Channel Aware Distributed Random Access *

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***Abstract*—We investigate distributed channel-aware random access for networks with arbitrary topologies and traffic distributions, where users can receive traffic from or send traffic to different users and different communication links may interfere with others. We consider heterogeneous channels, where the random channel gains of different links may have different distributions. To resolve the network contention in a distributed way, each frame is divided into contention and transmission periods. The contention period is used to resolve conflicts near optimally and to schedule users with better channel states with higher probabilities while assuring fairness among all users. The proposed scheme completely resolves contention of networks with arbitrary topologies and is robust to any channel uncertainty. Besides, it performs close to central schedulers.**

***Index Terms*–** channel aware, random access, distributed scheduling, fairness

I. Introduction

Random access algorithms provide the means to share network resources among users under distributed control. Traditional contention based random access methods include pure, slotted, and reservation Aloha schemes, *carrier sense multiple access* (CSMA) and CSMA with collision avoidance schemes, *multiple access with collision avoidance for wireless* (MACAW) schemes, and so on [1], [2]. These *medium access control* (MAC) approaches do not use CSI. Hence, when the MAC decides to transmit a frame, the channel may be in a deep fade. On the other hand, the MAC may not transmit even though the channel is in a good state, which wastes channel resources. Recently, opportunistic random access schemes have been studied in [3]–[7] and the references therein to use CSI for performance improvement. With opportunistic random access, each user exploits its own CSI to decide the contention behavior and users with better channel states have higher contention probabilities. A channel-aware Aloha is proposed in [3] to improve the uplink access contention for cellular type networks; users transmit data whenever their channel gains are above pre-determined thresholds. Since the channel state is random, the transmission is randomized. This scheme is then further studied in [4]–[6] in different scenarios. In [7], users and the base station negotiate through mini time slots before data transmission such that the user with the best channel condition always wins the contention and transmits data.

These opportunistic random access schemes are for wireless networks where users transmit to a common receiver, e.g., a base station. However, this scenario does not fit many wireless communication environments, such as sensor, *ad hoc*, and mesh networks. Our work in this area [8]–[11] so far has been focused on designing channel-aware Aloha schemes for these types of networks, where users can receive traffic from or send traffic to different users and different communication links may interfere with others. We have shown that the consideration of both the channel state and the spatial-temporal traffic distribution significantly improves network performance. Aloha based schemes have low channel utilization efficiency because of the collision of the entire data frame. To further improve network performance, in this paper, we develop a scheme with signaling negotiation ahead of the data transmission to avoid collisions. We consider heterogeneous channels where the channel gains of different links may have different distributions. To resolve the network contention in a distributed way, each frame is divided into contention and transmission periods. The contention period is used to resolve conflicts near optimally and to schedule users with better channel states with higher probabilities while assuring fairness among all users.

The rest of this paper is organized as follows. First we describe the system in Section II. In Section III, we design the *channel aware distributed random access* (CADRA) scheme. Then in Section IV, we optimize CADRA. The robustness of CADRA is analyzed in Section V. Finally, we demonstrate the performance improvement with simulations in Section VI and conclude the paper in Section VII.

II. System Description

Consider a network where users are not necessarily within the transmission ranges of all others, that is, some users may not be able to receive packets from others due to weak received signal power. All channels are assumed to be reciprocal when there is no interference. Each user has knowledge of its own CSI and makes an independent transmission decision. A receiver cannot decode any packet if the channel is simultaneously used by another user within its interference range, i.e., a collision happens. Each user may choose to send packets to or receive packets from different users. An example is illustrated in Figure 1, where arrows indicate traffic flows and dashed circles, marked by italic numbers, denote the transmission ranges of the corresponding users*.

The backoff-after-collision approach in traditional CSMA can resolve contention. However, it ignores channel and multiuser diversity and deferring transmission without considering channel variations may result in data communications in deep fades. To fully exploit network diversity, the contention should be designed such that users with favorable channel conditions

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*Without loss of generality, we assume that the transmission and interference ranges are identical.

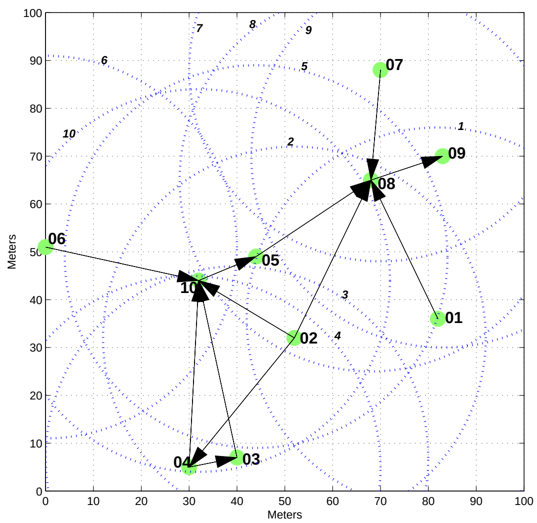

Fig. 1: A network example.

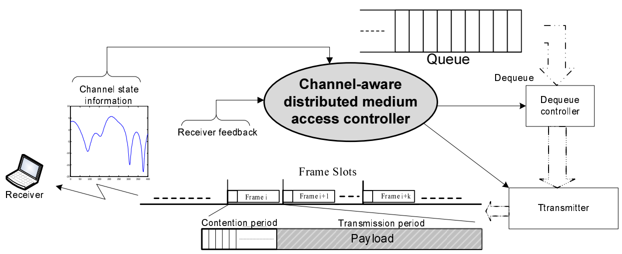

Fig. 2: Traffic, energy, and channel aware medium access.

have higher probability of accessing the channels and the transmission should follow immediately after the contention resolution as otherwise the channel may change to an unfavorable state. Considering this, we design a new distributed random access scheme in the following sections. Since this novel scheme uses channel knowledge to improve network performance, we call it *channel-aware distributed random access* (CADRA).

The process of the proposed channel-aware random access is illustrated in Figure 2. Each user has a queue with an infinite length for each traffic flow that needs to be sent and we assume the queue always has packets to be delivered. A dequeue controller fetches a desired amount of data and send it to the transmitter following the order of the medium access controller. The medium access controller collects information on channel states and decides when and how to transmit. As shown in Figure 2, the channel access time is divided into frame slots of length, T_f, and each slot consists of both contention and transmission periods. Block fading is assumed [12], that is, the channel state remains constant within each frame slot and is independent from one to another. The contention period is further divided into a maximum of $\widehat{K}$ *contention resolution slots* (CRSs) of length T_c, one for each contention resolution. Users failing in all CRSs will be idle in the current frame slot. Users that succeed in any CRS will send data in that frame slot with optimized link adaptation. The objective is to select users with relatively better channel conditions for payload transmission and the selection should also assure fairness among all users. We use CSI to control the access contention and the contention is randomized because wireless channels are inherently random. In the following, let h_{ij} be the channel gain of Link (i, j), the one from User i to j, with probability density function $f_{ij}(h)$ and distribution function $F_{ij}(h)$. Both $f_{ij}(h)$ and $F_{ij}(h)$ are assumed to be continuous to facilitate our discussion. Here we assume that the channel gains of different links are independent but not necessarily identically distributed.

III. Channel-Aware Medium Access Control

There are two types of contention. We denote Type-I and Type-II to be those among links with the same transmitter and with different transmitters, respectively. For example, the contention between Links $(2, 4)$, $(2, 8)$, and $(2, 10)$ in Figure 1 is Type-I and the contention between Links $(2, 4)$ and $(4, 3)$ is Type-II. Here we do not consider the case that two users are sending traffic to each other since the reciprocal channel between them is always the same for their transmission and they can negotiate easily to share the channel, e.g. in a time division fashion.

The Type-I contention can be easily resolved by the transmitter as it has CSI of all its links and choosing the one with the best CSI will result in the best system performance while assuring fairness, i.e., User i chooses Link (i, j) that satisfies

$$j = \arg\max_{l} F_{il}(h_{il}). \tag{1}$$

Note that $F_{il}(h_{il})$ is the probability that the channel gain of Link (i, l) is worse than h_{il}. The link with the highest $F_{il}(h_{il})$ is the one with the best instantaneous channel condition relatively and criterion (1) effectively exploits the multiuser diversity. Furthermore, $F_{il}(h_{il})$ is uniformly distributed between 0 and 1 for all (i, l). Hence, these links have the same probability of being scheduled and the scheme is fair.

We focus on resolving Type-II contention. The contention period is used to resolve this type of contention. The basic idea is to resolve the contention from one CRS to another and in each CRS, links with higher gains are selected in a distributed way to continue the following contention. Finally, only one link is selected within each local area and all interferers are informed that they should not send any data in the current frame slot. To facilitate the discussion of Type-II contention, REQUEST, BUSY, SUCCESS, IDLE, and OCCUPIED signals are defined. Each CRS consists of the following three steps.

1) *Transmitters send REQUEST*: If User i has neither received a BUSY signal from j nor detected a SUCCESS signal destined to others, and
$$h_{ij} > \widehat{H}_{ij}[k], \tag{2}$$
where $\widehat{H}_{ij}[k]$ is a predetermined threshold that is adjusted CRS-by-CRS, then it sends REQUEST to User j.
2) *Receivers notify BUSY, SUCCESS, IDLE*:
   - BUSY: User j responds BUSY if it receives REQUEST correctly and has received OCCUPIED in the previous CRSs.

- SUCCESS: User j responds SUCCESS if the REQUEST is received correctly and no OCCUPIED signals received in the previous CRSs.
- IDLE: User j broadcasts IDLE to all users that want to send traffic to User j if no OCCUPIED signals received in the previous CRSs and no signals detected at Step 1.

Note that the BUSY or SUCCESS feedback is sent only when there is no collision, i.e., the contention succeeds.

3) *Transmitters broadcast OCCUPIED and start sending data*: If User i has received SUCCESS, it goes to the win state and broadcasts OCCUPIED to notify those within its transmission range that they should not receive data in this frame slot.

As an example, observe the contention among only Links $(6, 10)$, $(10, 5)$, and $(8, 9)$ in Figure 1. If all the three links have good channel gains and send REQUEST in CRS 1, only User 9 receives REQUEST without collision and it sends back SUCCESS to User 8 at the second step while Users 5 and 10 remain silent. At the third step, User 8 broadcasts OCCUPIED. Then CRS 2 starts. Users 6 and 10 may still send REQUEST, depending on the adjusted threshold. Suppose both send and only User 5 receives a collision-free REQUEST. At the second step, User 5 responds BUSY to User 10. Nothing happens at Step 3. In CRS 3, only User 6 may still send REQUEST and User 10 will respond BUSY.

IV. Access Optimization

In this section, we optimize the access parameters. The following notations are used. All links carrying traffic are denoted by set $\mathcal{L}[1] = \{(i, j)\}$. Denote the interfering neighbor set of User i by $\mathcal{N}_i$. Each user may choose to send packets to or receive packets from several users, with $\mathcal{T}_i$ the set of users receiving packets from i and $\mathcal{S}_j$ the set of users sending packets to j. For example, $\mathcal{N}_4 = \{2, 3, 10\}$, $\mathcal{T}_4 = \{3, 10\}$, and $\mathcal{S}_4 = \{2\}$ in Figure 1. We want to optimize the throughputs of all users in the network. The arithmetic-mean metric leads to the design for sum throughput maximization, but assures no fairness since some users may have zero throughput. The geometric-mean metric takes both throughput and fairness among all users [13] into consideration. Therefore, we will find the thresholds in (2) to maximize the geometric mean of the throughputs of all links, i.e.,

$$\{\widehat{H}^*_{ij}[k]\} = \arg\max_{\{\widehat{H}_{ij}[k]\}} \prod_{(i,j)} T_{ij} = \arg\max_{\{\widehat{H}_{ij}[k]\}} \sum_{(i,j)} \log(T_{ij}), \quad (3)$$

where T_{ij} is the average throughput of Link (i, j).

It is not feasible to globally optimize (3) because after the contention in each CRS, new local knowledge is collected according to receiver feedback and the detection of signals broadcasted from neighboring users. This knowledge is generally different from one CRS to another and can not be obtained in advance. To fully exploit this knowledge, the contention will be optimized sequentially, i.e., in a CRS-by-CRS way, and use newly collected knowledge to improve the contention behaviors afterward.

In the following, denote the probability that User i sends a REQUEST to User j in CRS k by $p_{ij}[k]$. The overall probability that User i sends REQUESTs to other users in CRS k is

$$p_i[k] = \sum_{j \in \mathcal{T}_i} p_{ij}[k]. \quad (4)$$

A. *CRS* 1

We first optimize CRS 1. The throughput on Link (i, j) out of CRS 1 is

$$T_{ij}[1] = R_{ij} p_{ij}[1](1 - p_j[1]) \prod_{m \in \mathcal{N}_j, m \neq i} (1 - p_m[1]), \quad (5)$$

where R_{ij} is the average data rate of payload transmission; $(1 - p_j[1]) \prod_{m \in \mathcal{N}_j, m \neq i} (1 - p_m[1])$ is the probability that neither user j nor its neighboring users except user i transmits, which means the successful contention of Link (i, j) in CRS 1. In Figure 1, the transmission from User 2 to User 4 succeeds only when neither User 4 nor its neighbors excluding User 2, i.e., users in $\mathcal{N}_4 \backslash \{2\} = \{3, 10\}$, transmit. Hence, $T_{2,4}[1] = R_{2,4} p_{2,4}[1](1 - p_4[1])(1 - p_3[1])(1 - p_{10}[1])$.

The contention probability for CRS 1 is given by

$$\{p^*_{ij}[1]\} = \arg\max_{\{p_{ij}[1]\}} \sum_{(i,j) \in \mathcal{L}[1]} \log(T_{ij}[1]). \quad (6)$$

Both $\log(p_{ij}[1])$ and $\log\big(1 - p_i[1]\big) = \log\big(1 - \sum_{j \in \mathcal{T}_i} p_{ij}[1]\big)$ are strictly concave functions of $p_{ij}[1]$. Hence $\sum_{(i,j) \in \mathcal{L}[1]} \log(T_{ij}[1])$ is strictly concave in $\{p_{ij}[1]\}$ and a unique global optimal $\{p^*_{ij}[1]\}$ can be determined by setting the first-order derivative of the objective function to be zero. The optimal contention probability can be readily obtained after some mathematical manipulations and

$$p^*_{ij}[1] = \frac{1}{|\mathcal{S}_i| + \sum_{m \in \mathcal{N}_i} |\mathcal{S}_m|}, \quad (7)$$

which is the inverse of the total number of received traffic flows within the interference range of User i. Intuitively, $p^*_{ij}[1]$ says that as the interference footprint (number of affected users) increases, the contention probability of User i should decrease.

The threshold should be chosen to satisfy the contention probability in (7). According to Section III, the contention probability of Link (i, j) is

$$\begin{aligned} p_{ij}[1] &= \mathtt{Pr}\{(i,j) \text{is chosen}; h_{ij} > \widehat{H}_{ij}[1]\} \\ &= \int_{\widehat{H}_{ij}[1]}^{\infty} f_{ij}(h) \Pr(j = \arg\max_{l \in \mathcal{T}_i} F_{il}(h_{il})) \mathrm{d}h \\ &= \int_{\widehat{H}_{ij}[1]}^{\infty} \Pr(F_{il}(h_{il}) < F_{ij}(h_{ij}) : l \neq j) \mathrm{d}F_{ij}(h) \\ &= \frac{1}{|\mathcal{T}_i|} \left(1 - F_{ij}^{|\mathcal{T}_i|}(\widehat{H}_{ij}[1])\right), \end{aligned} \quad (8)$$

where $|\cdot|$ denotes the number of elements in the set.

From (8) and (7), the optimal threshold is

$$\widehat{H}^*_{ij}[1] = F_{ij}^{-1}\left[\left(1 - \frac{|\mathcal{T}_i|}{|\mathcal{S}_i| + \sum_{m \in \mathcal{N}_i} |\mathcal{S}_m|}\right)^{\frac{1}{|\mathcal{T}_i|}}\right]. \quad (9)$$

The optimal threshold (9) depends on the number of users receiving packets from User i, $|\mathcal{T}_i|$, the number of users sending packets to User i, $|\mathcal{S}_i|$, and the total number of users sending packets to the interfering neighbors of User

i, $\sum_{m\in\mathcal{N}_i}|\mathcal{S}_m|$. The first two require only local knowledge while the third can be obtained through signalling exchange. This exchange incurs only trivial signalling overhead since it will be triggered only when either a traffic session or the network topology changes sufficiently. Besides, this type of knowledge is typical in many protocols, such as route discovery in mobile *ad hoc* networks [14], [15]. Hence, it can be readily obtained. Consider User 4 in Figure 1. $|\mathcal{T}_4| = 2$, $|\mathcal{S}_4| = 1$, $|\mathcal{S}_2| = 0$, $|\mathcal{S}_3| = 1$, and $|\mathcal{S}_{10}| = 4$. Hence, $\widehat{H}^*_{4,3}[1] = F^{-1}_{4,3}\left[(1-\frac{2}{1+1+4})^{1/2}\right] = F^{-1}_{4,5}(0.667)$. If Link $(4,3)$ experiences Rayleigh fading with average gain h_a, $\widehat{H}^*_{4,5}[1] = 1.1h_a$.

B. CRS k, $k > 1$

In the following CRSs, links whose transmitters have not been notified SUCCESS or BUSY continue the contention. The new threshold is chosen such that the contention probability is $p_{ij}[k]$. There are three possibilities adjusting the threshold.

- *Adjustment* (AD) I: If in the previous CRS, User i sent a REQUEST and no feedback is received, indicating a collision, all links involved in this collision should increase their thresholds to reduce the probability of collision. From previous knowledge, $h_{ij} > \widehat{H}^*_{ij}[k-1]$ and $h_{ij} < \widehat{H}^M_{ij}$, where $\widehat{H}^M_{ij}$ is the minimum threshold in all the previous CRSs such that $h_{ij} < \widehat{H}^M_{ij}$ and initially $\widehat{H}^M_{ij} = \infty$. The new threshold satisfies
$$\Pr\left(h_{ij} > \widehat{H}^*_{ij}[k] \middle| \; h_{ij} > \widehat{H}^*_{ij}[k-1], h_{ij} < \widehat{H}^M_{ij}\right) = p_{ij}[k]. \tag{10}$$
Solving Equation (10) for $\widehat{H}^*_{ij}[k]$, we have
$$\begin{aligned}\widehat{H}^*_{ij}[k] =& F^{-1}_{ij}\Big((1-p_{ij}[k])F_{ij}(\widehat{H}^M_{ij}) \\ &+ p_{ij}[k]\cdot F_{ij}(\widehat{H}^*_{ij}[k-1])\Big).\end{aligned} \tag{11}$$
- AD II: If User i applied AD I or II, did not send REQUEST, and received IDLE from j in the previous CRS, indicating User i is still contending and all other contending users, if any, have channel states below their thresholds, User i should decrease the threshold. Similar to the first case, the new threshold satisfies
$$\Pr\left(h_{ij} > \widehat{H}^*_{ij}[k] \middle| \; h_{ij} < \widehat{H}^*_{ij}[k-1]; h_{ij} > \widehat{H}^m_{ij}\right) = p_{ij}[k], \tag{12}$$
where $\widehat{H}^m_{ij}$ is the maximum threshold in all the previous CRSs such that $h_{ij} > \widehat{H}^m_{ij}$ and initially $\widehat{H}^m_{ij} = 0$. Solving equation (12), we have
$$\begin{aligned}\widehat{H}^*_{ij}[k] =& F^{-1}_{ij}\Big(p_{ij}[k]\cdot F_{ij}(\widehat{H}^m_{ij}) \\ &+ (1-p_{ij}[k])F_{ij}(\widehat{H}^*_{ij}[k-1])\Big).\end{aligned} \tag{13}$$
- AD III: In other cases, the threshold is kept the same, i.e.,
$$\widehat{H}^*_{ij}[k] = \widehat{H}^*_{ij}[k-1]. \tag{14}$$
This usually happens when no REQUEST was sent and no IDLE was received in a previous CRS and User i temporarily quits the contention. In this case, User i would contend again only if it receives IDLE in the future CRSs.

Denote all the competing links in CRS k by $\mathcal{L}[k]$. With the same approach as in CRS 1, the optimal contention probability for $(i,j)\in\mathcal{L}[k]$ is
$$p^*_{ij}[k] = \frac{1}{|\mathcal{S}_i[k]| + \sum_{m\in\mathcal{N}_i[k]}|\mathcal{S}_m[k]|}, \tag{15}$$
where $\mathcal{S}_n[k]$ and $\mathcal{N}_n[k]$ are users that can contend in CRS k. A user may contend if and only if its threshold will be changed as in ADs I or II. However, who will adjust their thresholds is unknown to others and $p^*_{ij}[k]$ cannot be determined locally. Instead, we give a suboptimal approach as follows
$$p_{ij}[k] = \begin{cases}\frac{1}{2}, & \text{AD I,}\\ p_{ij}[k-1], & \text{AD II.}\end{cases} \tag{16}$$
Here we assign one half for AD I because after the selection in CRS 1, it is most likely that only one other link is contending with Link (i,j) if a collision happens. For AD II, an IDLE signal most likely indicates that the contention scenario is not changed and $p_{ij}[k]$ keeps the same.

V. Robustness Analysis

In this section, we give the robustness of CADRA. Readers are referred to the journal version of this paper for more details and proofs. In the following, we say a link wins the contention if it transmits data in the transmission period. The complete resolution of contention is defined as follows.

Definition 1. *The contention of a network is completely resolved if*

1) *all links that have won the contention can transmit without collision;*
2) *if any additional link that has not won the contention transmits, it will collide with at least one link that has won the contention.*

Thus, complete resolution results are states in which the network capacity is fully exploited.

Theorem 1. *With probability one, the contention of networks with any topology can be completely resolved by CADRA if sufficient CRSs are allowed.*

Theorem 1 indicates that CADRA achieves performance comparable to that of a centralized scheduler. Compared to the centralized scheduler, CADRA loses throughput due to the CRSs used for resolving network contention. Denote the throughputs of CADRA and the centralized scheduler by T_{CADRA} and $T_{Centralized}$, respectively. Then we define the efficiency, γ, of CADRA as follows,
$$\gamma = \frac{T_{CADRA}}{T_{Centralized}} = 1 - \frac{\overline{K}T_c}{T_f}, \tag{17}$$
where $\overline{K}$ is the average number of CRSs necessary for completely resolving the network contention. In the following, to show $\overline{K}$ is bounded, we assume a link contends again only if all neighbors of the receiver have resolved their contention and the receiver sends IDLE to the receiver since it can still receive data. Besides, assume sufficient CRSs.

For a network with N traffic flows, each interfering with all others, an upper bound of $\overline{K}_N$ is given by the following theorem.

Theorem 2. *For a network with N links, each interfering with all others, the average number of CRSs necessary to completely resolve the network contention satisfies*

$$\overline{K}_N \leq \frac{\widehat{M}_N}{1-(1-\frac{1}{N})^N} + \frac{(1-\frac{1}{N})^N}{(1-(1-\frac{1}{N})^N)^2}, \quad (18)$$

where $\widehat{M}_N = \sum_{n=1}^{N} \binom{N}{n} (\frac{1}{N})^n (1-\frac{1}{N})^{N-n} (\log_2(n)+1)$. *Furthermore,*

$$\overline{K}_N < \overline{K}_\infty \leq 2.43. \quad (19)$$

Based on Theorem 2, the following theorem gives a general upper bound of $\overline{K}$ for any type of networks.

Theorem 3. *For any type and size of network, the average number of CRSs necessary to completely resolve the contention satisfies*

$$\overline{K} < \frac{2.43 \cdot \overline{L}}{\beta}, \quad (20)$$

where the transmission coexistence factor, $\overline{L}$, is the average number of links that win the contention in one frame slot and the contention coexistence factor, β, is the average number of simultaneous resolutions in each CRS.

From Theorems 1 and 3, we have the following proposition.

Proposition 1. *The efficiency of CADRA satisfies*

$$\gamma > 1 - \frac{2.43 \cdot \overline{L} T_c}{\beta T_f}. \quad (21)$$

For a network where each user interferer with all others, the efficiency is

$$\gamma > 1 - \frac{2.43 \cdot T_c}{T_f}. \quad (22)$$

T_c and T_f are determined by the round-trip time of signal propagation and the channel coherence time respectively. If $T_f \gg T_c$ as in slow-fading channels, CADRA performs almost the same as the centralized scheduler, which is generally impractical because of poor scalability and the huge overhead of CSI collection. For example, it is shown in [16] that the round trip time for 802.11 wireless *local area networks* (LAN) is within 10 μs and for cellular networks, with 6 km radius, is within 50μs. On the other hand, the channel coherence time is hundreds of milliseconds in indoor office or home environment and tens of milliseconds in cellular networks with 900 MHz carrier frequency and user speed 72 km/h [17]. Hence in both wireless LAN and cellular networks, the efficiency of CADRA is close to unity.

Now suppose that that all users have imperfect channel state information $\{\widetilde{h}_{ij}\}$ and $\{\widetilde{F}_{ij}()\}$ and control the medium access. From the proofs of Theorems 1, 2, and 3, we see that they are independent of the channel distribution of any user. Hence, they also hold for the operations of CADRA based on $\{\widetilde{h}_{ij}\}$ and $\{\widetilde{F}_{ij}()\}$. Besides, suppose the centralized scheduler compared in (17) has the same imperfect channel knowledge. Then the efficiency of CADRA is still given by (17). Therefore we have the following theorem about the robustness of CADRA.

Theorem 4. *The conclusions in Theorems 1, 2, and 3 and Proposition 1 hold when all users have imperfect channel knowledge and CADRA is robust to any channel uncertainty.*

VI. Simulation Experiments

In each simulation trial, users are randomly dropped and uniformly distributed in a square area with side length of 100 meters. Each user has a transmission range of 40 meters and selects neighboring users randomly for data transmission. The number of selected receivers is uniformly distributed between 1 and half of the number of neighboring users. A network topology in one trial has been illustrated in Figure 1. Rayleigh block fading channel with the average fading level, h_o, is assumed. Hence, $F(h) = 1 - e^{-\frac{h}{h_o}}$. The data rate in each frame is given by $R(h) = W \ln(1 + \frac{hP}{N_o})$, where $W = 100$ KHz, is the system bandwidth, $P = 0.01$ watt, is the transmit power, and $N_o = 0.0001$ watt, is the noise power. The length of each frame slot is 20 ms and the CRS is 0.2 ms each.

First, consider the network topology given in Figure 1 and let $h_o = 1$. The contention process for a set of channel states in a frame slot is illustrated by Table I, where blanks indicate no values or no actions. Each user chooses a receiver with the best channel gain, e.g., User 2 selects User 4. In the first CRS, Links $(4, 3)$ gets access. Users $2, 3$, and 10 detect SUCCESS and decide to stop contention since some neighboring users will receive data in this frame slot. In the second CRS, only Users 1, 5, 7, and 8 contend but none send REQUEST even their thresholds are lowered. In the third CRS, only User 7 sends REQUEST and wins the contention. Hence, three CRSs completely resolve Type-II contention and Links $(4, 3)$ and $(7, 8)$ will send data in this frame slot. Note that this result also fully exploits the network capacity as transmission of any other users will produce interference and reduce the network throughput. Figure 3 shows the probability mass function of the number of CRSs for completely resolving contention where there are different numbers of users in the network. We can see that heavier network load requires only slightly more CRSs. The average numbers of CRSs in these four cases are 2.35, 3.74, 4.92, and 6.00, while the corresponding standard deviations are 1.66, 2.39, 3.11, and 4.00, respectively. Figure 4 compares the throughput of the proposed CADRA scheme and the DOMRA scheme in [11] when there are different numbers of active users. Significant performance improvement can be observed. When there are 15 active users, the throughput of CADRA outperforms DOMRA by approximately 50% because of the separate design of signalling contention and data transmission.

VII. Conclusion and Future Work

We have designed a distributed channel-aware random access scheme without making any assumption on network topology and traffic distribution. The proposed scheme completely resolves network contention at a trivial signaling cost and performs closely to the centralized scheduler. Besides, it is also robust to any channel uncertainty. The generality of the design allows its application in different types of wireless networks, such as cellular networks, sensor networks, and mobile *ad hoc* networks, to improve quality of service.

TABLE I: Contention process for a set of channel states in Figure 1

User i	1	2	3	4	5	6	7	8	9	10
Receivers	8	4;8;10	10	3;10	8	10	8	9		5
Channel gains h	**0.66**	**1.36**;0.63;0.61	**0.91**	**2.98**;1.36	**0.49**	**1.33**	**0.94**	**0.23**		**0.11**
Selected receiver j	8	4	10	3	8	10	8	9		5
CRS 1 $H_{ij}[1]$	1.61	2.30	1.79	1.70	2.20	1.39	1.61	1.79		1.95
CRS 1 Step 1				REQ						
CRS 1 Step 2	IDL	TKN	TKN	SUC	IDL		IDL	IDL		TKN
CRS 1 Step 3				OCP						
CRS 2 $H_{ij}[2]$	1.02				1.56	1.39	1.02	1.19		
CRS 2 Step 1										
CRS 2 Step 2	IDL				IDL		IDL	IDL		
CRS 2 Step 3										
CRS 3 $H_{ij}[3]$	0.72				1.21	1.39	0.72	0.86		
CRS 3 Step 1							REQ			
CRS 3 Step 2	TKN				TKN		SUC	TKN		
CRS 3 Step 3							OCP			

TKN: detect SUCCESS of others and stop contention; REQ: send REQUEST; SUC: feed back SUCCESS; OCP: broadcast OCCUPIED; IDL: send IDLE to transmitter; BSY: feed back BUSY.

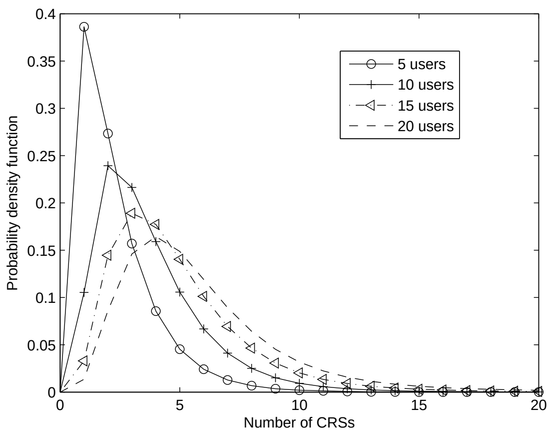

Fig. 3: Probability density function of the number of CRSs necessary for complete contention resolution.

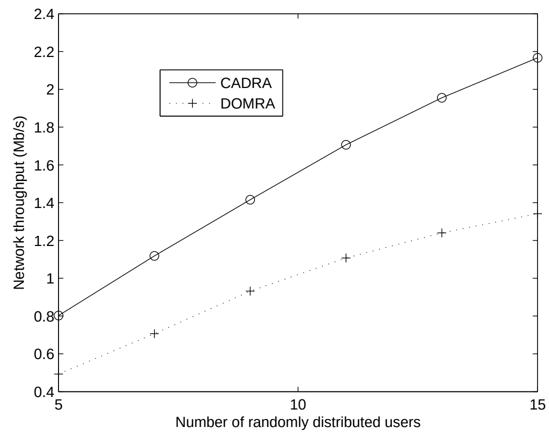

Fig. 4: Throughput comparison of CADRA and DOMRA.

References

[1] D. Bertsekas and R. Gallager, *Data Networks (2nd Edition)*. Englewood Cliffs, NJ: Prentice Hall, 1992.

[2] V. Bhaghavan, A. Demers, S. Shenker, and L. Zhang, "MACAW: A media access protocol for wireless lan's," in *Proc. Sigcomm 1994*, Oct. 1994.

[3] X. Qin and R. Berry, "Exploiting multiuser diversity for medium access control in wireless networks," in *Proc. IEEE INFOCOM 2003*, Apr. 2003, pp. 1084–1094.

[4] S. Adireddy and L. Tong, "Exploiting decentralized channel state information for random access," *IEEE Trans. Inf. Theory.*, vol. 51, no. 2, pp. 537–561, Feb. 2005.

[5] ——, "Optimal channel-aware aloha protocol for random access in wlans with multipacket reception and decentralized channel state information," vol. 56, no. 6, pp. 2575–2588, June 2008.

[6] Y. Yu and G.B. Giannakis, "Opportunistic medium access for wireless networking adapted to decentralized csi," *IEEE Trans. Wireless Commun.*, vol. 5, no. 6, pp. 1445–1455, June 2006.

[7] X. Qin and R. Berry, "Opportunistic splitting algorithms for wireless networks," in *Proc. IEEE INFOCOM 2004*, Apr. 2004, pp. 1662–1672.

[8] G. W. Miao, Y. (G.) Li, A. Swami, and N. Himayat, "Cross-layer optimization based on partial local knowledge (special paper)," in *Proc. IEEE WCNC 2008*, Mar. 2008, pp. 1513–1518.

[9] G. W. Miao, Y. (G.) Li, N. Himayat, and S. Talwar, "Cochannel interference avoidance MAC in wireless cellular networks," in *Proc. IWCMC 2008*, Aug. 2008, pp. 62–67, also to appear in *IEEE Trans. Commun.*

[10] G. W. Miao, Y. (G.) Li, and A. Swami, "Decentralized cross-layer optimization for multichannel Aloha wireless networks," in *Proc. IEEE Globecom 2007*, Nov. 2007, pp. 4456–4460.

[11] ——, "Decentralized optimization for multichannel random access," to appear in *IEEE Trans. Commun.*

[12] R. J. McEliece and W. E. Stark, "Channels with block interference," *IEEE Trans. Inf. Theory.*, vol. 30, no. 1, pp. 44–53, Jan. 1984.

[13] M. Pischella and J.-C. Belfiore,, "Power control in distributed cooperative OFDMA cellular networks," vol. 7, no. 5, pp. 1900–1906, May 2008.

[14] A. Qayyum, L. Viennot, and A. Laouiti, "Multipoint relaying: an efficient technique for flooding in mobile wireless networks," in *Technical Report Research Report RR-3898*, Project HIPERCOM, INRIA, Feb. 2000.

[15] J. Lipman, P. Boustead, and J. Judge, "Neighbor aware adaptive power flooding in mobile *ad hoc* networks," in *Int. J. Foundations of Comp. Sci.*, vol. 14, no. 2, Apr. 2003, pp. 237–252.

[16] K. K. Leung, B. McNair, L. J. Cimini, J. H. Jr. Winters, "Outdoor IEEE 802.11 cellular networks: MAC protocol design andperformance," in *Proc. IEEE ICC 2002*, vol. 1, 2002, pp. 595–599.

[17] A. Kumar, D. Manjunath, and J. Kuri, *Wireless Networking*. Morgan Kaufmann, 2008.