Power-controlled Channel Access Protocol for Wireless Networks with Full-duplex and OFDMA Capabilities

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***Abstract*—Recent research has demonstrated the feasibility of full-duplex (FD) communication over the same frequency channel. This capability, facilitated by new self-interference suppression techniques, has great potential to increase the network capacity. However, exploiting FD in the context of a multi-user, multi-channel network is still being debated. This paper focuses on the channel access issue and presents a novel multi-channel MAC (MMAC) protocol for wireless ad hoc networks with FD and orthogonal frequency-division multiple access (OFDMA) capabilities. Through these capabilities, a node can simultaneously carry out multiple transmissions and/or receptions over the same or different channels. In our MMAC protocol, a pair of nodes negotiate data channels, transmission rates, transmission powers, and transmission modes (e.g., FD or half-duplex) in a distributed manner so that their spectral usages are minimized while their rate demands are still met. Extensive ns3 simulations show that our MMAC protocol increases the end-to-end network goodput by up to 150% and decreases the end-to-end delay by up to 300% compared with an OFDMA-based protocol without FD.**

***Index Terms*—Multi-channel MAC protocol, full-duplex, OFDMA, wireless ad hoc networks, self-interference suppression.**

I. Introduction

Increasing the throughput of a wireless network has always been a key design objective. Numerous approaches have been proposed in the literature for this purpose. One such approach that has recently attracted significant attention is based on full-duplex (FD) communication over the same frequency channel [1]–[4]. For example, in [1] a gain of 110% in PHY-layer throughput was achieved with FD. Other FD benefits include avoiding transmitter deafness and resolving various hidden-terminal problems [1] [5].

The literature on FD and self-interference suppression (SIS) spans several decades. By definition, SIS is a method for canceling the interference generated by the *transmit path*, as it appears at the *receive path* of the same node. As shown in Figure 1, the near-end signal (e.g., self-interference) can be partially suppressed using a *circulator*, along with analog and digital cancellation components, which sample the transmitted signal before sending it over the air interface. These components ensure that the sampled signal has the same amplitude but opposite polarity relative to the transmitted signal. Circulators have been used in radar systems for decades to radiate pulses while receiving echoed pulses via the same antenna (see [6] and the references therein).

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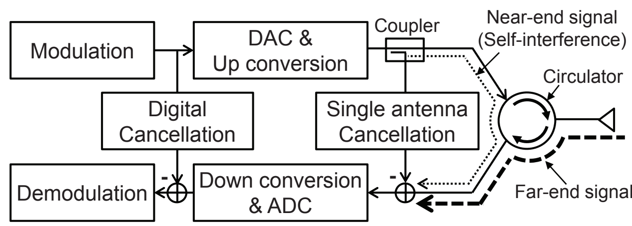


Fig. 1. Basic configuration for FD transceiver.

Ideally, the near-end and the sampled signals cancel out, allowing a (desired) far-end signal to be received. However, in practice, some residual self-interference may remain after SIS. This is due to several factors, such as the nonlinearity of RF devices. In [1], 30 dB and 45 dB SIS were achieved using digital and two-antenna cancellation, respectively. In [4], 15 dB and 30 dB SIS were achieved using a circulator and single-antenna cancellation, respectively. A better circulator design can achieve a higher SIS (e.g., 50 dB suppression in [7]). In combination, we believe that 75 dB or more SIS is quite possible, even with a single-antenna transceiver.

The concept of SIS is related to echo cancellation (EC) in acoustic systems. These systems are similar to wireless FD communications in the sense that you have a loudspeaker that generates sound and a microphone that picks up that sound and feeds it back into the acoustic system. There is rich literature dealing with the issue of EC in acoustic systems (e.g., see [8] and the references therein). SIS issues arise in wired telephony as well. In a four-wire circuit, the transmit path is isolated from the receive path. The two paths are merged through a hybrid coupler to share the same medium in what is called as the two-wire circuit [9]. At the hybrid coupler, some interference leaks from the transmit side to the receive side, leading to self-interference. This issue was of great interest to researchers at Bell Labs several decades ago [10].

While the concept of FD communications has been around for some time in the fields of acoustics [8], radar [7], and wired telephony [9], it is relatively new in wireless communications. Conventional wireless systems (e.g., satellite or cellular) communicate over long distances and require very high transmit powers, making FD operation difficult to achieve (a little residual self-interference can overwhelm the LNA in the receive chain). Therefore, the transmit and receive paths have to be adequately separated in time, frequency, or space.

In WLANs, the signal travels shorter distances, reaching its destination in a relatively healthy condition. This makes FD communications more feasible, even with partial SIS. To the best of our knowledge, the first academic work to discuss and implement FD in a wireless environment is [11]. Industry also had an early interest in this topic [12]. It is worth mentioning that SIS is used in wireless systems not only for FD communication, but also to suppress spectral leakage from adjacent channels [13].

The significance of the recent works on SIS is that they demonstrated actual wireless FD systems and showed the performance impact of this technology. Numerous well-known network problems can *potentially* be mitigated using FD/SIS, including hidden terminals and transmitter deafness. In multi-hop wireless networks, the end-to-end delay may be significantly decreased by forwarding packets while receiving others. These issues and others have sparked a race in the networking community to solve existing networking problems using FD technology. In [5], a new MAC protocol was proposed for single-channel FD-capable networks. A new collision resolution scheme with FD capability was presented in [14]. Flow optimization was presented in [15] for two-hop relay networks with FD capability. In [16], opportunistic multi-path routing was extended to incorporate FD operation.

In parallel with FD operation, wireless systems can also utilize orthogonal frequency-devision multiple access (OFDMA) to improve the network performance. Many infrastructure networks already incorporate OFDMA as the transmission method of choice. In its most ambitious implementation, OFDMA allows a node to transmit over some subcarriers while simultaneously receiving over others (the destination for the transmitted subcarriers may be different from the origin of the received subcarriers). Signal leakage between adjacent subcarriers is still a problem, and techniques similar to those used with SIS can be applied here (naturally, the interference problem is less challenging in the OFDMA case). In [17], the authors demonstrated an ad hoc network with OFDMA capability, using off-the-shelf devices. In [18], a new multi-channel MAC (MMAC) protocol with OFDMA capability was proposed for wireless ad hoc networks. A MAC/routing cross-layer protocol was presented in [19] for OFDMA-based cognitive radio networks.

As efforts to boost SIS and enable various OFDMA configurations continue to progress, there is a critical need to revisit network protocols and modify them to accommodate/exploit these new capabilities. In particular, it is not clear if the *single-link* performance gain due to FD/OFDMA scales to the *network level*, where multi-hop operation, hidden terminals, collisions, etc., interact in a complex manner to achieve a certain end-to-end performance. To answer this question, one must first design an FD/OFDMA-aware channel access protocol for a multi-hop, multi-channel wireless network. As part of this design, a node should be able to determine which subcarriers to use for transmission/reception and the transmission powers/rates of these subcarriers. No such protocol currently exists.

Compared with conventional MMAC protocols (which are often based on CSMA/CA), designing an FD/OFDMA-capable MMAC protocol presents several challenges. In the FD mode, a node can send while receiving so the conventional sender and receiver concepts are not applicable anymore. Because a channel can be reused for FD operation with/without power control, the channel state can no longer be designated as simply busy/idle. For FD communications, a node has to consider not only the multiple access interference (MAI) from other nodes, but also its residual self-interference. The combined interference should be accounted for in the node's own data transmission as well as other neighboring transmissions.

We present a novel MMAC protocol for wireless ad hoc networks, called *full-duplex MAC* (FULL-MAC), which allows a pair of nodes to examine available channels (subcarriers) and transmission rates while considering residual self-interference and MAI. Subsequently, these nodes select channels, transmission modes (e.g., FD or half-duplex), transmission rates, and transmission powers such that the number of selected channels is minimized and the rate demands are satisfied. FULL-MAC operates in a distributed manner. Simulation results show that this protocol increases the end-to-end goodput by up 150%, and decreases the delay by up 300%, compared with an OFDMA-based protocol without FD capability.

The rest of this paper is organized as follows. Section II gives various definitions and states our assumptions. In Section III, we introduce FULL-MAC. Simulation results and conclusion are presented in Section IV and V, respectively.

II. Definitions and Assumptions

The integration of FD and OFDMA into a wireless ad hoc network gives rise to several modes of communication. The following terminology is used to characterize these modes:

- Half-duplex (HD): In this case, a node is either transmitting or receiving, but not both.
- Full-duplex over different channels (FD-D): In this case, a node is transmitting and simultaneously receiving but over different channels.
- Full-duplex over the same channel (FD-S): In this case, a node is transmitting and simultaneously receiving over the same channel(s).

When FD capability is available, the concept of sender and receiver can be confusing. In this paper, we refer to the node that initiates the communication process by sending an *request-to-send* (RTS) the *initiator*. The next-hop node towards the ultimate destination is referred to as the *responder*. The path from the initiator to the responder is referred to as the *forward path* and the reverse path is referred to as the *backward path*.

Upon receiving an RTS packet from the initiator, the responder selects data channels from an available list. In conventional MMAC protocols, a channel is labeled as *busy* or *idle* during the channel selection process. In our setup, we need to account for other possibilities, as follows:

- Fully-utilized channel (FU): We consider a channel to be fully utilized from the perspective of a given node if that node is transmitting and receiving simultaneously over that channel.

- Half-utilized transmitting channel (HU-T): A channel is HU-T from the point of view of a given node if that node is transmitting but not receiving over that channel.
- Half-utilized receiving channel (HU-R): We consider a channel to be HU-R when a given node is receiving but not transmitting over that channel.
- Un-utilized channel (UN): A channel is UN when a given node is not receiving nor transmitting over that channel.

In designing FULL-MAC, we make the following assumptions:

- OFDMA/FD: It is assumed that all nodes in the network have OFDMA and FD capabilities. Without loss of generality, we assume that all nodes have the same radio capabilities. However, the amount of SIS (as a fraction of the node's transmit signal power) can vary from one node to another.
- Single transceiver: Nodes can operate over multiple channels with a single transceiver by using OFDMA and suppressing the spectral leakage. The feasibility of this assumption has been validated in several works (e.g., [20]).
- Single antenna: The FD communications are feasible with a single antenna, using a circulator, as presented in [4].
- Channel model: We assume a flat channel fading, i.e., the OFDM subcarrier's bandwidth is less than the channel coherence bandwidth. We also assume that the channel is symmetric, i.e., the channel gain from node A to node B is the same as the channel gain from B to A.

III. Proposed Full-duplex MAC Protocol

A. Protocol Overview

We first provide a general overview of FULL-MAC. Consider a multi-rate, power-controlled wireless ad hoc network. For any two nodes to communicate, they must first exchange control packets, allowing them to negotiate and agree on their transmission parameters. This happens over a set of dedicated OFDM subcarriers, acting as a fixed control channel. Other subcarriers constitute data channels. The initiator starts by sending an RTS packet. The responder executes a channel and transmission rate assignment algorithm that allocates data channels, transmission rates, and powers. Through proper interference management, the assigned channels/rates/powers ensure that ongoing communications are not disturbed. In conventional power control protocols, a node is only concerned with the MAI from other users. In an FD system, we also have to consider self-interference. Power computation is discussed in the next section. Once transmission power calculation and frequency assignment have been done, a *clear-to-send* (CTS) packet is sent back, carrying this information. A third control packet, called *determined-to-send* (DTS), is then broadcasted by the initiator to inform nodes that have not received the CTS packet (i.e., neighbors of the initiator who are not neighbors of the responder) of the selected channels. Data communications then occur over the assigned data channels. An acknowledgement packet (ACK) follows a successful data transmission, but is sent over the control channel. ACK transmission can be delayed until the control channel becomes idle.

B. Transmission Power Control

To determine the appropriate transmission powers for data channels, we consider similar ideas to those used in the *single-channel* POWMAC protocol [21]. Specifically, to support a transmission level l ($l = 1, \cdots, L$), the transmission power from node i to node j over channel k is set to:

$$P_i^{(k,l)} = \frac{\Gamma_l \eta_{\max} N}{G_{ij}^{(k)}} \tag{1}$$

where Γ_l is the SINR threshold for the lth transmission rate, $\eta_{\max}$ is the "maximum load factor" (MLF), N is the thermal noise, and $G_{ij}^{(k)}$ is the channel gain from node i to node j over channel k.

The MLF is a pre-specified upper bound (e.g., $\eta_{\max} = 7$ dB in [21]) on the load factor (LF), a metric that reflects the amount of interference at a given receiver. Formally, the LF for a node j over channel k is defined as:

$$\eta_j^{(k)} \triangleq \frac{N + \sum\limits_{m \in \mathcal{T}_j} P_m^{(k)} G_{mj}^{(k)} + P_j^{(k)} \chi_j}{N} \tag{2}$$

where $\mathcal{T}_j$ is the set of currently transmitting nodes in node j's neighborhood, $P_m^{(k)}$ is the transmitting power of node m over channel k, and χ_j is the *SIS factor* of node j (a fraction that reflects the SIS capability of node j's radio). We later explain how to obtain χ_j. In (2), the second and third terms in the numerator represent MAI and the residual self-interference, respectively. The LF concept was previously used in satellite communications and wireless cellular systems [22], [23]. It was also used to solve the near-far problem in CDMA cellular systems, mange co-channel interference, and enable admission control, among other uses. For example, in a CDMA cellular system, if the base station experiences a too high LF, it will not admit any new mobile terminals to its cell. In an ad hoc network, the situation is more involved due to the absence of a centralized control. As shown later in this paper, during the initial control exchange between two nodes, the LF will be used to decide whether the prospective transmission is feasible or not, in a distributed manner. Nodes update their LFs upon overhearing CTS and DTS packets.

When node j receives an RTS packet from node i over the control channel, denoted by c, it estimates c's channel gain, as follows:

$$G_{ij}^{(c)} = \frac{P_{\mathrm{RX},j}^{(c)}}{P_{\max}} \tag{3}$$

where $P_{\max}$ and $P_{\mathrm{RX},j}^{(c)}$ are the maximum transmission power and the received power at node j over c, respectively. Control packets are sent at power $P_{\max}$. The responder estimates $G_{ij}^{(k)}$

for a data channel k as follows:

$$G_{ij}^{(k)} = G_{ij}^{(c)} \left(\frac{f_c}{f_k}\right)^{\alpha} \quad (4)$$

where f_c and f_k are the center frequencies of channels c and k, respectively, and α is the path loss exponent.

Essentially, $\eta_j^{(k)}$ in (2) represents the total interference power at node j on channel k, scaled by the thermal noise. This is somewhat analogous to the definition in [21]. The difference is that there is a self-interference term in the nominator in (2), which contributes to the overall undesired noise. It is important to notice that the SIS capability (i.e., the value of χ_j) impacts the performance significantly. If χ_j is relatively high, then self-interference will consume much of the LF, preventing other potential concurrent transmissions from taking place in the vicinity of the receiving node.

C. Measuring SIS Factor

So far, we have assumed that χ_j is given a priori for a node j. Because of the non-linearities of RF components and the imperfect measurements, χ_j may not be perfectly known, and may in fact vary with time. In this section, we outline a simple procedure for estimating χ_j on-the-fly.

While node i transmits a signal and measures its SIS factor, its neighbors have to keep silent over the same channel. Note that RTS/CTS exchanges prevent the neighbors from causing interferences during the subsequent DTS transmission. When node i transmits a preamble (before the actual DTS packet), it disables the digital cancellation component and measures the received power $P_{\text{RX},i}^{(c)}$ at its receive path. The power attenuation due to the passive SIS components (i.e., circulator and single-antenna cancellation) can be obtained as follows:

$$C = \frac{P_{\text{RX},i}^{(c)} - N}{P_{\max}}. \quad (5)$$

Note that the DTS packet (including the preamble) is sent at power $P_{\max}$.

After transmitting the preamble, node i enables the active SIS component (i.e., digital cancellation) and sends the DTS packet. Suppose that node i transmits a symbol $s(t)$. The version of $s(t)$ that node i will receive at its own receive-path can be expressed as follows:

$$r(t) = \sqrt{C} s(t) + n(t) \quad (6)$$

where $n(t)$ is the noise at time t. Ideally, node i can completely cancel out the self-interference because it knows C and $s(t)$. Let $\hat{r}(t)$ denote the received symbol at time t after digital cancellation. We assume that the noise process is stationary ergodic, and can be measured *a priori* (i.e., $N = 1/M \sum_0^M n^2(t)$ with sufficiently many M samples). Then, the SIS factor of node i at time t is estimated as $\chi_i(t) = (\hat{r}^2(t) - N)/s^2(t)$ and this has to be averaged over the DTS duration.

Initially, χ_i is set to one. If node i receives a CTS packet before χ_i has been estimated through the above process, the FD-S communication will be disabled until a new estimate is obtained.

D. Feasibility Conditions

In the channel and transmission rate selection process, the responder must check the transmission feasibility of communicating over each channel. To communicate over channel k using the lth transmission rate, $l = 1, ..., L$, node i's transmission power to node j must satisfy the following conditions:

$$P_{\min,i}^{(k)} \leq P_i^{(k,l)} \leq P_{\max,i}^{(k)} \quad (7)$$

where

$$P_{\min,i}^{(k)} \stackrel{\text{def}}{=} \frac{\Gamma_1 \eta_j^{(k)} N}{G_{ij}^{(k)}} \quad (8)$$

$$P_{\max,i}^{(k)} \stackrel{\text{def}}{=} \min \left\{ \min_{m \in \mathcal{N}_i} \left\{ \frac{\text{RIM}_m^{(k)}}{G_{im}^{(k)}} \right\}, \frac{\text{RIM}_i^{(k)}}{\chi} \right\} \quad (9)$$

where Γ_1 is the SINR threshold associated with the lowest transmission rate, $\text{RIM}_i^{(k)}$ is the *residual interference margin* at node i over channel k, and $\mathcal{N}_i$ is the set of node i's neighbors that are currently receiving signals over channel k. The power $P_{\min,i}^{(k)}$ represents the minimum power needed to achieve the lowest-rate SINR threshold Γ_1 (this can be seen by substituting $\eta_j^{(k)}$ in (8) for its expression in (2)). $P_{\max,i}^{(k)}$ is the maximum allowable transmission power that node i can use over channel k without disturbing ongoing receptions in that node's vicinity. In (9), the first factor is the maximum transmission power that node i is allowed to use without impacting any of the ongoing receivers in its neighborhood. The second factor is the maximum transmission power that node i can use without affecting its own reception while simultaneously transmitting on channel k.

A reasonable way to set $\text{RIM}_i^{(k)}$ is as follows:

$$\text{RIM}_i^{(k)} = \frac{\text{IM}_i^{(k)}}{n+1} \quad (10)$$

where

$$\text{IM}_i^{(k)} \stackrel{\text{def}}{=} \left(\eta_{\max} - \eta_i^{(k)}\right) N. \quad (11)$$

In (11), $\text{IM}_i^{(k)}$ is the total residual interference margin that node i can tolerate on channel k and n is the number of potentially interfering nodes in the neighborhood of i. $\text{IM}_i^{(k)}$ is divided by n to give each potentially interfering node "a fair share of interference" that can be introduced into the neighborhood without halting node i's ongoing reception. In the denominator, we add 1 because the node may itself go into FD-S mode. We assume that each node can estimate n from overheard control exchanges and by measuring the actual utilization of a data channel in that node's neighborhood.

E. Channel and Transmission Rate Selection

Let UN_i, HU-T$_i$, and HU-R$_i$ denote the sets of UNs, HU-Ts, and HU-Rs for node i, respectively. Let D_{ij} denote the rate demand (in bits/second) for a prospective transmission node i to node j, and let $I_i^{(k)}$ denote the instantaneous measured interference over channel k at node i. When node i sends an RTS packet to node j over the control channel, it includes UN_i, HU-T_i, HU-R_i, and $I_i^{(k)}$ $\forall k \in \text{UN}_i \cup \text{HU-T}_i$. The RTS packet also contains $P_{\max,i}^{(m)}$ $\forall m \in \text{UN}_i \cup \text{HU-R}_i$ as well as D_{ij}.

Upon receiving the RTS packet, node j executes the channel and transmission rate selection algorithm. The goal of this algorithm is to assign as few channels as possible to the $i \leftrightarrow j$ communications while satisfying the given rate demands. Let $\mathcal{I}$ and $\mathcal{R}$ denote the set of (channel, transmission-rate) pairs that an initiator and responder can use, respectively, according to the feasibility conditions in (7). Let $x^{(k,l)}$ and $y^{(k,l)}$ be binary variables, taking a value of 1 if channel k and transmission rate l are selected by the initiator and responder, respectively, and zero otherwise. The channel selection problem can be formulated as the following optimization problem:

$$\underset{\{x^{(k,l)},y^{(k,l)}\}}{\text{maximize}} \left\{ \sum_{(k,l)\in\mathcal{I}} x^{(k,l)} + \sum_{(k,l)\in\mathcal{R}} y^{(k,l)} \right\} \tag{12}$$

subject to

$$\begin{aligned}
&P_{\min,i}^{(k)} x^{(k,l)} \le P_i^{(k,l)} x^{(k,l)} \le P_{\max,i}^{(k)} x^{(k,l)}, \forall (k,l) \in \mathcal{I} \\
&P_{\min,j}^{(k)} y^{(k,l)} \le P_j^{(k,l)} y^{(k,l)} \le P_{\max,j}^{(k)} y^{(k,l)}, \forall (k,l) \in \mathcal{R} \\
&\sum_{(k,l)\in\mathcal{I}} \gamma_l x^{(k,l)} \ge D_{ij} \\
&\sum_{(k,l)\in\mathcal{R}} \gamma_l y^{(k,l)} \ge D_{ji} \\
&\sum_l x^{(k,l)} \le 1 \quad \forall k \\
&\sum_l y^{(k,l)} \le 1 \quad \forall k \\
&x^{(k,l)} \in \{0,1\} \quad \forall k,l \\
&y^{(k,l)} \in \{0,1\} \quad \forall k,l
\end{aligned} \tag{13}$$

where γ_l is the lth transmission rate (in bits/second), $l = 1, \cdots, L$. It is easy to see that the above formulation is a binary integer linear program, which is known to be NP-hard.

We can modify the above formulation to produce different heuristic channel assignment strategies. For example, to minimize the total transmission powers, we can use the following objective instead of (12):

$$\underset{\{x^{(k,l)},y^{(k,l)}\}}{\text{minimize}} \left\{ \sum_{k\in\mathcal{I}} P_i^{(k,l)} x^{(k,l)} + \sum_{k\in\mathcal{R}} P_j^{(k,l)} y^{(k,l)} \right\}. \tag{14}$$

Instead of minimizing the number of allocated channels as in (12), the objective function in (14) aims at minimizing the sum of the transmission powers for the forward and backward paths, subject to constraints (13).

We present a heuristic algorithm to solve (12). In a nutshell, our heuristic algorithm sorts channels in a decreasing order of transmission rate and incrementally adds channels until the rate demands D_{ij} and D_{ji} are satisfied. Note that D_{ij} is conveyed in a RTS packet. Let $\mathcal{S} = \mathcal{I} \cap \mathcal{R}$ denote the set of feasible FD-S (channel, rate) pairs for the $i \leftrightarrow j$ communication. Because FD-S channels are likely to have higher capacity than HD-only channels, the algorithm first searches $\mathcal{S}$, then $\mathcal{I}$, and finally $\mathcal{R}$.

The pseudocode of the algorithm is shown in Algorithm 1. The algorithm examines all channels $k = 1, \ldots, K$. If the initiator is not currently transmitting and the responder is not currently receiving over channel k, the algorithm examines all transmission rates $l = 1, \cdots, L$. If a given (k,l) pair satisfies the feasibility conditions in (7), it is added to $\mathcal{S}$, and the algorithm stops examining channel k. Note that for a given channel, the highest possible transmission rate is selected. A similar process is used to determine $\mathcal{R}$.

From $\mathcal{I}$ and $\mathcal{R}$, we determine $\mathcal{S}$. The elements in the sets $\mathcal{S}$, $\mathcal{I}$, and $\mathcal{R}$ are then sorted in a decreasing order of transmission rate. Let $\tilde{\mathcal{I}}$ and $\tilde{\mathcal{R}}$ denote the resulting sets of (channel, transmission-rate) pairs that are selected by the initiator and responder, respectively, for the upcoming data transmission(s). The first element (k,l) is taken from $\mathcal{S}$ and added to $\tilde{\mathcal{I}}$. After that, γ_l is deducted from the rate demands D_{ij} and D_{ji}. This process is repeated until D_{ij} and D_{ji} reach zero or $\mathcal{S}$ becomes empty. If the rate demands are not satisfied, the algorithm repeats a similar process for $\mathcal{I}$ and then for $\mathcal{R}$.

F. CTS/DTS/DATA/ACK Transmissions

After selecting the channels and their transmission rates, node j (i.e., the responder) transmits a CTS packet. The CTS packet contains $\tilde{\mathcal{I}}$, $\tilde{\mathcal{R}}$, the transmission rates, transmission powers, RIMs, and the transmission durations. Transmission powers and RIMs are calculated using (1) and (10), respectively. If not enough channels are available to meet the rate demands, node j transmits a negative CTS (NCTS) packet.

Upon receiving the CTS packet, node i (the initiator) broadcasts a DTS packet that contains the same information as the CTS packet. When overhearing any CTS or DTS packets, any neighboring node m updates its $\mathcal{T}_m$ and $\mathcal{N}_m$ sets.

After transmitting a DTS packet, node i begins its data transmissions over the selected channels in $\tilde{\mathcal{I}}$ and simultaneously data receptions over the selected channels in $\tilde{\mathcal{R}}$. At the same time, node j begins data transmissions over its assigned channels in $\tilde{\mathcal{R}}$ and data receptions over the assigned channels in $\tilde{\mathcal{I}}$. Once the control channel becomes idle, an ACK is sent over the control channel after a random amount of time.

G. Control Channel Access

In FULL-MAC, each node performs a binary exponential backoff (BEB) to access the control channel. Before starting the backoff process, node i checks whether the intended target j is ready to receive. In conventional MMAC protocols, this is done by checking a *busy node list*, which contains nodes that are currently transmitting or receiving. Because of FD and OFDMA capabilities, we need to account for other possibilities.

Algorithm 1

procedure CHANNEL-RATE-SELECTION
  $\mathcal{I} \leftarrow \emptyset$, $\mathcal{R} \leftarrow \emptyset$
  for $k = 1 \to K$ **do**
    if $k \in \{\text{UN}_i \cup \text{HU-R}_i\} \cap \{\text{UN}_j \cup \text{HU-T}_j\}$ **then**
      for $l = L \to 1$ **do**
        if $P_{\min,i}^{(k)} \le P_i^{(k,l)} \le P_{\max,i}^{(k)}$ **then**
          $\mathcal{I} \leftarrow \mathcal{I} \cup \{(k,l)\}$
        else
          break
        end if
      end for
    end if
    if $k \in \{\text{UN}_i \cup \text{HU-T}_i\} \cap \{\text{UN}_j \cup \text{HU-R}_j\}$ **then**
      for $l = L \to 1$ **do**
        if $P_{\min,j}^{(k)} \le P_j^{(k,l)} \le P_{\max,j}^{(k)}$ **then**
          $\mathcal{R} \leftarrow \mathcal{R} \cup \{(k,l)\}$
        else
          break
        end if
      end for
    end if
  end for
  $\mathcal{S} \leftarrow \mathcal{I} \cap \mathcal{R}$, $\mathcal{I} \leftarrow \mathcal{I} - \mathcal{S}$, $\mathcal{R} \leftarrow \mathcal{R} - \mathcal{S}$
  Sort $\mathcal{S}$, $\mathcal{I}$, and $\mathcal{R}$ in a decreasing order of transmission rate
  $\tilde{\mathcal{I}} \leftarrow \emptyset$, $\tilde{\mathcal{R}} \leftarrow \emptyset$
  while $D_{ij} + D_{ji} > 0 \; and \; \mathcal{S} \neq \emptyset$ **do**
    Pop (k,l) from $\mathcal{S}$
    $\tilde{\mathcal{I}} \leftarrow \tilde{\mathcal{I}} \cup \{(k,l)\}$, $\tilde{\mathcal{R}} \leftarrow \tilde{\mathcal{R}} \cup \{(k,l)\}$
    $D_{ij} \leftarrow \max\{D_{ij} - \gamma_l, 0\}$, $D_{ji} \leftarrow \max\{D_{ji} - \gamma_l, 0\}$
  end while
  while $D_{ij} + D_{ji} > 0 \; and \; \mathcal{I} \neq \emptyset$ **do**
    Pop (k,l) from $\mathcal{S}$
    $\tilde{\mathcal{I}} \leftarrow \tilde{\mathcal{I}} \cup \{(k,l)\}$
    $D_{ij} \leftarrow \max\{D_{ij} - \gamma_l, 0\}$
  end while
  while $D_{ij} + D_{ji} > 0 \; and \; \mathcal{R} \neq \emptyset$ **do**
    Pop (k,l) from $\mathcal{S}$
    $\tilde{\mathcal{R}} \leftarrow \tilde{\mathcal{R}} \cup \{(k,l)\}$
    $D_{ji} \leftarrow \max\{D_{ji} - \gamma_l, 0\}$
  end while
  if $D_{ij} + D_{ji} = 0$ **then**
    Report $\tilde{\mathcal{I}}$ and $\tilde{\mathcal{R}}$
  else
    Report not enough channels
  end if
end procedure,

We assume that node i knows the sets UN_j, HU-T_j, and HU-R_j of its neighbor j by overhearing CTS and/or DTS packets. Node i can begin the BEB process if the following conditions are met:

$$\left(\left|(\text{UN}_i \cup \text{HU-R}_i) \cap (\text{UN}_j \cup \text{HU-T}_j)\right|\right) \gamma_1 \ge D_{ij} \tag{15}$$

$$\left(\left|(\text{UN}_i \cup \text{HU-T}_i) \cap (\text{UN}_j \cup \text{HU-R}_j)\right|\right) \gamma_1 \ge D_{ji}.$$

Note that node i cannot estimate the channel capacity between itself and node j because it does not know the amount of interference at node j. If the above conditions are not met, node i considers another target node from its MAC queue and repeats the same procedure.

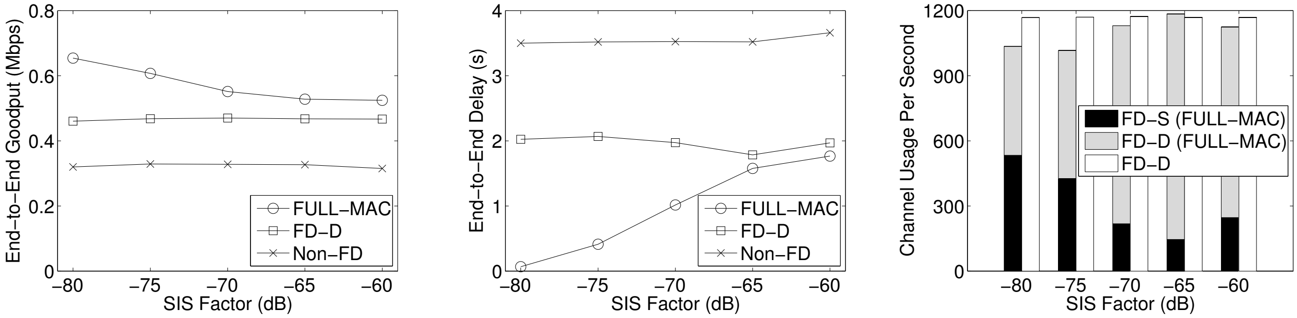
TABLE I
SIMULATION PARAMETERS.

Parameter	Default Value
Simulation area	150×150 meters
Number of nodes	20
Number of data channels	19
Number of control channels	1
Channel bandwidth	4 MHz
Frequency range	$2.4 - 2.46$ GHz
Path loss factor (α)	2.7
Traffic rate (λ)	80
Maximum load factor ($\eta_{\max}$)	10
SIS factor (χ)	-70 dB
Power mask	0 dBm
Noise floor (N)	-95 dBm
Transmission rate (γ_1)	2 Mbps
SINR threshold (Γ_1)	3
Rate demand (D)	4 Mbps
Packet size	1000 bytes
RTS retransmission limit	6
Minimum contention window size	16
Maximum contention window size	1024

IV. SIMULATION RESULTS

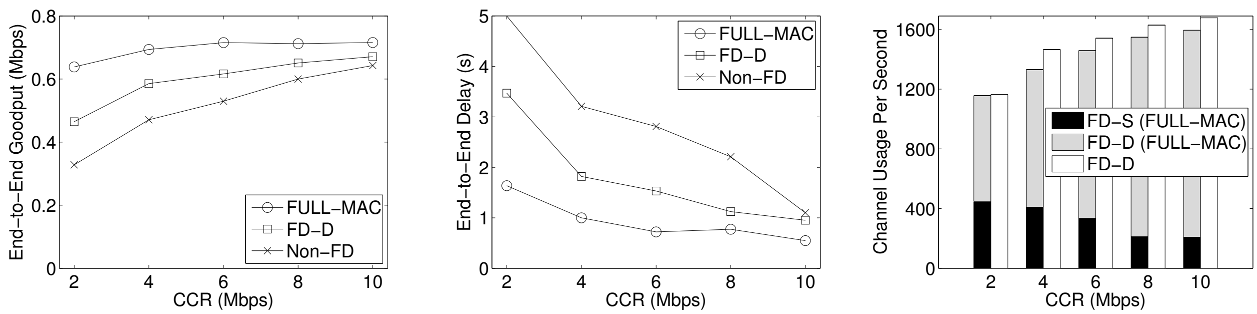
We use NS3 to evaluate FULL-MAC and compare its performance with two similar MMAC protocols: one without FD-S capability (hereafter called FD-D), and one without FD-S and FD-D capabilities (hereafter called Non-FD). In our simulations, 20 nodes are randomly distributed over a square. Nodes are divided into 5 sources, 5 destinations, and 10 relays. Five bidirectional sessions are established between the sources and destinations, respectively. Both source and destination nodes generate packets to each other. Packet generation at a node (source or destination) follows a Poisson process with rate λ (in packets/second). If the source and destination nodes are not within range, a min-hop route is established. Note that source and destination nodes can also be relay nodes to other source-destination pairs. For simplicity, in the simulations we take $\gamma_1 = 2$ Mbps and $\chi_i = \chi \forall i$. Unless indicated otherwise, the default parameter values in Table I are used.

Figure 2(a) shows the average end-to-end goodput for FULL-MAC, FD-D, and Non-FD as a function of χ. As expected, a higher value for χ results in higher goodput and lower end-to-end delay. A higher χ means that more FD-S communications can take place. As shown in Figure 2(b), FULL-MAC achieves significant improvement in the average



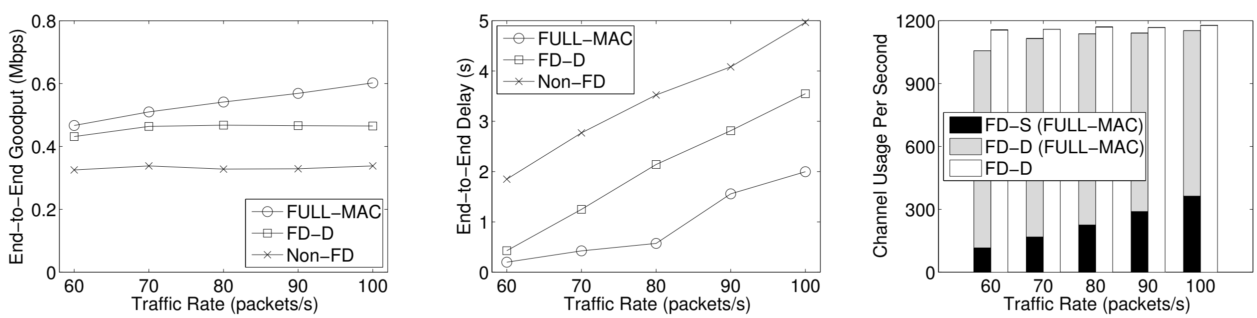
(a) (b) (c)

Fig. 2. Impact of self-interference suppression factor on performance.



(a) (b) (c)

Fig. 3. Impact of control channel transmission rate on performance.



(a) (b) (c)

Fig. 4. Impact of traffic load on performance.

end-to-end delay, compared with FD-D. The control channel is the performance bottleneck because its capacity is much smaller than that of data channels, i.e., the control-channel access delay dominates the end-to-end delay. Figure 2(c) depicts the histogram of various communication modes for FULL-MAC and FD-D vs. χ. Notice that under FULL-MAC, a given channel may be operated as FD-S, FD-D, or HD. The histogram in Fig 2(c) represents the factual of time that each mode is used over various channels.

Figures 3(a) and (b) depict the average end-to-end goodput and delay as functions of the control channel transmission rate (CCR). For both FULL-MAC and FD-D, the average end-to-end goodput increases and the average end-to-end delay decreases, as the CCR increases. For FULL-MAC, the control channel is not the performance bottleneck as long as CCR $\geq$ 6 Mbps. A pair of nodes can communicate in FD mode if both of them have a packet to transmit to each other. Thus, the likelihood of operating in the FD mode decreases as the CCR increases (see Figure 3(c)). For the same reason, the performance gap between FULL-MAC and FD-D (and Non-FD) decreases as the CCR increases.

Figure 4(a) examines the average end-to-end goodput as a function of the traffic load λ. The goodput for FD-D is steady for $\lambda \geq 70$ because the control channel is so congested that no more data channels can be utilized. For FULL-MAC, as λ increases, the frequency of FD-S usage increases (see Figure 4(c)). Consequently, the average end-to-end goodput of FULL-MAC keeps increasing with λ. FULL-MAC reduces the end-to-end delay by around 50% and 150%, compared with FD-D and Non-FD, respectively, regardless of λ.

To study the performance when data channels are the bottleneck, we set the CCR to 10 Mbps. Figure 5(a) depicts the average end-to-end goodput as a function of the number of data channels. As this number increases, the average end-to-end goodput for FD-D increases. When the number of data channels exceeds 7, the average end-to-end goodput of FULL-MAC stops increasing because data channels are no longer the performance bottleneck. As shown in Figure 5(b), the average end-to-end delay of FD-D and Non-FD is very sensitive to the number of available data channels. The average end-to-end delay of FULL-MAC is much lower than that of FD-D, regardless of the number of data channels. The reason is that FULL-MAC has a very low queuing delay at the MAC buffer because its control and data channels are not congested. Figure 5(c) shows the blocking probability of transmission requests as a function of the number of data channels. In here, the blocking probability is defined as the ratio of the number of NCTS transmissions (because a receiver has no available data channel) to the number of RTS transmissions. FULL-MAC reduces the blocking rate by around 50% compared with FD-D, regardless of the number of data channels.

Because of residual self-interference, the transmission range with FD communication is shorter than that with HD communication. To see the impact of this on performance, we vary the length of the square simulation area (denoted by $\mathcal{L}$). Figure 6 shows the performance as a function of $\mathcal{L}$. Because nodes are randomly distributed over the square, the smaller $\mathcal{L}$, the higher the node density. From Figure 6(a), we can see that the average end-to-end goodput for FD-D and Non-FD decrease, as the network becomes more sparse. The reason is that the number of hops increases with $\mathcal{L}$. The average end-to-end goodput of FULL-MAC decreases more sharply than that of FD-D and Non-FD. The reason is that the frequency of FD-S usage reduces with $\mathcal{L}$, as shown in Figure 6(c). Because we randomly distribute nodes over the square, the average distance between senders and receivers increases with $\mathcal{L}$. Figure 6(b) also shows that the performance gain from FD communications diminishes as $\mathcal{L}$ increases.

Figure 6 implies that the use of FD-S does not significantly improve the *multi-hop* performance. In anticipation of future advances in SIS techniques, we set χ to -90 dB and $\mathcal{L}$ to 350 meters. As shown in Figures 7(a) and 7(b), both FULL-MAC and FD-D suffer a slight performance degradation as the MLF ($\eta_{\max}$) increases. The reason is that the number of hops increases with $\eta_{\max}$. FD-D and Non-FD show more performance degradation than FULL-MAC because the frequency of FD-S usage increases as $\eta_{\max}$ increases. As shown in (11) and (9), the interference margin and the maximum transmission power increase with $\eta_{\max}$. Hence, the feasibility of FD-S communication becomes more likely with higher $\eta_{\max}$. FULL-MAC outperforms FD-D and Non-FD in terms of the end-to-end delay, as shown in Figure 7(b).

V. Conclusions

In this paper, we proposed FULL-MAC, a MMAC protocol for wireless ad hoc networks with FD and OFDMA capabilities. Incorporating these capabilities via a *circulator*, a node can simultaneously have multiple transmissions and/or receptions over different and/or same channels using a single-antenna transceiver. In our protocol, nodes select the transmission mode (i.e., HD, FD-S, or FD-D) as well as resources (i.e., channel, rate, and power) in a distributed manner so that the number of concurrent transmissions can be maximized. To do this, the MAI and the residual self-interference are carefully considered in the mode/channel/rate/power selection. Results showed that our protocol significantly improves performances: increasing the end-to-end goodput by up to 80% and 150%, and decreasing the end-to-end delay by up to 200% and 300%, compared with an OFDMA-based protocol without FD-S and without FD-S and FD-D, respectively.

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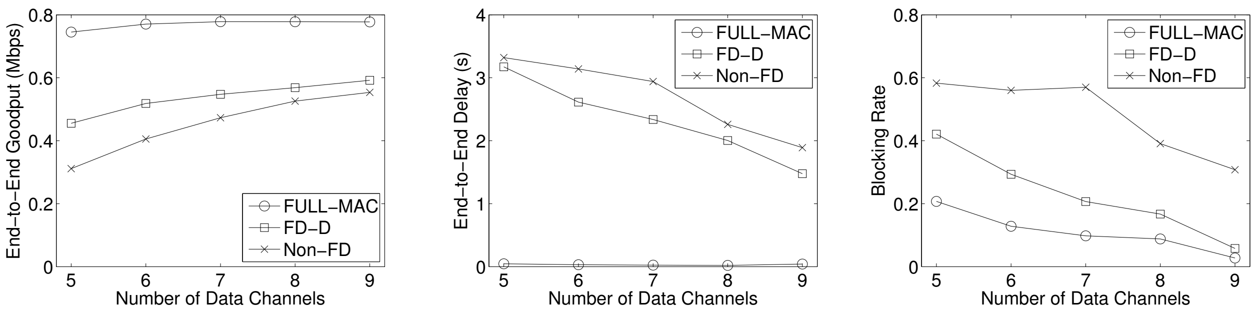
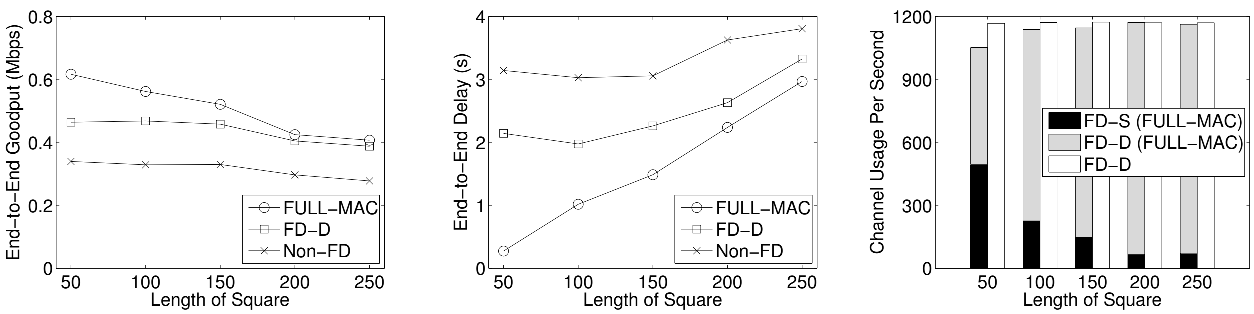


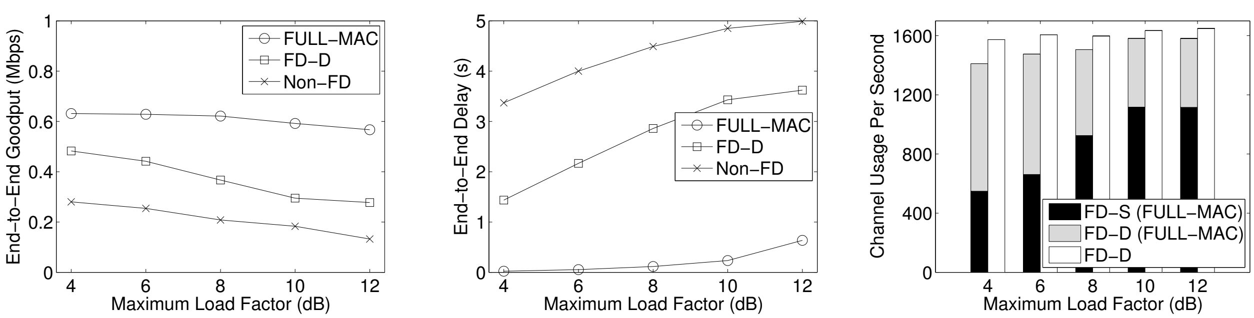
(a) (b) (c)

Fig. 5. Impact of the number of data channels on performance.



(a) (b) (c)

Fig. 6. Impact of network size on performance.



(a) (b) (c)

Fig. 7. Impact of maximum load factor on performance.

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