An Interference Aware Distributed Resource Management Scheme for CDMA-Based Wireless Mesh Backbone

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***Abstract*— In this paper, with a cross-layer design principle, we propose an interference aware distributed resource management scheme for a code-division multiple access (CDMA)-based wireless mesh backbone (consisting of a number of wireless routers at fixed sites). Specifically, benefiting from the fixed location of wireless routers, the power allocation is based on the length of the transmission path, so as to ensure a certain level of fairness among the routers. For a new call arrival, based on the maximum sustainable interference concept, each existing receiver (rather than the potential sender) estimates its experienced interference level under the hypothesis that the new call is admitted. If the interference is not tolerable, the existing receiver rejects the new call by sending a blocking-signal. The main advantages of our proposed scheme are the low control message overhead for easy implementation, and the accurate interference estimation. Simulation results are presented to evaluate the performance of our scheme.**

***Index Terms*— CDMA, cross-layer design, resource management, wireless mesh networks.**

I. Introduction

WIRELESS mesh networking is a promising candidate for future broadband wireless access, and has received much attention in the past few years. Fig. 1 shows an architecture for the wireless mesh networking in a three-tier hierarchy [1]. The third tier consists of wireless access networks, which may include wireless local area networks (LANs) and/or ad hoc networks. The second tier is the wireless mesh backbone, formed by a number of wireless routers. A wireless router is usually located at a fixed site. It can provide wireless Internet access to access networks under its coverage, and provide relay services for neighboring routers as well. The first tier is formed by gateways, which connect the wireless mesh backbone to the wireline Internet backbone. The three-tier hierarchy has many merits in terms of scalability and reliability, benefiting from the self-organization nature of the wireless mesh backbone.

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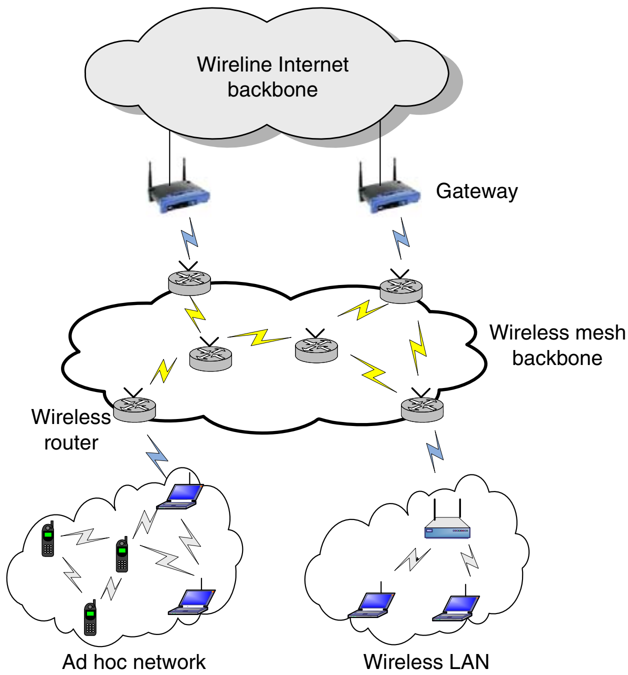

Fig. 1. An architecture for wireless mesh networking.

Quality-of-service (QoS) satisfaction (in terms of throughput, timeliness, etc.) is challenging for the multi-hop relay services provided by the wireless mesh backbone. Generally, radio resource management (e.g., admission control, allocation of resources in terms of time, transmit power, and rate) in wireless access networks is well investigated in the open literature to achieve QoS provisioning. Due to the ad hoc nature of the wireless mesh backbone, it may seem plausible to apply existing resource management schemes [2], [3] designed for traditional wireless mobile ad hoc networks. However, two unique characteristics of the wireless mesh backbone determine that existing resource management schemes may not work well. First, in mobile ad hoc networks, the resource management schemes should be designed to deal with node mobility. The limited power supply at a node also poses a challenge in resource management. However, the wireless routers in the wireless mesh backbone are usually located at fixed sites, and thus can be provided with wired power.

Therefore, the node mobility[1] and power consumption should not be the main consideration for the resource management [1]. Second, the traffic volume in the wireless mesh backbone is very likely to be much higher than that in an ad hoc network, because a wireless router may need to i) aggregate traffic for several access networks, and ii) relay traffic for its neighboring routers from/to the wireline Internet backbone. In such a *backbone*, fine-granularity QoS provisioning is desired or required. Carrier sense multiple access (CSMA)-based random access schemes, the major stream for resource management in traditional ad hoc networks, may not be a choice, due to their limited QoS provisioning capability. Thus reservation-based resource management schemes should be more suitable for the wireless mesh backbone. When resources are reserved for each active link, fine-granularity QoS can be achieved.

This paper presents an effective distributed resource management scheme for a code-division multiple access (CDMA)-based wireless mesh backbone, taking into account the unique networking characteristics. Specifically, based on the location information and the estimated interference level at the routers, adaptive time slot/power/rate allocation can be achieved. In addition, the existing receivers determine (in a distributed manner) whether or not a new call can be admitted into the wireless mesh backbone. The merits of our proposed scheme are four-fold: 1) it is fully distributed; 2) each link does not need to have the knowledge of other links in terms of transmit power, tolerable interference, etc., thus requiring low information exchange overhead and increasing the robustness and scalability of the resource management scheme; 3) accurate interference estimation can be achieved at each receiver; and 4) fine-granularity QoS can be achieved by resource reservation. If a call is admitted into the network, it can use the reserved resources until the completion of the call. As many symbols are used in this paper, Table I summarizes important ones.

The rest of this paper is organized as follows. Section II introduces CDMA-based resource management, and discusses the related work. Section III describes the system model under consideration. In Section IV, the proposed interference aware distributed resource management scheme is presented in detail. Performance evaluation is given in Section V, followed by concluding remarks in Section VI.

II. CDMA-Based Resource Management Schemes

For a transmission in a CDMA-based wireless mesh backbone, one of the following three codes can be used for distributed code assignment: common code, receiving code of the receiver, or sending code of the sender [4]. When a common code is used by all the nodes[2], two nearby transmissions may collide. The usage of the receiver's receiving code facilitates the traffic monitoring at the receiver, as the receiver only needs to monitor its own receiving code. A collision happens when two senders send traffic to the same receiver simultaneously. When the sending code of the sender is used, transmissions from different senders do not collide at a same receiver. The drawback is that the receiver should be aware of the sending code of a potential sender in advance.

TABLE I
Summary of Important Symbols Used

Symbol	Definition
d_{ij}	distance from node i to node j
G_a/G_p	spreading gain of an ACK/probe
g_{ij}	path gain from node i to node j
I_j	interference received plus background noise power at node j
P^t_{ij}	transmit power level from sender node i to receiver node j
$P^{r,p}_k(m)$	probe power level received at node k at minislot m
P^r_k	power level of the desired signal received at receiver node k
s_a/s_d	selected slot for ACK/data
Γ_a/Γ_d	required E_b/N_0 value for ACK/data transmission
α	path attenuation exponent
β_a/β_p	ratio of transmit power level of an ACK/probe to that of data transmission

Although collisions among CDMA-based transmissions can be avoided by an appropriate code assignment, interference still exists. For a link where the sender and receiver are far apart, a nearby interferer in the neighborhood of the receiver is very likely to corrupt the desired reception at the receiver. This is the notorious *near-far problem*, which has been well investigated in CDMA cellular networks with central controllers (i.e., base stations).

To address the near-far problem in the wireless mesh backbone with no central controller, it is necessary to control the interference, so as to keep the received signal bit energy to interference plus noise density ratio (E_b/N_0) at each receiver above a required value. For link from sender i to receiver j, the following inequality should hold

$$(E_b/N_0)_{ij} = \frac{G_i P^t_{ij} g_{ij}}{I_j} \geq \Gamma_d \tag{1}$$

where G_i is the spreading gain, P^t_{ij} is the transmit power, g_{ij} is the path gain from node i to node j, I_j is the interference received from other links plus background noise power at node j, and Γ_d is the required E_b/N_0 value for data transmission. For the link from node i to j, a maximum sustainable interference (MSI_{ij}) or interference margin [5], [6] is defined as the maximum additional interference that can be tolerated by the link's receiver (i.e., node j) with satisfaction of the E_b/N_0 requirement. We have

$$\frac{G_i P^t_{ij} g_{ij}}{I_j + \mathrm{MSI}_{ij}} = \Gamma_d. \tag{2}$$

Eq. (2) can be rewritten as

$$\mathrm{MSI}_{ij} = \frac{G_i P^t_{ij} g_{ij}}{\Gamma_d} - I_j. \tag{3}$$

[1]Although the mobility of wireless routers is not significant, the mobility of mobile stations in the access networks connected to the wireless mesh backbone may still lead to challenging problems. This issue is not addressed in this paper as we focus on the wireless mesh backbone.

[2]In this paper, the terms "wireless router" and "node" are used interchangeably.

As long as the MSI values of all links are kept non-negative, the reception quality of all links can be guaranteed. Before transmission, each new sender checks whether or not its transmission will lead the MSI of any existing link to a negative value. If yes, the sender defers its transmission; otherwise, the sender transmits. Hence, it is essential to let a potential sender know the MSI values of all ongoing transmissions in its neighborhood. In [7], a busy-tone channel is suggested to be used by an existing receiver to send a busy-tone signal with power level inversely proportional to the receiver's MSI. Based on received busy-tone power, a potential new sender estimates its allowed transmit power level such that all existing receivers can keep non-negative MSI values. However, the method suffers from estimation inaccuracy due to possible overlap (in the time duration) of busy-tone signals from different existing receivers. In [6], it is suggested that the total available bandwidth be divided into a data channel and a control channel. The MSI information is exchanged via the request-to-send (RTS)/clear-to-send (CTS) dialogue in the control channel. However, the message exchange overhead may lead to inefficiency. A control channel is suggested in [5][3], which is based on link reservation. The MSI of each active link is broadcast at a common control channel. However, it is possible that the MSI broadcasts from different links may collide with each other. The incomplete and out-of-date information may degrade the system performance.

Another critical problem of the preceding MSI-based resource management schemes lies in that the potential sender rather than the existing receivers makes the decision on whether or not the potential transmission (if admitted) will lead to a negative MSI at a nearby existing receiver. A potential sender estimates the increased interference level at each existing receiver under the hypothesis that the potential link is admitted. Thus, we term the schemes *sender-centric*. However, the interference estimation in the sender-centric schemes may not be accurate due to the following reason. Consider the case when there are two or more potential senders in a network. Assume that each of the potential senders has the MSI information of a target existing receiver, and the potential transmission of each sender generates less interference to the target existing receiver than the MSI. So all the potential senders decide to transmit. It is possible that the desired reception at the target existing receiver is corrupted because the aggregate interference from all potential senders may be larger than the MSI.

In the following, we develop a new resource management scheme for the wireless mesh backbone which can overcome the preceding problems of existing sender-centric schemes.

III. System Model

We consider a wireless mesh backbone with a number, N, of wireless routers at fixed sites with wired power supply. Each wireless router has a unique sending code and a unique receiving code. Due to the fixed network topology, each wireless router also has the information of the location, sending and receiving codes of other wireless routers.

[3]Although ultra-wideband networks are considered in [5], its resource sharing principle can be applied to CDMA-based networks.

Traffic Model – A simple traffic model is considered, in which all the traffic arrivals are of the same type. The traffic arrives at each node in bursts. Since the traffic aggregating is at the wireless mesh backbone, the bursts normally have a large size.

QoS Model – QoS in radio resource management can be classified based on a hierarchy of two different levels: bit-level and packet-level. Bit-level QoS is to ensure reception quality, normally represented by an upper bound on transmission bit error rate (BER). The BER guarantee can be achieved by satisfying a required E_b/N_0 value Γ_d for each link. On the other hand, transmission rate (i.e., throughput), timeliness (i.e., delay and jitter), and fairness are the main consideration in packet-level QoS. Here, for bit-level QoS, an E_b/N_0 bound is required for each traffic link, i.e., for link from sender i to receiver j, inequality (1) should hold; for packet-level QoS, a minimal transmission rate should be guaranteed for each link.

IV. The Interference Aware Distributed Resource Management Scheme

To provide multi-hop relay services in the wireless mesh backbone, generally the resource management at the link layer and routing at the network layer interact with each other. As the first step in our research, we consider separated designs on routing and resource management, and assume that a routing protocol is in place. How to achieve an optimal or sub-optimal joint design of routing and resource management is an interesting issue for further research.

A. Time Frame Structure

In the wireless mesh backbone, it is possible that two links with potential large mutual interference have traffic to send at the same time. Hence, when one is transmitting, the other should not transmit. This means a temporal exclusion mechanism is needed [8]. A slotted time frame structure facilitates temporal exclusion. Links with small mutual interference can transmit at a same slot, while those with large mutual interference should transmit at different slots.

The available frequency band is partitioned into two parts, an information band and a (small) blocking-signal band. Time is partitioned into fixed-size frames, as shown in Fig. 2. Each frame consists of a number (L) of slots. In the information band, CDMA technology is applied. Data packets can be transmitted in a slot. Each slot is further divided into M minislots, and a potential sender can transmit a probe (to be discussed) at one minislot. In the blocking-signal band, CDMA technology is not applied. Rather, a single-frequency channel is used. For each slot, the M minislots in the blocking-signal band are synchronized with the M minislots of the probes in the information band. Blocking-signal is sent and monitored at each minislot. In each band, a node cannot receive and send simultaneously.

B. Location Based Power Allocation

For multi-hop networks, typically two power allocation schemes are used: uniform power allocation and linear power allocation [9]. In uniform power allocation, a common transmit

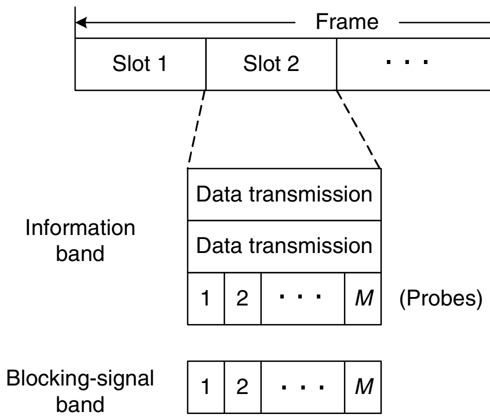

Fig. 2. Time frame structure in the proposed resource management scheme.

power level is used [10]. In linear power allocation [11][12], the transmit power of a sender i to a receiver j is proportional to d_{ij}^{α}, where d_{ij} is the distance from node i to node j, and α is the path attenuation exponent. In other words, a minimal power level is assigned to deal with the path attenuation. In [9], worst-case analysis is given for different power allocation schemes, and a non-linear power allocation scheme is presented to improve system efficiency.

In our research, we consider the linear power allocation with adaptation to fairness. In specific, if a link experiences large interference in its neighborhood, it may result in a low transmission rate at the link. To address this problem, when a target link is expected to experience large interference from other links (e.g., due to many other traffic sources in the neighborhood), the target link should have large transmit power. Consequently, when node i intends to transmit to node j, we propose to determine the transmit power level at node i by

$$P_{ij}^{t} = P \cdot d_{ij}^{\alpha} \cdot \sum_{k \neq i, k \neq j} d_{kj}^{-\alpha} \qquad (4)$$

where P is a constant. In (4), the term d_{ij}^{α} is to compensate for the path attenuation of the link from node i to node j, and the summation term represents a factor of the interference level generated by other nodes. As node i has the location information of other nodes, the power allocation takes advantage of the location awareness from the fixed topology of the wireless mesh backbone. Note that without the fairness consideration, a totally different power assignment can be used such as uniform power allocation, linear power allocation, or non-linear power allocation [9].

C. Call Admission and Slot/Rate Allocation

We consider the basic traffic unit to be a burst. A burst consists of a number of network-layer packets that arrive at the sender consecutively. A *call* refers to the transmission of a burst from its sender to its receiver. The aggregate traffic at a node is very likely to form relatively large bursts. In order to guarantee the QoS of the burst transmission, when a call is admitted to the network, it is desired that the sender can transmit continuously with the allocated resources (i.e., time slot, transmit power, and rate) until the call completion. In other words, resource reservation is preferred. Also, each new transmission is required not to corrupt the reception of ongoing transmissions. Different from existing sender-centric resource management schemes [5]–[7], in our *receiver-centric* scheme proposed here, the existing receivers rather than the potential sender make the admission decision of a new call, since a possible corruption happens at a receiver rather than a potential sender. The associated call admission and slot/rate allocation procedure is as follows.

In the information band, upon a call arrival at node i for destination node j, node i monitors node j's sending code at each slot of the first available frame. It also measures the received interference level (caused by all the existing transmissions) at each slot. Among all the slots at which node j's transmission is not detected[4], node i selects the slot (say slot s_d) with the minimal measured interference level. At the selected slot, node i randomly selects a minislot $m \in \{2, ..., M\}$ (minislot 1 is used for all the existing receivers to estimate interference level, to be discussed), and transmits a probe which is spread by a common probe code with a very large spreading gain G_p, and with power $\beta_p P_{ij}^t$ (where $\beta_p \ll 1$ such that the probe is not likely to corrupt any existing transmission). The large spreading gain is to facilitate probe reception and power measurement at an existing receiver, with very small probe power. The purpose of the probe is to let the existing receivers determine whether or not the potential transmission is allowed. No bit-information is carried by the probe. Therefore, if multiple probes are sent simultaneously by different potential senders (with the same or different target receivers), each existing receiver can collect energy from all the probes with the aid of a RAKE receiver. This can help to achieve accurate estimation of potential interference increase at the existing receiver, to be elaborated in Section IV-D.

At each slot, all the existing receivers measure the received interference level at minislot 1, and monitor the common probe code throughout minislot 2 to minislot M. After detection of a probe at a minislot $m \in \{2, ..., M\}$, an existing receiver determines whether or not the data transmission from the sender of the probe will corrupt its own reception. If yes, the receiver sends a blocking-signal at minislot m' in the blocking-signal band to inform the potential sender that its data transmission is not allowed, where

$$m' = \begin{cases} m+1 \text{ (at the current slot)}, & \text{if } m < M \\ 1 \text{ (at the next slot)}, & \text{if } m = M. \end{cases} \qquad (5)$$

The details of the decision-making process at the receiver (whether or not to transmit the blocking-signal) are given in Section IV-D.

After a potential sender i sends the probe at minislot m of its selected slot s_d, it detects the blocking-signal at minislot m' in the blocking-signal band. If the detected blocking-signal power exceeds a threshold (referred to as *blocking-signal detection threshold*), it selects another slot and follows the procedure discussed above. Otherwise, at slot s_d of the next frame (in the information band), it sends a request message spread by the destination node j's receiving code with transmit power P_{ij}^t and a large channel coding rate (hence we assume

[4]Note that node j cannot send and receive at the same time in the information band.

that the request can be received correctly if it is the only request to destination j at the slot). The request also indicates the interference level that node i measures at each slot. Upon the reception of the request at slot s_d, the destination j estimates the E_b/N_0 of the potential transmission, based on the received power level of the request message and its own interference estimation at the slot. If the estimated E_b/N_0 is above the requirement Γ_d, the destination j selects a slot (say slot s_a) for the transmission of the acknowledgements (ACKs). Specifically, the destination j selects a slot from the available slots[5] with the minimal interference level (experienced by the sender i) indicated in the request message. Then it determines whether or not an ACK channel can be set up at slot s_a. The transmit power of the ACK should be small (so as not to corrupt other existing transmissions), and is selected as $\beta_a P_{ji}^t$ ($\beta_a \ll 1$). The spreading gain of the ACK is G_a, a very large value so as to guarantee the correct reception. For the selected slot s_a, the destination j checks whether or not

$$\frac{G_a \beta_a P_{ji}^t g_{ji}}{I_i(s_a)} \geq (1+\delta)\Gamma_a \tag{6}$$

where $I_i(s_a)$ is the interference plus noise level experienced by the sender i at slot s_a, δ is a margin factor, and Γ_a is the E_b/N_0 requirement of the ACK. If the above inequality holds, node j will send a request confirmation (via its sending code with power $\beta_a P_{ji}^t$ and spreading gain G_a) to node i at slot s_a, and, at the same slot in subsequent frames, send ACKs to acknowledge data transmissions from node i to j. Upon reception of the request confirmation, node i transmits at its selected slot s_d of the subsequent frames using its sending code with power level P_{ij}^t until the burst is completed.

D. Interference Estimation and Blocking-Signal Power Level

In this subsection, we discuss how an existing receiver can estimate its experienced interference increase under the hypothesis that the potential new calls are admitted, and what the blocking-signal power level should be if the interference is not tolerable and the potential new calls should be rejected.

We first consider the case with only one potential sender that sends a probe at a specific minislot m ($2 \leq m \leq M$). At each slot, besides the desired data reception, any existing receiver (say node k) measures its experienced interference plus noise level, denoted by I_k, from other existing links at minislot 1. We assume the interference level does not change during the slot. The receiver then monitors the common probe code at minislots 2 to M. If a probe is detected at minislot m, node k measures the received probe power, denoted by $P_k^{r,p}(m)$, and estimates its interference increase due to potential data transmission from the probe sender as $P_k^{r,p}(m)/\beta_p$ (as β_p is the ratio of probe transmit power to data transmit power). Then node k determines whether or not the potential interference increase will corrupt its reception, i.e., it checks whether or not

$$\frac{G_k P_k^r}{I_k + \frac{1}{\beta_p}\sum_{l=2}^{m-1} P_k^{r,p}(l)\cdot\big(1-f(l)\big) + \frac{P_k^{r,p}(m)}{\beta_p}} \geq (1+\delta)\Gamma_d \tag{7}$$

where G_k is the spreading gain of reception at node k, P_k^r is the power level of the desired signal received at node k, and $f(l)$ is an indication function given by

$$f(l) = \begin{cases} 1 & \text{if a blocking-signal is detected at minislot} \\ & \quad l+1 \text{ of the current slot (when } l < M\text{) or} \\ & \quad \text{at minislot 1 of the next slot (when } l = M\text{)} \\ 0 & \text{otherwise.} \end{cases} \tag{8}$$

In the denominator of the left side in (7):

- The first term (i.e., I_k) is the measured (at minislot 1) interference level at node k generated by other existing links;
- The second term (i.e., $\frac{1}{\beta_p}\sum$) is the interference to be generated by new senders admitted at minislot 2 to $m-1$. If a blocking-signal is detected at minislot $l+1$ where $2 \leq l \leq m-1$, the new sender that sends a probe at minislot l is not allowed to transmit its data traffic. If no blocking-signal is detected at minislot $l+1$, it is expected that the sender transmitting a probe at minislot l is admitted (i.e., is allowed to send its data in subsequent frames), and thus the generated interference should be considered;
- The third term (i.e., $\frac{P_k^{r,p}(m)}{\beta_p}$) is the potential interference by the new sender which sends a probe at minislot m.

When the inequality (7) does not hold, node k sends a blocking-signal at minislot m' given by (5).

We then consider the case with two or more (denoted by n) potential senders (with node IDs ranging from 1 to n) each of which sends a probe at minislot m. Denote their potential data transmit power levels as $P_1^t, P_2^t, ..., P_n^t$. As no bit-information is carried by the probe, the existing receiver (i.e., node k) cannot distinguish the probes sent from different senders. The RAKE receiver can collect all the detected probe energy. Thus, the probe power level received by node k at minislot m is

$$P_k^{r,p}(m) = \sum_{s=1}^{n} \beta_p \cdot P_s^t \cdot g_{sk}. \tag{9}$$

As node k cannot distinguish one sender's probe from another, it assumes that there is only "one probe sender," and estimates the interference generated by potential data transmission of the "probe sender" as $P_k^{r,p}(m)/\beta_p$, which is represented by

$$P_k^{r,p}(m)/\beta_p = \sum_{s=1}^{n} P_s^t \cdot g_{sk}. \tag{10}$$

Thus $P_k^{r,p}(m)/\beta_p$ can be exactly the received interference level at node k from all the potential senders' data transmissions. This means that, although an existing receiver does not have the information of the number of potential senders, the interference estimation is still accurate. After the estimation, the existing receiver decides whether or not it should send a blocking-signal.

The transmit power level of the blocking-signal should be carefully determined. A large transmit power level may unnecessarily cause a large number of potential senders (some of which may not affect much the target existing receiver's reception) to give up transmissions; while a small transmit power level may not be able to block the potential senders that generate large interference. The principle is to block senders

[5]The available slots are those not being used by the sender i to transmit and not being used by the destination j to receive packets.

with potential significant interference to the target receiver. If the target receiver is in a dense neighborhood, it is very likely that its neighbors with a potential to generate large interference are close to the target receiver. Therefore, the transmit power level of a blocking-signal can be small. On the other hand, when the neighbors are far away, a relatively large transmit power level should be used for a blocking-signal. Thus, the transmit power level of a blocking-signal from the target existing receiver, i.e., node k, is chosen as

$$P_k^B = \frac{P^B}{\sum_{s=1,s\neq k}^{N} d_{ks}^{-\alpha}} \tag{11}$$

where P^B is a constant.

In the proposed resource management scheme, each existing receiver estimates potential increase in its experienced interference level (at the physical layer) to determine whether or not a new call can be admitted. Hence, the proposed scheme is based on a cross-layer design principle, and is termed *interference aware*.

E. Adaptive Transmission Rates

If a fixed transmission rate is used, it is possible that the bandwidth is not fully utilized. For instance, when the traffic load is light, at each slot there may be only a very limited number of active links, and each link has to transmit at a low rate even though the E_b/N_0 is much higher than the required value. If an adaptive transmission rate is adopted according to the predicted interference level, a larger transmission rate can be achieved and thus with a shorter delay. Generally, there are two solutions to achieve adaptive transmission rates: variable spreading gain CDMA and multi-code CDMA. Here we use multi-code CDMA so as to keep a large enough spreading gain. The chip rate is fixed. Each link can transmit several substreams, with mutually orthogonal subcodes generated by multiplying the sending code of the link's sender and the rows of Hadamard-Walsh matrix. For sender i to receiver j, the total transmit power for all the substreams is P_{ij}^t given by (4).

We denote the minimal and maximal number of substreams that a link can use by $C_{\min}$ and $C_{\max}$, respectively. Consider an admitted link from sender i to receiver j. At a time it has C_{old} substreams with fixed spreading gain G_i for each substream. The receiver j measures the desired signal power level and interference level, and estimates interference due to newly admitted transmissions at the same slot (based on the probes and blocking-signals). It then sends (in the ACK) to its sender (node i) the value of the E_b/N_0 in its reception of a substream, given by

$$E_b/N_0 = \frac{G_i \cdot P_j^r / C_{\text{old}}}{I_j + \frac{1}{\beta_p}\sum_{l=2}^{M} P_j^{r,p}(l)\cdot\big(1-f(l)\big)} \tag{12}$$

where P_j^r is the total received (at receiver j) signal power from node i including all substreams, I_j is experienced interference plus noise level experienced by the receiver j measured at minislot 1 of the data transmission slot, $P_j^{r,p}(l)$ is probe power detected by receiver j at minislot l, and $f(l)$ is given in (8). Node i then determines the maximal allowable substream

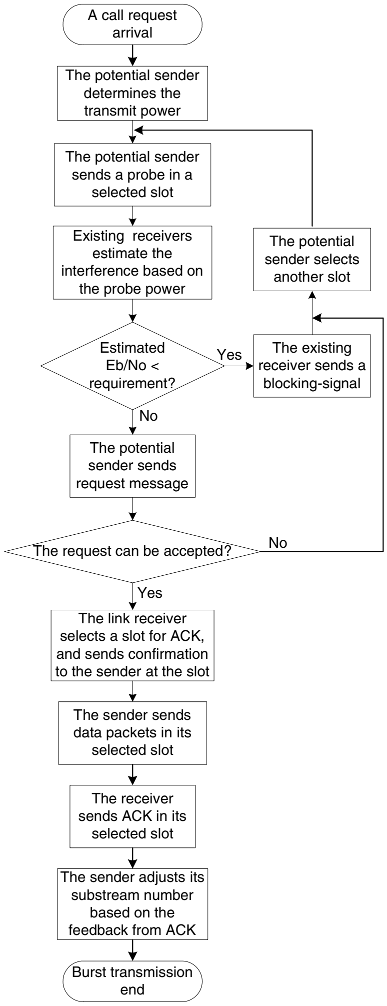

Fig. 3. The flowchart of the proposed resource management scheme.

number denoted by C_{new} such that the E_b/N_0 requirement Γ_d is guaranteed with a margin factor δ. We have

$$\frac{G_i \cdot P_j^r / C_{\text{new}}}{I_j + \frac{1}{\beta_p}\sum_{l=2}^{M} P_j^{r,p}(l)\cdot\big(1-f(l)\big)} \geq (1+\delta)\Gamma_d. \tag{13}$$

Considering C_{new} should be bounded by $C_{\max}$, we have

$$C_{\text{new}} = \min\Big(C_{\max}, \lfloor \frac{E_b/N_0}{(1+\delta)\Gamma_d}\cdot C_{\text{old}} \rfloor\Big) \tag{14}$$

with $\lfloor\cdot\rfloor$ being the floor function. As each admitted link can transmit at least $C_{\min}$ substreams, a minimal transmission rate can be guaranteed for the link.

The flowchart shown in Fig. 3 summarizes the proposed scheme. The advantages of our proposed receiver-centric scheme comparing to previous sender-centric schemes [5]–[7] are as follows:

(1) Previous sender-centric schemes require each existing link to broadcast its MSI value to its neighborhood, resulting in high control message overhead. Such information is not needed in our scheme, thus avoiding the information exchange overhead;
(2) Our scheme is a burst-level reservation scheme. In comparison with the contention based packet-level random

TABLE II
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value	Parameter	Value
L	10	Slot time	5 ms	M	10
α	2.4	$C_{\max}$	64	$C_{\min}$	4
G_p	1600	G_a	1600	β_p	0.01
β_a	0.01	Γ_d	5 dB	Γ_a	5 dB

access schemes in the literature, our scheme reduces the handshaking message overhead significantly. When a burst is admitted, fine-granularity QoS can be achieved via resource reservation;

(3) In previous schemes, to determine whether or not a potential sender can transmit, the sender estimates the potential interference increase at each existing receiver under the hypothesis that the potential link is admitted. However, the estimation is subject to inaccuracy due to the possibility of two or more potential senders at the same time, as discussed in Section II. Our scheme does not have the drawback because the existing receivers rather than the potential sender estimate the potential interference increase at the receivers, and determine whether or not the potential new transmission is allowed.

Furthermore, from a practical point of view, our scheme is scalable because: 1) it is a distributed scheme, where each sender decides by itself (according to information in the blocking-signal band) whether or not its link can be admitted and, if admitted, determines in what slot and at what rate it can transmit; and 2) it is simple with small overhead, as each node does not need to know the status of other existing links.

V. PERFORMANCE EVALUATION

To evaluate the performance of our proposed resource management scheme, computer simulations are carried out by using Matlab. CDMA is used for multiple access in a wireless mesh backbone. The chip rate is 50 Mega chips per second (Mcps). Because of the dominant effect of multiple access interference in CDMA transmissions, background noise is ignored. In CDMA-base networks, a RAKE receiver can collect signal energy from different paths. Hence, we assume that there is no fading, and the transmit power is attenuated only due to path loss with exponent $\alpha = 2.4$ [13], [14]. The burst arrival at each node is a Poisson process. Each burst has a size of 1 Mega bits. The spreading gain for each substream in data traffic transmission is 64. Other simulation parameter values are listed in Table II.

A. Comparison With Sender-Centric CDMA Resource Management Scheme

We first compare our proposed receiver-centric scheme with alternative schemes under the MSI concept. One alternative scheme is the sender-centric CDMA resource management scheme where RTS/CTS dialogue in a separate control channel is used to exchange MSI information [6]. As the performance of the sender-centric scheme largely depends on the coverage of the RTS/CTS signals, we simulate a small area for fair comparison where the RTS/CTS signal of any node can be heard by all the nodes in the simulated area. In specific, 7 links are simulated, where the nodes are uniformly distributed in a 1 km $\times$ 1 km square. Fig. 4 shows the comparison of aggregate throughput between the sender-centric scheme and our receiver-centric scheme. It can be seen that, when the traffic load increases, the sender-centric scheme gets saturated quickly, and our scheme performs much better. This is due to the overhead of using RTS/CTS to exchange MSI values in the sender-centric scheme, while there is no need to exchange the exact MSI values among the nodes in our receiver-centric scheme.

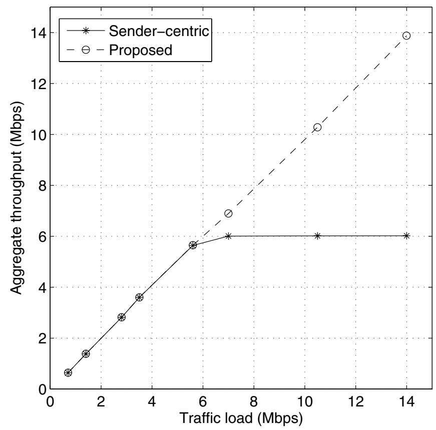

Fig. 4. Aggregate throughput of the sender-centric scheme and our proposed receiver-centric scheme.

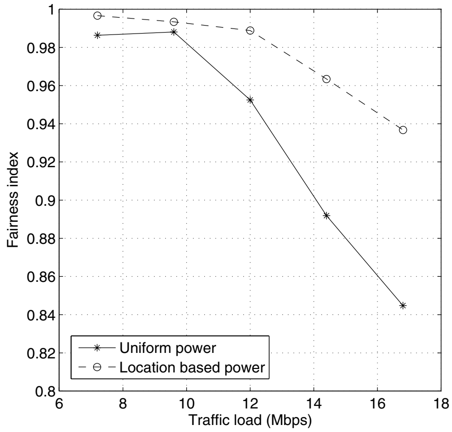

Fig. 5. Fairness Index of the uniform power and location based power allocation strategies in the two-cluster topology.

B. Uniform Power Allocation Versus Proposed Location Based Power Allocation

In order to demonstrate the advantage of using the proposed location based power allocation over the uniform power allocation [10], we investigate a cluster topology of the wireless mesh backbone. A two-cluster scenario is considered. Each cluster covers 10 km $\times$ 10 km area, and the centers of the two clusters are 30 km apart. In each cluster, nodes are uniformly distributed. There are 24 active links, half of which are intra-cluster links (over a short distance) and the other half are inter-

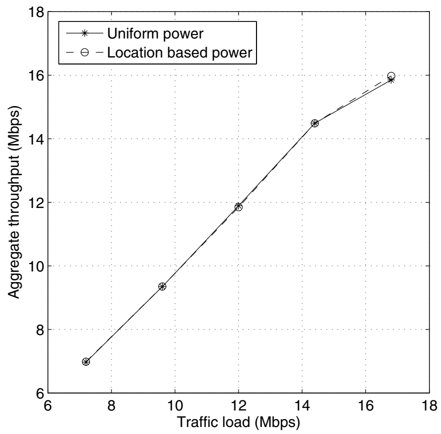

Fig. 6. Aggregate throughput of the uniform power and location based power allocation strategies in the two-cluster topology.

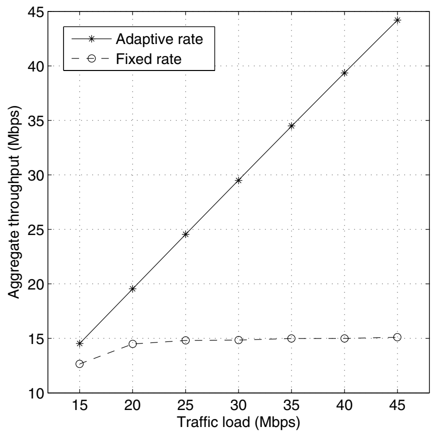

Fig. 7. Aggregate throughput of the adaptive rate and fixed rate schemes.

cluster links (over a long distance). We compare the fairness performance of the two power allocation strategies. The fairness is measured by Jain's Fairness Index (FI) [15] given by $\mathrm{FI} = \frac{(\sum_{i=1}^{N_a} T_i)^2}{N_a \cdot \sum_{i=1}^{N_a} T_i^2}$, where T_i is the throughput of the ith link and N_a is the number of active links. The higher the Fairness Index value, the better the fairness performance. Fig. 5 shows the fairness performance of the two power allocation strategies in the two-cluster scenario. It is observed that the location based power allocation has better fairness performance than the uniform power allocation. With an increase of the traffic load, the Fairness Index of the uniform power allocation drops faster than that of the location based power allocation. This can be explained as follows. When the traffic load is light, each link can have a very large E_b/N_0 value, and transmit with the maximum number of substreams when either of the power allocation strategies is applied. Therefore, each link achieves almost the same throughput. As the traffic load increases, there are more active links at a slot. With the uniform power allocation, the links over a long distance are very likely to have a smaller E_b/N_0 value due to a larger path attenuation than the links over a short distance. Thus, the long-distance links usually have a smaller number of substreams and thus

TABLE III

AVERAGE BURST DELAY (UNIT: SECOND) IN ADAPTIVE RATE AND FIXED RATE SCHEMES VERSUS TRAFFIC LOAD (UNIT: MBPS)

Load	15	20	25	30	35	40	45
Adaptive	0.36	0.38	0.40	0.43	0.46	0.48	0.55
Fixed	8.99	16.90	23.27	27.18	30.32	32.23	35.37

a smaller transmission rate than the short-distance links. On the other hand, with the location based power allocation, each sender adjusts its transmission power according to its distance to the destination and to other nodes, so that each receiver experiences a similar E_b/N_0 value, resulting in a similar transmission rate and throughput. Fig. 6 shows that the aggregate throughput of the two power allocation strategies are very close. The location based power allocation gains better fairness performance than the uniform power allocation without reducing the throughput.

C. Adaptive Versus Fixed Transmission Rate

A random topology scenario is considered. Fifty nodes are randomly distributed in a 30 km $\times$ 30 km area where the node density of the 10 km $\times$ 10 km center area (e.g., the downtown area in a city) is larger than the remaining area. For comparison, the fixed rate scheme is also simulated, in which each sender only transmits $C_{\min}$ substreams regardless of the received E_b/N_0 value. Fig. 7 compares the aggregate throughput of both schemes with different traffic loads. It is clear that the adaptive rate scheme outperforms the fixed rate scheme. When the traffic load increases, the throughput of the fixed rate scheme remains close to 15 Mbps, indicating that it has reached the capacity. On the other hand, the throughput of the adaptive rate scheme increases rapidly with the traffic load. Table III compares the average burst delay (from the instant of a burst arrival to the instant that the whole burst has been transmitted) of the two schemes. The average burst delay in the adaptive rate scheme is much smaller than that in the fixed rate scheme. The results demonstrate that the adaptive rate scheme outperforms the fixed rate scheme.

D. E_b/N_0 Violation due to Probes and ACKs

In our proposed scheme, the probes and ACKs are sent with very small power. It is possible that the interference generated by them may cause the E_b/N_0 of an existing link to drop below the E_b/N_0 requirement, referred to as E_b/N_0 *violation*. In order to protect the data reception of existing links, the E_b/N_0 margin factor δ as in (7) is used in our proposed scheme. To demonstrate the effect of δ value on the E_b/N_0 violation, we set the blocking-signal detection threshold to be zero in the simulation, so that all the potential senders in the system can detect the blocking-signal if any. Thus, no E_b/N_0 violation is caused by undetected blocking-signals. Table IV compares the E_b/N_0 violation probability, defined as the ratio of the number of slots in which the E_b/N_0 of a link is below the requirement to the total number of slots used, with different δ values in the random topology scenario. With an increase of δ from 0.01 to 0.15, the E_b/N_0 violation probability drops from 1.03% to 0.25%. An appropriate δ value should be

TABLE IV
E_b/N_0 VIOLATION PROBABILITY WITH DIFFERENT E_b/N_0 MARGIN FACTOR δ

δ	0.01	0.03	0.06	0.09	0.12	0.15
Violation prob. (%)	1.03	0.6	0.42	0.34	0.30	0.25

chosen according to the requirement on the E_b/N_0 violation probability.

E. Impact of Blocking-Signal Detection Threshold

In addition to probes and ACKs, another factor may lead to the E_b/N_0 violation. In the proposed scheme, when an existing receiver sends a blocking-signal, the potential senders with large interference to the existing receiver should detect the blocking-signal and not start their transmissions. If the blocking-signal detection threshold is too large, the potential senders cannot detect the blocking-signal, and they will start their transmissions and cause the E_b/N_0 violation of the existing receiver. On the other hand, if the blocking-signal detection threshold is too small, some potential senders with small interference to the target existing receiver may be unnecessarily blocked and, further, the potential senders may need to send more probes, thus resulting in a larger delay. For each receiver, we define its neighborhood coverage as the distance to its neighbor[6] with the longest distance, and its blocking-signal coverage as the distance where its blocking-signal can be detected. For the wireless mesh backbone, if the blocking-signal detection threshold is the maximal value such that each receiver's blocking-signal coverage is at least ξ ($\xi \in \mathbb{R}$) times its neighborhood coverage, we say that the wireless mesh backbone is with a relative blocking-signal coverage ξ. We vary the relative blocking-signal coverage ξ to see its impact on the E_b/N_0 violation probability, average probe number per call, and aggregate throughput, as shown in Table V. From Table V, with a smaller ξ, more nodes are unable to detect the blocking-signal, leading to a larger E_b/N_0 violation probability. In the extreme case, when ξ goes to 0 (no node can detect the blocking-signal), the E_b/N_0 violation probability is as high as 30.5%. When ξ goes to infinity (all nodes can detect each blocking-signal), the E_b/N_0 violation probability is 0.8%, but the average probe number per call increases to more than 6. Thus, there should be a tradeoff between the E_b/N_0 violation probability and average probe number per call. This can be shown from the throughput values in Table V. When ξ takes a value between 0.5 and 1, the maximal throughput can be achieved.

F. Impact of Packet/Burst Size

In this research, we consider traffic in the unit of burst rather than packet. As long as a burst is admitted, the packets in the burst are transmitted consecutively at the selected slot. To fit the link layer frame size, a packet at the network layer can be segmented into multiple link layer frames, or multiple small-size packets can be aggregated to form a link layer frame [16].

[6]Two nodes are neighbors if they are connected by a direct link in the routing protocol.

TABLE V
E_b/N_0 VIOLATION PROBABILITY, AVERAGE PROBE NUMBER PER CALL, AND AGGREGATE THROUGHPUT WITH DIFFERENT RELATIVE BLOCKING-SIGNAL COVERAGE ξ

Relative blocking-signal coverage ξ	0	0.25	0.5	1	2	∞
E_b/N_0 violation prob. (%)	30.5	11.5	3.5	1.5	1.4	0.8
Probe number/call	1.0	1.8	3.0	4.7	5.8	6.5
Throughput (Mbps)	37.4	49.5	55.4	55.3	52.8	52.4

So the packet size does not affect the system performance. The impact of variable burst size is also investigated by simulations. We consider an exponentially distributed burst size with mean value 1 Mega bits. As similar performance is observed to that with fixed burst size, we omit the detailed results here.

VI. CONCLUSIONS

We have proposed a CDMA-based receiver-centric resource management scheme for the wireless mesh backbone with a fixed topology. The scheme applies adaptive power, slot, and rate allocation by using the location information and the interference information, to achieve fairness and effectiveness. The existing receivers (rather than the potential senders) determine whether or not new calls should be admitted. Compared with the previous sender-centric resource management schemes, the proposed scheme has much lower control message exchange overhead, and can achieve more accurate interference estimation. With a routing protocol in place, our scheme can provide a solution for future broadband wireless access with fine-granularity QoS. Our on-going research is to jointly design the routing and resource management schemes in the wireless mesh backbone.

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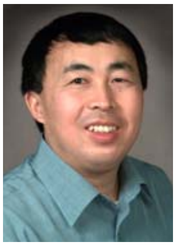

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