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On Improving Network Connectivity by Power-Control and Code-Switching Schemes for Multihop Packet Radio Networks

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Abstract- **Packet Radio Network (PRN) consists of low or even no mobility stations each assigned with a code to prevent transmission from collision. A PRN with strong connectivity will help to reduce the route length and provide more alternatives for routing, improving the overall throughput and end-to-end delay. With power control mechanism, each station could be assigned with a power level to change the neighborhood relation and improve network connectivity. Assigning high transmitting power level to a station can enhance the network connectivity but may increase the number of neighbors, raising collision problem for parallel transmissions among neighbors. How to assign appropriate power level to improve the network connectivity with a constraint of limited codes is one of the most important issues in PRNs. Given a network topology and a set of codes that has been assigned to stations, the proposed power control and code switching mechanism assigns each station with a power level and a code to improve the network connectivity. Based on the matrix-based operation, the power control and code switching metrics in network connectivity problem are generally identified and efficiently resolved. Simulation study reveals that the proposed mechanism increases network throughput and provides a variety of route selection thus improves the performance of a given PRN.**

I. INTRODUCTION

Packet Radio Networks were published in 1969 at the University of Hawaii[1]. A PRN is constructed by some stations which are equipped with radio transceivers and are connected through radio frequencies in a geographical area. Two types of Packet Radio Network can be classified as single-hop PRN and multi-hop PRN. A PRN is called *single-hop* PRN while stations in the network can communicate with all the other stations directly while packet transmission of stations in a multi-hop PRN may require intermediate stations to forward the data packets to destination in a *multi-hop* manner. Because of the low mobility and location aware for each station, the networks of PRNs are stable in comparing with ad hoc networks.

The performance of a multi-hop PRN relies upon the network connectivity which could be improved by assigning different power level to each station. A station assigned with a high power level will enlarge the transmission range and thus increase the number of neighbors. The strong network connectivity can reduce the number of forwarding nodes for multi-hop routing and provide a variety of routes, improving the network throughput and reducing the end-to-end delay. However, the increasing the number of neighbors may raise the expose and hidden terminal problems therefore requires either more codes or code switching to make different code assignment among neighbors, allowing them to be able to transmit packets in parallel without collision. How to enhance the network throughput by improving network connectivity while the size of code set is maintained without growing up and the network is guaranteed collision free is one of the most important issues in PRNs.

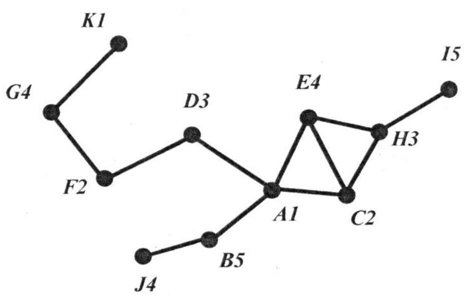
Code assignment and power control are two dimensions of most important issues in PRN. Improper code assignment will either raise the collision problem or consume too many codes. In literature, [7] classified the type of collisions in PRN into two types, namely primary (or direct) collision and secondary collision. The primary collision arises from the situation the stations can overhear the transmission from his one-hop neighbor whereas the secondary (or hidden) collision arises when two stations with two-hop distance transmit packet simultaneously thus their common neighbors receive the two transmissions at the same time. These two types of collision could be resolved by careful code assignment so that different codes are assigned to two-hop neighboring stations.

Since the available codes have been treated as the resource in PRN, the target of code assignment problem is to assign minimal number of collision-free codes for stations to avoid primary and secondary collisions. A number of previous studies [2][3][4][5] have proposed code assignment schemes. In [2], a two-phase algorithm is proposed where the first phase uses a breath-first-search tree to maintain the code-assigning order and the second phase minimizes the number of control packets required for code exchange. A token-based scheme [3] uses control segments to schedule transmission segments. The control channel is used to increase the utilization of the transmission segment. In literature, a number of code assignment protocols have been proposed to avoid the primary and secondary collisions. Study [4] proposes a transmitter-oriented code assignment scheme and finds 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 has been developed to obtain maximal independent sets in PRN broadcasting scheduling [5]. Although these studies developed efficient code assignment strategies for a given PRN, however, the network topology and relation between network connectivity and throughput are not discussed. Given a connected PRN where each station has been assigned a code to guarantee collision-free transmission, how to improve the network connectivity by adopting power control mechanism is an important and will be the key factor impacts on network throughput.

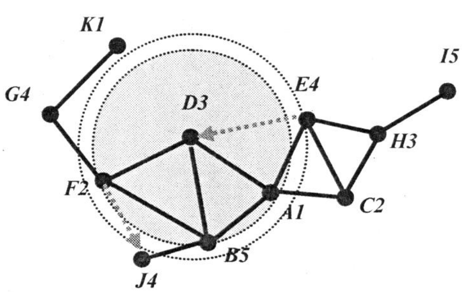
Some other studies concentrate on developing power control mechanisms to improve the network connectivity of PRN. The PRN topology can be changed by adjusting station's transmitting power level. In [6], a power adjustment mechanism is proposed to reduce collision by formulating the topology control problem as a constrained optimization problem. Previous work [7] presents a protocol to construct 1-edge and 2-edge-connected networks and minimize the transmission power of each node in the network. Under assumptions of fixed and variable power, the optimal transmission range can be evaluated in PRN [8]. [9] proposes a power adjustment protocol for improving the throughput of PRN. They increase the powers of stations to construct more links between stations in a given PRN and use degree-based and distance-based schemes to manage the sequences of link construction. Although a lot of researchers tried to improve the network connectivity by adopting power control mechanism in recent years, however, much effort should be involved to construct a topology of PRN with maximal connectivity under the constraints of using the same code set and providing collision free transmissions.

This paper aims at developing a power control and code switching mechanisms to improve the network connectivity of a multi-hop PRN. Matrix-base computations are employed to adopt power control and code switching mechanisms and provide solution to improve the network connectivity for a given PRN. The proposed power control and code switching mechanisms mainly consist of two phases. To improve the network connectivity, the first phase assigns each station with a appreciate power level to construct new links between two stations while the primary and secondary collisions can be avoided. In the second phase, adaptive code switching scheme is adopted to exchange codes of a pair so that additional links can be added while the primary and secondary collision problem can be overcome. The impacts of the proposed scheme are investigated. Performance results reveal that the proposed mechanism improves the network throughput and reduces the end-to-end delay thus enhances the performance of PRN.

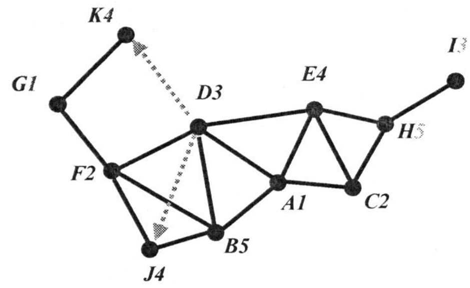
The rest of this paper is organized as follow. Section presents the preliminary and basic concepts of this study. The matrix-based power control and code switching mechanisms are proposed in Section . Section presents the performance study of the proposed mechanisms. Finally, conclusions are drawn in Section .



(a) The original PRN topology.



(b) Topology after applying distance-based scheme.



(c) Topology after performing code switching scheme.

Figure 1. Examples of topology after applying power control and code switching schemes.

II. Preliminary and Basic Concepts

A PRN consists of a number of low mobility or stationary stations each assigned with a transmission code to prevent transmissions of nearby stations from collision. Following the *transmitter-based* assumption [2], packet transmissions of stations are based on the code assigned to them. By different initial powers of each station in the network, stations can establish links with other stations within their transmission range and finally a certain network topology is formed by these links. Figure 1(a) shows an example of PRN, in which each station has a different transmission range and the number associated with each node is the assigned code.

In literature, power control has been used to adjust the transmission range in order to create more links between stations and establish a network with higher connectivity. To illustrate the impact of power control scheme on network topology, some notations are defined in the following. Let notation (A, B) denote a pair of nodes A and B. Furthermore, notations $\overrightarrow{AB}$ and $\overline{AB}$ denote a unidirectional link from A to B and bi-directional link between A and B, respectively. The distance of two nodes A and B is denoted as $d(A, B)$. Let X and Y are single or two-hop neighbors. Pair (X, Y) is said to be *code collision* if they have been assigned with the same code. Any common neighbor of nodes X and Y is said to be *victim station*. In [9], distance-based and degree-based schemes are proposed to create more links in a PRN by assigning some stations with appreciate power levels. In distance-base scheme, the link with shorter length has the higher priority to construct additional links.

In the following, example of Fig. 1 is taken to illustrate the distance-based scheme proposed in [9] and the basic idea of our mechanism. Figure 1(b) shows the resultant PRN by applying distance-base scheme on the topology given by Figure 1(a). Firstly, any pair of two nodes that have no link between them are identified. All the identified pairs are then sorted according to their length as a list (F, J), (F, B), (D, B), (D, E), (D, J) and (D, K). According to the order, the scheme checks each pair (i, j) if any primary and secondary collisions occur when adding a link between stations i and j. The following steps list the processes of the distance-based scheme:

1. Failure on constructing link $\overline{FJ}$: Increasing power level of F can be granted, but increasing power level of J will cause station F to be a collision station. A unidirectional link $\overrightarrow{FJ}$ is created.

2. Success on constructing link $\overline{FB}$: No primary and secondary collisions occur if a link is constructed between nodes F and B.

3. Success on constructing link $\overline{BD}$: No primary and secondary collisions occur when constructing a link between nodes D and B.

4. Failure on constructing link $\overline{DE}$: The increase of node E's power level can be granted, but increasing power level of node D will cause a secondary collision at node H. Thus a unidirectional link $\overrightarrow{ED}$ is created.

5. Failure on constructing link $\overline{DJ}$: In this example, the distance of nodes D and J is bigger than the one of nodes D and E. Since link $\overline{DE}$ is not allowed to be constructed, link $\overline{DJ}$ cannot be granted. No unidirectional link can be constructed between nodes D and J.

6. Failure on constructing link $\overline{DK}$: Since distance of nodes D and K is bigger than distance of nodes D and E and link $\overline{DE}$ is not allowed to be added, link $\overline{DK}$ can not be granted. No unidirectional link can be constructed between nodes D and K.

Figure 1(b) shows the resultant PRN after applying the distance-based scheme on a given PRN as shown in Fig. 1(a). Two bi-directional links and two unidirectional links are additional constructed on original PRN.

The major reason that a link cannot be created is the constraints of primary or secondary collisions. Link $\overline{FJ}$ is unable to be constructed because that nodes J and G use the same code and the construction of link between nodes J and F will raise the secondary collision problem. However, in this case, if nodes J or G can exchange their codes, the secondary collision problem can be avoided and an extra bi-directional link can be constructed, increasing the network connectivity. Therefore, the network connectivity can get benefit from adopting the code switching scheme to resolve the primary or secondary collision problems. Consider Fig. 1(b). Node J can not enlarge its power level to construct a link to F due to the same code has been allocated to nodes J and G, causing secondary collision occurred at node F. However, the code switching of nodes G and K makes nodes J and G have different codes, resulting additional unidirectional link constructing from J to F could be granted without secondary collision. In addition, the code switching operation also could be applied for stations H and I. This exchange also assigns different code on stations D and H, thus preventing station E from secondary collision. Figure 1(c) is the topology after applying the code switching scheme on PRN shown in Figure 1(b). Since the distance of pair (D, E) is larger than one of pairs (D, K) and (D, J), two unidirectional links between pairs (D, K) and (K, J) are automatically created owing to wireless nature. Comparing Fig. 1(c) with Fig 1(b), there are four unidirectional links have been additionally constructed.

The code switching scheme considers all the possible opportunities for code switching between any two stations in the PRN, trying to resolve the collision problem and enhance the network connectivity as possible. Given any primary or secondary collision, the code switching scheme tries to eliminate the collisions by exchange codes without increasing the size of code set. In the next section, a matrix-based model is proposed to generally represent the relations among code assignment, link creation, and network topology. A matrix-based computation scheme is then accordingly proposed to implement the power control and code switching mechanisms. Applying the proposed mechanism, an efficient topology of PRN with stronger connectivity can be constructed in a simple way.

III. Matrix-Based Code Switching and Power Adjustment

This section proposes power control and code switching mechanism for a given PRN to enhance the network connectivity, improving the network throughput and transmission delay. A matrix based model is proposed to generalize the representation of important characteristics of PRN including directional network topology, code assignment relation and transmission collisions. Through basic matrix operations on the defined matrices, the power control and code switching mechanism can be implemented and utilized for improving the network connectivity.

<u>Definition:</u> ***Topology Matrix (M_t)***

Given a PRN, a *Topology Matrix* M_t specifies the connections relation between stations. The value of a matrix entry $M_t(i, j)$ would be either 0 or 1, respectively represent whether or not station i connects to station j. That is,

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

The topology matrix of Fig.1 (a) can be represented as shown in Fig.2.

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

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

<u>Definition:</u> ***Code Matrix (M_c)***

Given a PRN with code assignment, a *Code Matrix* M_c specifies the relation between stations and their code assignment. The value of a matrix entry $M_c(i, j)$ would be either 0 or 1, denoting whether or not station i is assigned with code j, respectively. That is,

$$M_c(i,j)=\begin{cases}0 & ,\text{if station } i \text{ does not use code } j\\ 1 & ,\text{if station } i \text{ uses code } j\end{cases}.$$

As an example, Fig. 3 depicts the Code Matrix of PRN shown in Fig. 1(a).

<u>Definition:</u> ***Collision Matrix (M^k_{col})***

The Collision Matrix M^k_{col} specifies the collision relation of code assignment and stations in considering k-hop neighboring nodes of a given PRN. The value of entry $M^k_{col}(i, j)$ would be either 0 or 1, respectively denoting whether or not any node, say x, uses code j will result in collisions at station i, where distance of nodes x and i is smaller than k hops. That is,

$$M_{col}^{k}(i,j)=\begin{cases}0 & ,otherwise\\ 1 & ,if\ code\ j\ results\ in\ collisions\ at\ station\ i\end{cases}$$

Consider the PRN shown in Fig. 1(a). As show in Fig. 4, the collision matrix M_{col} with $k=1$ presents the single hop collision information for each station. For instance, the collision code set of single hop collision of station B is {1, 4, 5} since entries (B, 1), (B, 4), and (B, 5) have value 1 in matrix M_{col}^{1}. This information indicates that any station assigned with code in set {1, 4, 5} but intending to establish a connection to station B will cause collisions.

$$Mc = \begin{array}{c} \\ A\\ B\\ C\\ D\\ E\\ F\\ G\\ H\\ I\\ J\\ K \end{array} \begin{array}{c} \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \\ \left[\begin{array}{ccccc} 1 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 1\\ 0 & 1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1 & 0\\ 0 & 1 & 0 & 0 & 0\\ 0 & 0 & 0 & 1 & 0\\ 0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 0 & 1\\ 0 & 0 & 0 & 1 & 0\\ 1 & 0 & 0 & 0 & 0 \end{array}\right] \end{array}$$

Figure 3. Code matrix of Fig. 1(a).

$$M_{col}^{1} = \begin{array}{c} \\ A\\ B\\ C\\ D\\ E\\ F\\ G\\ H\\ I\\ J\\ K \end{array} \begin{array}{c} \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \\ \left[\begin{array}{ccccc} 1 & 1 & 1 & 1 & 1\\ 1 & 0 & 0 & 1 & 1\\ 1 & 1 & 0 & 1 & 1\\ 1 & 1 & 1 & 0 & 0\\ 1 & 1 & 0 & 1 & 1\\ 0 & 1 & 1 & 1 & 0\\ 1 & 1 & 0 & 1 & 0\\ 0 & 1 & 1 & 1 & 1\\ 0 & 0 & 1 & 0 & 1\\ 1 & 0 & 0 & 1 & 0\\ 1 & 0 & 0 & 0 & 0 \end{array}\right] \end{array}$$

Figure 4. 1-hop collision matrix of PRN shown in Fig. 1.

Definition: **Code Switch Matrix (M_{switch})**

Given a PRN, a *Code Switch Matrix* M_{switch} specifies the code exchange relation between stations. The value of a matrix entry $M_{switch}(i, j)$ would be either 1 or 0, respectively representing whether or not station i is able to exchange code with station j. That is,

$$M_{switch}(i,j)=\begin{cases}0 & ,if\ station\ i,j\ can\ not\ exchange\ code\\ 1 & ,if\ station\ i,j\ can\ exchange\ code\end{cases}$$

The code switch matrix of Fig.1 (a) can be represented as shown in Fig. 5. For instance, station E can exchange code with stations C, G, J since entries (E, 3), (E, 7), and (E, 10) have value 1 in matrix M_{switch}.

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

Figure 5. Code switch matrix of PRN shown in Fig. 1.

- ***Matrix-based computation scheme***

The matrix based computation scheme proposed in this paper comprises two phases, namely *link search phase* and *code switching phase*. In the link search phase, any possible additional links that can be constructed in a given PRN without code change are generated by assigning stations with a appreciate power level. In the code switching phase, the adaptive code switching scheme is applied to resolve the primary or secondary collisions, intending to establish more links to improve the network connectivity of the PRN. Details about the two phases are described in below.

- *Phase1: Link Search Phase*

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

In order to check the existence of primary and secondary collision, a centralized algorithm is required for maintaining codes assigned to all one-hop neighbors of each node. To make ease the matrix computation, another notation, $M_{c'}$, is introduced to denote another representation form of M_c. The difference between $M_{c'}$ and M_c is that we put station ID in entry $M_{c'}(i, j)$, representing the ID of victim station when station i increases its power level to reach station j so that a unidirectional link from i to j is constructed. Matrix $M_{c'}$ provides useful information for exploring the victim stations. The code switching scheme thus can be applied to remove the code collision. Figure 6 depicts the $M_{c'}$ of M_c as shown in Fig. 3.

Equation (1) is used to obtain the link collision matrix $M_{link\text{-}c}$. Computation of $M_t \bullet M_{c'}$ obtains the codes assigned to neighboring nodes of each station.

$$M_{link-c}(i,j) = M_t \bullet M_{c'} \bullet (M_c)^T \tag{1}$$

Having obtained the codes assigned to neighbors for each station, the next is using this information to check the existence of collisions. The link between x and y is collision free if the code of x is different from the codes of y's one-hop neighbors. As show in equation (1), the Link Collision Matrix $M_{link\text{-}c}$ can be obtained by the product of M_t, $M_{c\text{-}1}$ and $(M_c)^T$ where $(M_c)^T$ is the transpose of M_c. An example of link collision matrix is shown in Fig. 7, which exhibits the link collision information for all pairs in the network. For instance, the value of matrix entry $M_{link\text{-}c}(6, 10)$ is 7, representing that if station J establishing a unidirectional link to F will result in collision because stations G and J use the some code.

By applying matrix operations on link collision matrix, as show in equations (2) and (3), two matrices, namely Bi-directional Grant Matrix $M_{grant\text{-}bi}$ and Unidirectional Grant Matrix $M_{grant\text{-}uni}$, can be derived. The Bi-directional Grant Matrix exhibits those pairs that are able to construct additional links without any collisions. $M_{grant\text{-}bi}$ can be obtained by executing the AND operation on inverse $M_{link\text{-}c}$ and the transpose of inverse $M_{link\text{-}c}$ as show in equation (2). Form equation (2), Bi-directional Grant Matrix can be obtained from matrix operations on link collision matrix $M_{link\text{-}c}$ shown in Fig. 7. The Uni-directional Grant Matrix depicts those pairs that constructing a link between the pair will result code collision at one neighbor. The uni-directional grant matrix can be obtained by executing the XOR operation on link collision matrix $M_{link\text{-}c}$ and the transpose of $M_{link\text{-}c}$ as shown in equation (3). The uni-directional grant matrix can be obtained by applying equation (3) on link collision matrix shown in Fig. 7.

$$M_{grant-bi}(i,j) = \overline{M_{link-c}}\ AND\ (\overline{M_{link-c}})^T \quad (2)$$

$$M_{grant-uni}(i,j) = M_{link-c}\ XOR\ (\overline{M_{link-c}})^T \quad (3)$$

Another essential condition for constructing a link between two stations is that the physical distance between them must smaller than the maximal transmission range. That is, $d(x, y) \leq$ *maximum power transmission range*. The physical distance between stations can be evaluated form the location information. Therefore, *Bi-directional Grant Matrix* and *Uni-directional Grant Matrix* can be refined by applying the distance condition to remove those pairs whose distance is larger than the maximal transmission range.

In the next phase, an adaptive code switching scheme is proposed to eliminate the victim stations that are indicated in *Uni-directional Grant Matrix*.

$$Mc' = \begin{array}{c} \\ A \\ B \\ C \\ D \\ E \\ F \\ G \\ H \\ I \\ J \\ K \end{array} \begin{array}{c} \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \\ \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 \\ 0 & 3 & 0 & 0 & 0 \\ 0 & 0 & 4 & 0 & 0 \\ 0 & 0 & 0 & 5 & 0 \\ 0 & 6 & 0 & 0 & 0 \\ 0 & 0 & 0 & 7 & 0 \\ 0 & 0 & 8 & 0 & 0 \\ 0 & 0 & 0 & 0 & 9 \\ 0 & 0 & 0 & 10 & 0 \\ 11 & 0 & 0 & 0 & 0 \end{bmatrix} \end{array}$$

Fig.6. The *Mc'* matrix.

$$M_{link-c}(i,j) = M_t^1 \bullet M_{c'} \bullet (M_c)^T$$

$$= \begin{array}{c} \\ A \\ B \\ C \\ D \\ E \\ F \\ G \\ H \\ I \\ J \\ K \end{array} \begin{array}{c} \begin{array}{ccccccccccc} A & B & C & D & E & F & G & H & I & J & K \end{array} \\ \begin{bmatrix} 1 & 2 & 3 & 4 & 3 & 5 & 5 & 4 & 2 & 5 & 1 \\ 1 & 2 & 0 & 0 & 0 & 10 & 10 & 0 & 2 & 10 & 1 \\ 1 & 0 & 3 & 8 & 3 & 5 & 5 & 8 & 0 & 5 & 1 \\ 1 & 0 & 6 & 4 & 6 & 0 & 0 & 4 & 0 & 0 & 1 \\ 1 & 0 & 3 & 8 & 3 & 5 & 5 & 8 & 0 & 5 & 1 \\ 0 & 0 & 6 & 4 & 6 & 7 & 7 & 4 & 0 & 7 & 0 \\ 11 & 0 & 6 & 0 & 6 & 7 & 7 & 0 & 0 & 7 & 11 \\ 0 & 9 & 3 & 8 & 3 & 5 & 5 & 8 & 9 & 5 & 0 \\ 0 & 9 & 8 & 0 & 8 & 0 & 0 & 0 & 9 & 0 & 0 \\ 0 & 2 & 0 & 0 & 0 & 10 & 10 & 0 & 2 & 10 & 0 \\ 11 & 0 & 0 & 0 & 0 & 7 & 7 & 0 & 0 & 0 & 11 \end{bmatrix} \end{array}$$

Figure 7. Link collision matrix of Fig. 1(a).

- *Phase2: Code Switching Phase*

In the previous phase, the obtained *Uni-directional Grant Matrix* depicts the existing collisions associated with some link constructions. In the code switching phase, a Code Switch Matrix will be utilized to remove code collisions. A *Code Switch Matrix* specifies the code exchange relation between stations. Code exchange could remove the code collisions but may introduce another code collision. The code exchange of two stations should guarantee that no primary and secondary collision is arisen. Equation (4) presents that the two-hop collision matrix can be obtained by the multiplication of two matrices, the square of M_t and M_c. This result will be used for advanced matrix operations as defined in Equation (5). In the equation (5), the $M_{no\text{-}switch}$ (i, j) represents the relation of any two stations i and j that i can not use the code assigned to j owing to the primary or secondary collisions and the value can be obtained by $M_c \bullet (M^2_{col} - M_c) - (M_t)^2$. The term $M_c \bullet (M^2_{col} - M_c)$ represents whether or not station i uses the code assigned to j will collide with any two-hop neighbor of i. And the subtract $(M_t)^2$ from $M_c \bullet (M^2_{col} - M_c)$ is to remove the redundant recording in $M_{no\text{-}switch}$ like the situation that i uses the code assigned to j and collides at j. Finally, the code switch matrix can be obtained by the product of inverse $M_{no\text{-}switch}$ AND transform of inverse $M_{no\text{-}switch}$. Figure 5 demonstrates the code switch matrix of PRN shown in Fig. 1(a).

$$M^2_{col}(i,j) = (M_t)^2 \bullet \ M_c \quad (4)$$

$$M_{no-switch}(i,j) = (M_c \bullet (M^2_{col} - M_c)^T) - (M_t)^2 \quad (5)$$

$$M_{switch}(i,j) = \overline{M_{no-switch}}\ AND\ (\overline{M_{no-switch}})^T \quad (6)$$

Having obtained the code switch matrix, the next step is to utilize the code switch matrix to eliminate victim nodes in the *Uni-directional Grant Matrix*. For instance, the value of matrix entry $M_{grant\text{-}uni}$ (J,F) is station ID 7 (denoting station G), indicating that station J connects to station F will cause station G to be a victim. Therefore, the value of matrix entry M_{switch} (G,K) being 1 denotes station G can exchange code with K to eliminate the collision of $M_{grant\text{-}uni}$ (J,F) and thus an additional unidirectional link between station F and J could be created. Repeatedly construct a new link in the similar way, several additional links could be constructed. The proposed code switching mechanism thus resolves the code collision problem and adds links on the given PRN to enhance the network connectivity of topology obtained from the first phase.

The selection policy decides the order of link construction. Different selection policies result in different capacity of link construction and thus impact on throughputs of PRN. In [9], distance-based and degree-based schemes are proposed for selection policy. In addition to the two schemes proposed in [9], this paper proposes another selection scheme, namely hop-oriented policy. The hop-oriented policy considers that the distance and hop count are not identical and treats reduction in hop counts as the metric to determine the order of link construction. That is, new link that saves more hop counts will have a higher priority to be constructed earlier. Simulation result shows that the hop-oriented scheme has a better performance than distance-based scheme at the dense network environment.

IV. PERFORMANCE STUDY

This section proposes the performance investigation of the proposed scheme. The simulation environment is described as follows. The number of devices varies, from 50 to 200, and is randomly deployed in an area of 1000 units * 1000 units. The transmission range is tunable and varies from 10 units to 210 units. Packet arrival rate is 1/100 and packet size is controlled in 1000 bytes. The source and destination for each packet is randomly selected and the running time lasts 100s. The saturation-degree-code-assignment proposed in [10] is adopted as the code assignment algorithm. Throughputs of various PRNs are compared. The 'origin', 'distance-based', and 'degree-based' respectively denote the original given PRN and the PRNs obtained by applying distance-based and degree-based schemes proposed in [9].

The power control protocol proposed in this paper is implemented by different link selection policies, including distance-based, degree-based, and hop-based policies. The 'hop-oriented', 'distance with CS', 'degree with CS' and 'hop with CS' respectively denotes the throughput of PRNs obtained by applying our power control mechanism with different link selection policies, where 'CS' denote the proposed 'code switching' mechanism is involved.

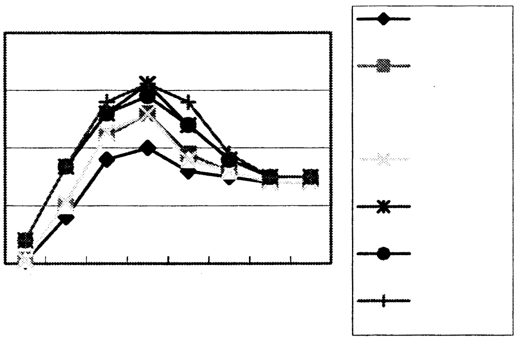


Fig.8. Effect of power adjustment and code switch at different initial power.

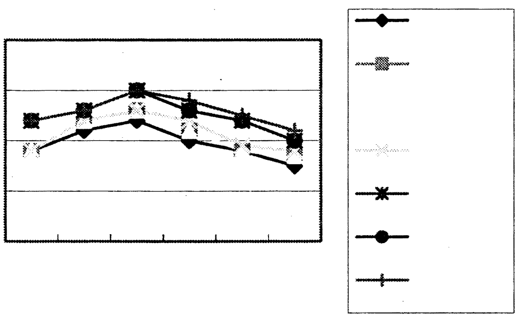


Fig.9. The throughput at different number of stations.

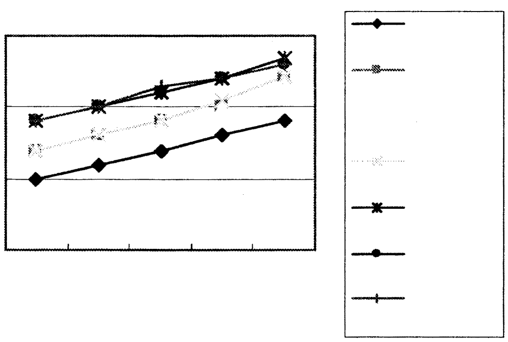


Fig.10. The throughput at different number of stations.

Fig. 8 compares the throughput of varies mechanisms. The number of stations is set by 50 and the initial transmission range varies from 10m to 210 m. In general, the throughput increases with the initial transmission range in case that the initial transmission range is smaller than 100 units,. The proposed power control mechanism incorporated with degree-based, distance-based and hop-oriented policies have higher throughputs than 'origin'. This is because that the proposed power control mechanism increases the number of links thus improves the network throughput. In addition, incorporating the proposed code switching mechanism with different policies additionally creates links and thus has a better throughput. The benefits of power control and code switch will decrease after the transmission range larger than 130 units. This is because of serious network congestion, resulting the benefit from additional links is small.

Figure 9 investigates the throughput at different number of stations. The number of stations varies from 50 to 300. The throughput increases with the number of stations when station number is smaller than 150. As depicted in Fig. 9, the power control and code switching scheme has a higher throughput than power control without incorporated with code switching scheme. The proposed mechanisms incorporated with different link selection policies also outperform the 'origin' protocol. Fig. 10 depicts the relation between throughput and data arrival rate. Higher data arrival rate introduces higher traffic load and thus increases the throughput. The proposed power control and code switching mechanism creates more links and provides a variety of route selections thus have a higher throughput than the compared scheme.

V. Conclusion

This paper proposed power control and code switching mechanisms to improve the network connectivity of multi-hop PRN. A two-phase matrix-based mechanism is presented to implement the power control and code switching schemes in considering metrics of network topology, code assignment, power control and code switching. In the link search phase, any possible link that does not raise collision problem will be constructed by assigning stations with an appreciate power level. In the code switching phase, the code switching scheme is applied to remove the primary or secondary collisions by code exchange of a pair of stations. Furthermore, a hop-oriented link selection scheme is proposed to arrange the order of link construction for the network. Simulation results reveal that the proposed power control and code switching mechanism works well in incorporated with various link selection policies. The proposed mechanisms increase the network connectivity and thus significantly improve the network throughput.

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