Power Fairness in A Scalable Ring-based Wireless Mesh Network with Variable Ring-width Design

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***Abstract*—The wireless mesh network (WMN) is a promising solution to support wireless broadband applications. However, mesh networks face the power unfairness issue. Compared to the users far away from the gateway, the users near the gateway have 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 its ring widths. On top of the ring-based cell structure, frequency planning is suggested to reduce the contending users, thereby making the system more scalable to accommodate more users. To investigate the overall tradeoffs among power fairness, capacity, and coverage, we develop an analytical model to evaluate the throughput and power consumption of the ring-based WMN using carrier sense multiple access (CSMA) medium access control (MAC) protocol in the unsaturated situation. Then, the optimization approach is applied to determine the best number of rings and the optimal ring widths, aiming to maximize cell capacity and coverage subject to the requirement of power fairness. Numerical results show that compared to the uniform ring-width strategy, the variable ring-width design criterion can improve cell capacity and coverage.**

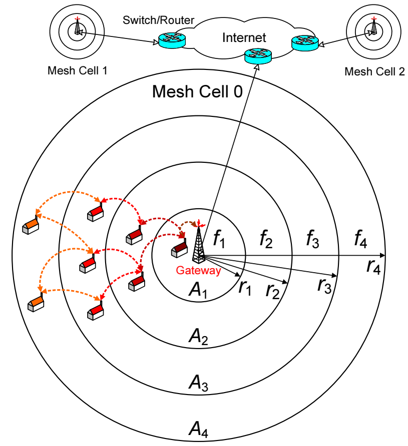

Fig. 1. Ring-based cell architecture for a scalable wireless mesh network, where each ring is allocated with different channel. (This is an example for the uniform ring-width strategy.)

I. Introduction

With the advantage of enhancing coverage 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. Clearly, WMNs have many advantages, including low-power communication, rapid network deployment with less cabling engineering, and lower infrastructure cost.

However, WMNs 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 work normally. As the number of users increases, the power unfairness problem becomes even more serious for the inner users. Therefore, while the coverage area is extended to serve more users, maintaining power fairness among users is a key challenge in 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] investigated the tradeoff between user throughput and coverage in a scalable WMN. In [5], the authors further investigated the interactions among capacity, coverage, and delay performances of a WMN. The power unfairness problem in the multihop networks is discussed in [6], [7]. In [6], the authors quantitatively analyzed the power unfairness problem in the multihop sensor networks. [7] 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 context of WMN. In [8], the authors investigated the tradeoffs among power fairness, coverage and throughput in a scalable WMN. However, the work in [8] considered a simple case where all the rings in a cell have the same width.

To overcome throughput bottleneck and power unfairness issues in WMNs, this paper employs a scalable ring-based WMN where the rings in a cell are allocated with different channels as shown in Fig. 1 [5]. The ring-based WMN has three advantages. First, ring-based frequency planning can reduce the number of contending users and collisions, thereby

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making the system more scalable to accommodate more users. Second, 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 facilitates the management of coverage, throughput, and power consumption. Three, by properly reducing the ring width of inner ring, the users near the gateway can transmit at higher data rate due to shorter hop distance. Therefore, the power efficiency of inner users is improved and in turn the power unfairness issue can be resolved.

This paper also investigates the optimal tradeoffs 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 apply an optimization approach to determine the optimal number of rings and the associated ring widths in a mesh cell, aiming to improve the overall performance tradeoff among coverage, capacity, and power fairness. To provide a guideline for network planning, we compare the uniform ring-width and variable ring-width strategies. In the uniform ring-width strategy (in Fig. 1), all the rings have the same width. In the variable ring-width strategy (see Fig. 2), the ring widths can vary for different rings. Clearly, by the variable ring-width strategy, we can reduce the ring width of inner ring to reduce the contending user and improve link capacity of inner users, while increase the ring width of outer ring to extend cell coverage. Therefore, as shown in numerical results, the variable ring-width strategy can achieve better cell coverage and capacity.

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. The mesh cell is divided into several rings A_i, i = 1, 2, $\cdots$, n, determined by n concentric circles centered at the gateway with radii $r_1 < r_2 < \cdots < r_n$. 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. The rings in a cell are allocated with different channels to reduce the number of contending users and improve the throughput. This frequency planning is simple, and 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}, respectively. By multichannel and multi-interface operations, the users can concurrently receive and deliver the relay traffic to improve throughput and delay.

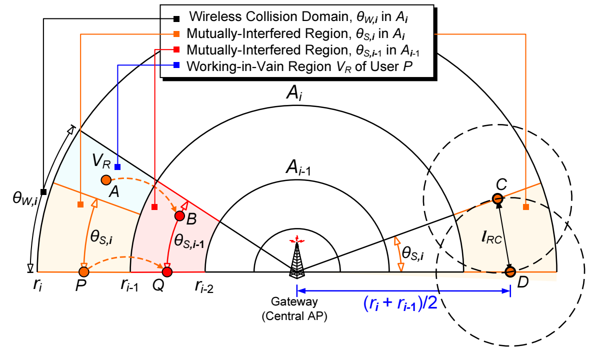

Fig. 2. Examples of wireless collision domain and mutually-interfered region. (This is an example for the variable ring-width strategy.)

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 in 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., $H_i(d) \geq R_i$. The hop distances for different users in a ring may vary. For simplicity, we assume that the average hop distance for the users in ring A_i 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 $PFI \geq PF_{req}$. PFI is the power fairness index defined in (16) 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, $d_{min} \leq (r_i - r_{i-1}) \leq d_{max}$.

B. MINLP Optimization Approach

The optimal capacity and coverage issues in a WMN can be formulated as a mixed-integer nonlinear programming

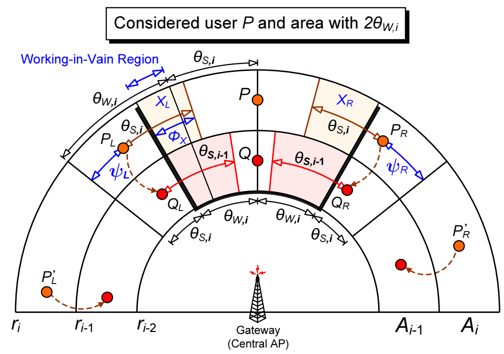

Fig. 3. The considered user P and two adjacent wireless collision domains, where user P is contending for the radio channel.

(MINLP) problem with the following decision variables: n (the number of rings in a mesh cell) and r_1, r_2, ..., r_n. The objective is to maximize the cell capacity subject to the power fairness requirement. 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 ρ 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.

$$\underset{n,r_1,r_2,\ldots,r_n}{\text{MAX}} \quad \rho\pi r_n^2 R_D \text{ (Overall throughput of a mesh cell)}$$

subject to

$$H_i(d) \geq R_i \tag{2}$$

$$PFI \geq PF_{req} \tag{3}$$

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

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* [9], [10]. 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 σ 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

$$T_v = \sum_{j=1}^{5} \nu_j T_j \ . \tag{5}$$

Here, ν_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 ν_1 and ν_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

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the mutually-interfered regions of P as shown in Fig. 3. Let ψ_L and ψ_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., ψ_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 (13). 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

$$\begin{aligned} p_v &= 1 - \Pr\{\psi_L, \psi_R \notin [\theta_{S,i}, \theta_{W,i}]\} \\ &= 1 - \left[1 - Z_{W,i}\frac{\theta_{W,i} - \theta_{S,i}}{\theta_{W,i}}\right]^2 . \end{aligned} \tag{6}$$

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 $\overline{\phi}_X$ 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.,

$$\begin{aligned} c_{1,i} &= \frac{\rho a_i}{2\pi} 2(\theta_{W,i} - Z_{W,i}\overline{\phi}_X) \\ &= \frac{\rho a_i}{\pi}(\theta_{W,i} - \frac{Z_{W,i}}{\theta_{W,i}}\int_0^{\theta_{S,i}} \psi_L d\psi_L) \\ &= \rho(r_i^2 - r_{r-1}^2)(\theta_{W,i} - \frac{Z_{W,i}\theta_{S,i}^2}{2\theta_{W,i}}) \end{aligned} \tag{7}$$

where ρ 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 ψ_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 τ 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 [11]. Under the impact of ring structure on frame contention, the unsuccessful transmission probability p_u is equal to

$$p_u = p_v + (1 - p_v)[1 - (1 - \tau(1 - P_0))^{C_{1,i}-1}], \tag{8}$$

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

$$\nu_1 = \tau(1 - p_u) \ \text{ and } \ \nu_2 = \tau p_u \ . \tag{9}$$

By the same reasoning, one can also calculate the probabilities ν_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 ρ 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

$$R_i = \frac{c_{i+1}}{c_i}R_{i+1} + R_D = \left[\frac{\sum_{j=i+1}^{n} c_j}{c_i} + 1\right] R_D. \tag{10}$$

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

$$\begin{aligned} \overline{B_k} &= (1 - p_u)\frac{W-1}{2} + p_u(1 - p_u)\frac{2W-1}{2} + \cdots \\ &\quad + {p_u}^{m_{bk}}(1 - p_u)\frac{2^{m_{bk}}W - 1}{2} \\ &\quad + {p_u}^{(m_{bk}+1)}(1 - p_u)\frac{2^{m_{bk}}W - 1}{2} + \cdots \\ &= \frac{[1 - p_u - p_u(2p_u)^{m_{bk}}]W - (1 - 2p_u)}{2(1 - 2p_u)} \end{aligned} \tag{11}$$

where p_u is the unsuccessful transmission probability with considering the impacts of ring structure in the physical layer, as defined in (8). Since a user sends RTS requests every $(\overline{B_k} + 1)$ slots on average [12], the transmission probability τ for an active user can be written as

$$\tau = \frac{1}{\overline{B_k} + 1} = \frac{2}{1 + W + p_u W \sum_{i=0}^{m_{bk}-1}(2p_u)^i} \ . \tag{12}$$

From (8) and (12), we can obtain the solution of τ 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

$$Z_{O,i} = \frac{\nu_1 T_1}{T_v}(1 - P_0) \text{ and } Z_{W,i} = \rho A_{W,i} Z_{O,i} \tag{13}$$

where ν_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

$$H_i(d) = \frac{\nu_1 T_1}{T_v} \cdot \frac{L}{T_S} = \frac{\nu_1 L}{T_v} \tag{14}$$

where L is the payload size of data frame. From (5)-(14), we can numerically obtain ν_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, $j = 1, 2, \ldots, 8$, and $d_1 > d_2 > \ldots > d_8$. 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 $d_{j+1} < d \le d_j$.

C. Power Consumption

Now we evaluate the average power consumption in the considered WMN. Suppose that all the users transmit at the same power. Generally, there are three power consumption modes for a mesh user, including the transmitting, receiving, and idle modes [13]. 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

$$\begin{aligned} p_{avg,i} &= \left[\frac{\sum_j \epsilon_j \nu_j T_j}{\sum_j \nu_j T_j}\right](1 - P_0) + p_{idle} P_0 \qquad (15) \\ &= \frac{\sum_{j=1}^{2} p_{tx} \nu_j T_j + \sum_{j=3}^{5} p_{rx} \nu_j T_j}{T_v} (1 - P_0) + p_{idle} P_0 \end{aligned}$$

where the first term represents the average power consumption for an active user. ϵ_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 [14], we define the power fairness index PFI for the ring-based WMN as

$$PFI = \frac{(\sum_{i=1}^{n} p_{avg,i})^2}{n(\sum_{j=1}^{n} p_{avg,i}^2)} \tag{16}$$

where n is the number of rings in a cell. In (16), $PFI = 1$ 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 tradeoffs among power fairness, capacity and coverage in a ring-based WMN. We compare the uniform ring-width and variable ring-width strategies. The MINLP problem is solved by the branch-and-bound method [15] along with the MATLAB optimization toolbox. The system parameters are summarized in Table I. Suppose that all the users transmit at the same power. Referring to the measured results [16], we assume that the average reception ranges for eight PHY modes in the IEEE 802.11a WLAN are $d_j = \{300, 282, 267, 244, 213, 167, 107, 52\}$ (m) for the given transmission power. In addition, the power consumption for transmitting/receiving/idle modes are assumed to be $(p_{tx}, p_{rx}, p_{idle}) = (1, 0.6, 0.15)$ (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.

TABLE I

System parameters for numerical examples.

Symbol	Item	Nominal value
L	Data frame payload size	4067 Bytes
ρ	User node density	$(90)^{-2}$users/m^2
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, 0.6 (power unit)
p_{idle}	Power consumption for IDLE mode	0.15 (power unit)

Figure 4 shows the optimal cell coverage and capacity against the number of rings (n) in a cell under different power fairness requirements. The optimization approach helps determine the optimal ring widths analytically under the constrains of the power fairness requirement, link capacity, and hop distance. In the figure, since the variable ring-width strategy reduces the ring width of inner ring to improve link capacity and increases the ring width of outer ring to extend cell coverage, the variable ring-width design can achieve better cell coverage and capacity. This figure also shows that the power fairness can be ensured at the cost of coverage. In this example, by the variable ring-width strategy, the maximal cell coverage and capacity for the case without power fairness requirement are 465 (m) and 33.5 (Mbps) at $n = 4$. To meet the power fairness requirement $PFI = 0.9$, the maximal coverage and capacity diminish to 424 (m) and 27.9 (Mbps) at $n = 3$. In this ring-based WMN, properly reducing the hop distances by decreasing the ring widths can improve the power efficiency and raise the link capacity. Meanwhile, the smaller cell coverage also lowers the traffic load of inner users. Due to better power efficiency and lower traffic load for the inner users, the power consumption of the inner users is reduced, and the power fairness can be achieved at the cost of coverage.

Figure 4 also shows that the number of rings n in a cell has a maximum value. In general, cell coverage increases as n increases. For handling the increasing relay traffic as n increases, the ring width (especially for the innermost ring) will be reduced to shorten the hop distance and improve the link capacity. However, since the ring width should be larger than the threshold 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 ring-width strategies.

In Fig. 5, the achieved power fairness index against the number of rings is shown. If without any power fairness

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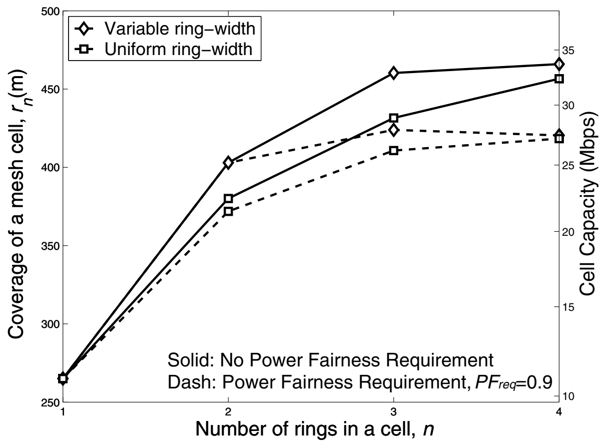

Fig. 4. Cell coverage and capacity (aggregated throughput) versus the number of rings n in a cell under different power fairness requirements.

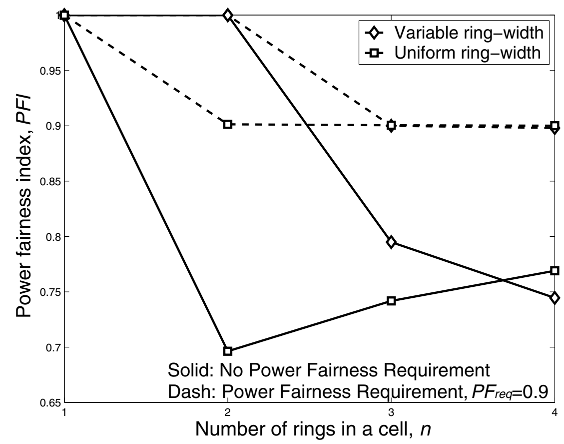

Fig. 5. Achieved power fairness PFI versus the number of rings in a cell.

requirement, the achieved power fairness index degrades below 0.8 for a larger n. This is because the users in the inner rings are more busy than the users in the outer rings in forwarding the relay traffic. Figure 5 also shows that with the optimization approach to design the optimal ring widths, the power fairness requirement $PF_{req} = 0.9$ can be met at the cost of cell coverage as shown in Fig. 4. In this mesh network, reducing the ring width and the hop distance can improve power efficiency and reduce the power consumption, especially for the heavy-loaded users near the gateway. In result, the power fairness can be ensured. In this example, without the power fairness requirement, the optimal cell coverage for the variable ring-width strategy at $n = 3$ is 460 (m). The corresponding optimal ring widths are $\{109, 130, 221\}$ (m), and the average power consumption for the users in ring A_i are $p_{avg,i}$ = $\{0.67, 0.62, 0.24\}$ (power unit). If setting the power fairness requirement PF_{req} = 0.9, the cell coverage diminishes to 424 (m) at $n = 3$, and the optimal ring widths are reduced to $\{105, 107, 212\}$ (m). Thanks to lower traffic load and higher power efficiency, the average power consumption can decrease to $p_{avg,i}$ = (0.45, 0.25, 0.17) and the power fairness index increases from 0.8 to 0.9. Clearly, since the power consumption is reduced, the network lifetime can be also prolonged.

In these figures, we investigate the interactions among the power fairness, capacity, and coverage in a WMN. It is obvious that the capacity and coverage can be enhanced simultaneously. One can also see that the variable ring-width strategy can achieve better cell coverage and capacity. 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 investigates a scalable ring-based WMN with power fairness guarantee. Subject to power fairness requirement, an optimization approach is proposed to maximize the cell capacity and coverage. We suggest 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 is developed to evaluate the throughput and power consumption. On top of the developed analytical model, the optimization approach is applied to determine the optimal number of rings and the associated ring widths. Numerical results show that a variable ring-width design criterion can improve cell coverage and capacity of a WMN. Besides, the goal of capacity enhancement with power fairness guarantee can be fulfilled at a cost of coverage performance.

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-infrastructured 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, "Throughput-coverage tradeoff in a scalable wireless mesh network," *Journal of Parallel and Distributed Computing*.

[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] L.-C. W. Jane-Hwa Huang and C.-J. Chang, "Power fairness in a scalable ring-based wireless mesh network," in *Proc. IEEE VTC*, Oct. 2007.

[9] 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.

[10] 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.

[11] D. Gross and C. M. Harris, *Fundamentals of Queueing Theory*, 3rd ed. New York: John Wiley & Sons, Inc, 1998.

[12] Y. C. Yay and K. C. Chua, "A capacity analysis for the IEEE 802.11 MAC protocol," *Wireless Network*, pp. 159–171, Jul. 2001.

[13] 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.

[14] 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.

[15] F. S. Hillier and G. J. Lieberman, *Introduction to Operations Research*, 7th ed. New York: McGraw-Hill, 2002.

[16] *Cisco Aironet 1230AG Series 802.11a/b/g Access Point*. [Online]. Available: http://www.cisco.com/