

# Power Fairness in A Scalable Ring-based Wireless Mesh Network

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**Abstract**—The wireless mesh network (WMN) is an essential low-power solution to support ubiquitous broadband services. However, mesh networks face the power unfairness and throughput bottleneck issues. Compared to the users far away from the gateway, the users near the gateway need to relay more traffic and consume more power. This paper proposes a scalable ring-based WMN that can ensure power fairness among users by adjusting the ring widths. On top of the ring-based WMN, frequency planning is suggested to overcome the throughput bottleneck issue for the inner-ring users near the gateway, thereby making the system more scalable to accommodate more users and facilitating coverage extension. We also investigate the overall tradeoffs of the ring-based WMN in terms of power fairness, capacity, and coverage. An analytical model is developed to evaluate the throughput and power consumption of the ring-based WMN using carrier sense multiple access (CSMA) MAC protocol in the unsaturated situation. Then, a mixed-integer nonlinear optimization problem aiming to maximize cell capacity and coverage subject to the constraint of power fairness is formulated. Applying this optimization approach, we obtain the optimal number of rings and the associated ring widths of the ring-based WMN.

**Index Terms**—Power fairness, capacity and coverage, wireless mesh network (WMN).

## I. INTRODUCTION

Thanks to the capabilities of enhancing coverage and capacity by low transmission power, the wireless mesh network (WMN) is an economical solution to support ubiquitous broadband access [1], [2]. Figure 1 shows a multi-hop WMN, where each user relays other users' traffic toward the central gateway and only the gateway directly connects to the Internet. WMN have many advantages over the infrastructure-based network, including low-power communication, rapid network deployment with less cabling engineering, and less cost.

However, due to multi-hop transmission, wireless mesh networks face the power unfairness problem. Specifically, the inner users near the gateway have to consume more power to relay more traffic for others, which induces the power unfairness problem for the inner users. When the users close to the gateway rapidly exhaust their battery energy, the whole mesh network will not function normally. As the number of users increases, the power unfairness problem becomes even more serious for the inner users. Therefore, while extending

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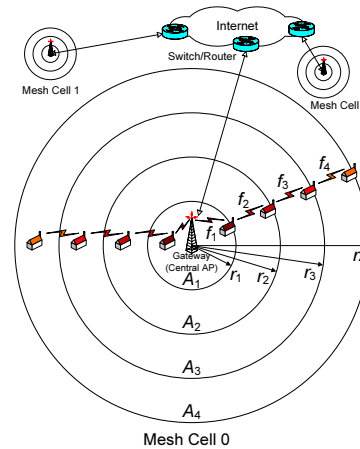


Fig. 1. Ring-based cell architecture for a scalable wireless mesh network, where each ring is allocated with different channel.

the coverage area to serve more users, maintaining power fairness among users is a key challenge for WMNs.

In the literature, the performances of WMNs have mainly been studied from two directions. On the one hand, authors in [3] demonstrated the advantage of a multihop WMN over a single-hop network in terms of coverage by simulations. On the other hand, the results in [2] showed that with  $k$  users in a WMN, the user's throughput decreases sharply as  $O(1/k)$  due to the throughput bottleneck at the gateway. [4] and [5] investigated the tradeoff between throughput and coverage in a scalable WMN. In addition, [6] focused on analyzing the power unfairness problem in the context of mesh sensor networks. [7] further suggested a specific approach to resolve the power unfair issue by reducing the hop distances of the nodes near the gateway (sink). These works considered the cases using the ideal medium access control (MAC) protocol without collisions and retransmissions, and assumed sufficient link throughput for each node. To our knowledge, fewer papers have studied the overall performances in terms of power fairness, coverage and throughput in the WMN.

To overcome the throughput bottleneck and power unfairness issues, we employ a scalable ring-based WMN where the rings in a cell are allocated with different channels as shown in Fig. 1 [5]. Under the ring-based cell structure, frequency planning can reduce the number of contending users, and thus make the system more scalable to accommodate more users and facilitate coverage extension. With the capability

of adjusting the ring width to control the hop distance and the data rate in the relay link between users, this ring-based cell structure also facilitates the management of coverage and throughput. In addition, by properly reducing the ring widths of inner rings, the users near the gateway can transmit at higher data rate due to shorter hop distance. Therefore, the power efficiency of WMN is improved and in turn the power unfairness issue can be resolved.

This paper also investigates the optimal tradeoff among throughput, coverage, and power fairness in the WMN. We develop an analytical model to evaluate the throughput and power consumption in the WMN considering the impacts of ring-based cell structure and frame contentions in the carrier sense multiple access (CSMA) MAC protocol. This model considers a general unsaturated case where the users are not always busy in sending traffic. Then, we formulate a mixed-integer nonlinear programming (MINLP) optimization problem aiming to improve the overall performance tradeoff among coverage, capacity, and power fairness. With this optimization technique, we find a systematic approach to determine the optimal number of rings and the associated ring widths in a mesh cell.

The rest of this paper is organized as follows. Sections II discusses the proposed WMN and the impact of ring structure on frame contentions. In Section III, we formulate an optimization problem to maximize cell capacity and coverage with the power fairness constraint. Section IV discusses the channel activity, and Section V elaborates the developed model for evaluating the throughput and power consumption in the considered WMN. Numerical examples are shown in Section VI. Concluding remarks are given in Section VII.

## II. SCALABLE RING-BASED WIRELESS MESH NETWORK

### A. Network Architecture

Figure 1 shows the ring-based WMN, where stationary mesh users with the relay capability form a multihop network to extend the cell coverage. In the figure, the mesh cell is divided into several rings  $A_i$ ,  $i = 1, 2, \dots, n$ , determined by  $n$  concentric circles centered at the gateway with radii  $r_1 < r_2 < \dots < r_n$ . The user in ring  $A_i$  connects to the gateway via an  $i$ -hop communication, and only the gateway connects to the Internet directly. Clearly, this WMN can be rapidly deployed in a large-scale area with less cabling engineering work.

The ring-based WMN operates in a multichannel with multi-interface fashion. Recall that there are multiple channels available in the wireless networks, e.g., twelve non-overlapping channels in the IEEE 802.11a WLANs. Thus we can allocate the rings in a cell with different channels to avoid co-channel interference and improve the throughput. This frequency planning is simple because it only needs to design each ring width to ensure a sufficient co-channel reuse distance without interference. Moreover, we assume that each node is equipped with two radio interfaces. Thus, the user in ring  $A_i$  can concurrently communicate with the users in rings  $A_{i-1}$  and  $A_{i+1}$  at different channels  $f_i$  and  $f_{i+1}$ ,

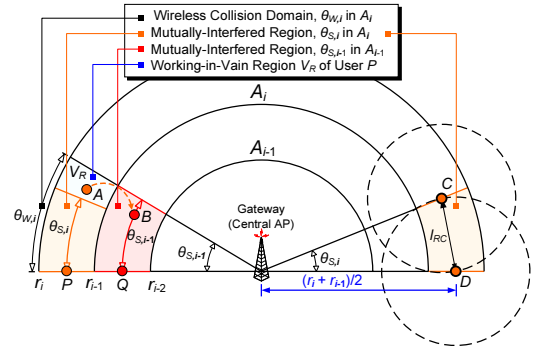


Fig. 2. Examples of wireless collision domain and mutually-interfered region.

respectively. By multichannel and multi-interface operations, the users can concurrently receive and deliver the relay traffic to improve throughput and delay. Besides, the system works well even employing the widely-used distributed CSMA/CA MAC protocol, thereby avoiding the compatibility issues.

Generally, spectrum and hardware costs are major concerns in the multichannel with multi-interface systems. However, there are multiple channels available in the wireless networks, e.g., twelve non-overlapping channels assigned for the IEEE 802.11a WLAN. The price of radio interface also goes down very rapidly, since the WLAN has become an off-the-shelf product.

### B. Frame Contention under Ring-based Cell Structure

To describe frame contention under the ring-based cell structure, we first define the *mutually-interfered region* as an area in which any two users can sense the activity of each other. In Fig. 2, the area including users C and D is an example of mutually-interfered region. For simplicity, we assume that the mutually-interfered region in ring  $A_i$  can be approximated as an annulus sector with a central angle of  $\theta_{S,i}$ . Let  $l_{RC}$  be the interference distance. Referring to Fig. 2, the central angle  $\theta_{S,i}$  of a mutually-interfered region in ring  $A_i$  is equal to

$$\theta_{S,i} = 2 \sin^{-1} \left( \frac{l_{RC}}{r_i + r_{i-1}} \right), \text{ for } l_{RC} < (r_i + r_{i-1}). \quad (1)$$

If  $l_{RC} \geq (r_i + r_{i-1})$ , we define  $\theta_{S,i} = 2\pi$  which means that the whole ring is in the same mutually-interfered region. Clearly, the area of a mutually-interfered region is  $A_{S,i} = (\theta_{S,i}/2\pi)a_i$  and  $a_i = \pi(r_i^2 - r_{i-1}^2)$  is the area of ring  $A_i$ .

Then, we define the *wireless collision domain* as the area in which at any instant at most one user can successfully transmit data traffic at a particular frequency. In Fig. 2, the wireless collision domain in ring  $A_i$  is also approximated as an annulus sector with a central angle of  $\theta_{W,i} = \theta_{S,i-1}$ , and its area is  $A_{W,i} = (\theta_{W,i}/2\pi)a_i$ . The phenomenon of  $\theta_{W,i} = \theta_{S,i-1}$  is due to the fact that the request-to-send/clear-to-send (RTS/CTS) mechanism is employed to avoid the hidden node problem. Referring to the example in Fig. 2, user A in ring  $A_i$  is sending data to user B in ring  $A_{i-1}$ . In the meantime, since users P and A are not in the same mutually-interfered region, user P in ring  $A_i$  can send an RTS request to users Q in ring  $A_{i-1}$ . However, user Q will not reply the CTS response to P,

because it has overheard the CTS of  $B$  and determined that the channel is busy. This example shows that nodes  $P$  and  $A$  are in the same wireless collision domain even though they are not in the same mutually-interfered region. Furthermore, the central angle  $\theta_{W,i}$  of wireless collision domain in ring  $A_i$  is determined by the angle  $\theta_{S,i-1}$  of mutually-interfered region in the inner ring  $A_{i-1}$ , that is,  $\theta_{W,i} = \theta_{S,i-1}$ .

The example in Fig. 2 also shows that the existence of transmitter in region  $V_R$  invalidates the RTS request of  $P$ . Hence, we define the region  $V_R$  with a central angle of  $(\theta_{W,i} - \theta_{S,i})$  as the *working-in-vain region* of  $P$ . Such an impact of the ring structure on frame contention will be incorporated into the analytical throughput model later.

### III. CAPACITY AND COVERAGE MAXIMIZATION

#### A. Problem Formulation

All the issues of throughput, coverage, and power fairness will impact the design of WMNs. From a deployment cost perspective, a larger cell coverage is better because of fewer gateways. From a throughput viewpoint, however, a smaller cell is preferred since fewer users contend for the same channel. This paper mainly focuses on the power fairness. To achieve the power fairness, a shorter hop distance is better, since it can improve the link capacity and power efficiency, especially for the heavy-loaded users in the inner rings. To find the optimal tradeoff among throughput, coverage, and power fairness, we formulate an optimization problem to determine the best number of rings and the optimal ring widths in a cell.

To begin with, we discuss the constraints in the considered optimization problem:

- To guarantee a minimum throughput for each user, the link capacity  $H_i(d)$  of a user in ring  $A_i$  should be greater than the carried traffic load  $R_i$ , i.e.,

$$H_i(d) \geq R_i. \quad (2)$$

The hop distances for the users in ring  $A_i$  may vary. For simplicity, we assume that the average hop distance is  $d = (r_i - r_{i-2})/2$ . In a real system, the next-hop node may be too far away from the current node. In this situation, it may need to deploy a pure relay station.

- To ensure the power fairness, it is required that

$$PFI \geq PF_{req}, \quad (3)$$

where  $PFI$  is the power fairness index defined in (19) and  $PF_{req}$  stands for the power fairness requirement.

- To ensure that the user at the boundary of ring can find a next-hop node in the inner ring to forward the traffic, the ring width  $(r_i - r_{i-1})$  should be less than the maximum reception range  $d_{max}$ . In this WMN, the channel allocated for the inner ring can be reused by the outer ring, if with a sufficient co-channel reuse distance. Hence, the ring width should be greater than a threshold  $d_{min}$  to ensure a sufficient co-channel reuse distance. Accordingly,

$$d_{min} \leq (r_i - r_{i-1}) \leq d_{max}. \quad (4)$$

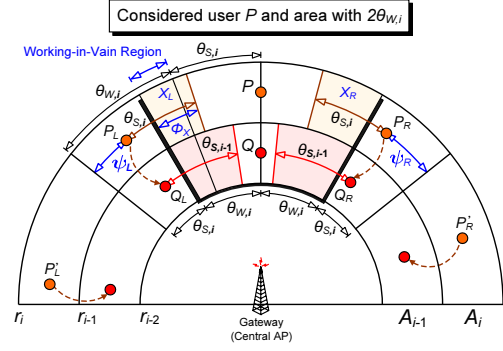


Fig. 3. The considered user  $P$  and two adjacent wireless collision domains, where user  $P$  is contending for the radio channel.

#### B. MINLP Optimization Approach

The optimal capacity and coverage issues in a WMN can be formulated as a mixed-integer nonlinear programming problem with the following decision variables:  $n$  (the number of rings in a mesh cell) and  $r_1, r_2, \dots, r_n$ . The objective is to maximize the cell capacity. In this ring-based WMN, optimal coverage and capacity can be achieved simultaneously since more users in a cell leads to higher cell capacity. Let the cell radius  $r_n$  be the cell coverage. Suppose that  $\rho$  is the user density and  $R_D$  is the traffic generated by each user. The cell capacity is defined as  $\rho\pi r_n^2 R_D$ . Then, the optimal ring widths can be determined by solving the following optimization problem.

$$\begin{aligned} \text{MAX}_{n, r_1, r_2, \dots, r_n} \quad & \rho\pi r_n^2 R_D \quad (\text{Overall throughput of a mesh cell}) \\ \text{subject to} \quad & \end{aligned}$$

$$H_i(d) \geq R_i \quad (5)$$

$$PFI \geq PF_{req} \quad (6)$$

$$d_{min} \leq (r_i - r_{i-1}) \leq d_{max}. \quad (7)$$

### IV. CHANNEL ACTIVITY IN THE RING-BASED WMN

From a user's viewpoint, there are five types of channel activities in a WMN: (1) successful frame transmission; (2) unsuccessful frame transmission; (3) empty slot, where all users are in backoff or idle; (4) successful frame transmission from other users; (5) unsuccessful frame transmission from other users. For clarity, the channel activity is described by a sequence of *activity time slots* [8], [9]. Subject to the backoff procedures, the duration  $T_j$  for channel activity type  $j$  is defined as  $T_1 = T_4 = T_S, T_2 = T_5 = T_C, T_3 = \sigma$ , where  $\sigma$  is the empty slot,  $T_S$  and  $T_C$  are the successful transmission time and collision duration, respectively. The average duration  $T_v$  of activity time slot is equal to

$$T_v = \sum_{j=1}^5 \nu_j T_j. \quad (8)$$

Here,  $\nu_j$  is the probability of channel activity type as calculated in the following, and  $\sum_{j=1}^5 \nu_j = 1$ .

At first, we derive the probabilities  $\nu_1$  and  $\nu_2$  of a user successfully/unsuccessfully sending a frame. In Fig.3, user  $P$  can successfully send data as long as no other user is transmitting

in the adjacent wireless collision domains of  $P$ . Consider user  $P$  and its two wireless collision domains influenced by two closest neighboring transmitters  $P_L$  and  $P_R$ , which are out of the mutually-interfered regions of  $P$  as shown in Fig. 3. Let  $\psi_L$  and  $\psi_R$  be the positions of  $P_L$  and  $P_R$ , respectively. If one of the transmitters  $P_L$  and  $P_R$  is within the working-in-vain regions of  $P$ , i.e.,  $\psi_L, \psi_R \in [\theta_{S,i}, \theta_{W,i}]$ , user  $P$  can still send the RTS request to user  $Q$ , but user  $Q$  cannot reply the CTS response, as discussed in Section II-B. Suppose that  $Z_{W,i}$  is the probability (average fraction of time) of a wireless collision domain in which a user is delivering data, as defined in (16). Clearly, the probability that there is a transmitter (like  $P_L$  or  $P_R$ ) affecting the considered area, and this transmitter is within the working-in-vain region of  $P$  is equal to  $Z_{W,i} \frac{\theta_{W,i} - \theta_{S,i}}{\theta_{W,i}}$ . Hence, the working-in-vain probability  $p_v$  of user  $P$  is

$$\begin{aligned} p_v &= 1 - \Pr\{\psi_L, \psi_R \notin [\theta_{S,i}, \theta_{W,i}]\} \\ &= 1 - \left[1 - Z_{W,i} \frac{\theta_{W,i} - \theta_{S,i}}{\theta_{W,i}}\right]^2. \end{aligned} \quad (9)$$

Now, we consider the case that both transmitters  $P_L$  and  $P_R$  are not in the working-in-vain regions of user  $P$ , i.e.,  $\psi_L, \psi_R \in [0, \theta_{S,i}]$ . In the considered area of angle  $2\theta_{W,i}$ , only the users in the area  $\{2A_{W,i} - (X_L + X_R)\}$  can send RTS frames as shown in Fig. 3. Those users in regions  $X_L$  and  $X_R$  will not send their requests since they can sense the transmissions of  $P_L$  and  $P_R$ . Let  $\bar{\phi}_X$  be the average central angle for region  $X_L$ , and  $A_{W,i}$  be the area of a wireless collision domain of user  $P$ . Therefore, the average number of contending users in the considered area of angle  $2\theta_{W,i}$  is equal to the average number of users in the area of  $\{2A_{W,i} - (X_L + X_R)\}$ , i.e.,

$$\begin{aligned} c_{1,i} &= \frac{\rho a_i}{2\pi} 2(\theta_{W,i} - Z_{W,i} \bar{\phi}_X) \\ &= \frac{\rho a_i}{\pi} (\theta_{W,i} - \frac{Z_{W,i}}{\theta_{W,i}} \int_0^{\theta_{S,i}} \psi_L d\psi_L) \\ &= \rho (r_i^2 - r_{i-1}^2) (\theta_{W,i} - \frac{Z_{W,i} \theta_{S,i}^2}{2\theta_{W,i}}) \end{aligned} \quad (10)$$

where  $\rho$  is the user density;  $a_i = \pi(r_i^2 - r_{i-1}^2)$  is the area of ring  $A_i$ ;  $\theta_{S,i}$  is the central angle of the mutually-interfered region as defined in (1);  $\phi_X = (\psi_L + \theta_{S,i}) - \theta_{S,i} = \psi_L$  is the central angle of region  $X_L$  and  $\psi_L$  is uniformly distributed in  $[0, \theta_{W,i}]$  as shown in Fig. 3. Subject to the RTS/CTS procedures, the frame collisions may only occur when the contending users concurrently deliver their RTS requests. Let  $\tau$  be the average probability of an active user sending the RTS request at the beginning of an activity slot. Suppose that  $R_i$  and  $H_i(d)$  are the carried traffic load and the link capacity of a node. Then,  $P_0 = 1 - R_i/H_i(d)$  is the average probability of a user being idle due to empty queue [10]. Under the impact of ring structure on frame contention, the unsuccessful transmission probability  $p_u$  is equal to

$$p_u = p_v + (1 - p_v)[1 - (1 - \tau(1 - P_0))^{C_{1,i-1}}], \quad (11)$$

where  $p_v$  is the probability that at least one transmitter is inside the working-in-vain regions of  $P$ , and user  $P$  will not receive

the CTS response. The second term represents the probability that the RTS request from  $P$  is collided with other RTS frames.

Thus, given that the considered user has a non-empty queue, the probability that this user successfully/unsuccessfully sends data frame in an activity slot can be expressed as

$$\nu_1 = \tau(1 - p_u) \quad \text{and} \quad \nu_2 = \tau p_u. \quad (12)$$

By the same reasoning, one can also calculate the probabilities  $\nu_j$ , for  $j = 3, 4, 5$ , as detailed in [5].

## V. THROUGHPUT AND POWER CONSUMPTION ANALYSIS

This section suggests an analytical method to evaluate the throughput and power consumption for the ring-based WMN, where the 802.11a WLAN is used as an example.

### A. Carried Traffic Load of a User Node

The traffic load of mesh node includes its own traffic and the forwarded traffic from other users. Assume that all the nodes in the inner ring  $A_i$  share the relayed traffic from the outer ring  $A_{i+1}$ . Let  $c_i = \rho\pi(r_i^2 - r_{i-1}^2)$  be the average number of nodes in ring  $A_i$  and  $\rho$  be the user density. Suppose that  $R_D$  and  $R_i$  represent the traffic load generated by each node and the total carried traffic load per node in ring  $A_i$ , respectively. For the outermost ring  $A_n$ ,  $R_n = R_D$ . Besides, we have that

$$R_i = \frac{c_{i+1}}{c_i} R_{i+1} + R_D = \left[ \frac{\sum_{j=i+1}^n c_j}{c_i} + 1 \right] R_D. \quad (13)$$

### B. MAC Throughput

To evaluate the MAC throughput in the ring-based wireless mesh network, we should consider the impacts of the physical layer ring structure on frame contention. Consider a binary exponential backoff procedure with the initial backoff window size of  $W$ . Let  $m_{bk}$  be the maximum backoff stage. The average backoff time can be calculated by [11]

$$\begin{aligned} \bar{B}_k &= (1 - p_u) \frac{W - 1}{2} + p_u (1 - p_u) \frac{2W - 1}{2} + \dots \\ &\quad + p_u^{m_{bk}} (1 - p_u) \frac{2^{m_{bk}} W - 1}{2} \\ &\quad + p_u^{(m_{bk}+1)} (1 - p_u) \frac{2^{m_{bk}} W - 1}{2} + \dots \\ &= \frac{[1 - p_u - p_u (2p_u)^{m_{bk}}] W - (1 - 2p_u)}{2(1 - 2p_u)}, \end{aligned} \quad (14)$$

where  $p_u$  is the unsuccessful transmission probability with considering the impacts of ring structure in the physical layer, as defined in (11). Since a user sends RTS requests every  $(\bar{B}_k + 1)$  slots on average [11], the transmission probability  $\tau$  for an active user can be written as

$$\tau = \frac{1}{\bar{B}_k + 1} = \frac{2}{1 + W + p_u W \sum_{i=0}^{m_{bk}-1} (2p_u)^i}. \quad (15)$$

From (11) and (15), we can obtain the solution of  $\tau$  and  $p_u$ .

Then we evaluate the MAC throughput of one user. With the activity slot concept, the average busy probability (average

fraction of time)  $Z_{O,i}$  of one user being sending data and the channel utilization  $Z_{W,i}$  of a wireless collision domain are

$$Z_{O,i} = \frac{\nu_1 T_1}{T_v} (1 - P_0) \text{ and } Z_{W,i} = \rho A_{W,i} Z_{O,i} \quad (16)$$

where  $\nu_1$  is the probability that one user successfully sends a frame in an activity slot,  $T_1 = T_S$  is the successful frame transmission time,  $T_v$  is the average duration of an activity slot, and  $\rho A_{W,i}$  is the number of users in a wireless collision domain. According to the IEEE 802.11a standard, the successful transmission time  $T_S$  and collision duration  $T_C$  can be calculated as in [5]. Then, the link capacity  $H_i(d)$  between two nodes at separation distance  $d$  can be expressed as

$$H_i(d) = \frac{\nu_1 T_1}{T_v} \cdot \frac{l}{T_S} = \frac{\nu_1 l}{T_v} \quad (17)$$

where  $l$  is the payload size of data frame. From (8)-(17), we can numerically obtain  $\nu_1$ ,  $T_v$ ,  $P_0$ , and  $H_i(d)$ .

The hop distance also impacts the throughput in WMNs. Assume that the average reception ranges for eight PHY modes are  $d_j$ ,  $j = 1, 2, \dots, 8$ , and  $d_1 > d_2 > \dots > d_8$ . In principle, two users with a shorter separation distance can transmit at a higher data rate. Therefore, the transmission PHY mode  $m_a$  is determined according to the separation distance  $d$  between two users, i.e.,  $m_a = j$ , if  $d_{j+1} < d \leq d_j$ . To achieve fairness from resource allocation perspective and avoid throughput degradation due to low-rate transmissions [12] and [13], we also suggest that all data frames have the same transmission time  $T_{DATA}(l, m_a)$ . Thus, the data payload  $l$  will be determined by the adopted PHY mode  $m_a$ .

### C. Power Consumption

Now we evaluate the average power consumption in the considered WMN. Generally, there are three power consumption modes for a mesh user, including the transmitting, receiving, and idle modes [14]. Suppose that all the users transmit at a fixed higher power to extend the cell coverage. Let  $p_{tx}$  and  $p_{rx}$  be the average consumed power in the transmitting and receiving modes;  $p_{idle}$  be the power consumption when the user is idle due to empty queue. With the activity slot concept, the average power consumption  $p_{avg,i}$  for a user in ring  $A_i$  can be expressed as

$$\begin{aligned} p_{avg,i} &= \frac{\left[ \sum_j \epsilon_j \nu_j T_j \right]}{\left[ \sum_j \nu_j T_j \right]} (1 - P_0) + p_{idle} P_0 \quad (18) \\ &= \frac{\sum_{j=1}^2 p_{tx} \nu_j T_j + \sum_{j=3}^5 p_{rx} \nu_j T_j}{T_v} (1 - P_0) + p_{idle} P_0 \end{aligned}$$

where the first term represents the average power consumption for an active user.  $\epsilon_j$  means the average consumed power for channel activity type  $j$ . Specifically,  $\epsilon_1 = \epsilon_2 = p_{tx}$ , and  $\epsilon_3 = \epsilon_4 = \epsilon_5 = p_{rx}$ .

Referring to [15], we define the power fairness index  $PFI$  for the ring-based WMN as

$$PFI = \frac{\left( \sum_{i=1}^n p_{avg,i} \right)^2}{n \left( \sum_{j=1}^n p_{avg,i}^2 \right)}, \quad (19)$$

TABLE I  
SYSTEM PARAMETERS FOR NUMERICAL EXAMPLES.

Symbol	Item	Nominal value
$\rho$	User node density	$10^{-4}$ users/m <sup>2</sup>
$R_D$	Demanded traffic of each user	0.4 Mbps
$d_{min}$	Min. of ring width	100 (m)
$d_{max}$	Max. reception range	300 (m)
$l_{RC}$	Interference distance ( $\gamma_I d_{max}$ )	400 (m)
$p_{tx}, p_{rx}$	Consumed power for Tx/Rx modes	1, 0.5 (power unit)
$p_{idle}$	Power consumption for IDLE mode	0.2 (power unit)

where  $n$  is the number of rings in a cell. By (19),  $PFI = 1$  means the perfect fairness, i.e., all the user have the same power consumption. In addition,  $PFI = 1/n$  stands for the absolute unfairness.

## VI. NUMERICAL RESULTS

This section investigates the interactions among power fairness, capacity and coverage in a ring-based WMN. We consider a simple case where all the ring widths in a cell are the same. The system parameters are summarized in Table I. The chosen frame payload sizes for eight PHY modes are {425, 653, 881, 1337, 1793, 2705, 3617, 4067} bytes [13]. Suppose that all the users transmitted at the same power. For this fixed transmission power system, referring to the measured results [16], the corresponding reception ranges are  $d_j = \{300, 263, 224, 183, 146, 107, 68, 30\}$  meters. In addition, the power consumption for transmitting/receiving/idle modes are assumed to be  $(p_{tx}, p_{rx}, p_{idle}) = (1, 0.5, 0.2)$  (power unit), which are normalized to  $p_{tx}$ . These reception ranges and power consumption may vary for different environments, hardware, and power-saving methods. However, the proposed optimization approach is general enough for different WMNs with various reception ranges and power consumption.

Figure 4 shows the cell coverage and capacity against the number of rings ( $n$ ) in a cell under different power fairness requirements. In the figure, the optimal cell coverage and capacity for the case without power fairness requirement are 444 (m) and 24.8 (Mbps) at  $n = 4$ . To meet the power fairness requirement  $PFI = 0.9$ , the optimal coverage and capacity diminish to 410 (m) and 21 (Mbps), respectively. In this figure, one can observe that the more the rings in a mesh cell, the better the coverage and capacity. However, the optimal solution is determined by the constrains of the power fairness requirement, mesh link throughput, and the hop distance.

Figure 4 also shows that the number of rings  $n$  in a cell has a maximum value. For handling the increasing relay traffic as  $n$  increases, the ring width will be reduced to shorten the hop distance and then improve the link capacity. However, since the ring width should be larger than  $d_{min}$  as discussed in Section III-A, there will exist a maximum value of  $n$ . In this example, the maximum allowable number of rings is  $n = 4$  for both cases.

In Fig. 5, the achieved power fairness against the number of rings is shown. If without any power fairness requirement, the achieved power fairness degrades as  $n$  increases. This phenomenon is due to the fact that the users in the inner rings get more and more busy in forwarding the increasing relay traffic as  $n$  increases. However, shrinking the ring

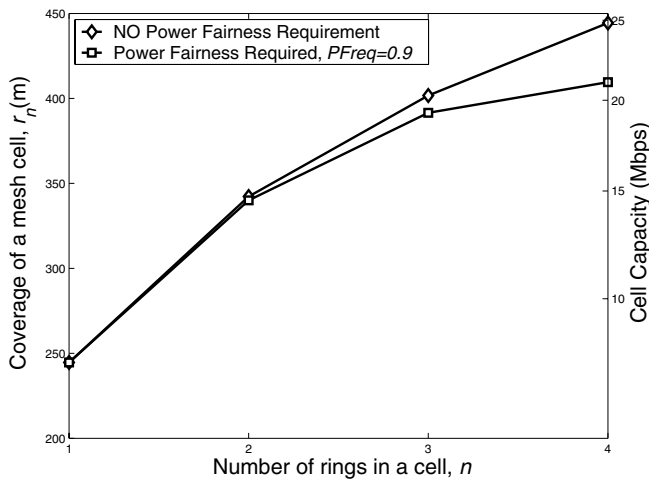


Fig. 4. Cell coverage and capacity (aggregated throughput) versus the number of rings  $n$  in a cell under different power fairness requirements.

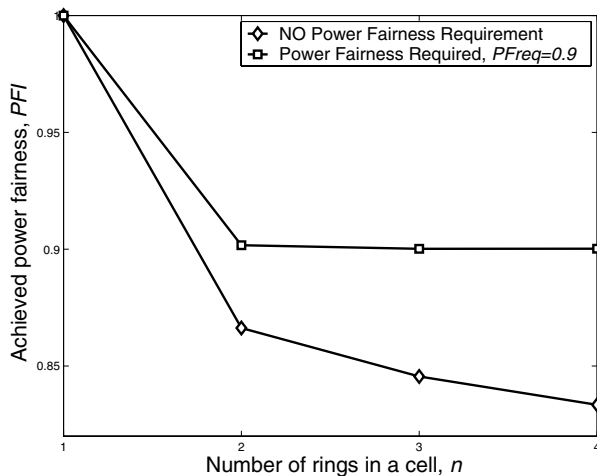


Fig. 5. Achieved power fairness  $PFI$  versus the number of rings in a cell.

width can improve the power fairness, since a shorter hop distance can raise the link capacity and power efficiency, especially for the heavy-loaded users near the gateway. From Fig. 5, it is observed that with the optimization approach to design the optimal ring width, the power fairness requirement  $P_{Freq} = 0.9$  can be fulfilled at the cost of cell coverage as shown in Fig. 4. For example, if the cell coverage is 444 (m) at  $n = 4$ , the average power consumption for the user in ring  $A_i$  is  $p_{avg,i} = (0.62, 0.38, 0.24, 0.21)$  (power unit). If the cell coverage diminishes to 410 (m), the hop distance decreases with a higher power efficiency. Then, the average power consumption can decrease to  $p_{avg,i} = (0.47, 0.29, 0.23, 0.21)$ , and thus the power fairness increases from 0.83 to 0.9. Clearly, since the power consumption is reduced, the network lifetime can be prolonged.

In these figures, we investigate the interactions among the power fairness, capacity, and coverage in a WMN. It is shown that the capacity and coverage can be enhanced simultaneously. Besides, with properly designing the deployment parameters, the power fairness can be ensured at the expense of lower coverage and capacity.

## VII. CONCLUSIONS

This paper has investigated a scalable ring-based WMN with power fairness guarantee. Subject to power fairness requirement, a mixed-integer nonlinear programming optimization problem has been formulated, aiming at maximizing the cell capacity and coverage. We have suggests frequency planning to improve the throughput, and to make the system more scalable to coverage. With properly adjusting the ring widths, power fairness among users can be also ensured. An analytical model has been developed to evaluate the throughput and power consumption. On top of the developed analytical model, the optimization approach has been applied to determine the optimal number of rings and the associated ring widths. Numerical results have shown that the goal of capacity enhancement with power fairness guarantee can be fulfilled at a cost of coverage performance.

Many interesting issues are worthwhile for future investigation form this work. These topics includes investigating the case with variable ring widths in a cell, the impacts of power control, and the power efficiency issues.

## REFERENCES

- [1] R. Pabst *et al.*, "Relay-based deployment concepts for wireless and mobile broadband radio," *IEEE Commun. Mag.*, vol. 42, no. 9, pp. 80–89, Sept. 2004.
- [2] J. Jun and M. Sichitiu, "The nominal capacity of wireless mesh networks," *IEEE Wireless Commun. Mag.*, vol. 10, no. 5, pp. 8–14, Oct. 2003.
- [3] S. Naghian and J. Tervonen, "Semi-structured mobile ad-hoc mesh networking," in *Proc. IEEE PIMRC*, Sept. 2003, pp. 1069–1073.
- [4] J.-H. Huang, L.-C. Wang, and C.-J. Chang, "Coverage and capacity of a wireless mesh network," in *Proc. IEEE WirelessCom*, June 2005, pp. 458–463.
- [5] —, "Capacity and QoS for a scalable ring-based wireless mesh network," *IEEE J. Select. Areas Commun.*, vol. 24, no. 11, Nov. 2006.
- [6] J. Li and P. Mohapatra, "An analytical model for the energy hole problem in many-to-one sensor networks," in *Proc. IEEE VTC*, Sept. 2005.
- [7] S. Olariu and I. Stojmenovic, "Design guidelines for maximizing lifetime and avoiding energy holes in sensor networks with uniform distribution and uniform reporting," in *Proc. IEEE INFOCOM*, Apr. 2006.
- [8] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Select. Areas Commun.*, vol. 18, no. 3, pp. 535–547, Mar. 2000.
- [9] X. J. Dong and P. Variya, "Saturation throughput analysis of IEEE 802.11 wireless LANs for a lossy channel," *IEEE Commun. Lett.*, vol. 9, no. 2, pp. 100–102, Feb. 2005.
- [10] D. Gross and C. M. Harris, *Fundamentals of Queueing Theory*, 3rd ed. New York: John Wiley & Sons, Inc, 1998.
- [11] Y. C. Yang and K. C. Chua, "A capacity analysis for the IEEE 802.11 MAC protocol," *Wireless Network*, pp. 159–171, Jul. 2001.
- [12] M. Heusse *et al.*, "Performance anomaly of 802.11b," in *Proc. IEEE INFOCOM*, Mar. 2003, pp. 836–843.
- [13] L. J. Cimini JR. *et al.*, *Packet Shaping for Mixed Rate 802.11 Wireless Networks*, United States Patent Application Number: US 20030133427, July 2003.
- [14] L. M. Feeney and M. Nilsson, "Investigating the energy consumption of a wireless network interface in an ad hoc networking environment," in *Proc. IEEE INFOCOM*, Apr. 2001, pp. 1548–1557.
- [15] R. Jain, D. Chiu, and W. Hawe, "A quantitative measure of fairness and discrimination for resource allocation in shared computer systems," *Technical Report DEC-TR-301*, Digital Equipment Corporation, Sept. 1984.
- [16] CISCO, *Cisco Aironet 1200 Series access point*. [Online]. Available: <http://www.cisco.com/en/US/products/hw/wireless/ps430/index.html>