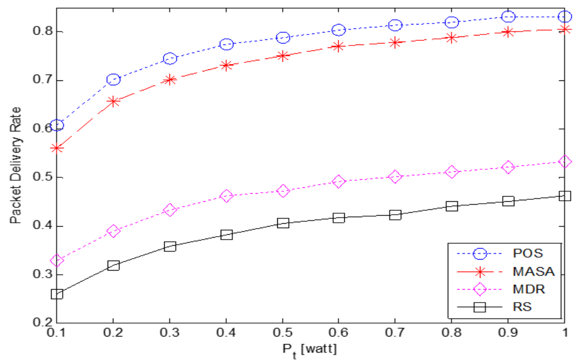
Figure 9. Throughput performance vs. *M* for *N=40*, N_r*=16*, *Pt=0.1* W, *BW=1* MHz, and *D=4* KB.

Figure 10 investigates the network performance of the different multicast algorithms as a function of the transmit power for different PU activity levels, i.e., P_I*=0.9*, *0.5*, and *0.1*. Specifically, Figures 10-a) and Figures 10-b) show that, under low PU activity of P_I*=0.9*, our proposed routing algorithm performs better than the MASA, MDR, and RS schemes in terms of throughput, surpassing them by up to *10%*, *48%*, and *68%*, respectively. In addition, the proposed POS-aware tree-based multicast routing algorithm outperforms the MASA, MDR, and RS schemes in terms of the packet delivery rate, outperforming the compared with multicast routing schemes by up to *8.6%*, *85%*, and *133%*, respectively.

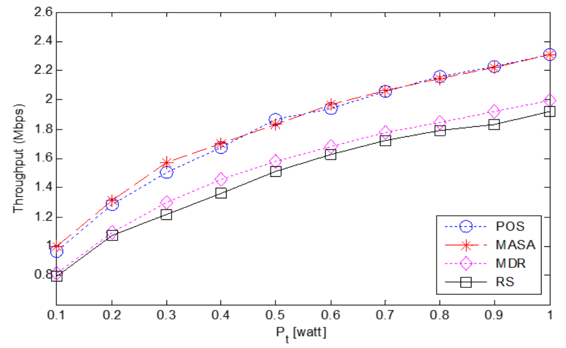
Under high PU activity (P_I*=0.1*), Figures 10-c) and Figures 10-d) show that the performance of our proposed tree-based POS-aware multicast algorithm is comparable to that of the MASA multicast routing scheme and outperforms the other two multicast routing schemes. This is due to the less availability of the PU channels when the P_I=0.1. Under moderate PU activity levels with P_I=0.5, other results (not shown here) depict that similar behavior to that for P_I=0.9 is observed, in which our proposed tree-based multicast routing algorithm significantly outperforms the MASA, MDR, and RS multicast schemes in terms of throughput as well as the PDR performance.



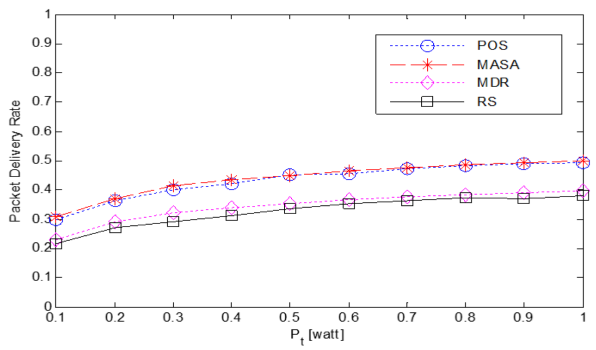
a) Throughput, PI =0.9.



b) PDR, PI =0.9.



c) Throughput, PI =0.1.



d) PDR, PI =0.1.

Figure 10. Network Performance vs. the transmission power under P_I=0.9 and 0.1 for N=40, N_r=16, M=20, BW=1 MHz, and D=4 KB.

6. Conclusions

This paper proposed a novel multi-hop multicast routing algorithm for CRNs using the tree-based topology concept. The proposed algorithm implemented a channel assignment mechanism based on the POS metric over the available channels. Our algorithm transformed the network topology into a multicast tree and applied the POS-based channel assignment algorithm to enhance network performance. The SPT and MST are considered to generate the multicast tree. The proposed protocol deals with each generated tree as multi-layer architecture for routing purposes. Specifically, the developed routing algorithm divided the constructed SPT or MST into multiple layers for routing decisions. Through simulations, we investigated the performance of the two variants of the proposed tree-based POS-based routing protocol (the SPT-based and MST-based algorithms). The results revealed that the SPT-based algorithm outperformed the MST-based algorithm in terms of throughput at the expense of higher tree construction complexity under different network conditions. Compared to reference multi-cast routing algorithms (MASA, MDR, and RS), the proposed SPT-based algorithm performs the best under various network conditions. This is because our proposed routing algorithm exploits a POS-based channel assignment, resulting in more reliable channel assignment decisions. Specifically, our proposed SPT-based multicast routing algorithm outperforms MASA, MDR, and RS algorithms in terms of PDR and throughput.

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Haythem Bany Salameh received his Ph.D. degree in electrical and computer engineering from the University of Arizona, USA, in 2009. He also holds a visiting professor position at Staffordshire University, UK. He is currently the Dean of Scientific Research and Graduate Studies at Al Ain University, Al Ain, United Arab Emirates. He is also with Yarmouk University (YU), Irbid, Jordan. He has authored or co-authored more than 160 highly esteemed research articles. He is on World's Top 2% Scientists List for various disciplines, compiled by Stanford University, in 2020, 2021, and 2022. His research interests include wireless networking, with an emphasis on dynamic spectrum access, cognitive radio networking, the Internet of Things, drone communication, flying networks, security, and protocol design. He has served and continues to serve on the technical program committee of many international conferences and serves as a reviewer for many international conferences and journals. He has supervised and examined more than 100 master's theses at most Jordanian universities. He was a recipient of the Jordan Science Research Support Foundation (SRSF) Prestigious Award for Distinguished Research in ICT in 2015, the Best Researcher Award for Scientific Colleges at YU in 2016, and the SRSF Award for Creativity and Technological Scientific Innovation, in 2017.

Mustafa Ali is currently a lecturer in the Department of Electrical Engineering, Faculty of Engineering, Mustansiriyah University, Iraq. He received his MSC degree in Telecommunications Engineering from Yarmouk University, Irbid, Jordan, His current research interests include cognitive radio networks, distributed protocol design, and antenna design with an emphasis on multicast protocol design and implementations for multimedia wireless networks.