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RESEARCH ARTICLE

Channel-switching and power control mechanisms for improving network connectivity in wireless mesh networks

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ABSTRACT

A Wireless Mesh Network (WMN) consists of fixed wireless routers, each of which provides service for mobile clients within its coverage area and inter-connects mesh routers to form a connected mesh backbone. Wireless mesh routers are assigned with a channel or a code to prevent collisions in transmission. With a power control mechanism, each router could be assigned with a power level to control connectivity, interference, spectrum spatial reuse, and topology. Assigning high transmitting power level to a router can enhance the network connectivity but may increase the number of neighbors and worsen the collision problem. How to assign an appropriate power level to each router to improve the network connectivity with a constraint of limited channels is one of the most important issues in WMNs. Given a network topology and a set of channels that has been assigned to mesh routers, the proposed channel-switching mechanism further reassigns each router with a power level and switches channels of routers to optimize both power efficiency and connectivity. A matrix-based presentation and operations are proposed to respectively identify and resolve the channel switching problems. Simulation study reveals that the proposed mechanisms increase network throughput and provides a variety of route selection, and thus improves the performance of a given WMN. Copyright © 2009 John Wiley & Sons, Ltd.

KEYWORDS
wireless mesh network; power control; channel switching

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1. INTRODUCTION

A WMN [1–3] operates like a network of fixed routers, except that they are connected only by wireless links and can be used on the last mile for extending or enhancing Internet connectivity of mobile clients located at the edge of the wired network. WMNs consist of static wireless mesh routers and end mobile clients. The static wireless routers are equipped with traffic aggregation capabilities (e.g. Access Points) and provide network connectivity to mobile clients within their coverage areas. The wireless mesh routers themselves form a multi-hop wireless backbone for relaying the traffic to and from the clients. Some of the wireless mesh routers are equipped with gateway functionality to enable connectivity to the wired Internet. All infrastructure resources that the mobile client access (e.g. web servers, Internet gateways) reside on the wired Internet and can be accessed via any wireless mesh router with gateway functionality. Thus, the wireless backbone of mesh routers mainly relays mobile clients' traffic to and from other mobile clients or Internet via the routers with gateway functionality. Each wireless mesh router may be equipped with multiple wireless interfaces each operating on a particular channel.

One of the major problems in a wireless network is the capacity degradation due to interferences from multiple simultaneous transmissions. The IEEE 802.11b/g and IEEE 802.11a standards provide 3 and 12 non-overlapped frequency channels, respectively, which could be used for simultaneous transmissions within a neighborhood. Hence, neighboring mesh routers utilizing different channels or codes can significantly increase the bandwidth capacity. To make use of commodity 802.11 radios, a channel or code is assigned to a radio interface for a period of time as long as traffic demand or topology does not change. For direct communication, two routers within the communication range need to have a common channel assigned to their interfaces. Mesh router pairs using different channels can transmit packets simultaneously without interference. However, a pair of routers that use the same channel and are within the interference range can interfere with each other's communication.

The performance of a multi-hop WMN relies upon the network connectivity which could be improved by assigning different power levels to mesh routers. A mesh router assigned with a high power level can enlarge its transmission range and thus increase its number of neighbors. The strong network connectivity reduces the number of forwarding nodes for a multi-hop routing and provides a variety of routes, thus improving the network throughput and reducing the end-to-end delay. However, increase in the number of neighbors may raise the exposed and hidden terminal problems. Hence, it may require either more channels or channel switching to distribute different channel assignments to the neighbors, and allow them to transmit packets simultaneously without collision. Enhancing the network throughput by improving the network connectivity, while the size of the given channel set is maintained and the network is collision-free guaranteed, is one of the most important issues in WMNs.

Code assignment and power control are two dimensions of the most important issues in WMN. Improper channel assignment will either raise the collision problem or consume too many channels. In literature, a number of researches have been proposed to cope with the channel assignment problem. Bertossi and Bonuccelli [4] initially classified the collisions into two types, namely primary (or direct) collision and secondary collision. Primary collision arises from a situation wherein the station can overhear the transmission from its one-hop neighbor, whereas the secondary (or hidden) collision arises when two stations with two-hop distance transmit packets simultaneously and cause their common neighbors to receive the two transmissions at the same time. These two types of collision could be resolved by careful channel assignment so that different channels are assigned to two-hop neighboring stations.

Since the available channels have been treated as the resource in a WMN, the target for the channel assignment problem is to assign a minimum number of collision-free channels for stations in order to avoid primary and secondary collisions. Several previous studies [1–3][5–9] have proposed some channel assignment schemes. In Reference [5], a two-phase algorithm was proposed wherein the first phase uses a breath-first-search tree to maintain the channel-assigning order, while the second phase minimizes the number of control packets required for channel exchange. A token-based Scheme [6] used control segments to schedule transmission segments. The control channel was used to increase the utilization of the transmission segment. Another study [7] proposed a transmitter-oriented code assignment scheme and found a spreading code for each node to use in transmitting packets with the constraint that all logical neighbors of a given node have different transmitting codes. A new heuristic-based algorithm was also developed to obtain maximum independent sets for broadcast scheduling [8].

Some other studies concentrated on developing power control mechanisms to improve the network connectivity for a given network topology such that each station is assigned a non-collision code. The network topology can be changed by adjusting the station's transmitting power level. In Reference [10], a power adjustment mechanism was proposed to reduce collision by formulating the topology control problem as a constrained optimization issue. Another previous work [4] presented a protocol to construct 1-edge and 2-edge-connected networks and minimize the transmission power of each node in the network. Under the assumptions of fixed and variable power, the optimal transmission range can be evaluated [11]. A previous research [12] proposed a power adjustment protocol for improving the throughput. The degree-based and distance-based mechanisms were proposed to increase the powers of the stations for constructing more links between stations for a given network. Although several researchers recently tried to improve the network connectivity by adopting a power control mechanism, more effort should be exerted in constructing a network topology with maximum connectivity under the constraints of using the same channel set and providing collision free transmissions.

This paper aims at developing channel-switching mechanisms to improve the network connectivity for a given multi-hop WMN whereby each station has been assigned with a channel. The proposed channel-switching mechanisms consist mainly of two phases. To improve the network connectivity, the first phase assigns each router with an appreciate power level to construct new links between routers so that the primary and secondary collisions can be avoided. In the second phase, an adaptive channel-switching scheme is further employed to exchange channels between a pair of stations so that additional links can be established without violating the primary and secondary collision constraints. Since the construction of one link might repress the construction of another link, the order of link constructions will determine the connectivity and throughput. Three link selection strategies, namely distance-based, degree-based, and hop-based mechanisms are proposed to further improve the network connectivity and the routing efficiency. The matrix-based representation and computations are employed to implement the channel switching mechanisms. The impacts of the proposed mechanisms are investigated. Performance results reveal that the proposed mechanisms improve the network throughput and reduce the end-to-end delay, thus enhancing the performance of the WMN.

The rest of this paper is organized as follows. Section 2 presents the preliminary and basic concepts of this study. The problem formulation and goals are proposed in Section 3. Section 4 details the matrix-based channel switching mechanisms. Section 5 gives the extensions for channel-switching mechanism. Section 6 presents the performance study of the proposed mechanisms while the conclusions are drawn in Section 7.

2. PRELIMINARY AND BASIC CONCEPTS

A WMN consists of a number of stationary mesh routers each assigned with a transmission channel to prevent the transmissions of nearby stations from collision. Following the *transmitter-based* assumption [5], packet transmissions of routers are based on the channel assigned to them. By using different initial powers for each router in the network, routers can establish links with other routers within their transmission range so that a certain network topology is formed through those links. Figure 1(a) shows an example of a WMN where each station has a different transmission range while the number associated with each node denotes its assigned channel.

In literature, power control was used to adjust the transmission range in order to create more links between mesh routers and establish a network with higher connectivity. To illustrate the impact of the power control scheme on the network topology, the following notations will be defined.

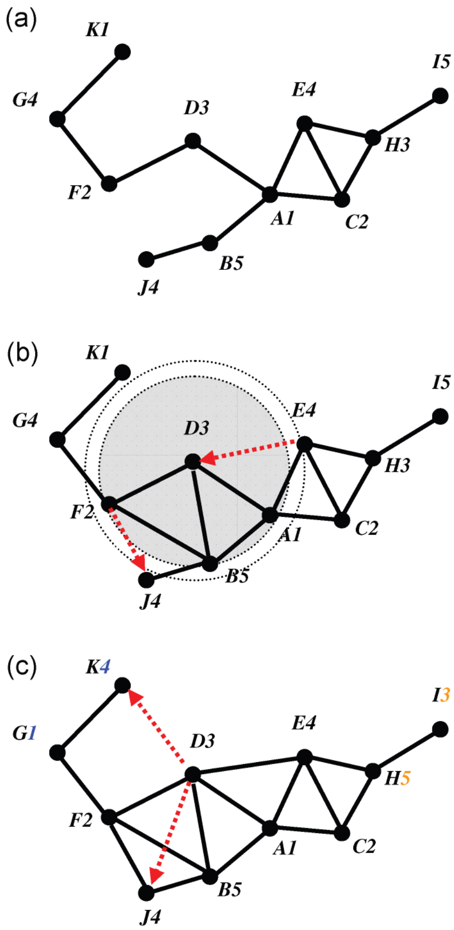

Figure 1. Examples for applying channel-switching mechanism. (a) The original WMN topology. (b) Topology after applying distance-based scheme. (c) Topology after applying channel-switching scheme.

Let notation (A, B) denote a pair of nodes A and B. Notations $\overrightarrow{AB}$ and $\overline{AB}$ denote a uni-directional link from A to B and bi-directional link between A and B, respectively. The distance between two nodes A and B is denoted by $d(A, B)$. Let X and Y be single or two-hop neighbors. Pair (X, Y) is said to be in *channel collision* if they are assigned with the same channel. Any common neighbor of nodes X and Y is considered a *victim station*. In Reference [12], distance-based and degree-based schemes are proposed to create more links in a network by assigning some stations with appreciate power levels. In the distance-based scheme, the link with a shorter length has a higher priority to construct additional links.

Figure 1 depicts an example to illustrate the distance-based scheme proposed in Reference [12] and the basic idea of our mechanism. Figure 1(b) shows the resultant network after applying the distance-based scheme on the topology given in Figure 1(a). In the first place, all pairs of nodes with no link between them are identified. Afterwards, all the identified pairs are sorted according to their length as a list (F, J), (F, B), (D, B), (D, E), (D, J), and (D, K). Based on this order, the scheme checks each pair (i, j) to determine if any primary and secondary collisions occurred when adding a link between stations i and j. The following steps list the processes of the distance-based scheme:

(1) Failure in constructing link $\overline{FJ}$: Increasing the power level of F can be granted, but increasing the power level of J will cause station F to be a collision station. Uni-directional link $\overrightarrow{FJ}$ is created.
(2) Success in constructing link $\overline{FB}$: No primary and secondary collisions occur if a link is constructed between nodes F and B.
(3) Success in constructing link $\overline{BD}$: No primary and secondary collisions occur when constructing a link between nodes D and B.
(4) Failure in constructing link $\overline{DE}$: The increase in node E's power level can be granted, but increase in the power level of node D will cause a secondary collision at node H. Thus, uni-directional link $\overrightarrow{ED}$ is created.
(5) Failure in constructing link $\overline{DJ}$: In this example, the distance of nodes D and J is larger than that of nodes D and E. Since link $\overline{DE}$ is not allowed to be established, link $\overline{DJ}$ cannot be granted. No uni-directional link can be constructed between nodes D and J.
(6) Failure in constructing link $\overline{DK}$: Since the distance of nodes D and K is larger than the distance of nodes D and E, and link $\overline{DE}$ is not allowed to be added, link $\overline{DK}$ cannot be granted. No uni-directional link can be constructed between nodes D and K.

Figure 1(b) shows the resultant network topology after applying the distance-based scheme on a given network shown in Figure 1(a). Two bi-directional links and two uni-directional links are added on the original network.

The major reason why a link cannot be created is the constraints of primary or secondary collisions. Link $\overline{FJ}$ cannot be constructed because nodes J and G use the same channel

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and thus, the construction of the link between nodes *J* and *F* will give rise to the secondary collision problem. However, in this case, the channel switching of nodes *G* and *K* can make nodes *J* and *G* acquire different channels and thus, an additional uni-directional link from *J* to *F* can now be established without a secondary collision. In addition, the channel-switching operation can also be applied on the stations *H* and *I* so that an additional link can be established from the station *D* to the station *E*. This exchange can assign different channels on stations *D* and *H*, and thereby prevent station *E* from secondary collision.

In the first phase of our proposed protocol, those pairs which construct uni-directional link and result in channel collisions are identified such as those of $\overrightarrow{FJ}$ and $\overrightarrow{ED}$ in Figure 1(a). In the second phase, the adaptive channel-switching scheme is applied to those links identified in the first phase in order to address the channel collision problem. For example, node *G* exchanges channel with node *K* so that the uni-directional link from *J* to *F* can be correctly established. In addition, node *I* exchanges channel with node *H* so that the uni-directional link from *D* to *E* can also be correctly established. Figure 1(c) depicts the resultant topology after applying the channel-switching scheme on the network topology shown in Figure 1(b). Since the distance of pair (D, E) is larger than those of (D, K) and (D, J), two unidirectional links between pairs (D, K) and (K, J) are automatically created owing to the wireless nature. Comparing Figure 1(c) with Figure 1(b), four uni-directional links were added in the former. Consequently, the network connectivity can be improved by applying the proposed channel-switching scheme.

3. PROBLEM FORMULATION AND GOALS

Consider the given network topology $G = (N, E, C)$, where *N* and *E* denote the set of stationary mesh routers and the set of links constructed in *G*, respectively, while *C* is the set of channels assigned on the links of *G*. There are power, channel, and collision-free constraints that should be satisfied for a valid network topology. The power constraint is for the maximum power transmission levels of all mesh routes to be identical to $P_{\max}$, whereas the channel constraint is that only channels in *C* can be assigned to the links. The collision-free constraint refers to the constraints of the primary and secondary collisions. The aim of the proposed channel switching schemes is to construct a valid network topology $G' = (N, E', C)$ such that $G \subseteq G'$, $E \subseteq E'$ and the number of edges in E' is maximum. Mathematically, the problem and goals of this work is formulated as follows.

Let $E' = E \cup \{e_{i,j} | i, j \in N, e_{i,j} \notin E\}$ and $|E'|$ denotes the number of edges in E'.

Objective Function:

$$\text{Maximize } \left|E'\right|$$

subject to

- *channel constraint:*

$$\bigcup_{\forall i \in N} c_i \in C$$

where c_i is the channel assigned to node *i*.
- power constraints:

$$P_i \leq P_{\max}, \forall i \in N$$

where P_i is the power level used by node *i*.
- *collision-free constraint*:

$$c_i \neq c_j, \forall i, j \in N, h(i, j) \leq 2$$

where $h(i, j)$ is the hop counts between nodes *i* and *j*.

The channel switching scheme exploits the opportunities for channel switching to improve the network connectivity and avoid the collision problem. Given any primary or secondary collision, the channel switching scheme tries to eliminate the collisions by exchanging channels without increasing the size of the channel set. In the next section, a matrix-based representation is proposed to generally represent the relations between channel assignment, link creation, and network topology. A matrix-based computation scheme is proposed to implement the power control and channel-switching mechanisms. By applying the proposed mechanism, an efficient topology of the WMN with a stronger connectivity can be constructed in a systematic way.

4. MATRIX-BASED CHANNEL SWITCHING AND POWER ADJUSTMENT

This section proposes power control and channel-switching mechanisms for a given WMN to enhance the network connectivity, improve the network throughput and reduce the transmission delay.

4.1. Notations and definitions

4.1.1. Definition: alphabet ID and numeric ID.

Each station in WMN will be identified by a unique *alphabet ID*. To facilitate the matrix operation, *a unique numeric ID* is assigned to each station corresponding to each alphabet ID. For simplicity, the alphabet ID set $\{A, B, \ldots\}$ corresponds to the numeric ID set $\{1, 2, \ldots\}$.

The numeric ID will be used in matrix operation instead of alphabet ID due to the requirement in the matrix operations. For example, numeric ID is used in *Link Collision Matrix* to denote the collision occurred at the station with ID = *k*.

4.1.2. Definition: topology matrix ($\mathbf{M}_t$).

Given a WMN, a *Topology Matrix* $\mathbf{M}_t$ specifies the connection relation between any pair of stations. $\mathbf{M}_t$ is a matrix

$$M_t = \begin{array}{c|ccccccccccc|} & A & B & C & D & E & F & G & H & I & J & K \\ \hline A & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ B & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ C & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ D & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ E & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ F & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ G & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\ H & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ I & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ J & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ K & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{array}$$

Figure 2. Topology matrix of Figure 1(a).

$$M_c = \begin{array}{c|ccccc|} & 1 & 2 & 3 & 4 & 5 \\ \hline A & 1 & 0 & 0 & 0 & 0 \\ B & 0 & 0 & 0 & 0 & 1 \\ C & 0 & 1 & 0 & 0 & 0 \\ D & 0 & 0 & 1 & 0 & 0 \\ E & 0 & 0 & 0 & 1 & 0 \\ F & 0 & 1 & 0 & 0 & 0 \\ G & 0 & 0 & 0 & 1 & 0 \\ H & 0 & 0 & 1 & 0 & 0 \\ I & 0 & 0 & 0 & 0 & 1 \\ J & 0 & 0 & 0 & 1 & 0 \\ K & 1 & 0 & 0 & 0 & 0 \end{array}$$

Figure 3. The channel matrix of Figure 1(a).

with size $n \cdot n$ where n is the number of nodes in the network. The value of entry $\mathbf{M}_t(i, j)$ would be either 1 or 0 denoting whether or not station i connects to station j, respectively. That is,

$$\mathbf{M}_t(i, j) = \begin{cases} 0 \text{ , } if\ there\ does\ not\ exist\ a\ link\ between\ i,\ j \\ 1 \text{ , } if\ there\ exists\ a\ link\ between\ i,\ j \end{cases}$$

Figure 2 gives the topology matrix of WMN shown in Figure 1(a). For example, node A connects to nodes B, C, D, and E. Therefore, $\mathbf{M}_t(1, 2)$, $\mathbf{M}_t(1, 3)$, $\mathbf{M}_t(1, 4)$, and $\mathbf{M}_t(1, 5)$ are all equal to 1 denoting that they are neighbors of node A in the network.

4.1.3. Definition: channel matrix ($\mathbf{M}_c$).

Given a WMN with a channel assignment, a *Channel Matrix* $\mathbf{M}_c$ specifies the relation between stations and their channel assignment. $\mathbf{M}_c$ is with size $m \cdot n$ where m is the number of channel used in the network and n is the number of nodes in the network. The value of a matrix entry $\mathbf{M}_c(i, j)$ would be either 1 or 0 denoting whether or not station i is assigned with channel j, respectively. That is,

$$\mathbf{M}_c(i, j) = \begin{cases} 0 \text{ , } if\ station\ i\ does\ not\ use\ code\ j \\ 1 \text{ , } if\ station\ i\ uses\ code\ j \end{cases}$$

Figure 3 depicts the channel matrix of WMN shown in Figure 1(a). For example, nodes A and B use channels 1 and 5, respectively. Therefore, the values of $\mathbf{M}_t(1, 1)$ and $\mathbf{M}_t(1, 5)$ are set to 1.

4.1.4. Definition: collision matrix ($\mathbf{M}^k_{col}$).

The Collision Matrix $\mathbf{M}^k_{col}$ specifies the collision relation of the channel assignment and stations when considering k-hop neighboring nodes for a given WMN. $\mathbf{M}^k_{col}$ is with size $m \cdot n$ where m is the number of channel used in the network and n is the number of nodes in the network. The value of entry $\mathbf{M}^k_{col}(i, j)$ would be either 1 or 0, denoting whether or not any neighbor of i within k-hop distance using channel j will result in collisions at station i, respectively. That is,

$$\mathbf{M}^k_{col}(i, j) = \begin{cases} 0 \text{ , } otherwise \\ 1 \text{ , } if\ code\ j\ results\ in\ collisions\ at\ station\ i \end{cases}$$

Consider the WMN shown in Figure 1(a). As shown in Figure 4, the collision matrix $\mathbf{M}_{col}$ with $k = 1$ presents the single hop collision information for each station. For instance, the collision channel set of single hop collision at station B is $\{1, 4, 5\}$ since entries $\mathbf{M}^1_{col}(B, 1)$, $\mathbf{M}^1_{col}(B, 4)$, and $\mathbf{M}^1_{col}(B, 5)$ have a value of 1. This information indicates that any station assigned with a channel in set $\{1, 4, 5\}$ but intends to establish a connection to station B will cause collisions. Therefore, this matrix can help check whether or not the established link between two nodes raises any collision.

4.1.5. Definition: channel switch matrix ($\mathbf{M}_{switch}$).

Given a WMN, a *Channel Switch Matrix* $\mathbf{M}_{switch}$ specifies the channel exchange relation between stations. $\mathbf{M}_{switch}$ is a matrix with size $n \cdot n$ where n is the number of nodes in the network. The value of entry $\mathbf{M}_{switch}(i, j)$ would

$$M^1_{col} = \begin{array}{c|ccccc|} & 1 & 2 & 3 & 4 & 5 \\ \hline A & 1 & 1 & 1 & 1 & 1 \\ B & 1 & 0 & 0 & 1 & 1 \\ C & 1 & 1 & 1 & 1 & 0 \\ D & 1 & 1 & 1 & 0 & 0 \\ E & 1 & 1 & 1 & 1 & 0 \\ F & 0 & 1 & 1 & 1 & 0 \\ G & 1 & 1 & 0 & 1 & 0 \\ H & 0 & 1 & 1 & 1 & 1 \\ I & 0 & 0 & 1 & 0 & 1 \\ J & 0 & 0 & 0 & 1 & 1 \\ K & 1 & 0 & 0 & 1 & 0 \end{array}$$

Figure 4. The 1-hop collision matrix of WMN shown in Figure 1.

$$M_{switch} = \begin{array}{c} \\ A \\ B \\ C \\ D \\ E \\ F \\ G \\ H \\ I \\ J \\ K \end{array} \begin{array}{c} \begin{array}{ccccccccccc} A & B & C & D & E & F & G & H & I & J & K \end{array} \\ \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \end{bmatrix} \end{array}$$

Figure 5. Channel switch matrix of WMN shown in Figure 1.

be either 1 or 0, representing whether or not station i is able to exchange channel with station j, respectively. That is,

$$\mathbf{M}_{\text{switch}}(i, j) = \begin{cases} 0 \text{ , } if \text{ } station \text{ } i \text{ } can \text{ } not \text{ } exchange \text{ } code \text{ } with \text{ } station \text{ } j \\ 1 \text{ , } if \text{ } station \text{ } i \text{ } can \text{ } exchange \text{ } code \text{ } with \text{ } station \text{ } j \end{cases}$$

The channel switch matrix of Figure 1(a) can be represented by Figure 5. For instance, station K can exchange the channel with stations G and I since entries (K, G), and (K, I) have a value of 1 in matrix $\mathbf{M}_{\text{switch.}}$ This matrix is mainly used for finding out additional links in the proposed algorithm.

4.1.6. Definition: link collision matrix ($\mathbf{M}_{\text{link}-\text{c}}$).

Given a WMN, a *Link Collision Matrix* $\mathbf{M}_{\text{link}-\text{c}}$ specifies the collision relation when constructing links between stations. $\mathbf{M}_{\text{link}-\text{c}}$ is a matrix with size $n \cdot n$ where n is the number of nodes in the network. The value of entry $\mathbf{M}_{\text{link}-\text{c}}(i, j)$ would be either k or 0, representing whether or not a collision will be occurred at the station with ID $= k$, respectively, when station j constructs an uni-directional link to station i. That is,

$$\mathbf{M}_{\text{link}-\text{c}}(i, j) = \begin{cases} 0 \text{ , } no \text{ } collision \text{ } if \text{ } i \text{ } constructs \text{ } a \text{ } link \text{ } to \text{ } j \\ k \text{ , } station \text{ } j \text{ } constructing \text{ } a \text{ } link \text{ } to \text{ } station \text{ } i \text{ } will \\ \quad collide \text{ } at \text{ } the \text{ } station \text{ } with \text{ } ID = k \end{cases}$$

The link collision matrix of Figure 1(a) can be represented by Figure 6. For instance, entry $\mathbf{M}_{\text{link}-\text{c}}(E, D)$ has value 8, which indicates that station D cannot construct a link to E because that link construction will create a collision between D and the station with ID 8 (denoting station H).

$$M_{link\text{-}c}(i, j) = \begin{array}{c} \\ A \\ B \\ C \\ D \\ E \\ F \\ G \\ H \\ I \\ J \\ K \end{array} \begin{array}{c} \begin{array}{ccccccccccc} A & B & C & D & E & F & G & H & I & J & K \end{array} \\ \begin{bmatrix} 1 & 2 & 3 & 4 & 5 & 3 & 5 & 4 & 2 & 5 & 1 \\ 1 & 2 & 0 & 0 & 10 & 0 & 10 & 0 & 2 & 10 & 1 \\ 1 & 0 & 3 & 8 & 5 & 3 & 5 & 8 & 0 & 5 & 1 \\ 1 & 0 & 6 & 4 & 0 & 6 & 0 & 4 & 0 & 0 & 1 \\ 1 & 0 & 3 & 8 & 5 & 3 & 5 & 8 & 0 & 5 & 1 \\ 0 & 0 & 6 & 4 & 7 & 6 & 7 & 4 & 0 & 7 & 0 \\ 11 & 0 & 6 & 0 & 7 & 6 & 7 & 4 & 0 & 7 & 11 \\ 0 & 9 & 3 & 8 & 5 & 3 & 5 & 8 & 9 & 5 & 0 \\ 0 & 9 & 0 & 8 & 0 & 0 & 0 & 8 & 9 & 0 & 0 \\ 0 & 2 & 0 & 0 & 10 & 0 & 10 & 0 & 2 & 10 & 0 \\ 11 & 0 & 0 & 0 & 7 & 0 & 7 & 0 & 0 & 7 & 11 \end{bmatrix} \end{array}$$

Figure 6. Link collision matrix of Figure 1(a).

4.1.7. Definition: bi-directional grant matrix ($\mathbf{M}_{\text{grant}-\text{bi}}$).

A *Bi-directional Grant Matrix* $\mathbf{M}_{\text{grant}-\text{bi}}$ is a symmetric matrix which specifies the legality of *bi-directional* link construction between stations. $\mathbf{M}_{\text{grant}-\text{bi}}$ is a matrix with size $n \cdot n$ where n is the number of nodes in the network. The value of a matrix entry $\mathbf{M}_{\text{grant}-\text{bi}}(i, j)$ would be either 1 or 0, representing whether or not stations i and j are able to construct a bi-directional link without collisions, respectively. That is,

$$\mathbf{M}_{\text{grant}-\text{bi}}(i, j) = \begin{cases} 0 \text{ , } if \text{ } stations \text{ } i, j \text{ } can \text{ } not \text{ } construct \text{ } a \text{ } bi-directional \text{ } link \\ 1 \text{ , } if \text{ } stationsi, j \text{ } can \text{ } construct \text{ } a \text{ } bi-directional \text{ } link \end{cases}$$

Note that the value of each entry of matrix $\mathbf{M}_{\text{grant}-\text{bi}}(i, j)$ can be obtained from matrix $\mathbf{M}_{\text{link}-\text{c}}(i, j)$ and $\mathbf{M}_{\text{link}-\text{c}}(j, i)$. More specifically, $\mathbf{M}_{\text{grant}-\text{bi}}(i, j)$ is 1 if both values of $\mathbf{M}_{\text{link}-\text{c}}(i, j)$ and $\mathbf{M}_{\text{link}-\text{c}}(j, i)$ are zero, indicating that the construction of two links, from i to j and from j to i, is valid without raising any channel collision. Figure 7 depicts the bi-directional grant matrix of Figure 1(a). For instance, the values of entries $\mathbf{M}_{\text{grant}-\text{bi}}(B, D)$ and $\mathbf{M}_{\text{grant}-\text{bi}}(D, B)$ are 1, indicating that stations B and D can construct a bi-directional link without any collision.

$$M_{grant\text{-}bi} = \begin{array}{c} \\ A \\ B \\ C \\ D \\ E \\ F \\ G \\ H \\ I \\ J \\ K \end{array} \begin{array}{c} \begin{array}{ccccccccccc} A & B & C & D & E & F & G & H & I & J & K \end{array} \\ \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \end{array}$$

Figure 7. Bi-directional grant matrix of Figure 1(a).

$M_{grant\text{-}uni} =$

	A	B	C	D	E	F	G	H	I	J	K
A	0	0	0	0	0	3	0	4	2	5	0
B	0	0	0	0	10	0	10	0	0	0	1
C	0	0	0	0	0	0	0	0	0	5	1
D	0	0	0	0	0	0	0	0	0	0	1
E	0	0	0	8	0	0	0	0	1	0	0
F	0	0	0	0	0	0	0	0	0	7	0
G	0	0	0	0	0	0	0	0	0	0	0
H	0	9	0	0	0	0	5	0	0	5	0
I	0	0	0	8	0	0	0	0	0	0	0
J	0	0	0	0	0	0	0	0	2	0	0
K	0	0	0	0	0	0	0	0	0	7	0

Figure 8. Uni-directional grant matrix of Figure 1(a).

4.1.8. Definition: uni-directional grant matrix ($\mathbf{M}_{\text{grant-uni}}$).

A *Uni-directional Grant Matrix* $\mathbf{M}_{\text{grant-uni}}$ specifies the legality of *uni-directional* link construction between stations. $\mathbf{M}_{\text{grant-uni}}$ is a matrix with size $n \cdot n$ where n is the number of nodes in the network. The value of a matrix entry $\mathbf{M}_{\text{grant-uni}}(i, j)$ would be either k or 0. Entry $\mathbf{M}_{\text{grant-uni}}(i, j)$ has a value k which denotes that constructing a link from i to j is legal but constructing a link from j to i will raise a collision at the station with ID $= k$. On the other hand, Entry $\mathbf{M}_{\text{grant-uni}}(i, j)$ has a value 0 if constructing a link from j to i is legal. That is,

$$\mathbf{M}_{\text{grant-uni}}(i, j) = \begin{cases} 0\ , & j \text{ can construct a link to } i \\ k\ , & i \text{ can construct a link to } j \text{ but } j \text{ constructing} \\ & \text{a link to } i \text{ will collide at the station with } ID = k \end{cases}$$

Note that the matrix $\mathbf{M}_{\text{grant-bi}}$ is symmetric but the $\mathbf{M}_{\text{grant-uni}}$ is asymmetric. The uni-directional grant matrix records each pair of stations in which one uni-direction link exactly exists between them. Similar to the bi-directional grant matrix, the value of each entry of matrix $\mathbf{M}_{\text{grant-uni}}(i,j)$ can also be obtained from matrix $\mathbf{M}_{\text{link-c}}(i,j)$ and $\mathbf{M}_{\text{link-c}}(j, i)$. More specifically, $\mathbf{M}_{\text{grant-uni}}(i, j)$ is k if $\mathbf{M}_{\text{link-c}}(j, i)$ is 0 and $\mathbf{M}_{\text{link-c}}(i,j)$ is k, indicating that constructing a link from i to j is legal but constructing a link from j to i will give rise to a collision at the station with ID $= k$.

The uni-directional grant matrix of Figure 1(a) is given in Figure 8. For instance, entry $\mathbf{M}_{\text{grant-uni}}(D, E)$ is 0 but entry $\mathbf{M}_{\text{grant-uni}}(E, D)$ is 8 (denoting station H). It means that the link construction from node E to node D is legal but the link from D to E will result in a collision at station H.

4.2. Matrix-based power control and channel-switching mechanisms

The *Matrix-based Channel-Switching* mechanisms proposed in this paper comprise of two phases: the *power control phase* and the *channel-switching phase*. The power control phase aims to legally establish all possible links without channel exchange by assigning each station with an appreciate power level. In the channel-switching phase, the adaptive channel-switching scheme is applied to resolve the primary or secondary collision problems in order to establish more links that will improve the network connectivity of the WMN.

4.3. Phase 1: power control phase

The purpose of this phase is to construct all possible links by adjusting the power level of some stations. Let x and y be any pair of nodes without any link existing between them. There are two conditions that should be satisfied to legally construct a new link between nodes x and y. The first condition is that there are no primary and secondary collisions after establishing a new link between x and y. The second condition is that x and y are within the maximum communication range.

In order to check the existence of primary and secondary collisions, it is necessary to maintain the channels of all one-hop neighbors at each node. To simplify the matrix computation, another notation, $\mathbf{M}_{c'}$, is introduced to denote another representative form of $\mathbf{M}_c$. Station i's numeric ID will be put in the entry $\mathbf{M}_{c'}$ (i, j) if station i uses channel j. The major difference between $\mathbf{M}_{c'}$ and $\mathbf{M}_c$ is that we put the station's numeric ID in the entry $\mathbf{M}_{c'}$ (i, j), instead of putting 1 in $\mathbf{M}_c$ to denote that station i uses channel j. Matrix $\mathbf{M}_{c'}$ provides useful information of the victim stations during the matrix operations as described below. Figure 9 depicts the $\mathbf{M}_{c'}$ of the $\mathbf{M}_c$ shown in Figure 3. For instance, a value 3 in entry $\mathbf{M}_{c'}(C, 2)$ denotes that channel 2 is assigned to station C and that the numeric ID for station C is 3.

Since $\mathbf{M}_t$ represents the network topology which defines the neighboring relationship between the stations, and the $\mathbf{M}_{c'}$ denotes the channel assigned to each station, then multiplying the two matrices $\mathbf{M}_t$ and $\mathbf{M}_{c'}$, gives the channels assigned to the neighboring nodes of each station. Following the example shown in Figure 1(a), Figure 10 is the result of multiplying matrices $\mathbf{M}_t$ and $\mathbf{M}_{c'}$.

For instance, the second row of $\mathbf{M}_t \bullet \mathbf{M}_{c'}$, represents the channels $\{1, 4, 5\}$ assigned to all the neighboring stations

$M_{c'} =$

	1	2	3	4	5
A	1	0	0	0	0
B	0	0	0	0	2
C	0	3	0	0	0
D	0	0	4	0	0
E	0	0	0	5	0
F	0	6	0	0	0
G	0	0	0	7	0
H	0	0	8	0	0
I	0	0	0	0	9
J	0	0	0	10	0
K	11	0	0	0	0

Figure 9. The $\mathbf{M}_{c'}$ matrix.

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$M_t \square M_{c'} =$

	1	2	3	4	5
A	1	3	4	5	2
B	1	0	0	10	2
C	1	3	8	5	0
D	1	6	4	0	0
E	1	3	8	5	0
F	0	6	4	7	0
G	11	6	0	7	0
H	0	3	8	5	9
I	0	0	8	0	9
J	0	0	0	10	2
K	11	0	0	7	0

Figure 10. Multiplication of matrices $\mathbf{M}_t$ and $\mathbf{M}_{c'}$ for the WMN shown in Figure 1(a).

of station *B* and these are used by those stations whose numeric IDs are 1, 10, and 2, respectively. This information can also help to derive the link collision matrix. Having obtained the channels assigned to the neighbors of each station, the next step is to use this information to check the existence of collisions. The link between *x* and *y* is collision-free if the channel of *x* is different from the channels of *y*'s one-hop neighbors. Thus, equation (1) can be used to obtain the link collision matrix $\mathbf{M}_{\text{link-c}}$.

$$\mathbf{M}_{\text{link-c}} = \mathbf{M}_t \bullet \mathbf{M}_{c'} \bullet (\mathbf{M}_c)^T \qquad (1)$$

Consider the 6th row of $\mathbf{M}_t \bullet \mathbf{M}_{c'}$, as shown in Figure 10, and the 10th column of $(\mathbf{M}_c)^T$, which can be obtained from the transposition of the matrix shown in Figure 3. Since the 6th row of $\mathbf{M}_t \bullet \mathbf{M}_{c'}$ denotes the channel set that is used by station *F*'s neighbors, and the 10th column of matrix $(\mathbf{M}_c)^T$ denotes the channel used by *J*, a value of 7 in the entry of $\mathbf{M}_{\text{link-c}}(F, J)$, as shown in Figure 6, denotes that station *J*, which establishes a uni-directional link to *F*, will result in collision because the *F*'s neighboring stations *G* (with numeric ID 7) and *J* use the same channel.

4.3.1. Definition: positive AND operation (pAND).

For any given two integers *i* and *j*, if $i>0$ and $j>0$, the result of *i* pAND *j* turns 1; otherwise it turns 0.

4.3.2. Definition: positive XOR operation (pXOR).

For any given two integers *i* and *j*, if *i* is not equal to *j*, the result of *i* pXOR *j* turns 1; otherwise it turns 0.

Based on the link collision matrix, the two matrices, namely bi-directional grant matrix $\mathbf{M}_{\text{grant-bi}}$ and uni-directional grant matrix $\mathbf{M}_{\text{grant-uni}}$, can be derived by applying equations (2) and (3). The bi-directional grant matrix exhibits those pairs that are able to construct bi-directional links without any collision. The matrix $\mathbf{M}_{\text{grant-bi}}$ can be obtained by executing the pAND operation on the complement of $\mathbf{M}_{\text{link-c}}$ and its transposition as shown in equation (2). Since $\mathbf{M}_{\text{link-c}}$ maintains the collision relations for node pairs, the complement of $\mathbf{M}_{\text{link-c}}$ depicts the pairs that are able to construct links without any collision. The pAND operation on the complement of $\mathbf{M}_{\text{link-c}}$ and its transposition is used to get a symmetric matrix where entry (i, j) with a value of 1 denotes that a link can be constructed between stations *i* and *j* without any collision. Applying equation (2), the bi-directional grant matrix of WMN shown in Figure 1(a) can be obtained as shown in Figure 7.

The uni-directional grant matrix depicts those pairs wherein to construct a directional link between the pair will result into channel collision, but to construct a reverse directional link between the same pair is valid. It can be obtained by executing the pXOR operation on the link collision matrix $\mathbf{M}_{\text{link-c}}$ and its transposition as shown in equation (3). The pXOR operation is used to explore any entry in $\mathbf{M}_{\text{link-c}}$, say (i, j), with the property that $(i, j) = 0$ but $(j, i) \neq 0$ or $(j, i) = 0$ but $(i, j) \neq 0$. For instance, entries (D, E) and (E, D) in $\mathbf{M}_{\text{link-c}}$ have values 0 and 8, respectively, and therefore, the entries (D, E) and (E, D) in $\mathbf{M}_{\text{grant-uni}}$ have a value of 1, indicating that only a directional link can be constructed between nodes *D* and *E*.

$$\mathbf{M}_{\text{grant-bi}} = \overline{\mathbf{M}_{\text{link-c}}} \text{ pAND } (\overline{\mathbf{M}_{\text{link-c}}})^T \qquad (2)$$

$$\mathbf{M}_{\text{grant-uni}} = \mathbf{M}_{\text{link-c}} \text{ pXOR } (\overline{\mathbf{M}_{\text{link-c}}})^T \qquad (3)$$

Another essential condition for constructing a link between two stations is that the physical distance between them cannot be larger than the maximum transmission range. That is, $d(x, y) \leq$ *maximum power transmission range*. The physical distance between stations can be evaluated from the location information. Hence, the *bi-directional grant matrix* and *uni-directional grant matrix* can be refined by removing those pairs whose distances are larger than the maximum transmission range. For example, both entries (k, i) and (i, k) in $\mathbf{M}_{\text{grant-uni}}$ have a value of 1, but $d(i, k)$ is larger than the *maximum power transmission range*. Thus, the values of entries (k, i) and (i, k) in $\mathbf{M}_{\text{grant-uni}}$ have to be changed from 1 to 0.

In the next phase, an adaptive channel-switching scheme is proposed to eliminate the victim stations that are indicated in the *uni-directional grant matrix*.

4.4. Phase 2: channel switching phase

In the previous phase, the obtained *uni-directional grant matrix* depicts the existing collisions associated with some of the links' establishment. In the channel switching phase, a channel switch matrix will be utilized to remove channel collisions. A *channel switch matrix* specifies the legality of the channel exchange between stations. Since channel exchange could remove the channel collisions but may introduce another channel collision, the channel exchange of two stations should guarantee that no primary and secondary collision will arise. Equation (4) shows that the two-hop collision matrix can be obtained by the multiplication of two matrices, the $(\mathbf{M}_t)^2$ and $\mathbf{M}_c$. This result will be used for advanced matrix operations as defined in Equation (5). Let $\mathbf{M}_{\text{no-switch}}(i, j)$ represent the number of collisions which occurred owing to the primary or secondary collisions when station i uses the channel assigned to j. In equation (5), matrix $\mathbf{M}_{\text{no-switch}}$ can be derived by $\mathbf{M}_c \bullet (\mathbf{M}_{col}^2 - \mathbf{M}_c) - (\mathbf{M}_t)^2$. The (i, j) entry of $\mathbf{M}_c \bullet \mathbf{M}_{col}^2$ maintains the number of channel collisions within i's two-hop neighbors if station i uses the channel assigned to j. However, (i, j) entry of $\mathbf{M}_c \bullet \mathbf{M}_{col}^2$ also counts the collision of the channel originally assigned to i, which is an invalid count since the channel of i was changed. Therefore, the (i, j) entry of matrix $\mathbf{M}_c \bullet (\mathbf{M}_{col}^2 - \mathbf{M}_c)$ eliminates the invalid count and represents the number of collisions that occurred between node i and its two-hop neighbors if station i using the channel assigned to j. Notice that station j also could be one of the two-hop neighbors of station i. Similarly, the (i, j) entry of $\mathbf{M}_c \bullet \mathbf{M}_{col}^2$ also counts the collision of channel originally assigned to j, which is an invalid count since the channel of j has been changed. As a result, the subtraction of $(\mathbf{M}_t)^2$ from $\mathbf{M}_c \bullet (\mathbf{M}_{col}^2 - \mathbf{M}_c)$ will remove the invalid count in $\mathbf{M}_{\text{no-switch}}$. Finally, the channel switch matrix can be obtained by equation (6). Figure 5 demonstrates the channel-switching matrix of the WMN shown in Figure 1(a)

$$\mathbf{M}_{col}^2 = (\mathbf{M}_t)^2 \bullet \mathbf{M}_c \quad (4)$$

$$\mathbf{M}_{\text{no-switch}} = (\mathbf{M}_c \bullet (\mathbf{M}_{col}^2 - \mathbf{M}_c)^{\mathrm{T}}) - (\mathbf{M}_t)^2 \quad (5)$$

$$\mathbf{M}_{\text{switch}} = \overline{\mathbf{M}_{\text{no-switch}}} \text{ AND } (\overline{\mathbf{M}_{\text{no-switch}}})^{\mathrm{T}} \quad (6)$$

Having obtained the channel switch matrix, the next step is to utilize the channel switch matrix to eliminate the victim nodes in the *uni-directional grant matrix*. For instance, the value of the matrix entry $\mathbf{M}_{\text{grant-uni}}$ (F, J) is the numeric ID 7 (denoting station G), which indicates that station J connecting to station F will cause station G to be a victim. However, the value of the matrix entry $\mathbf{M}_{\text{switch}}(G, K)$ is 1 which denotes that stations G and K can exchange their channels to eliminate the collision of $\mathbf{M}_{\text{grant-uni}}$ (F, J) and thus, an additional unidirectional link between stations F and J can be created. By repeatedly constructing a new link in a similar way, several additional links can be constructed. Therefore, the proposed channel switching mechanism resolves the channel collision problem and adds links to the given WMN to enhance the network connectivity of the topology obtained from the first phase.

4.5. Link selection policies

From the previous steps, all possible links that can be additionally constructed to a given WMN can be found. It is possible that a newly constructed link can change the topology of WMN and may even restrain the other new links' construction. Thus, the link selection policy is proposed in order to decide on the order of link construction. A good selection policy for link construction can result to higher network connectivity. Different selection policies can result into different capacities of link construction and have an impact on the throughputs of the WMN. In Reference [12], the distance-based and degree-based schemes were proposed for link selection policy. Aside from the two schemes proposed in Reference [12], this paper proposes another policy, namely the hop-based link selection policy. The Hop-based policy assumes that the distance and hop count are not identical and takes into account the reduction in hop counts as the major metric for determining the order of link construction. That is, a new link which saves more hop counts will have a higher priority of being constructed. The number of hops between two stations can be derived by $(\mathbf{M}_t)^k$ which specifies the hop relation between any pair of stations. Recall that the value of a matrix entry $(\mathbf{M}_t)^k(i, j)$ is 1 or 0 denoting whether or not stations i and j are k hop neighbors, respectively. Therefore, the link construction between i and j can save $k - 1$ hops if $(\mathbf{M}_t)^k(i, j)$ is 1.

The proposed mechanisms should be performed when some old stations are removed from the network due to shutdown or when some new stations join the network. In this situation, the channel usage or network topology will be changed. From the simulation results, the degree-based scheme performs better than the other two mechanisms and is the preferred scheme for the WMN. However, the hop-based mechanism reduces the hop difference between the nodes in the network and hence, has a better performance in the environment whose traffic changes frequently. The distance-based mechanism will establish more links and is appropriate for a high-density environment. The three mechanisms have their own characteristics and work better for different environments. Therefore, when the network throughput downgrades to a predefined threshold, the topology constructed by the applied mechanism might not be appropriate. The proposed mechanisms will be initiated in order to apply the best one for constructing a better topology.

The procedures of the proposed mechanisms are outlined as following.

4.6. Power control and channel switching mechanism

Input: location and assigned channel of each node in the network.
Output: a new channel assignment and new constructed links.

4.7. Phase 1: power control phase

(1) Derive $\mathbf{M}_t$, $\mathbf{M}_c$ and $\mathbf{M}_{c'}$.Collect the assigned channel and the location of each station in the network to obtain $\mathbf{M}_t$, $\mathbf{M}_c$ and $\mathbf{M}_{c'}$.
(2) $\mathbf{M}_{\text{link-c}} = \mathbf{M}_t \bullet \mathbf{M}_{c'} \bullet (\mathbf{M}_c)^{\mathrm{T}}$
Apply equation (1) to obtain the link collision matrix $\mathbf{M}_{\text{link-c}}$.

(3) $\mathbf{M}_{\text{grant-bi}} = \overline{\mathbf{M}_{\text{link-c}}}$ pAND $(\overline{\mathbf{M}_{\text{link-c}}})^{\mathrm{T}}$

$\mathbf{M}_{\text{grant-uni}} = \mathbf{M}_{\text{link-c}}$ pXOR $(\overline{\mathbf{M}_{\text{link-c}}})^{\mathrm{T}}$

Derive the grant matrix $\mathbf{M}_{\text{grant-bi}}$ and unidirectional grant matrix $\mathbf{M}_{\text{grant-uni}}$ using equations (2) and (3).

(4)
```
for(i= 1,i<=n; i++){
    for(j= 1,j<=n; j++){
        if(M_grant-bi(i, j) >T_max) M_grant-bi(i, j)= 0;
        if(M_grant-uni(i, j)>T_max) M_grant-uni(i, j)= 0;
    }
}//n is number of nodes in the network
```

Check each link in $\mathbf{M}_{\text{grant-bi}}$ and $\mathbf{M}_{\text{grant-uni}}$ and remove it if its length is longer than $T_{\max}$ where $T_{\max}$ is the *maximum transmission range*.

4.8. Phase 2: channel switching phase

(5) $\mathbf{M}^2_{\text{col}} = (\mathbf{M}_{\mathrm{t}})^2 \bullet \mathbf{M}_{\mathrm{c}}$
Obtain the two-hop collision matrix $\mathbf{M}^2_{\text{col}}$ by applying equation (4).

(6) $\mathbf{M}_{\text{no-switch}} = (\mathbf{M}_{\mathrm{c}} \bullet (\mathbf{M}^2_{\text{col}} - \mathbf{M}_{\mathrm{c}})^{\mathrm{T}}) - (\mathbf{M}_{\mathrm{t}})^2$.
Obtain $\mathbf{M}_{\text{no-switch}}(i, j)$ by applying equation (5).

(7) $\mathbf{M}_{\text{switch}} = \overline{\mathbf{M}_{\text{no-switch}}}$ AND $(\overline{\mathbf{M}_{\text{no-switch}}})^{\mathrm{T}}$
Derive the channel switch matrix $\mathbf{M}_{\text{switch}}(i, j)$ by using equation (6).

(8) Let L be the list that contains all the non-zero entries (i, j) in $\mathbf{M}_{\text{grant-bi}}$ and $\mathbf{M}_{\text{grant-uni}}$. Sort L based on the following link selection policies:
- *Distance-based*: sort L in an ascending order of distance between stations i and j.
- *Degree-based*: sort L in an ascending order of degree between stations i and j.
- *Hop-based*: sort L in a descending order of saving hop counts between stations i and j.

(9) Consider the first entry (i, j) in L. The link between i and j can be established without any primary and secondary collision if any of the following two conditions is true:
(i) $\mathbf{M}_{\text{grant-bi}}(i, j) = 1$
$\mathbf{M}_{\text{grant-uni}}(i, j) = k$ and l exists such that
(ii) entry
$\mathbf{M}_{\text{switch}}(k, l) = 1$

(10) If link between i and j is established in the previous step, perform the following four steps:
(1) Update the network topology and set $\mathbf{M}_{\mathrm{t}}(i, j) = 1$ and $\mathbf{M}_{\mathrm{t}}(j, i) = 1$.
(2) If channel switching operation is applied in step 9, update the channel matrix by setting $\mathbf{M}_{\mathrm{c}}(k, c_l) = 1$ and $\mathbf{M}_{\mathrm{c}}(l, c_k) = 1$.
(3) Update $\mathbf{M}_{\text{switch}}$ if any value of $\mathbf{M}_{\mathrm{t}}$ or $\mathbf{M}_{\mathrm{c}}$ is changed.
(4) Remove entry (i, j) from L and repeat step 9 until L is empty.

The basic concepts behind each step of the proposed mechanisms are given below. In the Power Control Phase, the major goal is to assign each node with an appreciate power level to help find out all possible links that could be added in the current network topology. To achieve this goal, we should identify those new links that might be additionally constructed without collision. Therefore, $\mathbf{M}_{\mathrm{t}}$, $\mathbf{M}_{\mathrm{c}}$ and $\mathbf{M}_{c'}$ Matrices should be used for exploiting the potential links that might be additionally established for improving the network throughput. Consequently, Step 1 collects the channel and location information of each station in the network. This information could be used in the later steps to help derive the collision relation between stations. Step 2 aims to find out the existence of primary and secondary collisions which help determine the possibility for establishing a new link between two nodes. Since $\mathbf{M}_{\mathrm{t}}$ represents the network topology which defines the neighboring relationship of stations, and the $\mathbf{M}_{c'}$ denotes the channel assigned to each station, multiplying the two matrices $\mathbf{M}_{\mathrm{t}}$ and $\mathbf{M}_{c'}$ obtains the channels assigned to all neighboring nodes of each station. Step 3 tries to find out the pairs that are able to construct bi-directional or directional links without any collision. Step 4 removes the pairs in $\mathbf{M}_{\text{grant-bi}}$ and $\mathbf{M}_{\text{grant-uni}}$ that the distance between nodes is longer than maximum transmission power.

The Channel Switching Phase aims to apply the channel switching mechanism which can additionally construct links for improving the network connectivity. Exchanging channels between two stations might be able to additionally construct new links without violating the primary and secondary collision constraints. Consequently, Step 5 derives the two-hop collision matrix which can be obtained by the multiplication of two matrices $(\mathbf{M}_{\mathrm{t}})^2$ and $\mathbf{M}_{\mathrm{c}}$. This result will be used for advanced matrix operations as defined in the next step. Steps 6 and 7 aims to find out the channel switch matrix which can be used to eliminate the victim nodes in the $\mathbf{M}_{\text{grant-uni}}$ and get more addable links. A *channel switch matrix* specifies the legality of the channel exchange between stations. Since channel exchange could remove the channel collisions but may introduce another channel collision, the channel exchange of two stations should guarantee that no primary and secondary collision will arise. Steps 8, 9, and 10 aim to decide the order of link construction based on different link selection policies. Different link selection policies can result in different capacities of link construction and have different impacts on the network throughputs. From the previous steps, all possible links that can be additionally constructed for a given WMN are found.

The complexity of the proposed mechanism is analyzed below. In step 1, the $\mathbf{M}_{\mathrm{t}}$, $\mathbf{M}_{\mathrm{c}}$ and $\mathbf{M}_{c'}$ can be easily obtained in time $O(n^2)$ where n is the number of nodes in the network. In steps 2 and 3, the derivations of matrices $\mathbf{M}_{\text{link-c}}$, $\mathbf{M}_{\text{grant-bi}}$, and $\mathbf{M}_{\text{grant-uni}}$ will take time equal to $O(n^3)$, $O(n^2)$, and $O(n^2)$, respectively. Step 4 will take time equal to $O(n)$. Therefore, the time complexity of phase 1 is $O(n^3)$. In Phase 2, Steps 5, 6, and 7 will take time equal to $O(n^3)$, $O(n^3)$, and $O(n^2)$, respectively. In step 8, the time complexity of sorting L is $O(n \log n)$. Both steps 9 and 10 take time equal to $O(n^2)$. The worst case that can happen is when there are n nodes in the network and only $n - 1$ links are established. In this case, the given network topology is connected with a minimum number of links. Hence, the proposed scheme needs to evaluate most of the links that can possibly be established. Similar to the above-mentioned complexity analysis, the most time consuming operations, steps 5 and 6 of phase 1, take time equal to $O(n^3)$. Consequently, the overall time complexity of the proposed mechanism is $O(n^3)$.

5. EXTENSIONS FOR CHANNEL-SWITCHING MECHANISM

In this section, the proposed mechanisms are extended in order to take the unbalanced traffic loads among stations into account. The objective of these mechanisms is to construct more links with higher traffic demand for improving the overall throughput.

In order to construct links for the nodes that have higher traffic demand, we need to maintain the average traffic loads for each node to decide the order of link construction. Therefore, a new matrix $\mathbf{M}_{\text{traffic}}$ is defined as follows.

5.1. Definition: traffic matrix ($\mathbf{M}_{\text{traffic}}$)

Given a WMN, a *Traffic Matrix* $\mathbf{M}_{\text{traffic}}$ specifies the average traffic relation between any pair of stations. $\mathbf{M}_{\text{traffic}}$ is a matrix with size $n \cdot n$ where n is the number of nodes in the network. The value of a matrix entry $\mathbf{M}_{\text{traffic}}(i, j)$ denotes the average traffic from station i to station j.

Step 8 reflects the major difference in designing link selection mechanisms that consider the traffic demand. In step 8, the link selection mechanisms should be modified to accomplish the target of considering traffic demand. Let L be the list that contains all the non-zero entries (i, j) in $\mathbf{M}_{\text{grant-bi}}$ and $\mathbf{M}_{\text{grant-uni}}$. For the distance-based mechanism, the link with shorter distance and higher traffic has higher priority to be selected. Therefore, the L will be sorted by the value of distance(i, j) * $\mathbf{M}_{\text{traffic}}(i, j)^{-1}$ in an ascending order, where distance(i, j) denotes the distance between stations i and j. For the degree-based mechanism, the link with less degree and higher traffic has higher priority to be selected. Therefore, the L will be sorted by the value of degree(i, j) * $\mathbf{M}_{\text{traffic}}(i, j)^{-1}$ in an ascending order, where *degree* (i, j) is the lower value of degrees of stations i and j. For the hop-based mechanism, the link that helps reduce more hop counts and with higher traffic has higher priority to be selected. Therefore, the L will be sorted by the value of *s-hop*(i, j) * $\mathbf{M}_{\text{traffic}}(i, j)$ in an descending order, where *s-hop*(i, j) denotes the reduced hop counts between stations i and j.

The detail algorithm of the proposed mechanism is modified as following.

5.2. Extended channel-switching mechanism

Input: location, traffic and assigned channel of each node in the network.
Output: a new channel assignment and new addable links.

5.3. Phase 1: power control phase

(1) Derive $\mathbf{M}_t$, $\mathbf{M}_{\text{traffic}}$, $\mathbf{M}_c$, and $\mathbf{M}_{c'}$.
Collect the channels being used and the positions of the stations in the network to obtain $\mathbf{M}_t$, $\mathbf{M}_{\text{traffic}}$, $\mathbf{M}_c$, and $\mathbf{M}_{c'}$.

(2) $\mathbf{M}_{\text{link}-c} = \mathbf{M}_t \bullet \mathbf{M}_{c'} \bullet (\mathbf{M}_c)^T$
Apply equation (1) to obtain the link collision matrix $\mathbf{M}_{\text{link}-c}$.

(3) $\mathbf{M}_{\text{grant}-\text{bi}} = \overline{\mathbf{M}_{\text{link}-c}}$ pAND $(\overline{\mathbf{M}_{\text{link}-c}})^T$

$\mathbf{M}_{\text{grant}-\text{uni}} = \mathbf{M}_{\text{link}-c}$ pXOR $(\overline{\mathbf{M}_{\text{link}-c}})^T$

Derive the grant matrix $\mathbf{M}_{\text{grant}-\text{bi}}$ and unidirectional grant matrix $\mathbf{M}_{\text{grant}-\text{uni}}$ by applying equations (2) and (3).

(4)
```
for(i= 1, i <=n; i++) {
    for(j= 1, j <=n; j++){
        if(M_grant-bi(i, j) > T_max) M_grant-bi(i, j)= 0;
        if(M_grant-uni(i, j)>T_max) M_grant-uni(i, j)= 0;
    }
} // n is number of nodes in the network
```

Check each link in $\mathbf{M}_{\text{grant}-\text{bi}}$ and $\mathbf{M}_{\text{grant}-\text{uni}}$ and remove it if its length is longer than $T_{\max}$ where $T_{\max}$ is the *maximum transmission range*.

5.4. Phase 2: channel switching phase

(5) $\mathbf{M}_{\text{col}}^2 = (\mathbf{M}_t)^2 \bullet \mathbf{M}_c$
Obtain the two-hop collision matrix by applying equation (4).

(6) $\mathbf{M}_{\text{no}-\text{switch}} = (\mathbf{M}_c \bullet (\mathbf{M}_{\text{col}}^2 - \mathbf{M}_c)^T) - (\mathbf{M}_t)^2$
Obtain $\mathbf{M}_{\text{no}-\text{switch}}(i, j)$ by applying equation (5).

(7) $\mathbf{M}_{\text{switch}} = \overline{\mathbf{M}_{\text{no}-\text{switch}}}$ AND $(\overline{\mathbf{M}_{\text{no}-\text{switch}}})^T$.
Derive the channel switch matrix $\mathbf{M}_{\text{switch}}(i, j)$ by applying equation (6).

(8) Let L be the list that contains all the non-zero entries (i, j) in $\mathbf{M}_{\text{grant}-\text{bi}}$ and $\mathbf{M}_{\text{grant}-\text{uni}}$. Sort L based on the following link selection policies:
- *Distance-based*: sort L in an ascending order of *distance*(i, j) * $\mathbf{M}_{\text{traffic}}(i, j)^{-1}$ where *distance* (i, j) denote the distance between stations i and j.
- *Degree-based*: sort L in an ascending order of *degree*(i, j) * $\mathbf{M}_{\text{traffic}}(i, j)^{-1}$ where *degree* (i, j) denotes the lower value of degrees of stations i and j.
- *Hop-based*: sort L in a descending order of *s-hop*(i, j) * $\mathbf{M}_{\text{traffic}}(i, j)$ where *s-hop*(i, j) denotes the reduced hop counts between stations i and j.

(9) Consider the first entry (i, j) in L. The link between i and j can be established without any primary and secondary collision if any of the following two conditions is true:
(i) $\mathbf{M}_{\text{grant}-\text{bi}}\ (i, j) = 1$

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(ii) $\mathbf{M}_{\text{grant-uni}}(i, j) = k$ and exists l such that entry $\mathbf{M}_{\text{switch}}(k, l) = 1$

(10) If link between i and j is established in the previous step, perform the following four steps:

(1) Update the network topology and set $\mathbf{M}_t(i, j) = 1$ and $\mathbf{M}_t(j, i) = 1$.

(2) If channel switching operation is applied in step 9, update the channel matrix by setting $\mathbf{M}_c(k, c_l) = 1$ and $\mathbf{M}_c(l, c_k) = 1$.

(3) Update $\mathbf{M}_{\text{switch}}$ if any value of $\mathbf{M}_t$ or $\mathbf{M}_c$ is changed.

(4) Remove entry (i, j) from L and repeat step 9 until L is empty.

The following measures the complexity of the three mechanisms that take the traffic into consideration. In step 1, additional matrix maintenance cost for $\mathbf{M}_{\text{traffic}}$ is equal to $O(n^2)$. In step 8, the three link selection policies are modified to considered the traffic factor and the additional cost is equal to $O(n^2)$. Consequently, the overall time complexity of the proposed mechanism is $O(n^3)$.

In the next Section, the performance study of the proposed power control and channel-switching mechanisms incorporating with the three link policies will be investigated.

6. PERFORMANCE STUDY

This section presents the performance investigation of the proposed mechanisms. The simulation environment is described as follows. The number of devices varies from 50 to 130. These devices are deployed in an area of 1000 units × 1000 units with uniform distribution. The transmission range is tunable and varies from 10 to 210 units. The packet arrival rate is 1/100 and the packet size is 1000 bytes. The source and destination for each packet are randomly selected and the running time lasts 100 s. The saturation-degree-channel-assignment proposed in Reference [13] is adopted as the channel assignment algorithm. Throughputs of various topology control mechanisms are compared. In the experiments, the term 'Basic' stands for the given WMN without applying any improvement scheme. The 'Distance-based' and 'Degree-based' denote the performances obtained by applying distance-based and degree-based schemes proposed in Reference [12], respectively. The mechanisms incorporated with the proposed channel switching scheme in this paper are denoted by *CS-distance*, *CS-degree*, and *CS-hop* which adopt the different link selection policies, namely, distance-based, degree-based, and hop-based policies, respectively. Each result is obtained from the average of 10 experiments. The 95% confidence interval is always smaller than 5% of the reported values.

Figure 11 compares the throughput of the various mechanisms. The number of nodes is set at 100 and the initial transmission range varies from 10 to 210 units. In general, the throughput increases with the initial transmission range

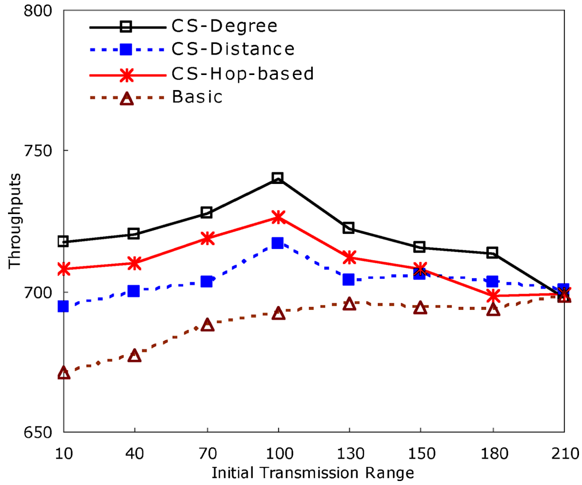

Figure 11. The throughput improvement of the channel switching mechanisms at different initial transmission range.

in case that the initial transmission range is smaller than 100 units. The proposed channel switching mechanism incorporated with the degree-based, distance-based and hop-based policies outperforms the 'Basic' in terms of throughput. This is because the proposed channel switching mechanism increases the number of links and hence improves the network throughput. The benefits of channel switching decrease when the transmission range gets larger than 130 units since the network congestion is increased due to the construction of new links. While the initial transmission range is equal to the maximum transmission range, all schemes have the same performance results because the proposed schemes are unable to increase the number of links by increasing the transmission power.

Figures 12–14 give the number of links that were additionally constructed by the different mechanisms while the number of nodes varied from 50 to 130. As shown in Figure 12, the proposed mechanisms constructed more links

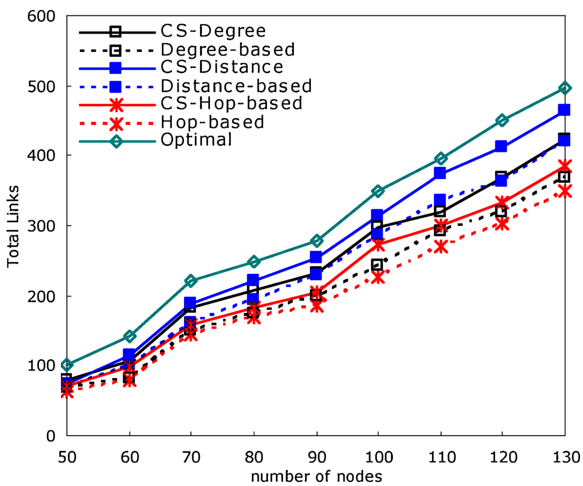

Figure 12. The comparison of the total number of links additionally constructed by applying the compared mechanisms.

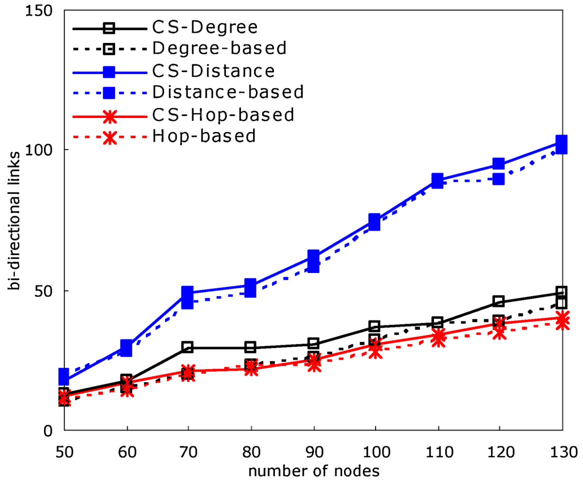

Figure 13. The comparison of the number of bi-directional links additionally constructed by applying the compared mechanisms.

than those mechanisms without any incorporated channel-switching scheme. To compare the proposed mechanism with the optimal number of added links, we apply linear program to derive the optimal throughput. A curve marked with 'Optimal' denotes the number of links added to the given network when the throughput is optimal. On the average, the distance-based and degree-based mechanisms have similar performance results, and both of them outperformed the hop-based mechanism. Figures 13 and 14 compare the number of bi-directional and uni-directional links constructed by the proposed mechanisms, respectively. Since the distance-based mechanism selects the closer nodes in order to construct new links and effectively exploit the opportunities for other nodes to construct new links, the number of additional bi-directional links constructed by the distance-based mechanism is larger than those of the degree-based

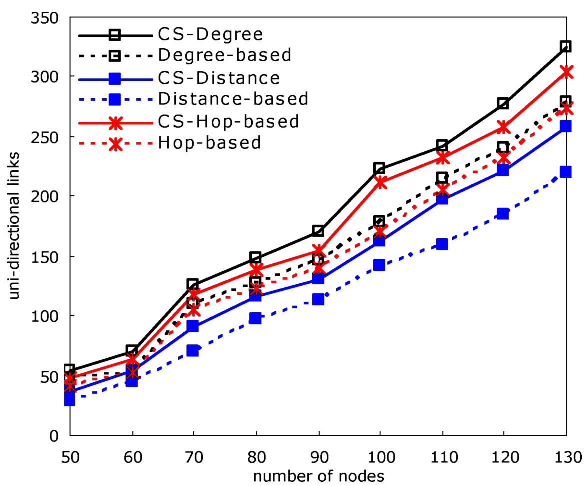

Figure 14. The comparison of the number of uni-directional links additionally constructed by applying the compared mechanisms.

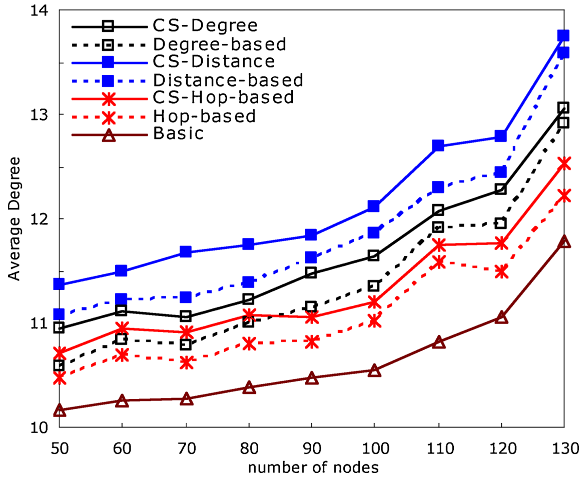

Figure 15. The comparison of average degree by applying the compared mechanisms.

and hop-based mechanisms. However, the degree-based and hop-based mechanisms have more opportunities to construct longer links as compared to the distance-based mechanism. As the network density increases, the difference between the distance-based and the other mechanisms also increases, as shown in Figure 13. This is owing to the fact that applying the degree-based and hop-based mechanisms in a dense WMN will significantly constrain the other nodes in constructing new links.

Figure 15 compares the average degree of the proposed mechanisms by varying the number of nodes. In general, the degree increases with the network density for all mechanisms. In particular, the proposed mechanisms incorporated with the channel switching scheme have larger degrees than those not incorporating the channel-switching scheme. The distance-based mechanism has the largest average degree since it constructs more links than the degree-based and hop-based mechanisms.

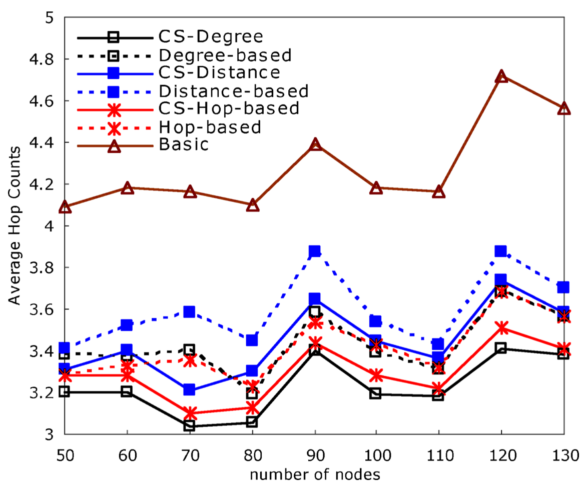

Figure 16. Performance study of average hops of routing path *versus* number of nodes.

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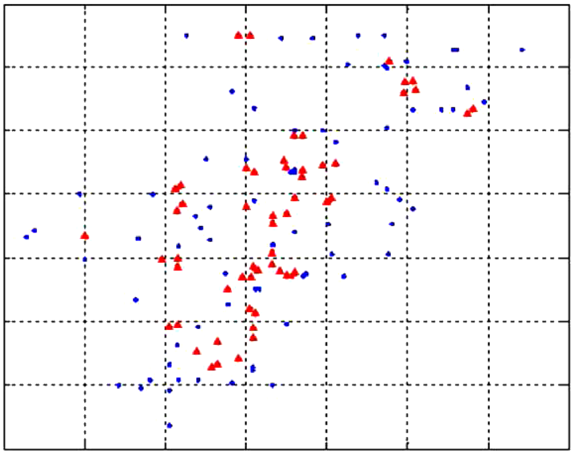

Figure 17. A screenshot of WMNs by applying distance-based channel switching mechanism. The network area is 1000 units × 1000 units.

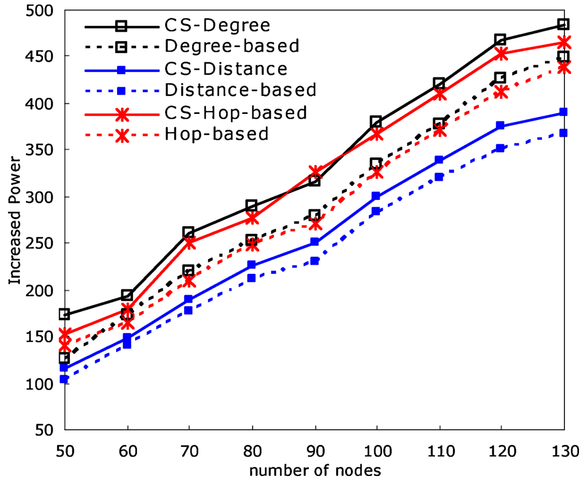

Figure 19. The comparison of the average increased power by varying the number of nodes in the network.

Figure 16 compares the proposed mechanisms in terms of the average hop counts. In general, the mechanisms incorporated with the channel switching scheme have smaller average hop counts than those mechanisms not incorporating the channel-switching scheme. Although the distance-based mechanism creates more links than the degree-based and hop-based mechanisms, the hop-based and degree-based mechanisms outperformed the distance-based mechanism. This is because the new links constructed by the distance-based mechanism are spread in areas with a higher density and are difficult to save hops significantly. On the other hand, the hop-based and degree-based mechanisms have more chances of constructing links in a sparse area and thus, are able to save more hops. Figures 17 and 18 show the screenshots of WMN by applying the distance-based and degree-based mechanisms, respectively. The nodes with and without increasing power to construct a new link are marked as red triangles and blue dots, respectively. The red triangles in Figure 18 are located in the sparse area in the network as compared to that of Figure 17. Those nodes that are located in the sparse area have a smaller degree and hence the degree-based mechanism tends to select these nodes to construct links.

Figure 19 investigates the improvement in performance in terms of the increased power after applying the proposed mechanisms. The larger the increase in power, the greater is the power consumption for maintaining the network structure. The increase in power grows with the network density for all the mechanisms. In particular, the mechanisms incorporated with the channel switching scheme have a larger increased power than those mechanisms not incorporating the channel-switching scheme. The degree-based and hop-based mechanisms have larger increased power than the distance-based mechanisms because the distance-based mechanism selects the closer nodes to construct new links and therefore, has lower values of increased power.

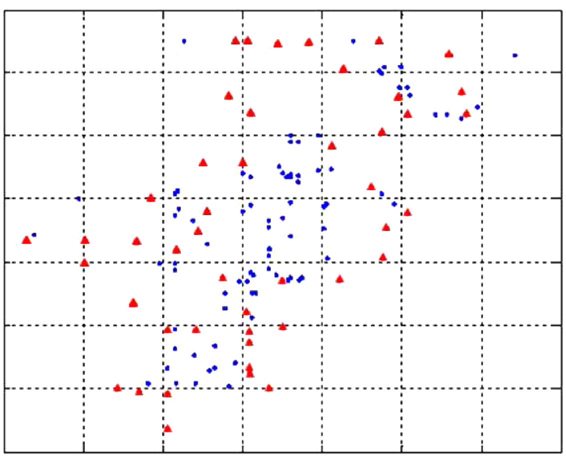

Figure 18. A screenshot of WMNs by applying degree-based channel switching mechanism. The network area is 1000 units × 1000 units.

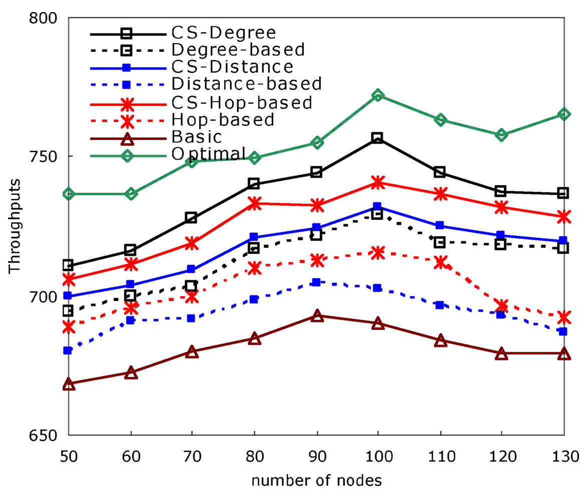

Figure 20. The throughput comparison by varying the number of nodes in the network under CBR traffic.

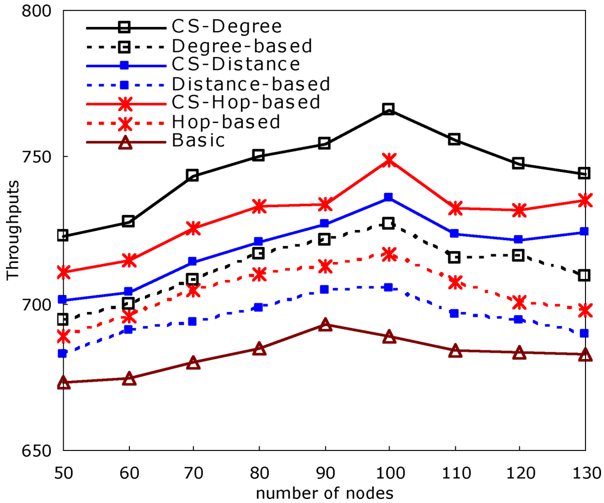

Figure 21. The throughput comparison by varying the number of nodes in the network under the traffic of Poisson distribution.

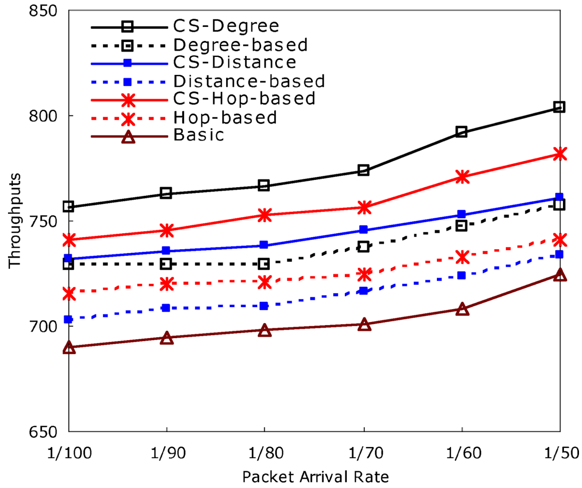

Figure 22. The throughput comparison by varying the packet arrival rate.

Figures 20 and 21 investigate the throughputs of the compared mechanisms at different number of nodes under CBR and TCP/IP traffic, respectively. The number of nodes varies from 50 to 130. As depicted in Figure 20, the mechanisms incorporating the channel switching have higher throughput than those not incorporating the channel switching scheme. The degree-based and hop-based mechanisms outperformed the distance-based mechanism because the distance-based has a larger average path length. In order to compare with the optimal results, we use liner programming to get the optimal throughputs and the corresponding additional number of links can be added in a given network. The throughput obtained by applying the proposed mechanism is less than 10% of optimal throughput in worst case.

In addition to the CBR traffic model, Figure 21 investigates the throughputs of the compared mechanisms under the traffic model of Poisson distribution. The data sources generate packets of fixed size and the number of packets generated is according to the Poisson distribution where the packet arrival rate is λ. In Figure 21, the throughput increases with the number of nodes when the number is smaller than 100. In general, the degree-based and hop-based mechanisms outperformed the distance-based mechanism in all cases. This is because the distance-based mechanism prefers to construct new links by spreading in higher density areas and hence, acquires larger average values of hop counts and path lengths as compared to the other two mechanisms. Since the throughput of all the mechanisms increased with the traffic, the variation of the traffic has a similar impact on each of the mechanisms. This is the reason why the curves in Figures 20 and 21 are similar.

Figure 22 depicts the relation between throughput and data arrival rate. A higher data arrival rate leads to a higher traffic load and thus increases the throughput. The mechanisms incorporated with the channel switching scheme create more links and provide a variety of route selections and thus, have higher throughputs than the mechanisms not incorporated with the channel switching scheme.

Figures 23 and 24 investigate the throughputs under elastic traffic type wherein the data sources generate packets according to different types of TCP services such as HTTP and FTP. In general, the throughput of all the mechanisms increased with the traffic. The degree-based and hop-based mechanisms outperform the distance-based mechanism. This is because the hop-based mechanism reduces the hop difference of node pairs in the network and hence, has a better performance in the environment whose traffic changes frequently like TCP or HTTP services. Since the distance-based mechanism prefers to construct a short link, the new links will be constructed for those pairs deployed in higher density areas, which results in larger hop counts and path lengths as compared to the other two mechanisms.

Figure 25 mainly investigates the performance improvement of the extended mechanisms that take traffic into

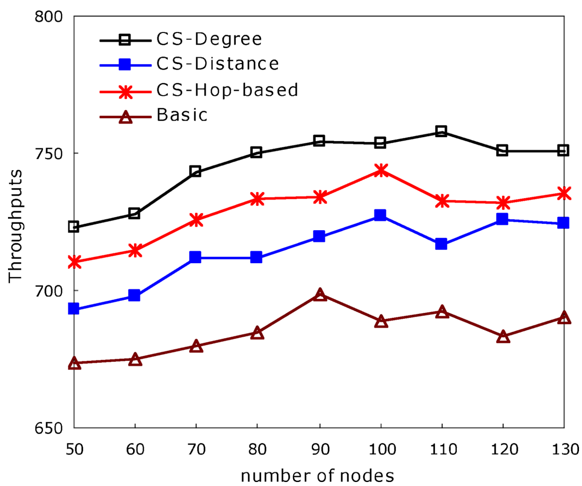

Figure 23. The throughput comparison by varying the number of nodes in the network under HTTP traffic.

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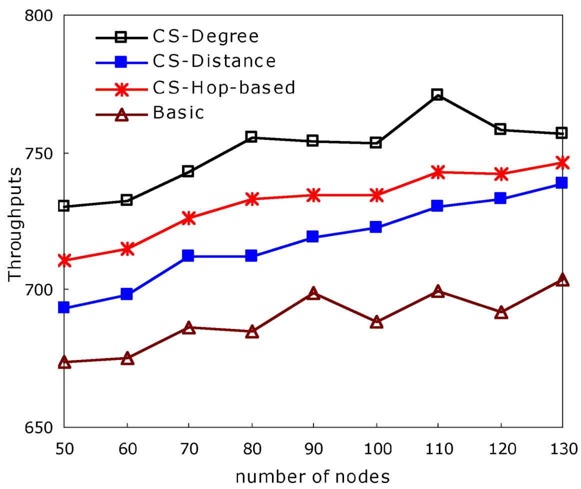

Figure 24. The throughput comparison by varying the number of nodes in the network under FTP traffic.

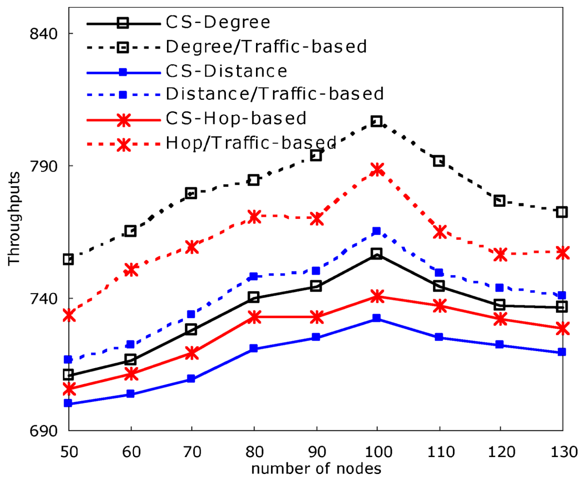

Figure 25. The throughput comparison by varying the number of nodes in the network under CBR traffic.

consideration. We refer to the extended mechanisms that take into account the traffic as distance/traffic-based, degree/traffic-based and hop/traffic-based mechanisms in Figure 25. The traffic-aware mechanisms are compared with the distance-based, degree-based, and hop-based mechanisms in terms of throughput. As a result, the traffic-aware mechanisms further improve 15% throughput of the non-traffic mechanisms in average.

7. CONCLUSION

This paper proposed channel-switching mechanisms to improve the network connectivity of the multi-hop WMN. A two-phase matrix-based representation is proposed to model the metrics of the network topology and channel assignment. The matrix-based operation is proposed to implement the channel collision detection and channel switching operation. In the power control phase, all possible links that do not raise the channel collision problem will be established by assigning some stations with appreciate power levels. In the channel-switching phase, the channel-switching scheme is further applied to remove the primary or secondary collisions and thus, is able to construct more links to improve the network connectivity. Furthermore, a Hop-based link selection policy is proposed to arrange the order of link construction for the WMN. Simulation results reveal that the proposed channel switching mechanism works well when incorporated with the various link selection policies. The proposed mechanisms increase the network connectivity and thus significantly improve the network throughput. In particular, the hop-based scheme has a better performance than distance-based scheme for a dense network environment.

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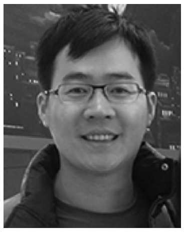

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