Channel Aware Distributed Medium Access Control*

Guowang Miao[†,♭] , *Student Member, IEEE*, Geoffrey Ye Li[†], *Fellow, IEEE*, and Ananthram Swami [♯], *Fellow, IEEE*
[†] School of ECE, Georgia Institute of Technology
[♯] CISD, Army Research Laboratory

***Abstract*—We investigate distributed channel-aware medium access control for wireless 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 each other. 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 while the transmission period is used to send payload in collision-free scenarios. We design a channel-aware Aloha scheme for the contention period to enable users with relatively better channel states to have higher probability of contention success while assuring fairness among all users. We show analytically that the proposed scheme completely resolves network contention and achieves throughput close to that using centralized schedulers. Besides, this scheme is also robust to any channel uncertainty. Simulation results demonstrate that the proposed scheme significantly improves network performance. The proposed random access approach can be applied to different wireless networks, such as cellular, sensor, and mobile *ad hoc* networks, to improve quality of service.**

Index Terms– channel aware, random access, distributed, scheduling, medium access control

I. Introduction

Because of fading, the quality of a wireless channel varies with both time and user. Wireless is a shared medium and communication performance is affected not only by individual communication links but also by the interaction among the links in the entire network. To fully exploit network resources, channel-aware medium access schemes have been proposed to adaptively transmit data and dynamically assign wireless resources based on *channel state information* (CSI). The key idea of channel-aware medium access control is to schedule a user with favorable channel conditions to transmit with optimized link adaptation according to CSI [1]–[4]. By exploiting the channel variations across users, channel-aware medium access control substantially improves network performance through multiuser diversity, whose gain increases with the number of users [1], [4]. The scheduling can be either centralized or distributed. With a central controller, the best performance is obtained by scheduling the user with the best channel state [2], [3], [5]. However, CSI feedback incurs huge overhead, especially for networks with a large number of users at high mobility, which results in poor network scalability. To reduce CSI feedback, distributed approaches are preferred.

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 [6], [7]. 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 [8]–[13] 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 [8] 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 [9]–[12] in different scenarios. In [13], users and the base station negotiate through mini time slots before the data transmission period such that the user with the best channel condition always wins the contention and transmits data.

All 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 [14], *ad hoc* [15], and mesh networks [16]. Our work in this area [17]–[20] 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 effi-

* This work was supported by Intel Corp. and the U.S. Army Research Laboratory under the Collaborative Technology Alliance Program, Cooperative Agreement DAAD19-01-20-0011.
* Part of this work is to be published at Globecom 2009.

♭ Corresponding author. Email: gmiao3@gatech.edu. Address: School of Electrical and Computer Engineering Georgia Institute of Technology, Atlanta, Georgia, 30332–0250

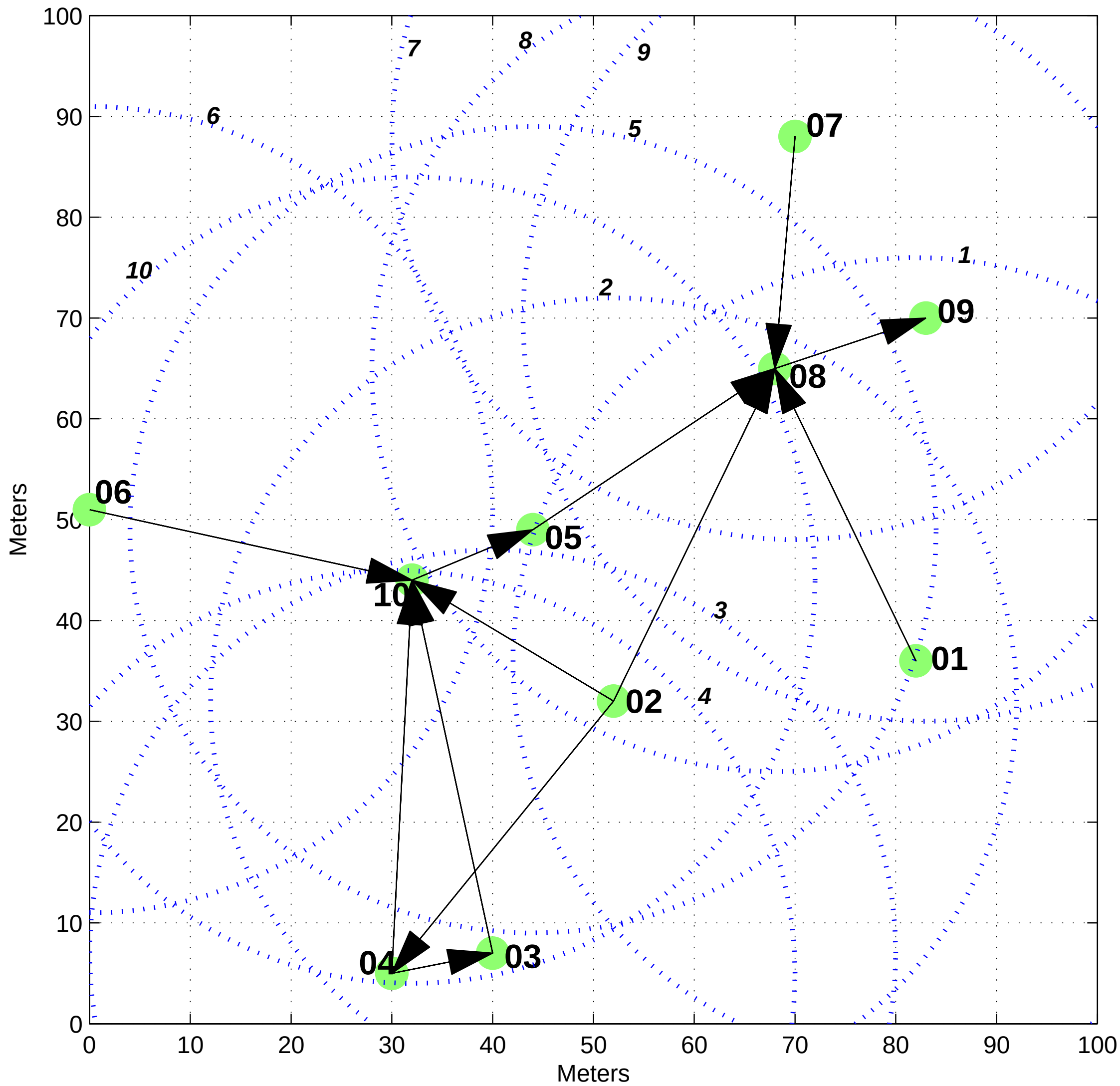

Fig. 1: A network example.

ciency 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, regardless of the network topology and traffic distribution. We consider heterogeneous channels where the channel gains of different links may have different distributions. To avoid the collision of data packets, we divide each frame into contention and transmission periods. The contention period is used to resolve the conflicts of all users while the transmission period is used to send data in collision-free scenarios. For the contention period, we design a channel-aware Aloha scheme to enable users with relatively better channel states to have higher probabilities of contention success 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 medium access scheme. Then in Section IV, we optimize the operation of CAD-MAC. The robustness of CAD-MAC is analyzed in Section V. Finally, we demonstrate the performance improvement with simulations in Section VI and conclude the paper in Section VII.

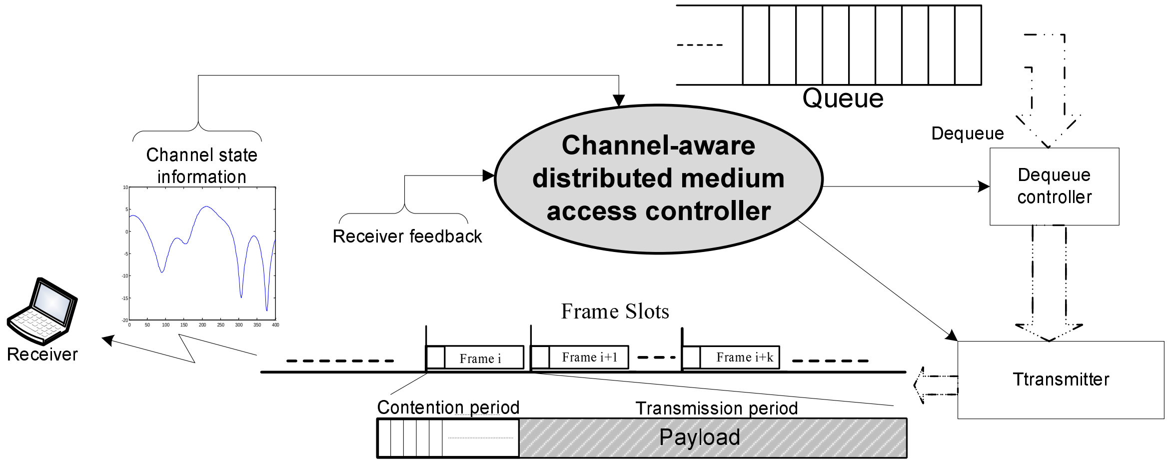

Fig. 2: Traffic, energy, and channel aware medium access.

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 decision on its transmission. A receiver cannot decode any packet successfully if the channel is simultaneously used by another user within the transmission range of the receiver, 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 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.

The backoff-after-collision approach in traditional CSMA can resolve contention. However, it ignores channel and multiuser diversity in wireless communications 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 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 medium access control* (CAD-MAC).

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

III. Channel-Aware Medium Access Control

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 [21], 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, each for one 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 actual number of CRSs may vary from frame to frame, depending on the contention results. The objective of the contention design is to select users with relatively better channel conditions for payload transmission and the selection should also assure fairness among all users. In this way, the network diversity can be exploited sufficiently. 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.

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 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

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

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 instantaneous 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. Random access is needed and a link with a better channel state should have a higher probability of success. 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 as follows.

- REQUEST: sent by a transmitter to request access;
- BUSY: sent by a receiver to deny access;
- SUCCESS: sent by a receiver to allow access;
- IDLE: sent by a receiver to petition for access;
- OCCUPIED: sent by a transmitter to prevent neighbors from data reception.

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

$$h_{ij} > \widehat{H}_{ij}[k], \quad (2)$$

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.

Five typical contention processes have been illustrated in Figure 3, where the solid arrows indicate signals between the observed pair of users and the empty arrows indicate signals sent from or detected by the interfering neighbors. 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 to prevent subsequent contention behaviors.

Remark 1: At Step 2, the BUSY or SUCCESS signals can always be received by User i correctly. This can be justified as follows. Suppose Links (i_1, j_1) and (i_2, j_2) succeed in their contention and Users j_1 and j_2 are sending BUSY or SUCCESS signals to i_1 and i_2 respectively. User i_1 does not interfere with j_2 and hence it can not receive any signal from j_2 since the channel is assumed to be reciprocal. Hence, User i_1 can receive the BUSY or SUCCESS signal without interference from j_2. Similarly User i_2 also receives the BUSY or SUCCESS signals correctly. On the other hand, The IDLE signals from different links may collide. Since only IDLE signals may collide at Step 2, users can detect them if they are neither BUSY nor SUCCESS signals. In the following, we assume the IDLE signals are received correctly.

Remark 2: At Step 3, the OCCUPIED signals may collide. However, as only the OCCUPIED signals are broadcasted and if any signal is detected, it will be the OCCUPIED signal.

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 desire 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 [22] 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

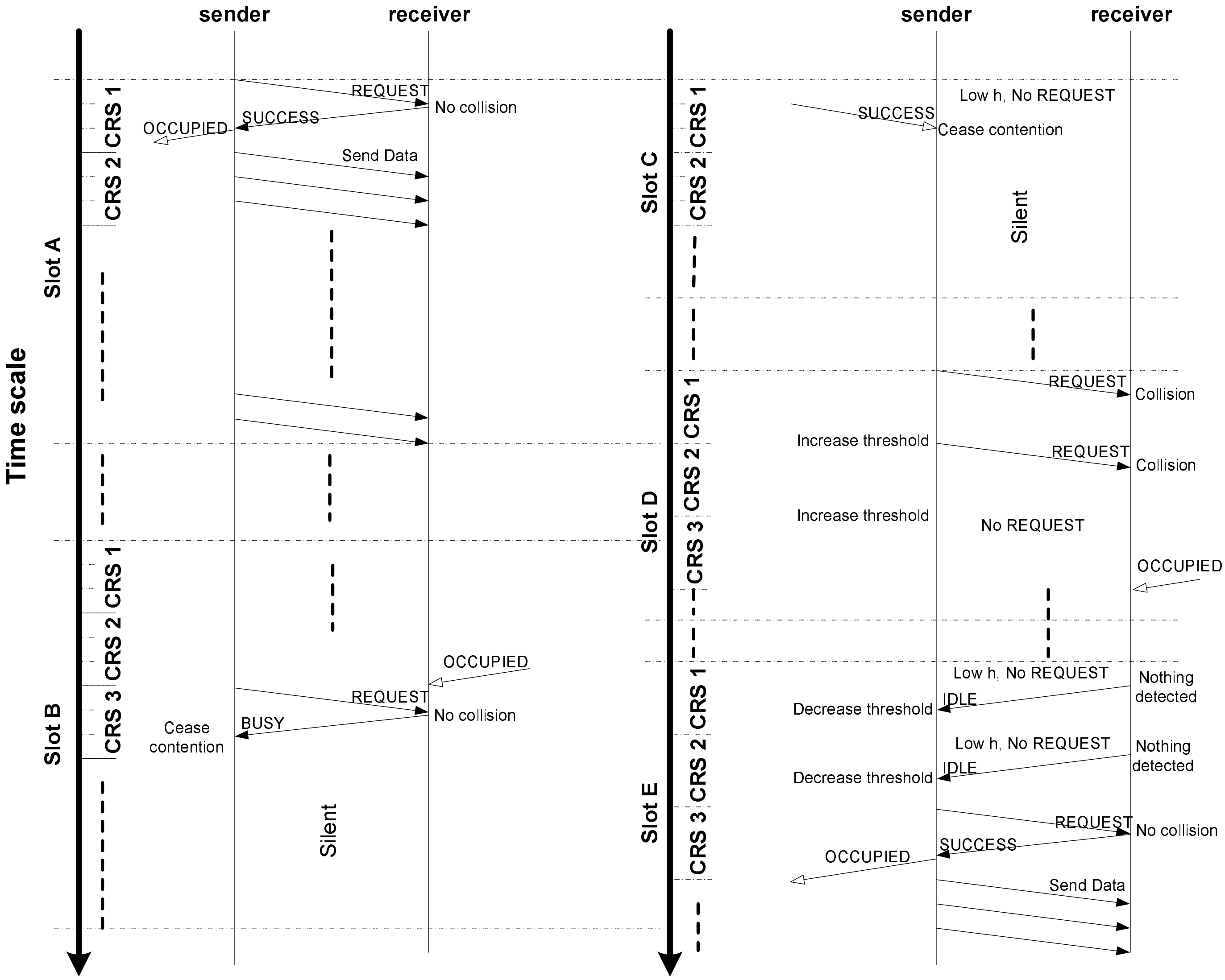

Fig. 3: Flowcharts of typical access contention.

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

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

A. CRS 1

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

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

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

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

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

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

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

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

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

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

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

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 routing discovery in mobile *ad hoc* networks [23], [24]. 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, $\widehat{H}^*_{4,3}[1] = F_{4,3}^{-1}\left[(1 - \frac{2}{1+1+4})^{1/2}\right] = F_{4,5}^{-1}(0.667)$. 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

$$\texttt{Pr}\left(h_{ij} > \widehat{H}^*_{ij}[k] \,\middle|\, h_{ij} > \widehat{H}^*_{ij}[k-1], h_{ij} < \widehat{H}^M_{ij}\right) = p_{ij}[k]. \tag{10}$$

  Solving Equation (10) for $\widehat{H}^*_{ij}[k]$, we have

$$\begin{aligned} \widehat{H}^*_{ij}[k] =& F_{ij}^{-1}\Big((1 - p_{ij}[k])F_{ij}(\widehat{H}^M_{ij}) \\ & + p_{ij}[k] \cdot F_{ij}(\widehat{H}^*_{ij}[k-1])\Big). \end{aligned} \tag{11}$$

- 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

$$\texttt{Pr}\left(h_{ij} > \widehat{H}^*_{ij}[k] \,\middle|\, h_{ij} < \widehat{H}^*_{ij}[k-1]; h_{ij} > \widehat{H}^m_{ij}\right) = p_{ij}[k], \tag{12}$$

  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

$$\begin{aligned} \widehat{H}^*_{ij}[k] \;=\; & F_{ij}^{-1}\Big(p_{ij}[k] \cdot F_{ij}(\widehat{H}^m_{ij}) \\ & + (1 - p_{ij}[k])F_{ij}(\widehat{H}^*_{ij}[k-1])\Big). \end{aligned} \tag{13}$$

- 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 analyze the robustness of CAD-MAC. We say a link wins the contention if it transmits data in the transmission period in the following.

The complete resolution of network 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. The following theorem states that CAD-MAC can completely resolve the network contention and is proved in Appendix I.

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

One example that CAD-MAC fails to resolve the contention is shown in Figure 4 where the two channels are *independent and identically distributed* (i.i.d.). When $h_{12} = h_{34}$, Users 1 and 3 have the same update of the thresholds and their REQUESTs always collide. However, the probability that $h_{12} = h_{34}$ is zero because the two channels are independently fading with continuous probability distribution function $F_{ij}(h)$.

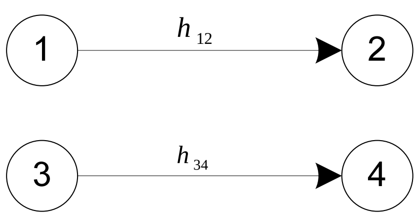

Fig. 4: A network in which all interfere with others.

Theorem 1 indicates that CAD-MAC achieves performance comparable to that of a centralized scheduler. Compared to the centralized scheduler, CAD-MAC loses throughput due to the CRSs used for resolving network contention. Denote the throughputs of CAD-MAC and the centralized scheduler by $T_{CAD-MAC}$ and $T_{Centralized}$, respectively. Then we define the efficiency, γ, of CAD-MAC as follows,

$$\gamma = \frac{T_{CAD-MAC}}{T_{Centralized}} = 1 - \frac{\overline{K}T_c}{T_f}, \tag{17}$$

where $\overline{K}$ is the average number of CRSs necessary for completely resolving the network contention. In the following, we show that $\overline{K}$ is bounded regardless of the network type and size. To simplify the analysis, we assume in the following that 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.

First, consider the case that each link interferes with all others and only one link wins the contention in each frame slot, such as in a network where all users send traffic to a common receiver or a small-scale *ad hoc* network where each user is within the transmission range of all others. 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, which is proved in Appendix II.

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*

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

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,*

$$\overline{K}_N < \overline{K}_\infty \leq 2.43. \tag{19}$$

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

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

$$\overline{K} < \frac{2.43 \cdot \overline{L}}{\beta}, \tag{20}$$

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.

Remark 1: In Theorem 3, the contention coexistence factor β indicates how many simultaneous resolutions occur in each CRS. Here one resolution is the process that all links, among whom only one link will win, adjust their thresholds using ADs I or II. Since multiple links may win in one frame slot, the resolutions that lead to the win of these links may happen in the same CRS, and β characterizes this overlap. Readers are referred to Appendix III for the strict definition of β. Obviously, both $\overline{L}$ and β depend on the distribution density and transmission range of all users.

For example, if each user interferes with all others and only one link wins, then $L = 1$, $\beta = 1$, and $\overline{K} < 2.425$ as in Theorem 2. If a network consists of 2 groups of users and the communication within different groups does not interfere with each other, then these two groups can resolve their contention within themselves to produce the two winners. Consequently, $L = 2$. For example, denote the CRSs for a two-cell cellular network using different frequency sets in the two cells to resolve the contention to be $\mathcal{K}_1 = \{1, 2, \cdots, k_1\}$ and $\mathcal{K}_2 = \{1, 2, \cdots, k_2\}$, respectively, where k_1 and k_2 are random and vary from one frame to another. Then the resolution overlaps from CRSs 1 to $\min\{k_1, k_2\}$ and there is only one resolution from CRSs $\min\{k_1, k_2\} + 1$ to $\max\{k_1, k_2\}$. Consequently, according to Appendix III,

$$\beta = \frac{\mathbf{E}(k_1 + k_2)}{\mathbf{E}(\max\{k_1, k_2\})}. \tag{21}$$

and

$$\overline{K} < \frac{4.86 \cdot \mathbf{E}(\max\{k_1, k_2\})}{\mathbf{E}(k_1 + k_2)}. \tag{22}$$

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

Proposition 1. *The efficiency of CAD-MAC satisfies*

$$\gamma > 1 - \frac{2.43 \cdot \overline{L}T_c}{\beta T_f}. \tag{23}$$

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

$$\gamma > 1 - \frac{2.43 \cdot T_c}{T_f}. \tag{24}$$

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, CAD-MAC 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 [25] 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 [26]. Hence in both wireless LAN and cellular networks, the efficiency of CAD-MAC 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 CAD-MAC 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 CAD-MAC is still given by (17). Therefore we have the following theorem about the robustness of CAD-MAC.

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

VI. Simulation Experiments

In this section, we demonstrate the performance of CAD-MAC in a network with random topologies. First we illustrate how CAD-MAC operates given a network instance. Then we show the cumulative distribution function of the number of CRSs that are used to completely resolve the network contention. Finally we compare the performance of CAD-MAC with the Aloha-based *decentralized optimization for multichannel random access* (DOMRA) scheme in [20], which also uses channel gains to optimize the access contention while assuring proportional fairness for the type of networks considered in this paper.

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 channel gains are independent with either the same or different averages. For homogeneous channels, $h_o = 1$ and for heterogeneous ones, h_o is uniformly distributed between 0.5 and 1.5. 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 the 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 5 shows the probability density function of the number of CRSs for completely resolving contention. To verify the impact of network load, we run simulations with 5, 10, 15, or 20 randomly distributed users, respectively. For each case, we run 1000 trials, each of which contains transmission of 5000 frame slots. 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 6 compares the throughput of the proposed CAD-MAC scheme and the DOMRA scheme in [20] when there are different numbers of active users. Again for each number of users, we run 1000 trials of simulation, each of which contains transmission of 5000 frame slots. Significant performance improvement can be observed. When there are 15 active users, the throughput of CAD-MAC 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. In the proposed scheme, each frame is divided into contention and transmission periods. The contention period is used to resolve the conflicts of all users while the transmission period is used to send payload in

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
	Step 1				REQ						
	Step 2	IDL	TKN	TKN	SUC	IDL		IDL	IDL		TKN
	Step 3				OCP						
CRS 2	$H_{ij}[2]$	1.02				1.56	1.39	1.02	1.19		
	Step 1										
	Step 2	IDL				IDL		IDL	IDL		
	Step 3										
CRS 3	$H_{ij}[3]$	0.72				1.21	1.39	0.72	0.86		
	Step 1							REQ			
	Step 2	TKN				TKN		SUC	TKN		
	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.

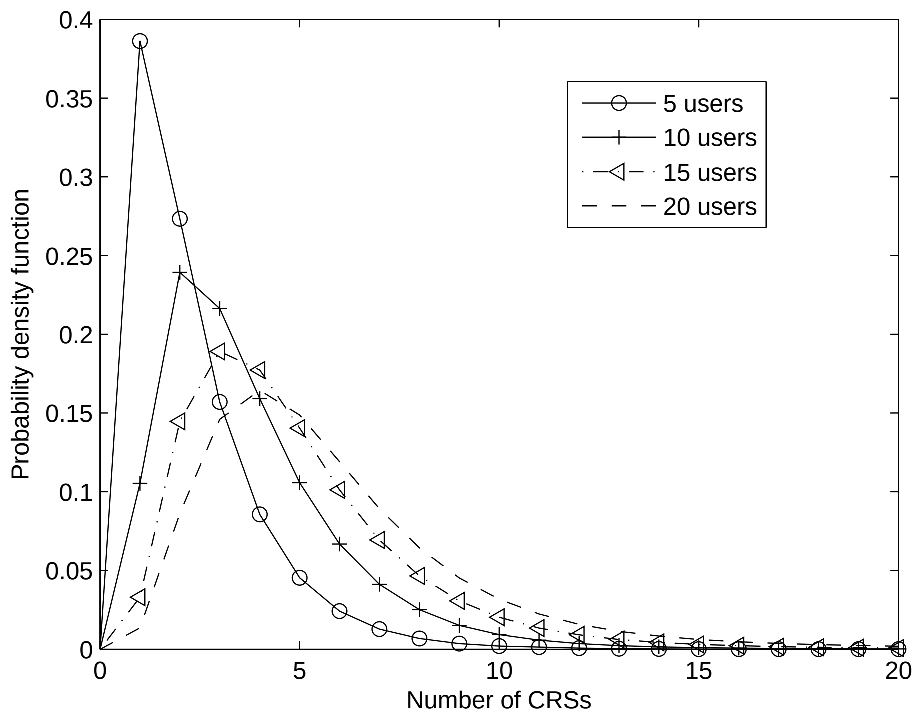

Fig. 5: Probability density function of the number of CRSs necessary for complete contention resolution.

collision-free scenarios. The proposed scheme can completely resolve network contention at a trivial signaling cost and performs closely to the centralized scheduler. Besides, it is also robust to any channel uncertainty. Simulation results have demonstrated that the proposed scheme significantly improves network performance as compared with existing schemes. 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.

In this research, we have not considered traffic characteristics, which influence MAC buffer status and thus its transmission probability. Hence, the contention needs to be improved to incorporate traffic characteristics in our future research. Furthermore, multichannel extensions of CAD-MAC are also desirable to exploit the diversity among different subchannels.

APPENDIX I
PROOF OF THEOREM 1

Proof: We prove that the two conditions of the definition hold for CAD-MAC.

$1)$ Suppose two links, (i, j) and (k, l), that have won the contention have collision and the transmission of User i

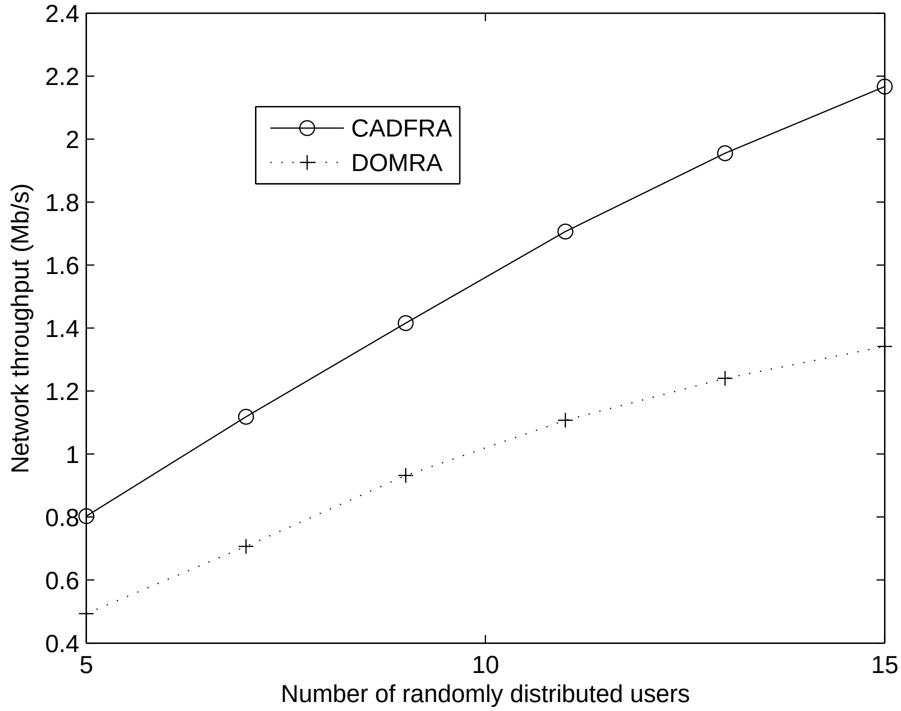

Fig. 6: Throughput comparison of CAD-MAC and DOMRA.

interferes with the reception of User l. First, (i,j) and (k,l) should not have won the contention at the same CRS since the REQUESTs of the two links collide at User l and User l will not acknowledge SUCCESS. If (i,j) receives SUCCESS first, the OCCUPIED signal of User i will prevent User l from acknowledging SUCCESS. If (k,l) wins first, the broadcasting of SUCCESS by User l will prevent User i from sending REQUEST. Hence, Condition 1 always holds.

2) To verify Condition 2, suppose that there exists a link (I,J) that has not won access and does not collide with any link that has won. Besides, within the interference range of Link (I,J), no other link could win as otherwise, after that link wins, Link (I,J) should not contend and the contention is completely resolved. There are two possibilities. (1) User I does not send any REQUEST all the time or (2) whenever User I sends a REQUEST, it collides with that of other links. We show in the following that both have zero possibility.

(1) User I does not send any REQUEST all the time. This indicates that $h_{IJ} < \widehat{H}_{IJ}[k]$ for all $k > K$, where $K > 0$. Obviously nobody that interferes with User J should send anything. Hence, User J will keep on sending IDLE signals to User I and $\widehat{H}_{IJ}[k]$ will be lowered successively. It is easy to see that in this case $\lim_{k\to\infty} \widehat{H}_{IJ}[k] = \widehat{H}_{IJ}^{m}$. Hence, the probability that $h_{IJ} < \widehat{H}_{IJ}[k]$ for all $k > K$ is zero and sooner or later User I will send a REQUEST and win.

(2) Whenever (I,J) sends a REQUEST, it collides with others. Denote the CRSs that (I,J) sends REQUESTs by $\mathcal{C} = \{c_1, c_2, \cdots\}$, where $c_1 < c_2 < \cdots$. Suppose there are N links that collide with (I,J). According to (16), the contention probability of any link using ADs I or II is $\frac{1}{2}$ after sending the first REQUEST. If using AD III, the contention probability is zero. We consider the CRSs after all the interfering links have sent the first REQUEST and denote $N_k \le N$ to be the number of interfering links that contends with probability $\frac{1}{2}$ in CRS k. The probability that (I,J) keeps on contending and never succeeds is given by

$$\begin{aligned} &\Pr\{(I,J) \text{ never wins}\} \\ &= \lim_{|\mathcal{C}|\to\infty} \prod_{k\in\mathcal{C}} \Pr\{\text{at least one interferer contends in CRS } k\} \\ &= \lim_{|\mathcal{C}|\to\infty} \prod_{k\in\mathcal{C}} \left(1-(1-\frac{1}{2})^{N_k}\right) \qquad \text{(I.25)} \\ &\le \lim_{|\mathcal{C}|\to\infty} \prod_{k\in\mathcal{C}} (1-(\frac{1}{2})^{N}) = \lim_{|\mathcal{C}|\to\infty} (1-(\frac{1}{2})^{N})^{|\mathcal{C}|} < \sigma \qquad \text{(I.26)} \end{aligned}$$

for any $\sigma > 0$. Hence, the probability that (I,J) never resolves its contention is zero. That is, with probability one, (I,J) always wins the contention when none of its neighbors can win and the network contention within the interference range of (I,J) can always be resolved. Theorem 1 follows immediately. ∎

Appendix II
Proof of Theorem 2

Proof: Suppose there are N links and in CRS 1, each has the contention probability $p_{i,j}[1] = \frac{1}{N}$. According to (16), the contention probability in CRS k is

$$p_{ij}[k] = \begin{cases} \frac{1}{N}, \text{IDLE in all the previous CRSs}, \\ \frac{1}{2}, \text{otherwise}. \end{cases} \qquad \text{(II.27)}$$

Denote by $\overline{k}_n$ the average number of CRSs necessary to resolve the collision involving n links. From (II.27), these links will contend with probability $\frac{1}{2}$ if they still contend in the following CRSs. Hence,

$$\overline{k}_n = \left(\frac{1}{2}\right)^n \left[\sum_{i=2}^{n} \binom{n}{i}(\overline{k}_i+1) + \binom{n}{0}(\overline{k}_n+1) + \binom{n}{1}1\right], \tag{II.28}$$

where $\left(\frac{1}{2}\right)^n \binom{n}{i}$ is the probability that i users have their gains above the thresholds and on average, $\overline{k}_i$ additional CRSs are needed if $i > 1$. If $i = 0$, all users have their gains below the thresholds and are involved in the following contention. If $i = 1$, the contention is resolved. It has been proved in [13] that $\overline{k}_n$ in (II.28) satisfies

$$\log_2(n) \le \overline{k}_n \le \log_2(n) + 1 \tag{II.29}$$

for all n. Before a collision happens, all users may have channel gains so low that several CRSs are necessary for them to lower their thresholds successively until some users are allowed to send REQUESTs. Hence, the average number of CRSs necessary for completely resolving the network contention is

$$\overline{K}_N = \sum_{i=0}^{\infty}\left((1-\frac{1}{N})^{Ni}\left(\sum_{n=1}^{N}\binom{N}{n}(\frac{1}{N})^n(1-\frac{1}{N})^{N-n}(\overline{k}_n+i+1)\right)\right), \tag{II.30}$$

where $(1-\frac{1}{N})^{Ni}$ is the probability that all users have their gains below their thresholds in all the first i CRSs and $\binom{N}{n}(\frac{1}{N})^n(1-\frac{1}{N})^{N-n}$ is the probability that in the $i+1$st CRS, n users send REQUESTs and collide. Let $M_N = \sum_{n=1}^{N}\binom{N}{n}(\frac{1}{N})^n(1-\frac{1}{N})^{N-n}(\overline{k}_n+1)$. Then,

$$\begin{aligned} M_N &\le \sum_{n=1}^{N}\binom{N}{n}(\frac{1}{N})^n(1-\frac{1}{N})^{N-n}(\log_2(n)+1) \\ &< \sum_{n=1}^{N}\binom{N}{n}(\frac{1}{N})^n(1-\frac{1}{N})^{N-n}(n+1) \\ &= 2-(1-\frac{1}{N})^N. \end{aligned} \tag{II.31}$$

Hence, $\overline{K}_N$ equals

$$\begin{aligned} \overline{K}_N &= M_N\sum_{i=0}^{\infty}(1-\frac{1}{N})^{Ni} + \sum_{i=0}^{\infty} i(1-\frac{1}{N})^{Ni} \\ &= \frac{M_N}{1-(1-\frac{1}{N})^N} + \frac{(1-\frac{1}{N})^N}{(1-(1-\frac{1}{N})^N)^2} \\ &< \frac{2-(1-\frac{1}{N})^N}{1-(1-\frac{1}{N})^N} + \frac{(1-\frac{1}{N})^N}{(1-(1-\frac{1}{N})^N)^2} \\ &= 1 + \frac{1}{[1-(1-\frac{1}{N})^N]^2} \\ &< 1 + [1-e^{-1}]^{-2}. \end{aligned} \tag{II.32}$$

Hence, $\overline{K}_N$ is bounded for all N and the right hand side of (II.30) converges. A tighter bound is

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

where $\widehat{M}_N = \sum_{n=1}^{N}\binom{N}{n}(\frac{1}{N})^n(1-\frac{1}{N})^{N-n}(\log_2(n)+1)$. As N goes to infinity, using computer calculation, we have

$$\overline{K}_N < \overline{K}_\infty \le 2.43. \tag{II.33}$$

■

Appendix III
Proof of Theorem 3

Proof: Let K be the number of CRSs necessary to completely resolve network contention in a frame slot and $\mathcal{K} = \{1, 2, \cdots, K\}$ the corresponding set of CRSs. Let L be the number of links winning the contention and $\mathcal{K}_l, i = 1\cdots, L$, the corresponding set of CRSs that the lth winning link is involved in the contention. Assume that $\mathcal{K}_l, l = 1, \cdots, L$ are independently and identically distributed and independent of L. Obviously,

$$\mathcal{K} = \bigcup_i \mathcal{K}_i \text{ and } K = |\mathcal{K}| \le \sum_i |\mathcal{K}_i|, \tag{III.34}$$

where $|\mathcal{X}|$ is the cardinality of set $\mathcal{X}$. Define the contention coexistence factor as

$$\beta = \frac{\mathbf{E}(\sum_i |\mathcal{K}_i|)}{\mathbf{E}(|\mathcal{K}|)}. \tag{III.35}$$

It is easy to see that β is the average number of simultaneous resolutions in each CRS. For example, if all users interfere with all others, then $L = 1$ and $\beta = 1$, meaning only one resolution in each CRS. If a network consists of L groups of users and the communication of any group does not interfere with that of any other group, then these L groups can resolve the contention within each group to produce L winners. If we further assume $\mathcal{K}_1, \mathcal{K}_2, \cdots, \mathcal{K}_L$ are independently and identically distributed, then $\beta = L$, indicating L simultaneous resolutions in each CRS on average. Then we have

$$\overline{K} = \mathbf{E}(K) = \mathbf{E}(|\mathcal{K}|) = \frac{\mathbf{E}(\sum_i^L |\mathcal{K}_i|)}{\beta}. \tag{III.36}$$

Furthermore, L is a stopping time for K_i and according to Wald's equation [27], we have

$$\overline{K} = \frac{\mathbf{E}(|\mathcal{K}_i|)\mathbf{E}(L)}{\beta}. \tag{III.37}$$

Obviously from Theorem 2, $\mathbf{E}(|\mathcal{K}_i|) < \overline{K}_\infty$. Hence,

$$\overline{K} < \frac{2.425 \cdot \mathbf{E}(L)}{\beta}. \tag{III.38}$$

■

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