Cross-Layer Optimization based on Partial Local Knowledge*

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Abstract—**This paper considers decentralized cross-layer optimization for multichannel random access with partial-local knowledge. In the network scenario considered, users are not necessarily within the transmission ranges of all other users, and each user may choose to send packets to or receive packets from different users simultaneously. A criterion for cross-layer optimization is provided leading to a *decentralized optimization for multichannel random access* (DOMRA) scheme. DOMRA can be applied to different types of wireless networks, such as wireless sensor networks and mobile ad hoc networks, to improve quality of service. Furthermore, DOMRA can be applied to optimize downlink transmissions in cellular networks for proposed *cochannel interference avoidance* (CIA) *medium access control* (MAC). CIA-MAC requires low signalling overhead and minor changes to existing mobile systems. The conditions for triggering CIA-MAC are investigated and a simple trigger mechanism is obtained. Simulation results confirm the significant performance improvement by the proposed schemes.**

Index Terms– decentralized, random access, multichannel, channel aware, cross-layer, co-channel interference

I. INTRODUCTION

Cross-layer optimization is becoming increasingly important in wireless communications. So far, significant research has been focused on centralized cross-layer scheduling, where the best performance can be obtained with the help of *channel state information* (CSI) from all active users. However, CSI feedback consumes a large amount of resources in centralized schemes, especially for MIMO and OFDM based networks. To reduce CSI feedback, decentralized cross-layer design approaches can be considered. For example, opportunistic random access schemes have been studied in [1], [2] and references therein. For opportunistic random access, each user exploits its own CSI for transmission control. In [2], each user transmits only if its channel fading level is above a certain predetermined threshold, which is chosen to maximize successful transmission probability. A channel aware multicarrier random access scheme has been proposed in [1], where each user selects some subcarriers with the best channel gains. All these schemes are for wireless networks where all users transmit to a common receiver. However, this scenario does not fit many wireless communication environments such as sensor networks, mobile ad hoc networks, and so on. Besides, existing policies [1], [2] are designed such that each user has the same transmission probability. Although this guarantees absolute fairness among all users, the network performance is not optimal when traffic flows are not uniformly distributed in the network or when link characteristics are not identical.

We consider multichannel wireless networks where users are not necessarily within the transmission ranges of the others. Each user may have packets to send to different destinations. A criterion for cross-layer optimization is provided leading to a *decentralized optimization for multichannel random access* (DOMRA). DOMRA can be applied to different types of wireless networks, such as wireless sensor networks and mobile ad hoc networks, to improve quality of service (QoS). We also illustrate the flexibility of DOMRA by designing a cost effective *co-channel interference avoidance* (CIA) *medium access control* (MAC) scheme for cellular network users experiencing severe interference.

The rest of the paper is organized as follows. In Section II, we describe the system model and give a criterion for cross-layer design. In Section III, a near optimal solution is provided. In Section IV, we will design the CIA-MAC. Simulation results will be presented in Section V followed by conclusion in Section VI.

II. CRITERION FOR CROSS-LAYER DESIGN

Consider a multichannel wireless network with K subchannels. All channels between pairs of users are reciprocal, i.e., when no interference exists, User A can reliably receive signal from User B if and only if User B can reliably receive signal from User A with the same channel gain. Each user has ideal knowledge of its own CSI and applies the same transmission control policy. No communication pair has instantaneous cooperation such as exchange of CSI, subchannel selections, and so forth. A user can not transmit and receive simultaneously on the same subchannel; however, it may transmit over a set of subchannels and receive over a different set of subchannels. A node cannot receive any signal successfully if any of its interfering neighbors is transmitting simultaneously on the same subchannel. Each user may have packets to send to or receive from different users. Each user

* This work was supported by the research gift of Intel, the U.S. Army Research Laboratory under the Collaborative Technology Alliance Program, Cooperative Agreement DAAD19-01-20-0011, and SABA Program of Motorola.

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is subject to both average and instantaneous transmit power constraints, i.e. $\mathbf{E}(P_t) \leq \overline{P}$ and $P_t \leq P_m$, where $\mathbf{E}$ is the expectation operator. Not all users are necessarily within the transmission ranges of the others, that is, users far away can use the same frequency band for reliable transmissions. For simplicity, those that can communicate with each other are assumed to experience homogeneous channels, i.e. the channel gains of different links are independent identically distributed with probability density $f(h)$ and distribution $F(h)$.

Denote the wireless network as a directed graph $G(\mathcal{V}, \mathcal{E}, \mathcal{L})$, where $\mathcal{V} = \{1, 2, ..., N\}$, $\mathcal{E} = \{(i,j)_k | i,j \in \mathcal{V}, i \neq j; k = 1, 2, ..., K\}$, and $\mathcal{L} = \{(i,j) | i,j \in \mathcal{V}, i \neq j,$ i and j can receive packets from each other$\}$ are the set of active users, the set of all links over all K subchannels, and the set of links available for communication. Denote by $\mathcal{N}_i = \{j | j \in \mathcal{V}, (i,j) \in \mathcal{L}\}$ the interfering neighbor set of User i. Each user may choose to send packets to or receive packets from several users, and $\mathcal{T}_i = \{j | (i,j) \in \mathcal{L}$, User i has packets to send to $j\}$ denotes the set of users receiving packets from User i, and $\mathcal{R}_j = \{i | (i,j) \in \mathcal{L}$, User i has packets to send to $j\}$ the set of users sending packets to j.

Figure 1 shows an example topology. The users are on a grid with unit spacing, and the transmission range is $\sqrt{2}$. The arrows show the traffic flows. For example, since $(4,6) \in \mathcal{L}$, any transmission by Users 4 or 6 will be received by the other though they have no packets to send to each other. So Users 4 and 6 constitute an interfering pair. It can be easily seen that $\mathcal{T}_3 = \{4, 6\}$, $\mathcal{R}_3 = \{1, 2\}$, while $\mathcal{N}_3 = \{1, 2, 4, 5, 6\}$.

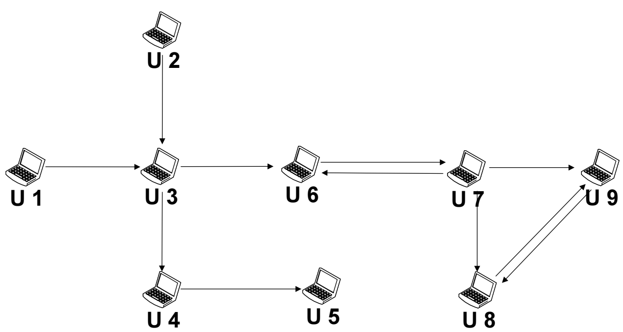


Fig. 1. Network architecture

Slotted Aloha is a typical random access scheme. In traditional slotted Aloha, the MAC layer makes decisions on transmission based on the buffer occupancy and the QoS requirement, and does not utilize knowledge of the physical layer. Hence, when the MAC decides to transmit a frame, the channel may be in deep fade, but the physical layer still carries out the transmission, and causes a waste of power. On the other hand, the MAC layer may decide not to transmit even though the channel power gain is high because it does not have this information from the PHY layer; this leads to wasted opportunities. With channel knowledge, the sender will transmit only when the channel power gain is above a certain threshold. Therefore, we propose the following *decentralized optimization for multichannel random access* (DOMRA).

DOMRA: *User i ($i \in \mathcal{V}$) decides to send packets to User j on subchannel k when 1). User i has packets to send to j, $j \in \mathcal{T}_i$; 2). on subchannel k, link (i,j) has the best channel power gain, $h_{(i,j)_k} = \max_{l \in \mathcal{T}_i} \{h_{(i,l)_k}\}$; 3). the channel power gain is above a threshold, $h_{(i,j)_k} \geq \overline{H}_{(i,j)_k}$, where $\overline{H}_{(i,j)_k}$ is predetermined for link $(i,j)_k$. The transmission is then optimized according to $\overline{H}_{(i,j)_k}$, CSI and capability constraints.*

Optimal choices of thresholds $\{\overline{H}_{(i,j)_k} | (i,j)_k \in \mathcal{E}\}$ and transmissions, i.e. mouldation and power allocation, will be determined for DOMRA in the following paragraphs so that the overall network performance can be optimized.

In DOMRA, the probability of a transmission on link $(i,j)_k \in \mathcal{E}$ is proved to be [3]

$$p_{(i,j)_k} = \frac{1}{|\mathcal{T}_i|} \left(1 - F^{|\mathcal{T}_i|}(\overline{H}_{(i,j)_k})\right) \tag{1}$$

where $|\cdot|$ denotes the number of elements in the respective set. The probability that User i transmits on subchannel k is

$$p_{i_k} = \sum_{j \in \mathcal{T}_i} p_{(i,j)_k} = \sum_{j \in \mathcal{T}_i} \frac{1}{|\mathcal{T}_i|} \left(1 - F^{|\mathcal{T}_i|}(\overline{H}_{(i,j)_k})\right). \tag{2}$$

Hence, the throughput on link $(i,j)_k$ is

$$T_{(i,j)_k} = R_{(i,j)_k} p_{(i,j)_k} (1 - p_{j_k}) \prod_{a \in \mathcal{N}_j, a \neq i} (1 - p_{a_k}), \tag{3}$$

where $R_{(i,j)_k}$ is the achieved average data rate given that user i has decided to transmit on link $(i,j)_k$, and depends on the modulation and power allocation policy. $(1 - p_{j_k}) \prod_{a \in \mathcal{N}_j, a \neq i} (1 - p_{a_k})$ is the probability that neither user j nor its neighboring users except user i will transmit on subchannel k, which means successful transmission on link $(i,j)_k$.

The average transmit power on link $(i,j)_k$ is the average of transmit power of all time slots, whether transmission happens or not on this link. According to the ergodicity of the channel, it is the average of transmit power over all channel states. In DOMRA, we can show that

$$\mathbf{E}(P_{(i,j)_k}) = \frac{1}{|\mathcal{T}_i|} \int_{\overline{H}_{(i,j)_k}}^{\infty} P_{(i,j)_k}(h) \mathrm{d}F^{|\mathcal{T}_i|}(h), \tag{4}$$

where $P_{(i,j)_k}(h)$ is the transmit power on link $(i,j)_k$ when the channel has power gain h and it depends on the modulation and power allocation policy. The achieved average data rate given that a user has decided to transmit on link $(i,j)_k$ is proved to be

$$R_{(i,j)_k} = \frac{\int_{\overline{H}_{(i,j)_k}}^{\infty} R(\eta(h)) \mathrm{d}F^{|\mathcal{T}_i|}(h)}{1 - F^{|\mathcal{T}_i|}(\overline{H}_{(i,j)_k})}, \tag{5}$$

where $\eta(h) = \frac{h P_{(i,j)_k}(h)}{N_o W / K}$ is the received SNR, N_o is the noise power per unit bandwidth, W is the total system bandwidth, and $R(\eta)$ is the instantaneous data rate when the channel has SNR η. $R(\eta)$ is assumed to be continuously differentiable with first order derivative $R'(\eta)$ positive and strictly decreasing in

η.

Both overall network throughput and fairness are considered. With proportional fairness, the objective is to maximize the product of throughput of all links [3]. Denote the transmission control of the whole network as $\mathcal{C} = \{\overline{\mathcal{H}}, \mathcal{P}\}$, where $\overline{\mathcal{H}}$ is the set of predetermined channel power gain threshold configurations and $\mathcal{P}$ is the set of power allocation policies. The optimal configuration of the whole network, $\mathcal{C}^* = \{\overline{\mathcal{H}}^*, \mathcal{P}^*\}$, that achieves proportional fairness among all subchannels carrying traffic flows is

$$\mathcal{C}^* = \arg \max_{\{\overline{\mathcal{H}}, \mathcal{P}\}} \sum_{(i,j)_k \in \mathcal{E}, j \in \mathcal{T}_i} \ln(T_{(i,j)_k}), \tag{6a}$$

subject to

$$\sum_{j \in \mathcal{T}_i, k=1,\ldots,K} \frac{1}{|\mathcal{T}_i|} \int_{\overline{H}_{(i,j)_k}}^{\infty} P_{(i,j)_k}(h) \mathrm{d}F^{|\mathcal{T}_i|}(h) \leq \overline{P}, \tag{6b}$$

and

$$\sum_k \left(\max_{h,j} P_{(i,j)_k}(h) \right) \leq P_m, \tag{6c}$$

where the throughput $T_{(i,j)_k}$ is given by (3). Problem 6 serves as cross-layer optimization criterion.

III. Cross-Layer Optimization

In the previous section, we have discussed a criterion for cross-layer design, which is to find the threshold configuration, $\overline{\mathcal{H}}$, the power allocation, $\mathcal{P}$, and the modulation policy. The global optimization of the problem is difficult and computationally expensive. Therefore, we find a sub-optimal solution. The objective of (6) is

$$\begin{aligned}\mathcal{C}^* = &\arg \max_{\{\overline{\mathcal{H}}, \mathcal{P}\}} \sum_{(i,j)_k \in \mathcal{E}, j \in \mathcal{T}_i} \Bigg(\ln \big(p_{(i,j)_k} (1 - p_{j_k}) \\ &\prod_{a \in \mathcal{N}_j, a \neq i} (1 - p_{a_k}) \big) + \ln \big(R_{(i,j)_k} \big) \Bigg).\end{aligned} \tag{7}$$

Equation (7) reveals two ways to improve the overall system performance. One is to reduce the probability of collisions in the whole network, whose effect is captured by the terms $p_{(i,j)_k}(1 - p_{j_k}) \prod_{a \in \mathcal{N}_j, a \neq i}(1 - p_{a_k})$. The other is to allocate power properly so that the achieved data rate of each individual user can be maximized. Hence, we decompose it into two related problems, and find a sub-optimal transmission control policy. Assuming all users transmit at the same data rate, the solution to find optimal MAC layer transmission control $\overline{\mathcal{H}}^*$ to resolve collisions in the whole network while guaranteeing proportional fairness is

$$\begin{aligned}\overline{\mathcal{H}}^* = &\arg \max_{\overline{\mathcal{H}}} \sum_{(i,j)_k \in \mathcal{E}, j \in \mathcal{T}_i} \Bigg(\ln \big(p_{(i,j)_k} (1 - p_{j_k}) \\ &\prod_{a \in \mathcal{N}_j, a \neq i} (1 - p_{a_k}) \big) \Bigg).\end{aligned} \tag{8}$$

The optimal power allocation $\mathcal{P}_i^*$ of each user $i \in \mathcal{V}$ to reach maximum average data rate is formulated by

$$\mathcal{P}_i^* = \arg \max_{\mathcal{P}_i} \sum_{j \in \mathcal{T}_i, k} R_{(i,j)_k}, \tag{9a}$$

subject to

$$\sum_{j \in \mathcal{T}_i, k=1,\ldots,K} \frac{1}{|\mathcal{T}_i|} \int_{\overline{H}_{(i,j)_k}}^{\infty} P_{(i,j)_k}(h) \mathrm{d}F^{|\mathcal{T}_i|}(h) \leq \overline{P}, \tag{9b}$$

and

$$\sum_k \left(\max_{h,j} P_{(i,j)_k}(h) \right) \leq P_m, \tag{9c}$$

where $\{\overline{H}^*_{(i,j)_k}\}$ is the solution given by (8) and $R_{(i,j)_k}$ is given by (5). It is easy to see that although problem (6) has been decomposed into problems (8) and (9) to resolve network collisions and improve individual transmission capability respectively, these two problems are closely coupled together through the optimal threshold configuration $\overline{\mathcal{H}}^*$.

Theorem 1: The optimal predetermined channel power gain threshold for any link $(i,j)_k \in \mathcal{E}$ where $j \in \mathcal{T}_i$, $\overline{H}^*_{(i,j)_k}$, as defined in (8), is given by

$$\overline{H}^*_{(i,j)_k} = F^{-1} \left[\left(1 - \frac{|\mathcal{T}_i|}{|\mathcal{R}_i| + \sum_{m \in \mathcal{N}_i} |\mathcal{R}_m|}\right)^{\frac{1}{|\mathcal{T}_i|}} \right]. \tag{10}$$

and the resulting transmission probability is

$$p^*_{(i,j)_k} = \frac{1}{|\mathcal{R}_i| + \sum_{m \in \mathcal{N}_i} |\mathcal{R}_m|} \tag{11}$$

The optimal threshold of User i is independent of the receiver but depend on the neighborhood information, including the number of users receiving packets from User i, $|\mathcal{T}_i|$, the number of users sending packets to User i, $|\mathcal{R}_i|$, and the total number of users sending packets to the interfering neighbors of User i, $\sum_{m \in \mathcal{N}_i} |\mathcal{R}_m|$. The first two are local information while $|\mathcal{R}_m|'s, m \in \mathcal{N}_i$, are information of interfering neighbors. $|\mathcal{R}_m|$, for all $m \in \mathcal{N}_i$, can be obtained through broadcast whenever this number changes. Since this knowledge needs to be broadcasted to notify the interfering neighbors, we call it two-hop knowledge. This broadcast incurs only trivial signaling overhead since only when either a traffic session or the network topology varies will it be needed.

If we assume that no user has two-hop knowledge, the number of flows that each interfering neighbor receives needs to be estimated. Since the transmission of each interfering neighbor $j \in \mathcal{N}_i$ will be detected by User i, i.e. $|\mathcal{T}_j|$ is available, User i can assume $|\mathcal{T}_j|$ to be $|\mathcal{R}_j|$. This is reasonable since for usual reliable data transmissions, a data flow is always accompanied by acknowledgement in the reverse direction. Hence, instead of (10), the transmission threshold with one-hop knowledge, i.e. local knowledge, is given by

$$\overline{H}^*_{(i,j)_k} = F^{-1}\left[(1-\frac{|\mathcal{T}_i|}{|\mathcal{R}_i|+\sum_{j\in\mathcal{N}_i}|\mathcal{T}_j|})^{\frac{1}{|\mathcal{T}_i|}}\right]. \qquad (12)$$

Consider a simple transmitter adaptation technique, channel inversion, which maintains a constant received power level for reliable reception. With channel power gain h, the transmit power is $P_t = P_r/h$, where P_r is the received power level. From (4), the average transmit power on link $(i,j)_k$ is

$$\mathbf{E}(P_{(i,j)_k}) = \frac{1}{|\mathcal{T}_i|}\int_{\overline{H}_{(i,j)_k}}^{\infty}\frac{P_{r(i,j)_k}}{h}\mathrm{d}F^{|\mathcal{T}_i|}(h). \qquad (13)$$

Hence, the instantaneous received power is

$$P_{r(i,j)_k} = |\mathcal{T}_i|\mathbf{E}(P_{(i,j)_k})\left(\int_{\overline{H}_{(i,j)_k}}^{\infty}\frac{\mathrm{d}F^{|\mathcal{T}_i|}(h)}{h}\right)^{-1}. \qquad (14)$$

According to (5), the average data rate is $R_{(i,j)_k} = \mathbf{E}\left(R(\eta(h))\right) = R(P_{r(i,j)_k})$. Solving the problem in (9), we have Theorem 2 for power allocation for channel inversion.

Theorem 2: By using channel inversion and assuming strict concavity of the data rate function $R(P_r)$, (9) has unique globally optimal reception power levels $P^*_{r(i,j)_k}$ on any link $(i,j)_k \in \mathcal{E}$ where $j \in \mathcal{T}_i$, and

$$P^*_{r(i,j)_k} = \min\left(\frac{\overline{P}}{K}\Big(\int_{\overline{H}^*_{(i,j)_k}}^{\infty}\frac{1}{h}\mathrm{d}F^{|\mathcal{T}_i|}(h)\Big)^{-1}, \frac{P_m\overline{H}^*_{(i,j)_k}}{K}\right), \qquad (15)$$

in which $\overline{H}^*_{(i,j)_k}$ is determined by *Theorem 1*.

However, when $\overline{H}^*_{(i,j)_k}$ is very small, (15) turns out to be very small due to the penalty of allowing transmission over deeply faded channels. Therefore $\overline{H}^*_{(i,j)_k}$ should be further modified to avoid transmissions over deeply faded channels. Define $\overline{H}_o$ as

$$\overline{H}_o = \arg\max_{\overline{H}} R(\frac{\overline{P}}{K\int_{\overline{H}}^{\infty}\frac{1}{h}f(h)\mathrm{d}h})(1-F(\overline{H})) \qquad (16)$$

which leads to maximum physical layer throughput when the physical layer is required to transmit regardless to the channel conditions. If $\overline{H}^*_{(i,j)_k}$ determined by *Theorem 1* is less than $\overline{H}_o$, then substitute it with $\overline{H}_o$.

With channel inversion, the instantaneous transmit power allocation $\mathcal{P}^*$ is:

$$P^*_{(i,j)_k}(h) = \begin{cases} \frac{P^*_{r(i,j)_k}}{h} & h \geq \overline{H}^*_{(i,j)_k} \\ 0 & otherwise \end{cases}. \qquad (17)$$

Assume that each user can vary both the transmit power and rate to achieve the best performance, and $R_{(i,j)_k}$ is given by (5). Then we have Theorem 3.

Theorem 3: Assume the data rate function $R(\eta)$ to be continuously differentiable and the first order derivative $R^{'}(\eta)$ is positive and strictly decreasing. For any link $(i,j)_k \in \mathcal{E}$ where $j \in \mathcal{T}_i$, (9) has a unique globally optimal power allocation given by: if $P_m < \frac{\overline{P}}{1-F^{|\mathcal{T}_i|}(\overline{H}^*_{(i,j)_k})}$, $P^*_{(i,j)_k}(h) = \frac{P_m}{K}$ for $h \geq \overline{H}^*_{(i,j)_k}$; otherwise,

$$P^*_{(i,j)_k}(h) = \begin{cases} \frac{P_m}{K} & \nu^* < R^{'}\left(\frac{hP_m}{n_oW}\right)\frac{hK}{n_oW}, \\ 0 & \nu^* \geq R^{'}(0)\frac{hK}{n_oW}, \\ R^{'-1}\left(\frac{\nu^* n_o W}{hK}\right)\frac{n_oW}{Kh} & \text{otherwise}, \end{cases} \qquad (18)$$

for $h \geq \overline{H}^*_{(i,j)_k}$. $R^{'-1}()$ is the inverse function of $R^{'}()$. $\nu^* \geq 0$ is uniquely determined by

$$\int_{\overline{H}^*_{(i,j)_k}}^{\infty} P^*_{(i,j)_k}(h)\mathrm{d}F^{|\mathcal{T}_i|}(h) = \frac{\overline{P}}{K}, \qquad (19)$$

where $\overline{H}^*_{(i,j)_k}$ is given by *Theorem 1*.

It should be noted from (18) that the power will be optimally distributed over both time and all subchannels. When $\nu^* \geq R^{'}(0)\frac{hK}{n_oW}$, although the MAC layer decides to transmit, the physical layer further optimizes the transmission performance and decides not to transmit. Assume the data rate function to be $R(\eta) = \frac{W}{K}\ln(1+\eta)$. The power allocation when $P_m \geq \frac{\overline{P}}{1-F^{|\mathcal{T}_i|}(\overline{H}^*_{(i,j)_k})}$ is given by

$$P^*_{(i,j)_k}(h) = \begin{cases} \frac{P_m}{K} & \frac{1}{\nu^*} - \frac{n_oW}{Kh} > \frac{P_m}{K} \\ 0 & \frac{1}{h} \geq \frac{K}{\nu^* n_o W} \\ \frac{1}{\nu^*} - \frac{n_oW}{Kh} & \text{otherwise} \end{cases} \qquad (20)$$

for $h \geq \overline{H}^*_{(i,j)_k}$, which is similar to the well-known water-filling power allocation scheme [4], [5]. Since the proposed power allocation scheme has maximum instantaneous power constraint, we call it capability-limited water filling.

IV. Cochannel Interference Avoidance MAC

DOMRA can be used in different types of wireless networks, such as wireless sensor networks and mobile ad hoc networks, to improve quality of service. In this section, we give an application and illustrate how to apply DOMRA flexibly.

In cellular systems, *cochannel interference* (CCI) is one of the major factors limiting system capacity. CCI can be avoided through exclusive channel assignment among neighboring cells, which usually leads to low spectrum efficiency, or mitigated by advanced digital signal processing techniques such as adaptive antenna arrays [6], which usually have high complexity and result in high costs for *mobile equipments* (MEs). Joint pre-encoding or cooperative scheduling techniques among *base stations* (BSs) have also been proposed in [7] and ([8]) to mitigate or avoid CCI, which usually require onerous instantaneous information exchange. Recently, contention based schemes have also been developed for CCI avoidance in addition to an intracellular centralized MAC protocol. In [9], without considering fairness, each ME or BS keeps on broadcasting busy-tone signals to prevent interferers from transmitting, and every BS or ME must listen to the mini-slots before transmission. We will develop a cost effective scheme to deal with the downlink transmissions with severe CCI. The developed scheme maintains backward compatibility with existing cellular networks and requires only minor changes to the existing BSs and MEs. Furthermore, it adds low signaling overhead and assures fairness.

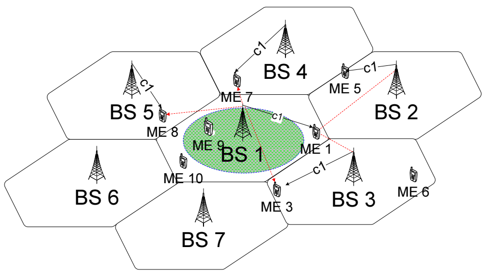


Fig. 2. Cochannel interference in cellular networks with reuse factor 1 (solid lines represent transmission links while dashed lines severely interfering links)

Consider only downlink transmission since complicated multiuser detection and cochannel interference cancelation algorithms can be used for uplink transmissions. MEs on cell boundaries, such as ME 1 in Figure 2, not only face the weakest signals but also the largest amount of interference from neighboring cells. We focus on the performance improvement of such MEs. Hence, MEs are categorized into two classes: those experiencing slight or no cochannel interference and those suffering from severe cochannel interference. The first class will be scheduled by traditional centralized MAC, while the second will be accepted by traditional call admission control policies and scheduled by the proposed MAC. Each ME measures the average *interference to carrier ratio* (ICR) of each neighboring BS that generates CCI. The ICR of neighboring BS m is

$$ICR_m = \frac{E(h_m P_m)}{E(hP)}, \tag{21}$$

where h and P are the channel power gain and transmit power of the desired link, while h_m and P_m correspond to the interfering link from BS m.

Severe Interferer: *If the ICR from any neighboring BS m satisfies $ICR_m \geq \Gamma_c$, where Γ_c, which we call trigger, is a predetermined severe interference threshold, the transmission of B_m always causes failure packet reception. BS m is called a severe cochannel interferer.*

If all BSs causing severe interference keep on transmitting, receptions at the interfered ME always fail. However, if the interferers do not transmit in some time slots, some frame receptions will succeed. It is unfair if an interfering BS is always silent or transmitting. If there is collaboration among BSs, then the interfering BSs may transmit in turn. However, the multi-user diversity cannot be fully exploited since signalling overhead is huge. If there is no collaboration among BSs, we arrange those BSs to transmit randomly when either identified as severe interferers or their receivers are experiencing severe CCI. Besides traditional MAC, a complementary MAC is used in the BS for optimizing the random transmissions either experiencing severe CCI or causing severe CCI to MEs in neighboring cells. The new complementary MAC aims to improve the cellular throughput through cochannel interference avoidance, which is, therefore, called *cochannel interference avoidance* MAC (CIA-MAC).

Each ME is assigned a channel, and consider the transmission optimization of a certain channel across the whole network. Denote all BSs and MEs managed by CIA-MAC as $\mathcal{B} = \{1, 2, \cdots, B\}$ and $\mathcal{M} = \{m_1, m_2, \cdots, m_B\}$ respectively, where m_i is the ME in the cell of BS i. Denote data links as $\mathcal{D} = \{(i, m_i), \forall i \in \mathcal{B}\}$, and all severely interfering links as $\mathcal{I}$. Correspondingly, in DOMRA, let $\mathcal{V} = \mathcal{B} \bigcup \mathcal{M}$, $\mathcal{E} = \mathcal{L} = \{(i,j)|(i,j)$ or (j,i) is in $\mathcal{D} \bigcup \mathcal{I}\}$, and $\mathcal{N}_i = \{(i,j)|(i,j) \in \mathcal{L}\}$. $\mathcal{T}_i = \{m_i\}$ and $\mathcal{R}_i = \emptyset$ for each $i \in \mathcal{B}$, while $\mathcal{R}_{m_i} = \{i\}$ and $\mathcal{T}_{m_i} = \emptyset$ for each $m_i \in \mathcal{M}$. Hence, CIA-MAC can be optimized through DOMRA.

The trigger is critical in determining whether a BS is a severe interferer or not. In general, we will choose the trigger to maximize the throughput of the overall network rather than that of any individual link. Therefore, the optimum trigger is defined as follows.

Optimum Trigger: *A trigger results in overall network throughput improvement when it is used to judge whether a BS is a severe interferer or not.*

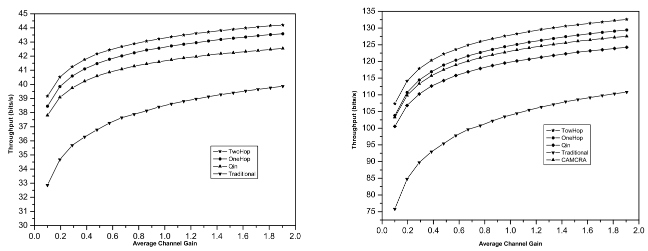
Triggers are different for different MEs, and it is hard for each ME to evaluate the variation of overall network throughput when one of its neighboring BS is judged as a severe interferer or not. In order to get a constant trigger and simplify the calculation, consider a network in which each ME is severely interfered by one neighboring BS, and the BS of the observed ME also brings severe cochannel interference to a ME of neighboring cells. According to (11), the transmission probability of each BS is $\frac{1}{2}$ by using CIA-MAC. Assume that the *cyclic redundancy check* (CRC) is ideal, and even one bit error inside a frame after CRC will result in drop of the frame. Besides, errors within a MAC frame are assumed to be uniformly and independently distributed. Then the frame error rate is $p_f = 1 - (1 - p_b)^{RL}$, where p_b is the bit error rate and given by $p_b = P_e(\eta)$, R is the average number of bits transmitted per symbol, L is the number of symbols per MAC frame, and RL is the number of bits per frame. The CIA-MAC is triggered when it achieves higher throughput than traditional cellular network MAC, where all BSs keep on transmitting. The trigger Γ_c is shown to be [10]

$$\Gamma_c = \frac{1}{P_e^{-1}\left[1 - \left(\frac{1}{4}(1 - P_e(\eta))^{LR\frac{R}{\overline{R}}}\right)^{\frac{1}{L\overline{R}}}\right]} - \frac{1}{\eta}. \tag{22}$$

where $\overline{R}$ is the average bits transmitted per symbol in traditional MAC. From (22), Γ_c depends on SNR and modulation policy, both of which are known to each ME, and Γ_c can be easily calculated for severe interferer judgement.

V. Simulation Results

Consider the wireless network in Figure 1. Assume Rayleigh fading channel and $R(P) = W \ln(1 + \frac{HP}{Wn_o})$. Assume one channel in the network , the overall network throughput of DOMRA with either two-hop or one-hop knowledge, the channel-aware Aloha in [2], and the optimal traditional Aloha in [11] are compared in Figure 3(a) with legends "TwoHop", "OneHop", "QIN", and "Traditional" respectively. Assuming five channels in the network, the overall network throughput of these schemes together with the multichannnel channel aware Aloha CAMCRA in [1] are compared in Figure 3(b). DOMRA outperforms these existing schemes significantly due to the exploitation of both multiuser diversity and inhomogeneous neighborhood knowledge.



(a) Single-subchannel network (b) Five-subchannel network

Fig. 3. Throughput comparison with proportional fairness constraint, where $P_m = 50\text{dBm}, \bar{P} = 43\text{dBm}, W = 100\text{Hz}$, and $N_o = 0.001\text{W/Hz}$.

Consider a cellular network with reuse factor 1, where each ME is severely interfered by one neighboring BS, while each BS causes severe cochannel interference to a ME in a neighboring cell. MEs are randomly distributed in each cell. Consider per cell spectral efficiency defined as the number of bits transmitted per unit bandwidth per cell. When 4QAM modulation is used, Figure 4 compares the spectral efficiencies of CIA-MAC with and without cross-layer design and traditional MAC where all BSs keep on transmitting. When the transmit power is 43 dBm, CIA-MAC has 33% spectrum efficiency improvement as compared with 4QAM. Even without cross-layer design, there is still 10% improvement.

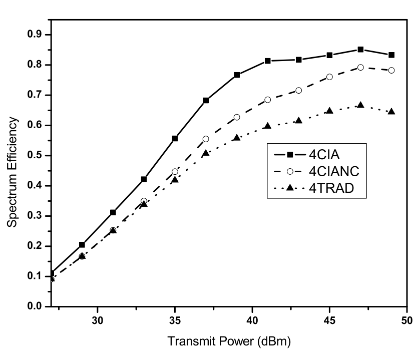


Fig. 4. Spectrum efficiency with different transmit powers

VI. Conclusions and Future Research

We have proposed a joint PHY-MAC layer optimization policy DOMRA for multichannel Aloha random access in wireless networks in which all users are not necessarily within the transmission range of each other and each user may have packets to send to or receiver from different users. System performance is optimized while proportional fairness is obtained with the consideration of the inhomogeneous characteristics of traffic distribution. The generality of the design allows its applications in different types of wireless networks. We showed how to apply DOMRA to optimize downlink transmissions in cellular networks where severe co-channel interference exists, and a cost effective CIA-MAC was proposed requiring low signalling overhead and only minor changes to existing mobile systems. Simulation results showed the significant performance improvement by the proposed schemes.

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