OMAR: Utilizing Multiuser Diversity in Wireless Ad Hoc Networks

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Abstract—One of the most promising approaches to improving communication efficiency in wireless communication systems is the use of multiuser diversity. Although it has been widely investigated and shown feasible and efficient in cellular networks, there is little work for the ad hoc networks, especially in real protocol and algorithm design. In this paper, we propose a novel scheme, namely, the Opportunistic Medium Access and Auto Rate (OMAR), to efficiently utilize the shared medium in IEEE 802.11-based ad hoc networks by taking advantage of diversity, distributed scheduling, and adaptivity. In an ad hoc network, especially in a heterogeneous ad hoc network or a mesh network, some nodes may need to communicate with multiple one-hop nodes. We allow such a node with a certain number of links to function as a clusterhead to locally coordinate multiuser communications. We introduce a CDF-based (Cumulative Distribution Function) K-ary opportunistic splitting algorithm and a distributed stochastic scheduling algorithm to resolve intra and intercluster collisions, respectively. Fairness is formulated and solved in terms of social optimality within and across clusters. Analytical and simulation results show that our scheme can significantly improve communication efficiency while providing social fairness.

Index Terms—Wireless ad hoc networks, multiuser diversity, opportunistic medium access, auto rate, cross-layer optimization.

1 Introduction

Providing high-rate and reliable communications is an important design goal in wireless ad hoc networks. However, limited spectrum, time-varying propagation characteristics, hostile interference, and distributed multiple access, together with complexity and energy constraints, impose significant challenges in developing techniques to achieve this objective.

One of the most effective approaches to combating scarce spectrum resources and channel variations is the use of multiuser diversity, which is made possible because different users usually have different instantaneous channel gains for the same shared medium. Opportunistic multiuser communications utilize the physical-layer information fed back from multiple users to optimize the medium access control, packet scheduling [1], [2], [3], [4], and rate adaptation [5], [6]. By allowing the users with good link qualities to transmit data using appropriately chosen modulation schemes, throughput and energy efficiency can be greatly improved.

Diversity techniques have been widely investigated and shown feasible and efficient in infrastructure-based wireless networks [7], [8], [9], [10], [11]; however, these schemes may not be applicable in multihop ad hoc networks because there is no base station to act as the central controller and no dedicated control channel to feed back the channel state in a timely fashion. Moreover, in ad hoc networks, the medium access control is distributed and each node randomly accesses the shared medium without prior channel information.

Most recent work on diversity in ad hoc networks is limited to *multipath diversity* [16], [17], [18], [19], [20], i.e., using multiple paths to opportunistically forward packets to enhance end-to-end reliability. Research on *multi-output link diversity* and *multi-input link diversity* is still open. The *multi-output link diversity* is the output multiuser diversity from one to many (from a node to multiple neighbors). A corresponding case of the multi-output link diversity in ad hoc networks is the downlink diversity in the cellular networks. Similarly, the *multi-input link diversity* is the input multiuser diversity from many to one (from multiple neighbors to a node), which corresponds to uplink diversity in the cellular networks. As far as we know, there is little work that provides realistic study on how to achieve these two types of diversity through MAC protocol design.

With the above observations, we present a novel 802.11-based MAC protocol that exploits these two kinds of multiuser diversity to improve channel efficiency and energy efficiency. The proposed scheme is designed to work efficiently for multihop ad hoc networks, especially heterogeneous ad hoc networks and mesh networks, where multiple nodes need to communicate with a relatively powerful node in the distributed manner. Since opportunistic medium access may easily lead to unfairness, we address the fairness in terms of social optimality.

The basic idea of our proposed scheme is as follows: Each node with a certain number of links is enabled to form a cluster and function as the clusterhead to coordinate multiuser communications locally. In each cycle of data transmission, the clusterhead initiates medium access (with certain probability in a multicluster scenario to ensure intercluster fairness), and then the cluster members (we call them users in the following) distributedly make medium

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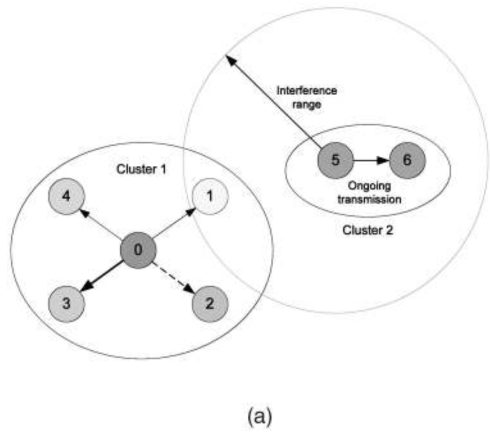

Fig. 1. (a) An illustration of multi-output link diversity. (b) An illustration of multi-input link diversity.

access decisions based on the observed instantaneous channel conditions. A CDF-based K-ary opportunistic splitting algorithm is used to guarantee that only the user with the best normalized instantaneous channel quality will win the channel. After successful collision resolution, a rate-adaptation technique is employed to achieve the highest reliable data rate for the selected user. In this way, we facilitate the exploitation of link diversity during the process of collision avoidance.

In our previous work [12], [13], we discussed MAC enhancement to utilize output link diversity. The scheme proposed in this paper differs from our previous work in its throughput scaling and social optimality. Two papers mostly related to ours are by Qin and Berry [14], [15]. They presented a channel-aware Aloha protocol and a binary opportunistic splitting algorithm, which is one of the first schemes that address the utilization of multiuser diversity in a distributed way. The contribution in our paper has the following features: First, we target the IEEE 802.11-based multihop ad hoc networks, the design of which is much different from that of Aloha-based single-hop networks. Second, we extend the CDF-based binary opportunistic splitting algorithm to the weighted CDF-based K-ray opportunistic splitting algorithm so that general optimization goals can be achieved in a more efficient way. Third, we propose a distributed intercluster collision resolution scheme to achieve the systemwide social optimality in multihop ad hoc networks.

Our design is in line with the 802.11 (DCF mode) standard in that our scheme inherits similar mechanisms to probe the channel and avoid collisions and the similar idea to resolve collisions. Thus, our scheme can be easily incorporated into future 802.11 standards. Theoretical analysis and simulation results demonstrate that our scheme can significantly improve communication efficiency while providing social fairness and can significantly increase energy efficiency and throughput.

The rest of paper is organized as follows: In Section 2, we illustrate our motivation and identify the design challenges. We then present the framework of our scheme in Section 3 and the basic CDF-based opportunistic medium access scheme in Section 4. The basic scheme is extended to the weighted CDF-based opportunistic medium access scheme in Section 5. In Section 6, we discuss the intercluster collision resolution with the objective of social optimality. Analytical and simulation results are provided in Section 7. Finally, we conclude the paper in Section 8.

2 Motivation and Design Challenges

2.1 Motivation

The ad hoc networks we consider in this paper are quite general. It could be a homogeneous ad hoc network, a heterogeneous ad hoc network, or a wireless mesh network. In all these networks, the channel quality of a link is normally time-varying due to such factors as fading, shadowing, noise, and interference. Moreover, different links usually experience independent instantaneous channel qualities. This phenomenon is widely referred to as the multiuser diversity in the literature [7], [8], [9].

For example, as shown in Fig. 1a, node 1 is interfered by ongoing transmission of node 5 and the link of $0 \rightarrow 2$ suffers deep fading or shadowing. The link of $0 \rightarrow 4$ has an instantaneous quality to support basic data rate transmission. The link quality of $0 \rightarrow 3$ happens to be "on-peak." Since only one of these links is allowed to communicate at a time, it is better for node 0 to transmit data to node 3 or 4 rather than node 1 or 2 at the current time. We refer to this as the multi-output link diversity. Similarly, the multi-input link diversity can be observed in the example shown in Fig. 1b.

By using link diversity via opportunistic transmissions, the Head-of-Line blocking problem [1] can be alleviated and higher throughput can be achieved.

2.2 Localized Opportunistic Transmission

Ideally, if there is a global scheduler which knows the systemwide channel information and topology with little cost, the efficiency will be maximally exploited by considering both link quality and space reuse of all active links. Unfortunately, global multiuser scheduling is impossible in multihop ad hoc networks, where no centralized scheduler is available and complete channel information and topology information are hard to obtain. Of course, it is still interesting to utilize the multiuser diversity locally. As shown in our previous work [12], [13], multiuser diversity gain can be significantly achieved without too many links in participation. In fact, even two links can produce substantial diversity gain.

Based on the above observation, we limit multiuser scheduling to a set of links with the same sending node or the same receiving node. Therefore, a node satisfying certain degree requirements can locally coordinate multiuser scheduling among its own input links or output links. We define the set of links with the same sending node or the same receiving node as a cluster and define the common sending node or receiving node as the clusterhead and others as cluster members or users. Since multiple clusters may share the same medium, intercluster contention resolution is necessary. In our protocol, the clusterhead represents the whole cluster to resolve intercluster channel contention. If a clusterhead successfully captures the channel floor, it immediately coordinates the multiuser diversity-based transmission within the cluster for a certain period.

As illustrated in Fig. 1, nodes 0-4 form one cluster and nodes 5-6 form another cluster. Node 0 coordinates the opportunistic transmissions to (from) nodes 1-4. Node 5 coordinates the transmission to node 6. We will further detail the cluster formation and maintenance in the next section.

Note this link-layer diversity-driven clustering is much different from the network-layer clustering [21], [22], [23]. The network-layer clustering is designed to improve routing scalability and simplify network management; the dimension of network-layer cluster may be across several hops; the cost to establish and maintain such network clusters is one of the major design issues. The link-layer clustering is a logical organization to utilize multiuser diversity locally, under which each cluster member is directly associated with clusterhead, and neighboring clusters do not need to exchange information between each other. Moreover, it is simple to establish and maintain a cluster, which is explained later.

2.3 Design Challenges

The first challenge is the MAC design for multiuser diversity-based transmissions within a cluster. One straight approach is that the clusterhead schedules transmissions based on the channel and queue information collected from all users. Although this approach is feasible in cellular networks where dedicated control channels (one for each user) are available, the cost of collecting channel and queue information can be forbiddenly high in single-channel ad hoc networks, especially when the number of users is large. Another approach is that each user distributedly makes a transmission decision based on its own instantaneous channel quality (known to each user by observation) and past channel quality distribution. The user with the higher normalized channel quality is granted higher priority, e.g., with smaller IFS (interframe space) to access the medium. In our paper, we design MAC based on the latter approach since it does not require the collection of channel information from others so that the overhead can be significantly reduced. Under this distributed approach, the challenge will be how we can make the user with the highest normalized channel quality win the channel in a more efficient way.

Our objective in utilizing multiuser diversity is to improve the system performance without sacrificing social fairness. We use intracluster fairness and intercluster fairness to characterize the fairness within and across clusters, respectively. Intracluster problem occurs when links in a cluster have different channel quality distributions. Opportunistic medium access may easily lead to unfairness when the channel states of different users are statistically heterogeneous. For example, in the saturated scenario with two users, the user with a poor average SNR (signal-to-noise-plus-interference-ratio) may be severely starved, while the one with a good average SNR may occupy the medium for most of the time. The intracluster problem becomes more complicated when links have different weights in terms of traffic and utility. The intercluster fairness problem always exists since intercluster channel contentions are normally location-dependent and clusters may carry different weights in terms of aggregate traffic and utility. The intercluster fairness problem is hard to solve because the traffic/topology/channel information of a cluster is normally unknown to another cluster. In this paper, we will address both intracluster and intercluster fairness problem in terms of social optimality within and across clusters.

3 Framework of Cluster-Based Multiuser Communications

In this section, we first present the general idea of clustering and opportunistic medium access. Then, we clarify some assumptions and notations to be used in the later discussions.

3.1 Multiuser Diversity-Driven Clustering

The general idea of cluster formation and maintenance is described as follows: When a node has more than one output link, it will form an output cluster; each output link joins the output cluster. When a node has more than one input link that is not associated with an output cluster, it will form an input cluster; each input link that is not associated with an output cluster joins the input cluster.

Each cluster is designated a unique Cluster ID to identify the cluster. The Cluster ID is a tuple comprised of the MAC address of the clusterhead, the direction flag (1 indicates input, 0 indicates output), and a sequence number. Meanwhile, each cluster member is allocated a local user ID for identification in the cluster. Then, the Cluster ID and the local user ID are sent to the cluster member as a global identity. We call this process the association process.

After a cluster is created, the clusterhead may periodically or reactively check the connectivity of associated links. If a link is disconnected, the clusterhead removes the link from its cluster and returns the local user ID to the user ID pool. We call it the deassociation process. Similarly, if a new link is established to be connected with the clusterhead, the clusterhead will allocate a new local user ID from the user ID pool to the new user and conduct the association process. Depending on the change of out-degree at the sender side and in-degree at the receiver side, a directed link may leave an input cluster to join an output cluster, and vice versa, by following the same rule as the cluster formation introduced earlier in this section.

3.2 Channel Aware Medium Access

Now, we briefly introduce intracluster medium access and collision resolution. In each cycle of data transmission, the clusterhead initiates medium access, while cluster members

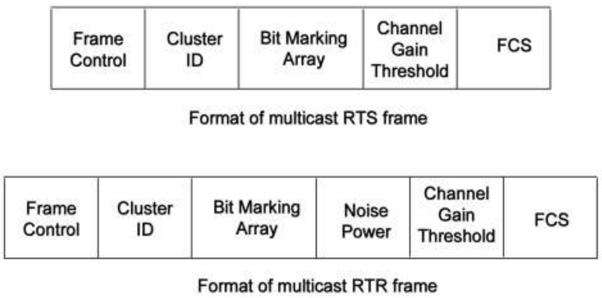

Fig. 2. Format of multicast RTS and RTR frame.

distributedly make medium access decisions based on the observed instantaneous channel conditions. In the multi-output scenario, the clusterhead is the sender of data traffic, so sender-initiated medium access control (SI Mode) is applied. The handshake before data transmission in sender-initiated medium access control includes an RTS (request-to-send) and CTS (clear-to-send) in sequence. We extend the unicast RTS to the multicast RTS and enhance CTS with channel awareness capability so that the handshake can probe the channel among multiple users as well as avoiding or resolving collisions within and outside the cluster. In the multi-input scenario, the clusterhead is the receiver of data traffic, so the receiver-initiated medium access control (RI mode) [24], [25] is applied. The handshake before data transmission in the receiver-initiated medium access control includes RTR (ready-to-receive), RTS, and CTS in sequence. We propose multicast RTR and channel-aware RTS (followed by CTS) to utilize multi-input link diversity as well as collision avoidance and resolution.

For the receiver-initiated medium access, it is better for the clusterhead to know the traffic information. We assume the clusterhead knows this information either by service level agreement on the flow level or the piggyback in the users' transmitted/received packets on the packet level. Related discussions can be found in [24], [25].

When the clusterhead has packets backlogged for several users (in the SI mode) or wants to receive packets from one of the backlogged users (in the RI mode), it will multicast RTS or RTR with the cluster ID to the chosen candidate users. Fig. 2 shows the formats of the multicast RTS frame and the multicast RTR frame. To notify a user of whether it is chosen or not, an array of n bits is included in the RTS or RTR, where n is the total number of cluster members. The $i\text{th}$ bit in the array corresponds to the user whose user ID is equal to i. If a bit is marked as 1, it means the corresponding user is chosen to compete for data reception or transmission; otherwise, it is not within the candidate list in the given cycle. When all the users in the cluster are candidates for data reception or transmission, the clusterhead may send RTS or RTR in the manner of groupcast without using the bit array to notify individual users. The groupcast frames are similar, but without the bit marking array.

The noise power included in the RTR frame indicates the noise plus interference power level at the clusterhead. Recall that, in the multi-input scenario, data traffic is transmitted from users to the clusterhead. It is the received SNR at the clusterhead that determines the achievable data rate. But, the medium access decisions are made in a distributed fashion at the users. So, it is desirable to let the users know the noise power level at the clusterhead. Assuming that the instantaneous channel gains between two nodes are identical in either direction, a candidate user can derive the channel gain. By the derived channel gain and informed noise power level at the clusterhead, users can estimate the received SNR and make the appropriate medium-access decision.

Since an RTS (RTR) has to be sent at the beginning of each cycle of data transmission for collision avoidance and channel probing and is normally sent at the basic rate in multirate ad hoc networks, the overhead of the RTS (RTR) is one of the major factors affecting the channel utilization ratio. With the clustering technique introduced above, the length of the RTS (RTR) is quite small and scalable to a very large group (one additional bit with one additional member). In addition, a large group may be partitioned into several smaller groups so that the scalability is still maintained.

Anyone except the candidate receivers who receives the multicast RTS (RTR) should tentatively keep silent to avoid possible collisions before the clusterhead receives the collision-free CTS (RTS). After a qualified user is selected and the transmission duration is determined and announced by CTS, the sender will include the duration in the subheader of DATA for the final NAV setting. The subheader is referred to as the reservation subheader (RSH), which has already been employed in the MAC header of data packets in IEEE 802.11e, RBAR [5], and OAR [6]. RSH is sent at the basic rate so that all overhearing nodes can decode.

Upon receiving a multicast RTS (RTR), each user checks the bit-marking array. If the corresponding bit is set to 1 and the observed instantaneous SNR is above the threshold indicated in the RTS (RTR) message, it is allowed to compete for the channel. For groupcast RTS (RTR), every user needs to evaluate the channel and prepare to compete for the channel if the observed channel condition is good enough.

If there is only one user who has the desired channel condition, the user captures the channel without a collision within the cluster. If there is no qualified user, the group head defers for a certain time and sends a multicast RTS (RTR) again. In case there is more than one qualified user, collisions may happen. Thus, a collision resolution scheme is required to find a qualified user. We provide a scheme termed the CDF-based K-ary opportunistic splitting algorithm in a later section. This scheme can quickly determine the user with the best normalized channel quality. We begin with the basic CDF-based K-ary splitting algorithm to guarantee timeshare fairness among users and generalize it into a weighted CDF-based K-ary opportunistic splitting algorithm to optimize local system performance.

The general idea and necessary procedures to utilize multi-input link diversity are similar to that of multi-output link diversity. Thus, we will focus on the multi-output link diversity in the following discussion.

3.3 Some Assumptions and Notations

In each cycle of contention resolution plus data transmission, we assume that, once a user captures the shared medium, it is allowed to transmit data up to TXOP. TXOP, a notion introduced in IEEE 802.11e, is the transmission opportunity within which a user can consecutively transmit data without contending for the channel. TXOP can be represented as the total transmission time T.

We assume low mobility throughout this paper. The channel is modeled as a block fading channel in which the instantaneous channel gain may vary randomly from one cycle to another, but is approximately constant during each cycle. Suppose the transmission power is fixed and, thus, the receiving power is almost constant during one cycle, but may be variable between cycles. Similarly, we assume that the noise plus interference power does not change much during one cycle, although it may change significantly when a user captures the channel in another cycle. So, the SNR is stable in each cycle but may randomly change from one cycle to another. Let h_i be the instantaneous SNR of user i, which is considered to be independent for different users. If the large-scale path loss changes very slowly in comparison with the instantaneous channel gain and noise power, h_i can be considered ergodic during a sufficiently long system observation period.

We note that, in the multihop scenario, the interference may partly depend on which set of nodes are actually transmitting. In other words, the instantaneous interference each user gets is spatially correlated to some extent, even though fading effects make the interference power random. However, since we avoid and resolve multihop intercluster collision based on carrier sensing, the interference can be kept low. Our simulation results validate this assumption.

Now, we assume h_i is a random variable with the probability density function $f_{H_i}(h)$. In practice, each user may know the distribution of its own SNR but not those of other nodes. Similarly, each user can determine its own instantaneous SNR just at the beginning of each cycle of data transmission, but not those of other nodes. The instantaneous channel state can be measured during the handshake of the collision avoidance process. The long-term SNR distribution can be derived via the iterative approach as follows: We denote SNRs required to support the lowest rate and the highest rate (constrained by the physical layer) as $h_{\min}$ and $h_{\max}$, respectively, and quantize the instantaneous channel quality as $h_{\min} + \frac{j}{M}(h_{\max} - h_{\min})$ $(0 \leq j \leq M)$, where $(h_{\max} - h_{\min})/M$ represents the quantization interval. Define k as the iteration index and P_j as the PMF (probability mass function) that the quantized channel quality equals $h_{\min} + \frac{j}{M}(h_{\max} - h_{\min})$. P_j can be updated as

$$P_j^{k+1} = \begin{cases} (1-\phi^k)P_m^k + \phi^k, & j = m \\ (1-\phi^k)P_j^k, & j \neq m, \end{cases} \tag{1}$$

where ϕ^k $(0 \leq \phi^k \leq 1)$ is the step size to update PMF. We can choose an appropriate step-size sequence to balance the convergence speed and smoothness. In our simulation, we set ϕ^k as $\frac{1}{\min(k, 1{,}000)}$.

Rate adaptation is based on the instantaneous SNR h evaluated at the beginning of each cycle of data transmission. Once the data rate is set, it will not be changed during the whole data transmission period. Let $R(h)$ be the rate at which a user can reliably transmit if the instantaneous SNR evaluated at the beginning of data transmission is h.

4 Opportunistic Medium Access with Timeshare Fairness (OMAR-B)

If channel quality of each user follows i.i.d distribution, we can directly use the SNR value as the criterion for medium access in each cycle of data transmission. Timeshare fairness is naturally preserved due to the statistical properties of the SNR. However, it fails to guarantee timeshare fairness if the SNRs are heterogeneously distributed among users.

One simple way to guarantee timeshare fairness while exploiting multiuser diversity is to use the normalized channel quality as the threshold for medium access and as the criteria to determine who will win the channel access. We map the instantaneous SNR of each user, i.e., h_i, into its own complementary cumulative probability $p_i = F_{H_i}(h_i) = \int_{h_i}^{\infty} f_{H_i}(h)dh$ (in the discrete case,

$$p_i = F_{H_i}(h_i) = \sum_{j=\frac{M(h_i - h_{\min})}{(h_{\max} - h_{\min})}}^{M} P_j,$$

where P_j is PMF introduced above) and take some $p(0 < p \leq 1)$ as the medium access threshold. In other words, users with the instantaneous SNR higher than $F_{H_i}^{-1}(p)$ are allowed medium access. Clearly, the lower p is, the higher the channel quality required for medium access is, which limits the number of users involved in the competition for the channel. Taking $F_{H_i}(h_i)$ as a random variable, we easily find that $F_{H_i}(h_i)$ is i.i.d across users with the normalized uniform distribution. This means that each user has the same probability to access the medium for any medium-access threshold p. Furthermore, the policy that the user with the lowest instantaneous $F_{H_i}(h_i)$ wins the channel will guarantee that each user has the same probability of capturing the channel. We call this scheme the basic opportunistic medium access control (OMAR-B).

Now, the question is how to design a distributed collision resolution algorithm to find the user with the best normalized instantaneous quality. In the following, we propose a fast carrier sensing-based splitting algorithm, namely, the *K-ary opportunistic splitting algorithm*, to resolve the collisions among the qualified users. The K-ary opportunistic splitting algorithm can be considered the extension of the binary-tree collision resolution algorithm introduced in [15].

4.1 CDF-Based K-Ary Opportunistic Splitting Algorithm

After receiving an RTS, user i with channel quality $h_i > F_{H_i}^{-1}(p)$ is allowed to compete for the channel and transmit a CTS at the beginning of minislot $m_{1,i}$ if there is no transmission in the previous $m_{1,i} - 1$ minislots. The detection of transmission of other users is based on carrier sensing without the need to decode the transmitted packet. The carrier sensing range is normally more than twice the transmission range [26]. Furthermore, CTS (as well as RTS) is applied with sufficient channel error coding and sent at the basic data rate. So, even with fading, a large carrier sensing range still allows users in the same cluster to check if the channel is busy or not. The minislot mentioned in this paper is $aSlotTime$ (20μs in 802.11b with DSSS), as defined in the 802.11 standard. The round of competition just

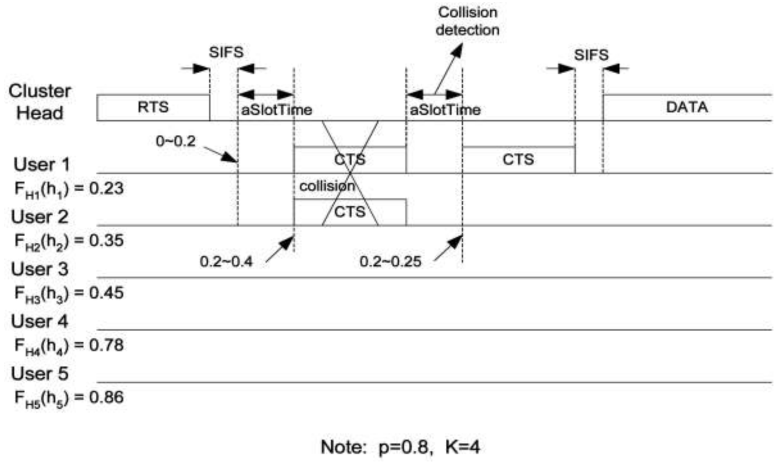

Fig. 3. An example of intracluster collision resolution.

following the RTS is the first round of competition. If there are at least two users in the above process that send CTS simultaneously, it goes to the second round of competition. The users involved with collisions can detect collisions by observing that there is no data transmission one minislot after the CTS. Let m_j $(1 \leq m_j \leq K)$ denote the number of minislot at the beginning of which collisions occur in the jth round of competition.

User i will participate in the second round of competition if it participated in the first-round competition, i.e., had channel quality better than $F_{H_i}^{-1}(\frac{m_1 p}{K})$. It will transmit CTS at the beginning of minislot $m_{2,i}$ if there is no transmission in the previous $m_{2,i} - 1$ minislots after it detects collisions.

In the $j\text{th}(j \geq 3)$ round of competition, user i involved with the $(j-1)\text{th}$ round of competition, i.e., user i with channel quality better than $F_{H_i}^{-1}(\sum_{k=1}^{j-2} \frac{(m_k-1)p}{K^k} + \frac{m_{j-1}p}{K^{j-1}})$, will participate in competition again and transmit a CTS at the beginning of minislot $m_{j,i}$ if there is no data transmission in the previous $m_{j,i} - 1$ minislots after it detects collisions, where

$$m_{j,i} = \begin{cases} \left\lceil \frac{F_{H_i}(h_i)}{p/K} \right\rceil, & j = 1 \\ \left\lceil \frac{F_{H_i}(h_i) - \sum_{k=1}^{j-1} (m_k - 1)\frac{p}{K^k}}{p/K^j} \right\rceil, & j \geq 2. \end{cases} \quad (2)$$

Fig. 3 shows an example of intracluster collision resolution with five users, medium access threshold $p = 0.8$, and $K = 4$. In the first round, those users with channel quality between 0 and 0.2 are expected to transmit CTS at the time SIFS after receiving RTS. Those users with channel quality between 0.2 and 0.4 are expected to transmit CTS at the time $SIFS + aSlotTime$ after receiving RTS and so on. Since no user is with channel quality less than 0.2, users 1 and 2 take the opportunity to transmit CTS at the time $SIFS + aSlotTime$ after receiving RTS. User 3 and user 4 may transmit CTS at $SIFS + 2 * aSlotTime$ and $SIFS + 3 * aSlotTime$, respectively, after receiving RTS, but observe that the channel is busy and, thus, they yield opportunity to user 1 and user 2. User 5 is not qualified and thus will not prepare to transmit CTS. User 1 and user 2 detect collision and enter the second round of channel contention. Since the channel quality of user 1 falls between 0.2 and 0.25, user 1 transmits CTS at the beginning of the first minislot after detecting collision. User 2 may transmit CTS at the beginning of the second minislot if it observes that channel stays idle after collision. Since user 1 has better quality and takes the opportunity, user 2 gives up. Now, the clusterhead receives collision-free CTS and starts DATA transmission.

When two of the best quality users, say user a and user b, have very close SNRs, which means that

$$|F_{H_a}(h_a) - F_{H_b}(h_b)| \to 0,$$

it may take a large number of competition rounds to resolve collisions. With the limitation of quantization in SNR distribution, it may be impossible to tell which one is better than the other. Besides, it is not worth finding the best one since not much SNR gain can be achieved even if the best one is found. We use the following algorithm to resolve collisions after certain rounds, say α, of competition.

In the $j\text{th}(j \geq \alpha)$ round of competition, user i involved with the $(j-1)\text{th}$ round of competition will randomly select a minislot, say $m_{j,i}$, among K minislots to transmit a CTS again after it detects collisions if there is no transmission in the previous $m_{j,i} - 1$ minislots in the $j\text{th}(j \geq \alpha)$ round of competition.

In practice, the maximal number of rounds to resolve collisions should not be too large; otherwise, the channel condition may change significantly after a user wins out. We limit the window size of opportunistic collision resolution, i.e., the total resolution time, to T_{ic}, which is a system parameter set by the clusterhead according to the number of backlogged users and channel coherence time. Fortunately, the average number of rounds of competition needed is very small, about $O(\log_K(n))$, where n is the number of qualified users. Lemma 1 shows the expected time required to resolve a collision.

Lemma 1. *Let EX_n denote the expected time required to resolve a collision with n involved users in sender initiated medium access by the carrier sense opportunistic splitting algorithm with K dimensional tree, we have*

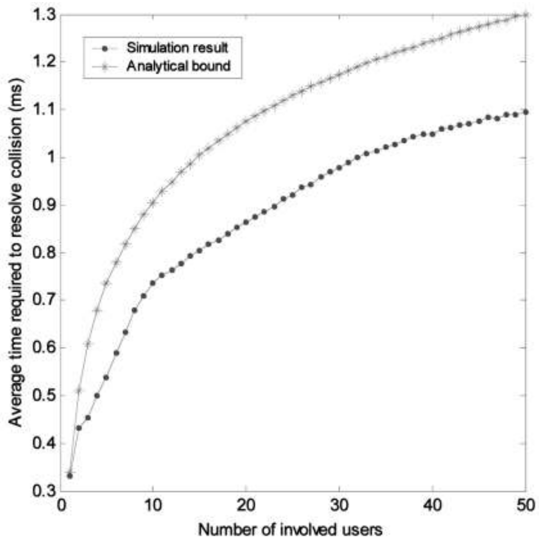

Fig. 4. Average time required to resolve collision.

$$EX_n \leq T_{ini} + \log_k(n)T_{crf} + \left(\log_k(n) + \frac{K}{2}\right)T_{id} + T_{crs} \quad (3)$$

for any $K \geq 2$ and $n \geq 1$, where

$T_{id} = aSlotTime,\ T_{ini} = RTS + SIFS,\ T_{crs} = CTS + SIFS,$ *and* $T_{crf} = CTS + aSlotTime.$

Proof. See Appendix A. □

Fig. 4 shows the analytical bound and simulation result. The parameter setting for the simulation is shown in Table 1. The lower bound of the expected time, denoted by EX_n^Q, required to resolve a collision by Qin and Berry's algorithm [15], is

$$EX_n^Q \geq T_{ini} + \log_2(n)T_{crf}^Q + T_{crs} \quad (4)$$

for any $n \geq 1$, where T_{crf}^Q denotes the round-trip time required for a user to transmit a small reservation packet and detect if a collision occurs. T_{crf}^Q is no less than T_{crf}. Since T_{crf} is normally tens of $aSlotTime$, we may easily find that the K-ary carrier sensing splitting algorithm reduces a lot of collision-resolution overhead when K is larger than 2.

4.2 Throughput Scaling

Suppose a user transmits data with fixed T after successfully capturing the medium. In other words, TXOP is T. For simplicity of analysis, we also consider that the packet transmitted in T is pure DATA. The throughput under the constraints of fairness is given in Proposition 1, which gives the lower bound we can achieve in the saturated case.

Proposition 1. *Let $S_B(p,n,i)$ and $S_B(p,n)$ denote the achievable throughput of user i and the total achievable throughput, respectively, with n independent backlogged users and the medium access threshold p for the pure output-link scenario. Under the basic opportunistic medium access control and the K-ary splitting tree algorithm, we have*

$$S_B(p,n,i) \geq \frac{R(p,n,i)\frac{T}{n}}{T_o(p,n,K) + T} \quad (5)$$

TABLE 1
Parameter Setting

Parameter	Value	Parameter	Value
B(Hz)	10^6	p_0	0.9
$T(\mu s)$	6000	$aSlotTime(\mu s)$	20
K	4	$T_{id}(\mu s)$	20
α	4	$T_{ini}(\mu s)$	300
$T_{ic}(\mu s)$	2000	$T_{crs}(\mu s)$	300
ξ	10^6	$T_{crf}(\mu s)$	320

and

$$S_B(p,n) \geq \frac{\sum_{i=1}^{n} R(p,n,i)\frac{T}{n}}{T_o(p,n,K) + T} \quad (6)$$

with time share fairness, where

$$R(p,n,i) = \sum_{k=1}^{n}\left(\binom{n}{k}p^k(1-p)^{n-k}\left(\int_0^p R\left(F_{H_i}^{-1}(t)\right)\frac{k}{p}\left(1-\frac{t}{p}\right)^{k-1}dt\right)\right), \quad (7)$$

$$T_o(p,n,K) = (1-(1-p)^n)\left(T_{ini} + \log_k\left(\frac{np}{1-(1-p)^n}\right)T_{crf} + \left(\log_K\left(\frac{np}{1-(1-p)^n}\right) + \frac{K}{2}\right)T_{id} + T_{crs}\right), \quad (8)$$

$R(h)$ is the transmission rate when SNR is h,

$T_{id} = aSlotTime,\ T_{ini} = RTS + SIFS,\ T_{crs} = CTS + SIFS,$ *and* $T_{crf} = CTS + aSlotTime.$

Proof. See Appendix B. □

5 Optimal Opportunistic Medium Access with General Optimization Goal (OMAR-E)

In the last section, the opportunistic medium access algorithm guarantees each user the same probability of accessing the channel. In other words, each user gains the same time fraction if TXOP is T. Now, we consider an extended version (OMAR-E) so that each user can get a different proportion of service time. By adjusting the weight vector, we can obtain the desired rate vector which optimizes the local system performance.

5.1 Weighted CDF-Based Opportunistic Medium Access

Let $W = \{w_1, \ldots, w_k, \ldots, w_n\}$ denote the weight vector, where $0 < w_i < 1(\forall i)$ and $\sum_{i=1,n} w_i = 1$. The general CDF-based opportunistic medium access policy is defined as

$$i^* = \arg\max_i \left\{(1 - F_{H_i}(h))^{1/w_i}\right\}, \quad (9)$$

whereby user i can win the channel with probability w_i.

Proposition 2. *The probability that user i is selected for transmission, given that $h_i = h$, is*

$$\Pr\{i^* = i | h_i = h\} = (1 - F_{H_i}(h))^{(1-w_i)/w_i} \quad (10)$$

and the average probability that user i can win the channel is w_i.

Proof.

$$\begin{aligned}&\Pr\{i^* = i | h_i = h\}\\&= \Pr\Big\{\big(1 - F_{H_j}(h_j)\big)^{1/w_j} \le (1 - F_{H_i}(h))^{1/w_i}, \forall j \ne i\Big\}\\&= \prod_{j \ne i} (1 - F_{H_i}(h))^{w_j/w_i} = (1 - F_{H_i}(h))^{(1-w_i)/w_i}\end{aligned} \quad (11)$$

and

$$\begin{aligned}\Pr\{i^* = i\} &= \int_0^\infty \Pr\{i^* = i | h_i = h\} f_{H_i}(h) dh\\&= \int_0^\infty (1 - F_{H_i}(h))^{(1-w_i)/w_i} d(1 - F_{H_i}(h))\\&= w_i.\end{aligned} \quad (12)$$

□

Here, we discuss the extended opportunistic splitting algorithm. Now, we set the threshold p to 1, which means each user is allowed to compete for the channel regardless of its instantaneous channel condition. Similarly to the basic K-ary splitting algorithm discussed in Section 4.1, in the first round of channel competition, user i will transmit a CTS at the beginning of minislot $m'_{1,i}$ if there is no transmission in the previous $m'_{1,i} - 1$ minislots after receiving RTS. User i will participate in the $j\text{th}(j \ge 2)$ round of competition if it participated in the last round of competition and collided with others. It will transmit a CTS at the beginning of minislot $m'_{j,i}$ if there is no transmission in the previous $m'_{j,i} - 1$ minislots after it detects collisions. The algorithm to calculate $m'_{j,i}$ is as follows:

$$m^*_{j,i} = \begin{cases} \left\lceil K\Big(1 - (1 - F_{H_i}(h_i))^{\frac{1}{nw_i}}\Big)\right\rceil, & j = 1\\ \left\lceil K^j\Big(1 - (1 - F_{H_i}(h_i))^{\frac{1}{nw_i}} - \sum_{k=1}^{j-1} (m_k - 1)\frac{1}{K^k}\Big)\right\rceil, & j \ge 2,\end{cases} \quad (13)$$

where n is the number of backlogged users.

We note that, when each user has equal weight, i.e., $w_i = w_j (\forall i \ne j)$, the extended opportunistic splitting algorithm is reduced to the basic one (OMAR-B) given medium access threshold $p = 1$. Generally speaking, the expected time to resolve collision in each cycle of data transmission will depend on the weight vector W. But, it would be a good approximation if we use the upper bound of EX_n shown in (1) to characterize the expected time to resolve collision by the extended opportunistic splitting algorithm. Let EX_n^+ denote the upper bound of EX_n. Suppose TXOP is T, then the service rate of user i is given by

$$\begin{aligned}S_E(n, i, w_i) &= \frac{T}{EX_n^+ + T}\int_0^\infty R(h)\Pr\{i^* = i | h_i = h\} f_{H_i}(h) dh\\&= \frac{T}{EX_n^+ + T}\int_0^\infty R(h)(1 - F_{H_i}(h))^{(1-w_i)/w_i} f_{H_i}(h) dh,\end{aligned} \quad (14)$$

where $R(h)$ is the transmission rate when SNR is h.

Proposition 3. *$S_E(n, i, w_i)$ is concave in w_i.*

Proof.

$$\begin{aligned}&S_E(n, i, w_i)\\&= \frac{T}{EX_n^+ + T}\int_0^\infty R(h)(1 - F_{H_i}(h))^{(1-w_i)/w_i} f_{H_i}(h) dh\\&= \frac{T}{EX_n^+ + T}\left(w_i R(\infty) - \int_0^\infty w_i (1 - F_{H_i}(h))^{1/w_i} R'(h) dh\right).\end{aligned} \quad (15)$$

□

Since nonnegative weighted sums and integrals preserve concavity, it is sufficient to show that $f(w_i) \equiv -w_i a_i^{1/w_i}$ is concave in w_i, given $0 < w_i \le 1$ and $0 \le a_i \le 1$. Since $f''(w_i) = -\frac{1}{w_i^3} a^{1/w_i} (\log a)^2 \le 0$, it completes the proof.

5.2 Determining the Optimal Weight Vector

Next, we want to optimize the system performance by choosing an appropriate weight vector. Define $U_i(x)$ as the utility function of user i in terms of average service rate x. Suppose it is strictly increasing, concave, differentiable, and additive. The optimal weight vector can be achieved by solving the optimization problem

$$\begin{aligned}NLP: \text{Maximize} \quad & \text{z} = \sum_{i=1}^n U_i(S_E(n, i, w_i))\\ \text{s.t.} \quad & \sum_{i=1}^n w_i \le 1 \text{ and}\\ & w_i \ge 0, \forall i.\end{aligned} \quad (16)$$

Proposition 4. *Optimal weight vector W^* is the weight vector which satisfies the K-T conditions of NLP.*

Proof. As shown by Proposition 3, $S_E(n, i, w_i)$ is concave in w_i. We also notice it is nondecreasing and differentiable. Since $U_i(x)$ is concave, differentiable, and nondecreasing in x, $U_i(S_E(n, i, w_i))$ is also concave, differentiable. and nondecreasing in w_i. Thus, z is a concave function in the weight vector W. The constraints function $\sum_{i=1}^n w_i$ is convex and differentiable. So, it completes the proof (please refer to [27] for details). □

It may be difficult to solve the K-T condition equations in practice. Fortunately, we can use the well-known water-filling technique [28] to find the optimal solutions and apply the K-T conditions to validate the optimality.

6 Contention Resolution between Clusters

Within a cluster, as we propose in the previous sections, we use opportunistic splitting algorithms to resolve collisions among qualified users. To deal with collisions between clusters, the legacy exponential backoff algorithm used in IEEE 802.11 can still be used but may not provide systemwide fairness. In order to optimize systemwide performance, we introduce a persistent-based contention resolution algorithm to resolve collision between clusters. This part of work extends the work in [29].

6.1 Modeling Global Optimization

The systemwide optimization problem can be formulated as follows:

$$\begin{aligned} \text{Maximize} \quad & Z = \sum_{j \in A} \sum_{i=1}^{n_j} U_i\big(r_j S_E(n_j, i, w_{ij})\big) \\ \text{s.t.} \quad & \sum_{i=1}^{n_j} w_{ij} \le 1, \forall j \in A \\ & \sum_{j \in A_k} r_j \le 1, \forall k \in A \\ & w_{ij} \ge 0, r_j \ge 0, \forall i, j, \end{aligned} \tag{17}$$

where j, k are indices of clusters, A is the set of all clusters, A_k is a subset of A which includes cluster k plus the clusters who share the channel with cluster k, r_j is the channel allocation rate (i.e., time fraction) for j, n_j is the number of associated users (active directed links) in cluster j, and w_{ij} is the weight for user i in cluster j.

The optimization problem can be easily solved using a convex optimization technique similar to that shown in Section 5. However, our goal is to achieve fully distributed channel allocation. Each cluster is supposed to control its channel allocation rate, which is adjusted in response to the feedback of contention with neighboring clusters. The optimization function of each cluster can be modeled as follows:

$$\begin{aligned} \text{Maximize} \quad & J(r_j) = \sum_{i=1}^{n_j} U_i\big(r_j S_E(n_j, i, w_{ij})\big) - \lambda(\theta_j) r_j \\ \text{s.t.} \quad & \sum_{i=1}^{n_j} w_{ij} \le 1 \\ & w_{ij} \ge 0, \forall (i, j), \end{aligned} \tag{18}$$

where θ_j is the perceived contention loss probability between cluster j and its neighboring clusters. The higher r_j is, the larger θ_j is. Here, $\lambda(\theta_j)$ is the shadow price in terms of contention loss probability. The shadow price function should be strictly increasing and convex in θ. The above optimization problem can also be represented as

$$\text{Maximize} \quad J(r_j) = \sum_{i=1}^{n_j} U_i\Big(r_j S_E(n_j, i, w_{ij}^*(r_j))\Big) - \lambda(\theta_j) r_j, \tag{19}$$

where $w_{ij}^*(r_j)$ denotes the optimal w_{ij} given a r_j. Optimal weight vector W_j^* is achieved by solving the following optimization problem:

$$\begin{aligned} \text{Maximize} \quad & z = \sum_{i=1}^{n_j} U_i\big(r_j S_E(n_j, i, w_{ij})\big) \\ \text{s.t.} \quad & \sum_{i=1}^{n_j} w_{ij} \le 1 \\ & w_{ij} \ge 0, \forall (i, j). \end{aligned} \tag{20}$$

Following the same proof as [30], we can show that $\sum_{j \in A} J(r_j)$ is maximized when each individual cluster j maximizes its own objective function $J(r_j)$. Further, as the shadow price becomes large with the increase of contention loss probability, the fully distributed solution also converges to a channel allocation scheme that maximizes the aggregate utility over all the clusters.

6.2 Distributed Implementation

In this section, we first propose a stochastic approximation algorithm running in each clusterhead to iteratively update the channel allocation rate based on the feedback of the intercluster collision probability. Then, we detail the protocol to resolve intercluster collisions in a persistent way by updating the medium access probability, i.e., the channel allocation rate.

6.2.1 Iteratively Derive Channel Allocation Rate

Note that the concave objective function $J(r_j)$ is maximized when

$$J'(r_j) = 0 \iff \sum_{i=1}^{n_j} U_i'\Big(r_j^* S_E(n_j, i, w_{ij}^*(r_j^*))\Big) - \lambda\Big(\theta_j^*\Big) = 0, \tag{21}$$

where r_j^* is the optimal channel allocation rate of cluster j and θ_j^* is the perceived contention loss probability when cluster j and its neighboring clusters access the medium with optimal channel allocation rate.

Now, we use a time-averaging stochastic approximation algorithm with feedback to update the channel allocation rate,

$$\begin{aligned} & r_j^{k+1} = \bar{r}_j^k + \xi \nu_k \left(\sum_{i=1}^{n_j} U_i'\Big(\bar{r}_j^k S_E(n_j, i, w_{ij}^*(\bar{r}_j^k))\Big) - \lambda\Big(\bar{\theta}_j^k\Big) \right), \\ & \bar{r}_j^k = (1 - \beta_k) \bar{r}_j^{k-1} + \beta_k r_j^k, \\ & \bar{\theta}_j^k = \begin{cases} (1 - \delta_k) \bar{\theta}_j^{k-1} + \delta_k, & \text{collision happens in cycle k} \\ (1 - \delta_k) \bar{\theta}_j^{k-1}, & \text{no collision in cycle k,} \end{cases} \end{aligned} \tag{22}$$

where ξ, ν_k, β_k, and δ_k are adjusting parameters. Following the standard proof in [31], we can show that r_j^k converges to r_j^* with probability 1. In our study, we take ξ as 10^6 and take ν_k, β_k, and δ_k as $\frac{1}{k}$; our simulations show that the convergence speed is quick.

6.2.2 Implementation Details

The state diagram of a clusterhead is shown in Fig. 5. At the initial state, k, r_j, and θ_j are, respectively, set to 100, 1/6, and 0. However, the setting of initial value for r_j and θ_j is quite flexible. With r_j optimized iteratively, the statistical approximation algorithm guarantees r_j converges to r_j^* with any initial state. The optimal weight vector W_j^* will be

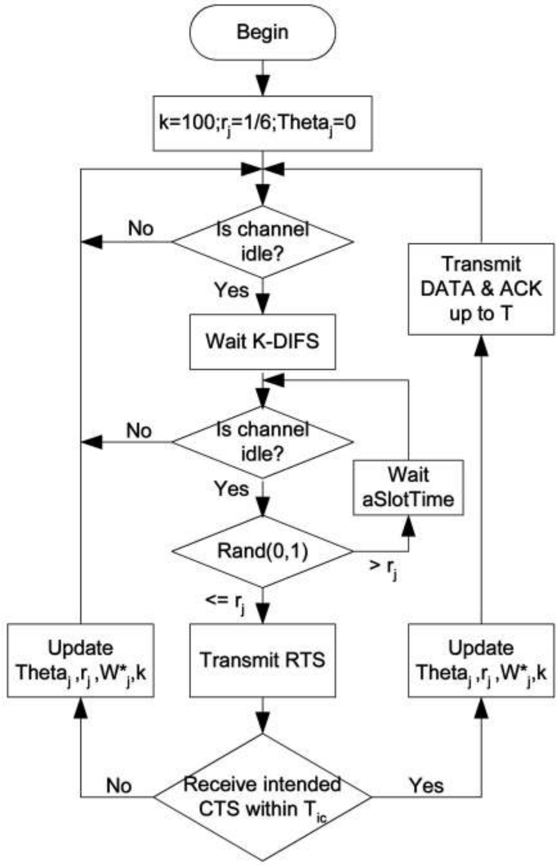

Fig. 5. State diagram of clusterhead.

derived iteratively by (20) with updated r_j. K-DIFS (K-ary DCF Inter-Frame Space) is equal to $(K+1)aSlotTime$. T_{ic} is defined in Section 4.1 and denotes the window size for intracluster opportunistic collision resolution.

7 Performance Evaluation

Three sets of simulations are presented in this section. We first study the throughput scaling effect and fairness in an isolated cluster. Then, we investigate efficiency and fairness across several clusters which are contending with each other. Finally, we consider the join effects of the number of users in each cluster and mobility on the efficiency, fairness, and stability of our scheme.

The parameter setting is shown in Table 1. The simulation tool we use is ns2. We provide two sets of simulations. The first set is to examine single-cluster performance. The second set is to investigate the efficiency and fairness of intercluster collision resolution.

7.1 Single-Cluster

We consider the saturated case in a local area ad hoc network with only one clusterhead. All the traffic is from the clusterhead to the users. The clusterhead can immediately initiate a new cycle of data transmission after the previous one completes. With the same assumption as the theoretical analysis in the previous sections, we assume that each packet can be correctly received once it is transmitted at the appropriate data rate and that ACK is not used. We set the protocol operations

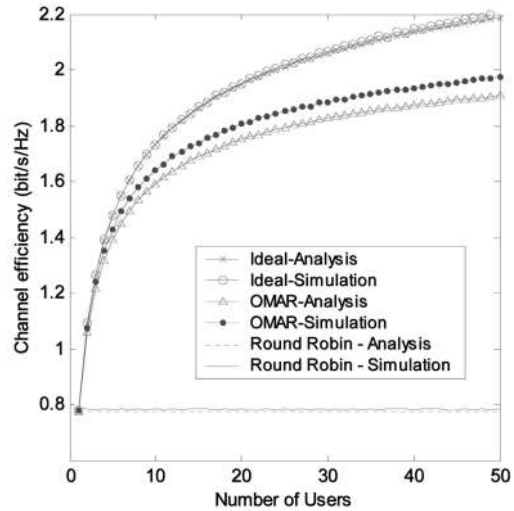

Fig. 6. Channel efficiency with time-share fairness.

in this way to facilitate the comparative study on the channel efficiency of different schemes. The channel is modeled as Rayleigh fading. Denote h_i as the instantaneous SNR. Then, we have $f_{H_i}(h) = e^{-h/\overline{h_i}}/\overline{h_i}$, where $\overline{h_i}$ is the average SNR of user i. We assume that the link qualities at different nodes are i.i.d. The achievable data rate of each link is formulated as a truncated Shannon rate, i.e., $R(h) = B\log_2(1+\min(h, h_{\max}))$, where $h_{\max}$ is the upper bound related to T (we set $h_{\max}$ as 100 in our performance evaluation).

7.1.1 Time-Share Fairness

We compare our scheme (OMAR-B) with the round-robin scheduler and the ideal scheduler. The ideal scheduler has full knowledge of the channel information prior to scheduling so that it can target the best quality user without overhead. For the analytical results, the formula to calculate the throughput of OMAR-B has been introduced in the previous sections. The formulae to calculate the throughput of the round-robin scheduler and the ideal scheduler are similar to that of OMAR-B and are omitted here.

We first consider the case with homogeneous channel condition. $\overline{h_i}$ is equal to 1 for each user. Fig. 6 shows one set of analytical and simulation results in which the medium access threshold for OMAR-B is 0.9. The simulation results are quite close to the analytical results. The OMAR-B performs much better than the round-robin scheduler and can scale well with the number of backlogged users. The channel efficiency of the OMAR-B can approach approximately 90 percent of that for the idea scheduler when TXOP is T. When the medium access thresholds for OMAR-B are set with different values, the performance is affected. However, the throughput scaling effects and the relationship between the theoretical results and simulation results are also observed.

Next, we consider heterogeneous channel conditions. Table 2 shows the channel condition and throughput result of each user. The simulation results match the analytical results very well. Almost every user of the OMAR scheme gets twice the throughput of the round-robin scheme.

TABLE 2
Throughput with Time-Share Fairness in Heterogeneous Case

Flow ID	0	1	2	3	4	5	6	7	8	Total
$\overline{h_i}$	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	
Ideal-Anl (bit/s)	139323	153259	165952	177609	188388	198413	207785	216584	224876	1672189
Ideal-Sim (bit/s)	140834	154745	167252	177787	187636	197637	207066	216356	223877	1673190
OMAR-Anl (bit/s)	128551	141410	153121	163877	173822	183073	191720	199838	207490	1542902
OMAR-Sim (bit/s)	132708	146138	157953	168142	177599	187697	197382	206643	213307	1587569
RR-Anl (bit/s)	60516	67753	74529	80904	86929	92644	98082	103271	108235	772863
RR-Sim (bit/s)	59938	67820	73932	80858	86931	93228	98136	103030	108196	772069

TABLE 3
Case Study of General Optimization

Parameter	Flow ID	0	1	2	3	4	5	6	7	8	9	Aggregate
	$\overline{h_i}$	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
	v_i	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	
case 1	OMAR(W^*)	0.071	0.078	0.084	0.091	0.097	0.103	0.110	0.116	0.122	0.128	1.0
	OMAR-utility	11.7	13.0	14.2	15.5	16.8	18.0	19.3	20.6	21.9	23.2	174.0
	RR-utility	11.3	12.4	13.5	14.6	15.8	16.9	18.0	19.2	20.3	21.4	163.4
case 2	OMAR(W^*)	0.014	0.027	0.043	0.063	0.084	0.106	0.130	0.153	0.178	0.202	1.0
	OMAR-utility	29.8	58.1	94.8	145.1	197.8	256.5	321.4	388.7	461.2	536.6	2490.0
	RR-utility	78.2	86.1	93.0	102.2	109.8	116.8	126.5	132.9	140.0	148.8	1134.4

7.1.2 General Optimization

We consider two cases. In the first case, the utility function of user i equals $U_i(x_i) = v_i \log(x_i)$, where x_i is the achievable throughput (bit/s). In the second case, the utility function of user i is equal to $U_i(x_i) = v_i * x_i/1{,}000$, where v_i is the assigning utility weight. As shown in Table 3, the higher the utility weight v_i, the higher the throughput and the higher the achieved utility. In the first case, even with $\log(\cdot)$ effects, the aggregate utility is still improved significantly in comparison with the round-robin scheme. For the second case, since the utility function is linear, the aggregate utility has been significantly improved.

7.2 Multicluster without Mobility

Here, we discuss the intercluster collision resolution. Global fairness is achieved by distributedly optimizing social optimality. Fig. 7 shows the simulated topology. There are three clusters with five, one, and three directed link flows, respectively. Suppose that the traffic on each link flow is greedy. The utility function of each flow is $U_i(x_i) = v_i \log(x_i)$, where v_i is the utility weight and x_i is the throughput (bit/s). In the first cluster, the clusterhead node 6 coordinates the receiver-initiated medium access to exploit multi-input link diversity. In cluster 3, node 7 coordinates the sender-initiated medium access to exploit the multi-output link diversity. The channel model and achievable rate function are formulated the same as the single-cluster case.

We use the stochastic approximation algorithm to distributedly achieve the optimal channel allocation rate for each cluster. The shadow price in terms of perceived collision probability is given by $\lambda(\theta) = 0.001\theta$. Fig. 8 shows the convergence speed of the time averaged stochastic

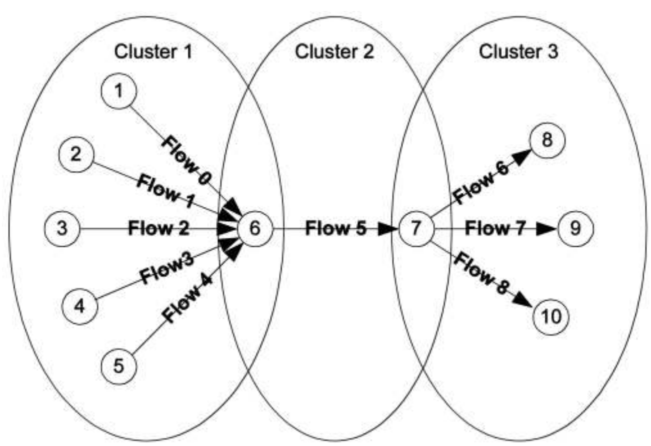

Fig. 7. Multicluster topology.

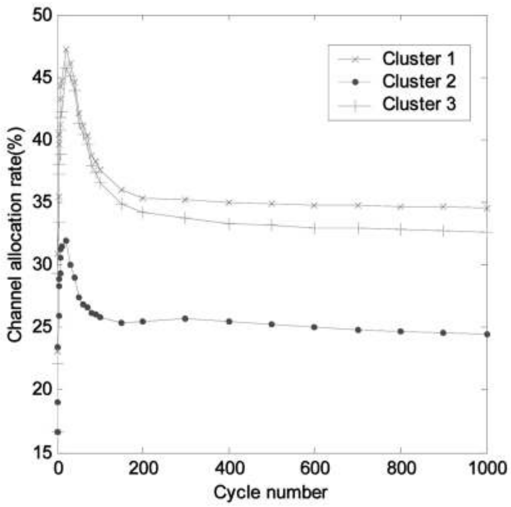

Fig. 8. Convergence speed of the channel allocation rate with the stochastic approximation algorithm.

approximation with feedback. It takes only about 200 cycles, i.e., 1.5 sec, to reach stability. We also find the slope of the shadow price function does not affect the convergence speed much as long as it is sufficiently large. The channel allocation rate of each cluster decreases (proportionally with each other) when the shadow price increases to a very large value. However, the throughput and utility are not affected much. The reason is that each clusterhead persistently accesses medium with the channel allocation rate minislot by minislot whenever a channel is free. Note that the minislot is relatively short to the TXOP. Thus, the wasted time for collision resolution is small.

We use throughput and utility to evaluate the performance gain in comparison with 802.11. Shown by Table 4, the aggregate utility and aggregate throughput have been improved by 6 percent and 54 percent, respectively. In 802.11, the throughput are equally shared. In OMAR, more timeshares are given to the user with a higher utility function, thus the aggregate utility is increased. Furthermore, OMAR exploits multiuser diversity, so the throughput of each user has been increased.

7.3 Multicluster with Mobility

We consider a heterogeneous ad hoc network with mobility in this set of study. Fig. 9 presents an abstraction of the simulated heterogeneous ad hoc network. Each powerful node forms a cluster and functions as the clusterhead. Each common node associates with the nearest powerful node. In the beginning, both powerful nodes and common nodes are evenly distributed over a $400m \times 600m$ area (but each common node is away from the nearest powerful node with 70m). Later on, common nodes move randomly, following the random-way point mobility model with minimal speed larger than 0.1 m/s. Each common node estimates its SNR distribution iteratively by (1). For simplicity, we consider that all the traffic is from powerful nodes to associated common nodes. The traffic of each link is saturated. The utility function of each link is $U_i(x_i) = \log(x_i)$, where x_i is the throughput (bit/s). Under this utility function, each user can obtain equal opportunity to access channel in a cluster, i.e., time-share fairness within a cluster can be achieved by OMAR. For 802.11, we use round-robin scheduling to

TABLE 4
Optimal Intercluster Collision Resolution

Flow ID	0	1	2	3	4	5	6	7	8	
$\overline{h_i}$	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	Aggregate
v_i	1.0	1.0	1.0	1.0	1.0	5.0	2.0	2.0	2.0	
OMAR-throughput	111665	111229	116085	113279	110363	172492	137754	145348	145591	1163807
OMAR-utility	11.6	11.6	11.7	11.6	11.6	60.3	23.7	23.8	23.8	189.7
802.11-throughput	108151	108150	108151	108152	108150	108151	36050	36051	36050	757057
802.11-utility	11.6	11.6	11.6	11.6	11.6	57.9	21.0	21.0	21.0	178.9

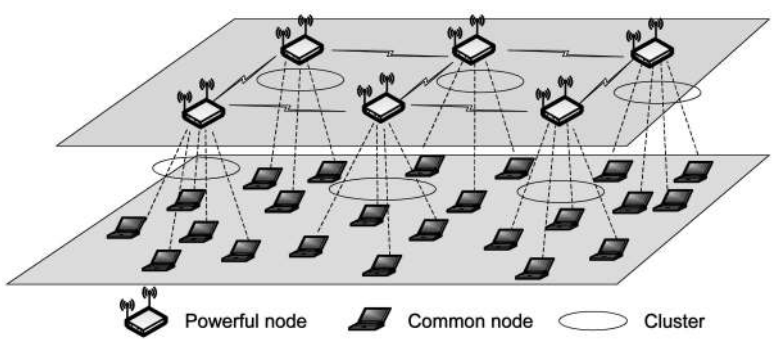

Fig. 9. An abstraction of the simulated heterogeneous ad hoc network.

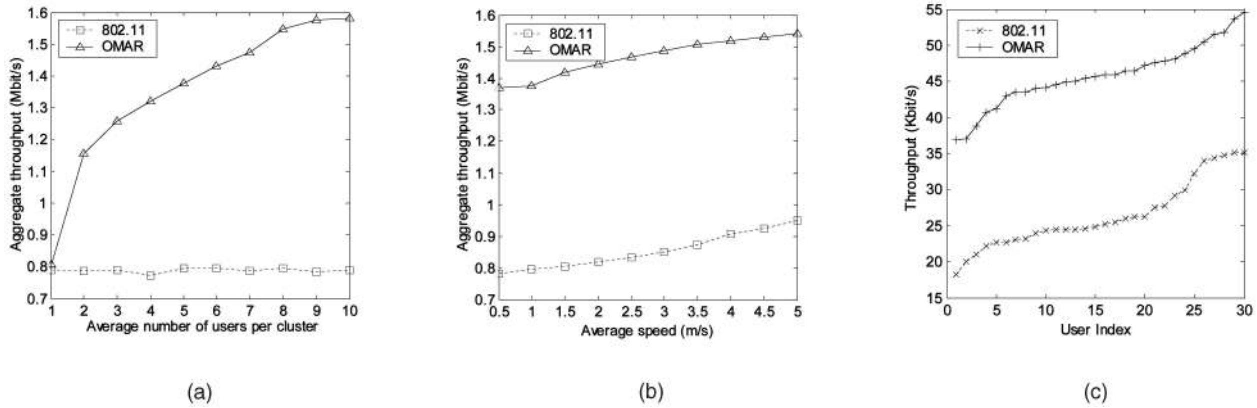

Fig. 10. (a) Throughput versus node density. (b) Throughput versus node mobility. (c) Throughput fairness.

guarantee the time-share fairness among the output links. The achievable data rate, in terms of the distance d, and the fading factor h, is

$$R(d,h) = B\log_2\left(1 + \left(\frac{250}{\max(25,d)}\right)^4 \frac{\min(h,h_{\max})}{156}\right), \qquad (23)$$

where h follows the Rayleigh distribution with expectation 1 and $h_{\max}$ equal to 100. The simulation time of each scene is 2,000s. The result of each scenario is averaged over 10 simulation results.

We first examine the effect of the node density on throughput. We vary the total number of nodes from six to 60 such that the average number of users in each cluster is from one to 10. Each common node moves at the average speed 1 m/s. As shown in Fig. 10a, the aggregate throughput can be significantly improved by utilizing multiuser diversity even though the number of users in each cluster is small, e.g., two. The performance gain steadily increases as the number of users increase. When the average number of users in each cluster is 10, the throughput by OMAR is about twice that under 802.11.

Then, we examine the effect of the node mobility on throughput. The average number of users in each cluster is five. As shown in Fig. 10b, both OMAR and 802.11 increase throughput as the average speed increases. This is reasonable. In the beginning, we put each node away from the nearest powerful node with 70m. Later on, some nodes get much closer to the associated powerful node even though some nodes get further. But, no matter how far away, each link in a cluster gets a similar opportunity to access channel. Considering the achievable rate function, (23), and the total simulation time, the aggregate throughput will increase as the speed increases from 0.5 m/s to 5 m/s. It is worthy to note that the performance gain of OMAR over 802.11 is affected when speed increases, mainly due to increasing clustering overhead and channel estimation error. However, the performance gain of OMAR over 802.11 is still substantial.

OMAR achieves higher aggregate throughput without sacrifice of individual fairness. Fig. 10c shows the throughput of each user in the scene with 30 common nodes moving at 1 m/s on average. Users are sorted according to throughput. Each user by OMAR achieves much higher throughput than that under 802.11. The reason that some nodes get higher throughput than others under the same scheme is mainly because of their shorter distances to associated powerful nodes after they randomly move.

8 Conclusion

In this paper, we propose the opportunistic medium access and auto rate protocol (OMAR) to improve system performance with the use of multiuser diversity. A diversity driven clustering technique is presented to coordinate multiuser communications locally. We introduce the CDF-based K-ary opportunistic splitting algorithm and a distributed stochastic scheduling algorithm to resolve intra and intercluster collisions, respectively. Fairness is maintained, with respect to social optimality, within and across clusters.

To the best of our knowledge, this is the first paper that takes the cross-layer optimization approach to exploit multiuser diversity in the 802.11-based ad hoc networks. Theoretical analysis and simulation results indicate that our scheme can significantly improve throughput without sacrifice of fairness. Other nice features of our proposed protocol are its simplicity for distributed implementation and its compatibility with popular 802.11 MAC standard.

Appendix A
Proof of Lemma 1

The proof of Lemma 1 is motivated by [15].

Proof. When there is only one user, $EX_1 = \frac{K-1}{2}T_{id} + T_{crs}$. For any $n \geq 2, K \geq 2$,

$$\begin{cases} EX_n = EX_{n,K} \\ EX_{n,i} = \frac{n}{i}\left(1-\frac{1}{i}\right)^{n-1}T_{crs} + \sum_{j=2}^{n}\binom{n}{j}\left(\frac{1}{i}\right)^j\left(1-\frac{1}{i}\right)^{n-j} \\ \left(EX_j + T_{crf}\right) + \left(1-\frac{1}{i}\right)^n\left(EX_{n,i-1}+T_{id}\right), 2 \leq i \leq K \\ EX_{n,1} = EX_n + T_{crf}. \end{cases} \qquad (24)$$

Let EC_n be the total number of rounds to resolve a collision with n involved users, in which $EC_n - 1$ rounds fail and the last round succeeds. Let EI_n be the total number of idle minislots spent during collision resolution. Then, we have

$$EX_n = (EC_n - 1)T_{crf} + EI_nT_{id} + T_{crs}. \quad (25)$$

To prove $EX_n \leq \log_K(n)T_{crf} + \left(\log_K(n) + \frac{K}{2}\right)T_{id} + T_{crs}$, we only need to prove $EC_n \leq \log_K(n) + 1$ and $EI_n \leq \log_K(n) + \frac{K}{2}$ when $n \geq 1$ and $K \geq 2$.

First, we examine EC_n. Since $EC_1 = 1$ and $EC_2 = \frac{k}{k-1}$, $EC_n \leq \log_K(n) + 1$ holds when $n = 1$ and $n = 2$ for any $K \geq 2$. According to (24), we have

$$\begin{aligned} EC_n = &\frac{1}{K^n}\binom{n}{1}\sum_{j=1}^{K-1} j^{n-1} + \frac{1}{K^{n-1}}(EC_n + 1) \\ &+ \frac{1}{K^n}\sum_{i=2}^{n-1}\binom{n}{1}\left(\sum_{j=1}^{K-1} j^{n-i}\right)(EC_i + 1), \end{aligned} \quad (26)$$

i.e.,

$$\left(1 - \frac{1}{K^{n-1}}\right)EC_n = \frac{1}{K^n}\sum_{j=1}^{K-1}\sum_{i=2}^{n-1}\binom{n}{i}^{n-i} EC_i + 1$$

when $n \geq 3$ and $K \geq 2$. Using the induction hypothesis, we have

$$\left(1 - \frac{1}{K^{n-1}}\right)EC_n \leq \frac{1}{K^n}\sum_{j=1}^{K-1}\sum_{i=2}^{n-1}\binom{n}{i}j^{n-i}(\log_k(i) + 1) + 1. \quad (27)$$

Let

$$c = \frac{1}{K^n}\sum_{j=1}^{K-1}\sum_{i=2}^{n-1}\binom{n}{i}j^{n-i} = 1 - \frac{1}{K^{n-1}} - \frac{n}{K^n}\sum_{j=1}^{K-1} j^{n-1}.$$

Using Jensen's inequality, for all $n \geq 3$, we have

$$\begin{aligned} &\frac{1}{K^n}\sum_{j=1}^{K-1}\sum_{i=2}^{n-1}\binom{n}{i}j^{n-i}\log_k(i) \\ &= c\left(\frac{1}{cK^n}\sum_{j=1}^{K-1}\sum_{i=2}^{n-1}\binom{n}{i}ij^{n-i}\log_k(i)\right) \\ &\leq c\log_k\left(\frac{1}{cK^n}\sum_{j=1}^{K-1}\sum_{i=2}^{n-1} i\binom{n}{i}j^{n-i}\right) \\ &= c\log_k\left(\frac{n}{Kc}\left(1 - \frac{1}{K^{n-2}}\right)\right). \end{aligned} \quad (28)$$

Substituting (28) into (27), it yields

$$\begin{aligned} &\left(1 - \frac{1}{K^{n-1}}\right)EC_n \\ &\leq c\log_k\left(\frac{n}{Kc}\left(1 - \frac{1}{K^{n-2}}\right)\right) + c + 1 \\ &= c\log_k\left(\frac{n}{c}\left(1 - \frac{1}{K^{n-2}}\right)\right) + 1. \end{aligned} \quad (29)$$

We can show that

$$\frac{c\log_k\left(\frac{n}{c}\left(1 - \frac{1}{K^{n-2}}\right)\right) + 1}{\left(1 - \frac{1}{K^{n-1}}\right)} \leq \log_k(n) + 1 \quad (30)$$

holds for all $K \geq 2, n \geq 3$. Thus, we get $EC_n \leq \log_K(n) + 1$ as desired.

Now, we will prove $EI_n \leq \log_K(n) + \frac{K}{2}$. Since $EI_1 = \frac{K}{2}$ and $EI_2 = \frac{1}{K(K-1)}\sum_{j=1}^{K-1} j^2$, $EI_n \leq \log_K(n) + \frac{K}{2}$ holds when $n = 1$ and $n = 2$ for any $K \geq 2$. According to (25), we have

$$\left(1 - \frac{1}{K^{n-1}}\right)EI_n = \frac{1}{K^n}\sum_{j=1}^{K-1}\sum_{i=2}^{n-1}\binom{n}{i}j^{n-i}EI_i + \frac{1}{K^n}\sum_{j=1}^{K-1} j^n \quad (31)$$

when $n \geq 3$.

Using the induction hypothesis and Jensen's inequality, we have

$$\begin{aligned} &\left(1 - \frac{1}{K^{n-1}}\right)EI_n \\ &= \frac{1}{K^n}\sum_{j=1}^{K-1}\sum_{i=2}^{n-1}\binom{n}{i}j^{n-i}EI_i + \frac{1}{K^n}\sum_{j=1}^{K-1} j^n \\ &\leq \frac{1}{K^n}\sum_{j=1}^{K-1}\sum_{i=2}^{n-1}\binom{n}{i}j^{n-i}\left(\log_k(i) + \frac{K}{2}\right) + \frac{1}{K^n}\sum_{j=1}^{K-1} j^n \\ &\leq c\log_k\left(\frac{n}{Kc}\left(1 - \frac{1}{K^{n-2}}\right)\right) + \frac{Kc}{2} + \frac{1}{K^n}\sum_{j=1}^{K-1} j^n. \end{aligned} \quad (32)$$

We can show that

$$\frac{c\log_k\left(\frac{n}{Kc}\left(1 - \frac{1}{K^{n-2}}\right)\right) + \frac{Kc}{2} + \frac{1}{K^n}\sum_{j=1}^{K-1} j^n}{\left(1 - \frac{1}{K^{n-1}}\right)} \leq \log_k(n) + \frac{K}{2} \quad (33)$$

holds for all $K \geq 2$, $n \geq 3$. So, $EI_n \leq \log_K(n) + \frac{K}{2}$ is satisfied as desired.

So, $EX_n \leq \log_K(n)T_{crf} + \left(\log_K(n) + \frac{K}{2}\right)T_{id} + T_{crs}$ satisfies for any $n \geq 1, K \geq 2$. □

Appendix B

Proof of Proposition 1

Proof. For any transformed SNR threshold p, each user has the same probability of being qualified and the qualified users have i.i.d SNR distribution with $Y_i \sim U[0, p]$.

The probability that there are k qualified users (i.e., those satisfying $h_i > F_{H_i}^{-1}(x)$) among n backlogged users is $\binom{n}{k}p^k(1-p)^{n-k}$. Let $MX_{k,p} \equiv \min\{Y_i, 1 \leq i \leq k\}$. It is easy to get $f_{MX_{k,p}}(t) = \frac{k}{p}\left(1 - \frac{t}{p}\right)^{k-1}, 0 \leq t \leq p$.

To provide time-share fairness, each winning user is allowed to transmit data with duration T. The average achievable rate of user i, given it wins out of n candidate users, is shown to be

$$\begin{aligned} R(p,n,i) &= \sum_{k=1}^{n}\binom{n}{i}p^k(1-p)^{n-k}\left(\int_0^p R\left(F_{H_i}^{-1}(t)\right)f_{MX_{k,p}}(t)dt\right) \\ &= \sum_{k=1}^{n}\left(\binom{n}{i}p^k(1-p)^{n-k}\left(\int_0^p R\left(F_{H_i}^{-1}(t)\right)\frac{k}{p}\left(1 - \frac{t}{p}\right)^{k-1}dt\right)\right). \end{aligned} \quad (34)$$

The average cycle duration is

$$T_{cyc} = \sum_{k=1}^{n} \binom{n}{i} p^k (1-p)^{n-k} EX_k + T. \tag{35}$$

According to Lemma 1, we have

$$\begin{aligned} T_{cyc} \leq T + \sum_{k=1}^{n} \Bigg(\binom{n}{i} p^k (1-p)^{n-k} \\ \Big(T_{ini} + \log_k(k) T_{crf} + \Big(\log_k(k) + \frac{K}{2} \Big) T_{id} + T_{crs} \Big) \Bigg). \end{aligned} \tag{36}$$

Using Jensen's inequality, we have

$$\begin{aligned} T_{cyc} \leq T + (1-(1-p)^n) \\ \Big(T_{ini} + \log_k \Big(\frac{np}{1-(1-p)^n} \Big) T_{crf} \\ + \Big(\log_k \Big(\frac{np}{1-(1-p)^n} \Big) + \frac{K}{2} \Big) T_{id} + T_{crs} \Big). \end{aligned} \tag{37}$$

Let

$$\begin{aligned} T_o(p,n,K) = (1-(1-p)^n) \\ \Big(T_{ini} + \log_k \Big(\frac{np}{1-(1-p)^n} \Big) T_{crf} \\ + \Big(\log_k \Big(\frac{np}{1-(1-p)^n} \Big) + \frac{K}{2} \Big) T_{id} + T_{crs} \Big), \end{aligned} \tag{38}$$

then $T_{cyc} \leq T_o(p,n,K) + T$. Since

$$S_B(p,n,i) = \frac{R(p,n,i)\frac{T}{n}}{T_{cyc}},$$

we have $S_B(p,n,i) \geq \frac{R(p,n,)\frac{T}{n}}{T_o(p,n,K)+T}$ with time-share fairness as desired. □

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REFERENCES

[1] P. Bhagwat, P. Bhattacharya, A. Krishna, and S.K. Tripathi, "Enhancing Throughput over Wireless LANs Using Channel State Dependent Packet Scheduling," *Proc. INFOCOM '96,* 1996.

[2] T.S. Eugene Ng, I. Stoica, and H. Zhang, "Packet Fair Queueing Algorithms for Wireless Networks with Location-Dependent Errors," *Proc. INFOCOM '98,* 1998.

[3] S. Lu, V. Bharghavan, and R. Srikant, "Fair Scheduling in Wireless Packet Networks," *IEEE/ACM Trans. Networking,* vol. 7, no. 4, Aug. 1999.

[4] Y. Cao and V.O.K. Li, "Scheduling Algorithms in Broad-Band Wireless Networks," *Proc. IEEE,* vol. 89, no. 1, Jan. 2001.

[5] G. Holland, N.H. Vaidya, and P. Bahl, "A Rate-Adaptive MAC Protocol for Multi-Hop Wireless Networks," *Proc. MobiCom '01,* 2001.

[6] B. Sadeghi, V. Kanodia, A. Sabharwal, and E. Knightly, "Opportunistic Medium Access for Multirate Ad hoc Networks," *Proc. MobiCom '02,* 2002.

[7] R. Knopp and P.A. Humblet, "Information Capacity and Power Control in Single-Cell Multiuser Communications," *Proc. Int'l Conf. Comm.,* 1995.

[8] D. Tse and S. Hanly, "Multi-Access Fading Channels: Part I: Polymatroid Structure, Optimal Resource Allocation and Throughput Capacities," *IEEE Trans. Information Theory,* vol. 44, no. 7, pp. 2796-2815, Nov. 1998.

[9] P. Bender, P. Black, M. Grob, R. Padovani, N. Sindhushayana, and A. Viterbi, "CDMA/HDR: A Bandwidth Efficient High Speed Wireless Data Service for Nomadic Users," *IEEE Comm. Magazine,* vol. 38, no. 7, pp. 70-77, July 2000.

[10] M. Hu and J. Zhang, "Opportunistic Multi-Access: Multiuser Diversity, Realy-Aided Opportunistic Scheduling, and Traffic-Aided Admission Control," *J. Special Topics in Mobile Networking and Applications,* vol. 9, pp. 435-444, 2004.

[11] D. Park, H. Seo, H. Kwon, and B.G. Lee, "Wireless Packet Scheduling Based on the Cumulative Distribution Function of User Transmission Rates," *IEEE Trans. Comm.,* vol. 53, no. 11, pp. 1919-1929, 2005.

[12] J. Wang, H. Zhai, and Y. Fang, "Opportunistic Packet Scheduling and Media Access Control for Wireless LANs and Multi-Hop Ad Hoc Networks," *Proc. IEEE Wireless Comm. and Networking Conf. (WCNC '04),* Mar. 2004.

[13] J. Wang, H. Zhai, Y. Fang, and M.C. Yuang, "Opportunistic Media Access Control and Rate Adaptation for Wireless Ad Hoc Networks," *Proc. IEEE Comm. Conf. (ICC '04),* June 2004.

[14] X. Qin and R. Berry, "Exploiting Multiuser Diversity for Medium Access Control in Wireless Networks," *Proc. INFOCOM '03,* 2003.

[15] X. Qin and R. Berry, "Opportunistic Splitting Algorithms for Wireless Networks," *Proc. INFOCOM '04,* 2004.

[16] P. Larsson, "Selection Diversity Forwarding in a Multihop Packet Radio Network with Fading Channel and Capture," *Mobile Computing and Comm. Rev.,* vol. 5, no. 4, pp. 47-54, 2001.

[17] S. Biswas and R. Morris, "Opportunistic Routing in Multi-Hop Wireless Networks," *Proc. Second Workshop Hot Topics in Networks (HotNets II),* Nov. 2003.

[18] R.R. Choudhury and N.H. Vaidya, "MAC-Layer Anycasting in Wireless Ad Hoc Networks," *Proc. Second Workshop Hot Topics in Networks (HotNets II),* Nov. 2003.

[19] S. Jain, Y. Lv, and S.R. Das, "Exploiting Path Diversity in the Link Layer in Wireless Ad Hoc Networks," technical report, WINGS Lab, July 2003.

[20] J. Wang, H. Zhai, W. Liu, and Y. Fang, "Reliable and Efficient Packet Forwarding by Utilizing Path Diversity in Wireless Ad Hoc Networks," *Proc. IEEE Military Comm. Conf. (Milcom '04),* Nov. 2004.

[21] C.-C. Chiang, G. Pei, M. Gerla, and T.-W. Chen, "Scalable Routing Strategies for Ad Hoc Wireless Networks," *IEEE J. Selected Areas in Comm.,* vol. 17, pp. 1369-1379, 1999.

[22] A.B. McDonald and T.F. Znati, "A Mobility-Based Framework for Adaptive Clustering in Wireless Ad Hoc Networks," *IEEE J. Selected Areas in Comm.,* vol. 17, no. 8, Aug. 1999.

[23] T. Hou and T. Tsai, "An Access-Based Clustering Protocol for Multihop Wireless Ad Hoc Networks," *IEEE J. Selected Areas in Comm.,* vol. 19, no. 7, July 2001.

[24] J.J. Garcia-Luna-Aceves and A. Tzamaloukas, "Receiver-Initiated Collision-Avoidance in Wireless Networks," *ACM Wireless Networks,* special issue on selected papers from MobiCom '99, vol. 8, nos. 2/3, pp. 249-263, 2002.

[25] Y. Wang and J.J. Garcia-Luna-Aceves, "A New Hybrid Channel Access Scheme for Ad Hoc Networks," *ACM Baltzer Wireless Networks J.,* vol. 10, no. 4, July 2004.

[26] Z. Fu, P. Zerfos, H. Luo, S. Lu, L. Zhang, and M. Gerla, "The Impact of Multihop Wireless Channel on TCP Throughput and Loss," *Proc. IEEE INFOCOM '03,* Apr. 2003.

[27] M. Bazaraa and C. Shetty, *Nonlinear Programming: Theory and Algorithms.* Wiley, 1993.

[28] R.G. Gallager, *Information Theory and Reliable Communication.* John Wiley and Sons, 1968.

[29] T. Nandagopal, T. Kim, X. Gao, and V. Bharghavan, "Achieving MAC Layer Fairness in Wireless Packet Networks," *Proc. MobiCom '00,* 2000.

[30] S. Kunniyur and R. Srikant, "End-to-End Congestion Control Schemes: Utility Funtions, Random Losses and ECN Marks," *Proc. INFOCOM '00,* Mar. 2000.

[31] H. Kushner and G. Yin, *Stochastic Approximation Algorithms and Applications.* Springer-Verlag, 1997.

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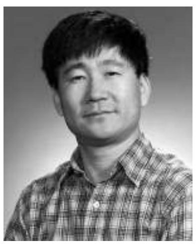

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