Online Channel Assignment, Transmission Scheduling, and Transmission Mode Selection in Multi-channel Full-duplex Wireless LANs

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Abstract. Although full-duplex transmission can be helpful for enhancing wireless link capacity, it may require extra energy to overcome the residual self-interference. In this paper, we investigate the trade-off between energy consumption and delay in a multi-channel full-duplex wireless LAN (WLAN). The goal is to minimize the energy consumption while keeping the packet queues stable. With Lyapunov optimization, we develop an online scheme to achieve the goals with optimized channel assignment, transmission scheduling, and transmission mode selection. We prove the optimality of the proposed algorithm and derive upper bounds for the average queue length and energy consumption, which demonstrate the energy-delay trade-off. The proposed algorithm is validated with simulations.

1 Introduction

Due to the dramatic increase of wireless data demands driven by the wide use of smartphones, tablets and other smart devices, there is an urgent need to improve the spectrum efficiency of existing wireless networks. Through effective self-interference cancellation, full-duplex transmission, i.e., transmitting and receiving simultaneously in the same band, has been successfully demonstrated [1]. With various self-interference cancellation techniques, full-duplex transmission has the potential to increase and even double the wireless link capacity [2].

Combined with RF interference cancellation and digital baseband interference cancellation, antenna cancellation can achieve a sufficient self-interference cancellation for full-duplex transmissions. In [2–4], analog and digital cancellation techniques were investigated. With full-duplex transmissions, various full-duplex links can be formed. For example, in the three-node full-duplex link scenario, one node (e.g., a base station) executes self-interference cancellation to transmit to and receive from two different half-duplex nodes simultaneously [5]. In the two-node link scenario, both nodes are capable of self-interference cancellation and can transmit to and receive from each other simultaneously [6].

Due to imperfect self-interference cancellation, the residual self-interference may still lead to a lower signal-to-interference-plus-noise ratio (SINR) and deteriorate the performance of a full-duplex link [7]. Additional power is needed to combat the residual self-interference to achieve a suitable SINR. As a result, full-duplex transmission may not always be helpful, and there is a trade-off between the energy cost and delay in the design of full-duplex wireless networks [8]. In [7, 8], the extra energy consumption and the limits of full-duplex transmission were investigated. Joint resource allocation and scheduling in wireless networks is a challenging problem, for which Lyapunov optimization has been applied and shown effective [9–12]. However, these prior works are all focused on half-duplex wireless networks. Many challenging issues that arise in full-duplex wireless networks have not been adequately addressed.

In this paper, we consider a multi-channel wireless LAN (WLAN) where both the access point (AP) and user equipments (UE) are capable of full-duplex transmission. Since full-duplex is not always more efficient than half-duplex, we aim to jointly consider the problems of channel assignment, transmission scheduling, and transmission mode selection for the AP and UEs. We develop a problem formulation to capture the trade-off between energy consumption and queue length (which is indicative of delay) in the multi-channel full-duplex WLAN, with the objective to minimize the overall energy consumption of the system and stabilize the packet queues at all the nodes. We then develop an effective solution algorithm based on the Lyapunov optimization framework. With the proposed algorithm, the overall optimization problem over the entire time period is first reduced to the maximization of a *drift-plus-penalty* for each node in each time slot. The reduced problem only depends on the queue lengths, wireless link rates, and energy consumptions in the current time slot. We then transform the reduced problem into a maximum weighted matching problem and solve it with the Hungarian Method [13].

The proposed algorithm is an online algorithm since it does not require any past and future information of the WLAN system. We prove that the proposed algorithm maximizes the *drift-plus-penalty* among all possible transmission modes and channel assignment schemes. Furthermore, we derive upper bounds on the average sum queue length and average total energy consumption under the proposed algorithm, which clearly demonstrate the energy-delay trade-off in the multi-channel full-duplex WLAN. The performance of the proposed algorithm is validated with simulations.

The remainder of this paper is organized as follows. The system model and problem formulation are presented in Section 2. The proposed scheduling algorithm is developed and analyzed in Section 3. A simulation study is presented in Section 4. Section 5 concludes this paper.

2 System Model and Problem Statement

2.1 System Model

We consider a WLAN with one AP, a set of UEs denoted as $\mathcal{N} = \{1, 2, ..., N\}$, and a set of orthogonal channels denoted as $\mathcal{S} = \{1, 2, ..., S\}$. The AP determines the channel assignment, transmission schedule, and transmission mode selection for both uplink and downlink transmissions. We assume that data is transmitted via the AP in packets, and there is no direct transmission among the UEs. The packets waiting for transmission are buffered and served in the First In First Out (FIFO) manner. We assume a discrete time system. The uplink queue lengths at the beginning of time slot t are denoted as $\boldsymbol{Q}^u(t) = \{Q_1^u(t), Q_2^u(t), ..., Q_N^u(t)\}$ and the downlink queue lengths are denoted as $\boldsymbol{Q}^d(t) = \{Q_1^d(t), Q_2^d(t), ..., Q_N^d(t)\}$, where $Q_i^u(t)$ is the backlog of the uplink queue maintained at UE i and $Q_i^d(t)$ is the backlog of the downlink virtual queue for UE i maintained at the AP.

At time slot t, the arrivals of packets to the uplink queues are denoted as $\boldsymbol{A}^u(t) = \{A_1^u(t), A_2^u(t), ..., A_N^u(t)\}$. The arrivals of packets to the downlink queues are denoted as $\boldsymbol{A}^d(t) = \{A_1^d(t), A_2^d(t), ..., A_N^d(t)\}$. In addition, we assume that the arrivals of packets, either to the uplink or downlink queues, are i.i.d over time. The expectations, i.e., the average arrival rates, are

$$\boldsymbol{\lambda}^u \triangleq \mathbb{E}\{\boldsymbol{A}^u(t)\} = \{\lambda_1^u, \lambda_2^u, ..., \lambda_N^u\} \text{ and } \boldsymbol{\lambda}^d \triangleq \mathbb{E}\{\boldsymbol{A}^d(t)\} = \{\lambda_1^d, \lambda_2^d, ..., \lambda_N^d\}. \quad (1)$$

Recall that there are $\mathcal{S} = \{1, 2, ..., S\}$ orthogonal channels. During each time slot t, a UE can transmit and/or receive on one of the channels in $\mathcal{S}$. The channel assignment decision is denoted as $\alpha_i(t)$, where $i \in \mathcal{N}$ and $\alpha_i(t) \in \{\mathcal{S} \cup \{0\}\}$ is the channel UE i uses at time slot t. Note that $\alpha_i(t) = 0$ indicates that no channel is assigned to UE i. In addition, each UE can choose from three transmission modes: *uplink*, *downlink*, or *full-duplex*. The transmission mode selection is denoted as $\beta_i(t) \in \{U,\ D,\ F\}$, where $\beta_i(t) = U$, $\beta_i(t) = D$, and $\beta_i(t) = F$ indicate that at time slot t, UE i selects half-duplex uplink, half-duplex downlink, and full-duplex transmission, respectively.

For the full-duplex mode, the residual self-interference is treated as interference. Let $C_i^u(t)|_{\alpha_i(t)=s,\beta_i(t)=F}$ and $C_i^d(t)|_{\alpha_i(t)=s,\beta_i(t)=F}$ be the uplink and downlink channel capacity of UE i at time slot t, respectively, given that channel s is assigned to UE i and the full-duplex mode is selected. We have

$$C_i^u(t)|_{\alpha_i(t)=s,\beta_i(t)=F} = B\log_2\left(1 + \frac{p_i^u(t)|h_s^u|^2}{N_0 + p_i^d \eta_d}\right) \quad (2)$$

$$C_i^d(t)|_{\alpha_i(t)=s,\beta_i(t)=F} = B\log_2\left(1 + \frac{p_i^d(t)|h_s^d|^2}{N_0 + p_i^u \eta_u}\right), \quad (3)$$

where B is the channel bandwidth; h_s^u and h_s^d are the channel gains between the AP and UE i for the uplink and downlink channel, respectively; $p_i^u(t) > 0$ and $p_i^d(t) > 0$ are the uplink and downlink transmit power, respectively; η_d and η_u are the self-interference cancellation ratio at the AP and a UE, respectively; and N_0 is additive white Gaussian noise power.

For half-duplex uplink transmission, the uplink channel capacity for UE i, given that it is assigned with channel s, is

$$C_i^u(t)|_{\alpha_i(t)=s,\beta_i(t)=U} = B\log_2\left(1 + \frac{p_i^u(t)|h_s^u|^2}{N_0}\right). \quad (4)$$

In this case, we have $p_i^u(t) > 0$ and $p_i^d(t) = 0$. For half-duplex downlink transmission, the downlink channel capacity for UE i, given that it is assigned with channel s, is

$$C_i^d(t)|_{\alpha_i(t)=s,\beta_i(t)=D} = B\log_2\left(1+\frac{p_i^d(t)|h_s^d|^2}{N_0}\right). \quad (5)$$

In this case, we have $p_i^u(t) = 0$ and $p_i^d(t) > 0$.

The dynamics of the uplink and downlink queues can be written as

$$Q_i^u(t) = \max\{Q_i^u(t) + A_i^u(t) - B_i^u(t), 0\} \quad (6)$$

$$Q_i^d(t) = \max\{Q_i^d(t) + A_i^d(t) - B_i^d(t), 0\}, \quad (7)$$

where $B_i^u(t) = \frac{T}{L}C_i^u(t)|_{\alpha_i(t),\ \beta_i(t)}$ and $B_i^d(t) = \frac{T}{L}C_i^d(t)|_{\alpha_i(t),\ \beta_i(t)}$ are the service rates in packets per time slot at time t for the uplink and downlink queues, respectively, T is the duration of a time slot, and L is the packet length in bits.

2.2 Problem formulation

As can be seen from (2)–(5), the overall throughput can be enhanced with full-duplex transmissions, but at the cost of higher energy consumption. The energy efficiency maybe degraded due to the residual self-interference. There is a trade-off between the overall queue length (which is indicative of delay) and energy efficiency with different transmission mode selections. Furthermore, both energy efficiency and throughput can be enhanced by transmitting only on good channels. However, there may be the extra delay to wait for the channel condition to be good from a deep fade.

The average total energy consumption of the system can be written as $\bar{P} \triangleq \limsup_{T\to\infty} \frac{1}{T}\sum_{t=0}^{T-1}\sum_{i=1}^{N}\mathbb{E}\{p_i^u(t) + p_i^d(t)|\alpha_i(t), \beta_i(t)\}$. We also define the average queue length as $\bar{Q} \triangleq \limsup_{T\to\infty} \frac{1}{T}\sum_{t=0}^{T-1}\sum_{i=1}^{N}\mathbb{E}\{Q_i^u(t) + Q_i^d(t)\}$. We schedule the uplink and downlink transmissions at the beginning of each time slot. According to the notion of *throughput-optimal* [10], the objective is to minimize the average energy consumption while keeping all the uplink and downlink queues stable. We have the following problem formulation.

$$\min: \bar{P} = \limsup_{T\to\infty} \frac{1}{T}\sum_{t=0}^{T-1}\sum_{i=1}^{N}\mathbb{E}\{p_i^u(t) + p_i^d(t)|\alpha_i(t), \beta_i(t)\} \quad (8)$$

$$\text{s.t. } \alpha_i(t) \neq \alpha_j(t), \text{if } \alpha_i(t) \in \mathcal{S} \text{ or } \alpha_j(t) \in \mathcal{S}, \text{ for all } i \neq j, i, j \in \mathcal{N} \quad (9)$$

$$\bar{Q} < \infty, \text{ for all } \{\boldsymbol{\lambda}^u, \boldsymbol{\lambda}^d\} \in \boldsymbol{\Lambda}, \quad (10)$$

where $\boldsymbol{\Lambda}$ is the capacity region of the WLAN system. Constraint (9) forbids two nodes accessing the same channel and Constraint (10) ensures that the schedule meets the notion of throughput-optimal.

3 Solution Algorithm and Performance Analysis

3.1 Lyapunov Optimization Based Scheduling Algorithm

Following the Lyapunov optimization framework, we first define the Lyapunov function $L(Q(t))$ as $L(Q(t)) \overset{\Delta}{=} \frac{1}{2}\sum\limits_{i=1}^{N}\left\{\{Q_i^u(t)\}^2 + \{Q_i^d(t)\}^2\right\}$, where $L(Q(0)) = 0$. Note that $L(Q(t))$ is small if and only if all the queue lengths are small; $L(Q(t))$ will become large if any of the queues is congested. The system is thus stable when $\mathbb{E}\{L(Q(t))\} < \infty$.

We then define the drift $\Delta(L(t))$ as

$$\Delta(L(t)) \overset{\Delta}{=} \mathbb{E}\{L(Q(t+1)) - L(Q(t))\,|Q(t)\}. \tag{11}$$

The system is stable when $\mathbb{E}\{L(Q(t))\} = \mathbb{E}\left\{\sum_{k=0}^{t-1}[L(Q(k+1)) - L(Q(k))]\right\} = \sum_{k=0}^{t-1}\mathbb{E}\{L(Q(k+1)) - L(Q(k))|Q(k)\} = \sum_{k=0}^{t-1}\Delta(L(k)) < \infty$. We can minimize the drift in every time slot t to maintain a finite expectation for $L(Q(t))$.

It follows the queue dynamics (6) and (7) that

$$\begin{aligned}
&\{Q_i^u(t+1)\}^2 + \{Q_i^d(t+1)\}^2 \\
&\leq \{Q_i^u(t) + A_i^u(t) - B_i^u(t)\}^2 + \{Q_i^d(t) + A_i^d(t) - B_i^d(t)\}^2 \\
&= \{Q_i^u(t)\}^2 + \{A_i^u(t) - B_i^u(t)\}^2 + 2Q_i^u(t)(A_i^u(t) - B_i^u(t)) + \\
&\quad \{Q_i^d(t)\}^2 + \{A_i^d(t) - B_i^d(t)\}^2 + 2Q_i^d(t)(A_i^d(t) - B_i^d(t)).
\end{aligned} \tag{12}$$

Substituting (12) into (11), we have

$$\Delta(L(t)) \leq \Phi + \mathbb{E}\left\{\sum_{i=1}^{N}\{Q_i^u(t)(A_i^u(t) - B_i^u(t)) + Q_i^d(t)(A_i^d(t) - B_i^d(t))\}\right\}, \tag{13}$$

where $\Phi = \frac{1}{2}\mathbb{E}\left\{\sum_{i=1}^{N}\{[A_i^u(t) - B_i^u(t)]^2 + [A_i^d(t) - B_i^d(t)]^2\}\right\}$, which is bounded if the arrival rate and service rate of each uplink and downlink queue are bounded. This is true if the arrival rates are within the capacity region of the system.

Defining $P(t) \overset{\Delta}{=} \sum_{i=1}^{N}\left\{p_i^u(t) + p_i^d(t)\right\}$, we then obtain the *drift-plus-penalty* $\Delta(L(t)) + V\mathbb{E}\{P(t)\}$ as in [12], by incorporating the energy penalty (i.e., the overall energy consumption at time t) with a positive coefficient V. Parameter V indicates the UEs' emphasis on energy consumption. That is, the more emphasis on energy consumption, the greater the value of V. In particular, $V = 0$ indicates that the UEs are not sensitive to energy consumption at all. Based on (13), we can derive an upper bound on the *drift-plus-penalty* as

$$\begin{aligned}
&\Delta(L(t)) + V\mathbb{E}\{P(t)\} \\
&\leq \Phi + \mathbb{E}\left\{\sum_{i=1}^{N}\{Q_i^u(t)(A_i^u(t) - B_i^u(t)) + Q_i^d(t)(A_i^d(t) - B_i^d(t))\} + VP(t)\right\}.
\end{aligned}$$

We minimize the second term on the right-hand-side $\Theta \triangleq \sum_{i=1}^{N}\{Q_i^u(t)(A_i^u(t) - B_i^u(t)) + Q_i^d(t)(A_i^d(t) - B_i^d(t))\} + VP(t)$ at each time slot t in order to minimize the *drift-plus-penalty*. Notice that Θ can be rewritten as $\Theta = \sum_{i=1}^{N}\{Q_i^u(t)A_i^u(t) + Q_i^d(t)A_i^d(t)\} - \sum_{i=1}^{N}\{Q_i^u(t)B_i^u(t) - Vp_i^u(t) + Q_i^d(t)B_i^d(t) - Vp_i^d(t)\}$. Then first term on the right-hand-side, $\sum_{i=1}^{N}\{Q_i^u(t)A_i^u(t) + Q_i^d(t)A_i^d(t)\}$, only depends on the arrival rates and the current queue lengths. Therefore, it doesn't affect the scheduling decision. We only need to maximize the second term of Θ, which is a function of both $\alpha_i(t)$ and $\beta_i(t)$.

Let the channel assignment be $\boldsymbol{\alpha}(t) = \{\alpha_1(t), \alpha_2(t), ..., \alpha_N(t)\}$ and the transmission mode selection be $\boldsymbol{\beta}(t) = \{\beta_1(t), \beta_2(t), ..., \beta_N(t)\}$. We have

$$\begin{aligned}\Psi(t)|_{\boldsymbol{\alpha}(t),\boldsymbol{\beta}(t)} &\triangleq \sum_{i=1}^{N}\{Q_i^u(t)B_i^u(t) - Vp_i^u(t) + Q_i^d(t)B_i^d(t) - Vp_i^d(t)\}|_{\alpha_i(t),\beta_i(t)} \\ &= \sum_{i=1}^{N} \psi_i(t)|_{\alpha_i(t),\beta_i(t)}, \qquad (14)\end{aligned}$$

where $\psi_i(t)|_{\alpha_i(t),\beta_i(t)} = \{Q_i^u(t)B_i^u(t) - Vp_i^u(t) + Q_i^d(t)B_i^d(t) - Vp_i^d(t)\}|_{\alpha_i(t),\beta_i(t)}$. Let the optimal channel assignment be $\boldsymbol{\alpha}^*(t) = \{\alpha_1^*(t), \alpha_2^*(t), ..., \alpha_N^*(t)\}$ and the optimal transmission mode selection be $\boldsymbol{\beta}^*(t) = \{\beta_1^*(t), \beta_2^*(t), ..., \beta_N^*(t)\}$. To find the optimal schedule $\{\boldsymbol{\alpha}^*(t), \boldsymbol{\beta}^*(t)\}$, we first need to identify the transmission mode for a given channel assignment $\alpha_i(t) = s$ for each UE i. That is,

$$\beta_i^*(t)|_{\alpha_i(t)=s} = \underset{\beta_i(t)\in\{U,D,F\}}{\arg\max}\{\psi_i(t)|_{\alpha_i(t)=s,\beta_i(t)}\}. \qquad (15)$$

Note that $\psi_i(t) = 0$ if no transmission is conducted. Therefore we have

$$\psi_i^*(t)|_{\alpha_i(t)=s} = \max\{\psi_i(t)|_{\alpha_i(t)=s,\beta_i^*(t)}, 0\} \qquad (16)$$

$$\boldsymbol{\psi}_i^*(t)|_{\alpha_i(t)} \triangleq \{\psi_i^*(t)|_{\alpha_i(t)=1}, \psi_i^*(t)|_{\alpha_i(t)=2}, ..., \psi_i^*(t)|_{\alpha_i(t)=S}\}. \qquad (17)$$

We need to find the maximum channel assignment $\boldsymbol{\alpha}^*(t)$ based on $\boldsymbol{\psi}_i^*(t)|_{\alpha_i(t)}$, for $i = 1, 2, ..., N$. The channel assignment problem can be transformed into a *maximum weighted bipartite matching problem*. In the bipartite graph $\mathcal{G}$, UEs and the channels represent the two independent sets of vertices: the set of UEs G_1 and the set of channels G_2. In graph $\mathcal{G}$, the weight of the edge between an vertex in G_1 (i.e., a UE i) and another vertex in G_2 (i.e., a channel s) is set to $\psi_i^*(t)|_{\alpha_i(t)=s}$. This way, the maximum weighted bipartite matching of graph $\mathcal{G}$ corresponds to the optimal channel assignment $\boldsymbol{\alpha}^*(t)$. The maximum weighted bipartite matching problem can be solved with the Hungarian Method [13]. The complexity of the Hungarian Method is $O(NS^2)$ if $N > S$, or $O(N^2S)$ if $N \leq S$.

When the optimal channel assignment is derived, the optimal transmission mode $\beta_i^*(t)$ for UE i is readily obtained as in (15), i.e., $\beta_i^*(t) = \beta_i^*(t)|_{\alpha_i^*(t)}$. Now we obtain the optimal schedule $\{\boldsymbol{\alpha}^*(t), \boldsymbol{\beta}^*(t)\}$ as well as the corresponding $\Psi(t)|_{\boldsymbol{\alpha}^*(t),\boldsymbol{\beta}^*(t)}$. Then we can assign the channels and decide the transmission mode for each UE based on the optimal schedule. Note that $\psi_i(t)|_{\alpha_i^*(t),\beta_i^*(t)} =$

Algorithm 1: Scheduling Algorithm for Channel Assignment and Transmission Mode Selection

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Update all uplink and downlink queues and estimate all channel conditions at
  the beginning of each time slot t ;
For each UE i, find the transmission mode β_i^*(t)|_{α_i(t)=s} as in (15) ;
Obtain the channel assignment matrix {ψ_1^*(t)|^T_{α_1(t)}, ψ_2^*(t)|^T_{α_2(t)}, ..., ψ_N^*(t)|^T_{α_N(t)}} ;
Apply the Hungarian Method and (15) to find the optimal schedule
  {α^*(t), β^*(t)} ;
if ψ_i(t)|_{α_i^*(t),β_i^*(t)} > 0 then
  | UE i transmits on channel α_i^*(t) with transmission mode β_i^*(t);
end
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0 if no transmission is scheduled for UE i; so UE i transmits if and only if $\psi_i(t)|_{\alpha_i^*(t),\beta_i^*(t)} > 0$.

The detailed algorithm for deriving the optimum schedule $\{\boldsymbol{\alpha}^*(t), \boldsymbol{\beta}^*(t)\}$ is presented in Algorithm 1, which is executed at the beginning of each time slot.

3.2 Performance Analysis

We have the following theorems for the performance of Algorithm 1. The proofs are omitted for lack of space.

Theorem 1. *The schedule $\{\boldsymbol{\alpha}^*(t), \boldsymbol{\beta}^*(t)\}$ obtained by Algorithm 1 achieves the maximum $\Psi(t)$.*

We also derive the upper bounds for the expectations of average sum queue lengths of all the uplink and downlink queues and the corresponding average total energy consumption as follows.

Theorem 2. *Assume that the arrival rates to the queues $\boldsymbol{\lambda}^u$ and $\boldsymbol{\lambda}^d$ are strictly within the system's capacity region, i.e., the system can be stabilized under certain $\{\boldsymbol{\alpha}(t), \boldsymbol{\beta}(t)\}$. Then the upper bounds on the average sum queue lengths and average energy consumption under Algorithm 1 can be derived as*

$$\limsup_{T\to\infty} \frac{1}{T} \sum_{t=1}^{T-1} \sum_{i=1}^{N} \mathbb{E}\{Q_i^u(t) + Q_i^d(t)\} \le \frac{1}{\epsilon}(\Phi + V\bar{P}) \tag{18}$$

$$\limsup_{T\to\infty} \frac{1}{T} \sum_{t=1}^{T-1} \sum_{i=1}^{N} \mathbb{E}\{p_i^u(t) + p_i^d(t)\} \le \bar{P}^* + \frac{\Phi}{V}, \tag{19}$$

where $\bar{P}^*$ is the minimum average energy consumption under any stable scheduling strategy, $\bar{P}$ is the average energy consumption under the proposed algorithm, $\epsilon > 0$ is the distance between the arrival rates $\{\boldsymbol{\lambda}^u, \boldsymbol{\lambda}^d\}$ and the system capacity region under the proposed algorithm, and Φ is given in (13).

4 Performance Evaluation

In this section, we evaluate the performance of the proposed algorithm through Matlab simulations. We assume that the maximum transmit power is 46 dBm at the AP and 23 dBm at the UEs. We assume that there is a 110 dB self-interference cancellation in both the uplink and downlink transceivers. For the wireless channels, we adopt the commonly used Okumura-Hata model for small and medium-sized cities. Each channel has a bandwidth of 360kHz. We assume that there are 12 UEs and 10 channels in the WLAN.

We compare the average energy consumptions and queue lengths of a half-duplex only system and a full-duplex system under different V values. The simulation results are presented in Figs. 1 and 2 for different traffic arrival rates. From the simulations, we find that the full-duplex system always outperforms the half-duplex only system with respect to both average queue length and energy consumption. Moreover, there is a trade-off between the average queue length and energy consumption for the full-duplex system under different V values.

Fig. 1 presents the average queue length versus traffic load. When $V = 0$, the scheme only minimizes the drift and does not care about energy consumption. In this case, the average queue length of the half-duplex case is always greater than that of the full-duplex case. Moreover, in the half-duplex only case, the queues cannot be stabilized when the arrival rate exceeds 25. In the full-duplex case, the queues can be stabilized until the arrival rate reaches 38. Clearly, full-duplex transmissions are helpful to keep the queue backlog low and increase the capacity region of the WLAN. It is also interesting to see that for all the full-duplex cases, the queues can be stabilized when the arrival rate is lower than 38, indicating that different V values do not affect the stability of the system. Moreover, the average queue length increases when V is increased, as indicated by the upper bound of average queue length (18) in Theorem 2.

Fig. 2 presents the average energy consumption versus traffic load. We find the average energy consumption of the half-duplex only case is smaller than that of the full-duplex cases under heavy load, when the queues become unstable. However, in the stable capacity region of the half-duplex only case (i.e., when the arrival rate is lower than 25), the average energy consumption of the half-duplex only case is greater than that of the full-duplex cases with $V > 50$. This is because when $V > 50$, the energy consumption is more seriously considered (i.e., in the drift-plus-penalty) and the UEs would transmit only when the energy efficiency is high. For the full-duplex case with $V = 0$, the average energy consumption is the highest among all the cases, since the proposed scheme does not consider energy efficiency. Furthermore, the energy consumption drops when the arrival rate is greater than 38. This is due to the unbalanced service rates of the uplink and downlink. When the queues are not stable, more uplink transmissions were made; the uplink transmit power is comparatively smaller than that of the downlink transmissions. Finally, it can be seen that the energy consumption decreases when V is increased, as indicated by the upper bound of average energy consumption (19) in Theorem 2.

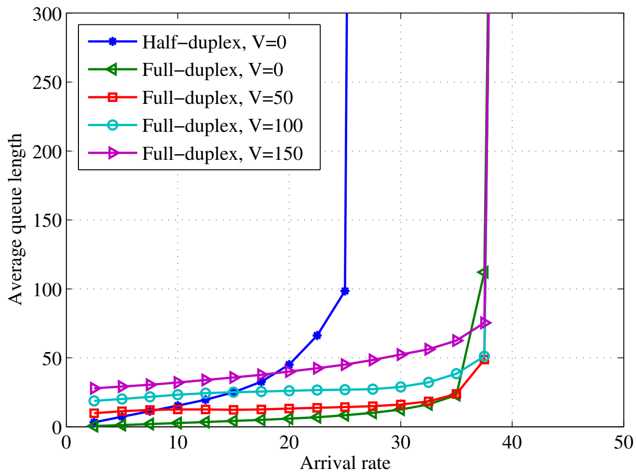

Fig. 1. Average queue lengths achieved by the proposed algorithm: half-duplex only with V=0, full-duplex with V=0, full-duplex with V=50, full-duplex with V=100, and full-duplex with V=150.

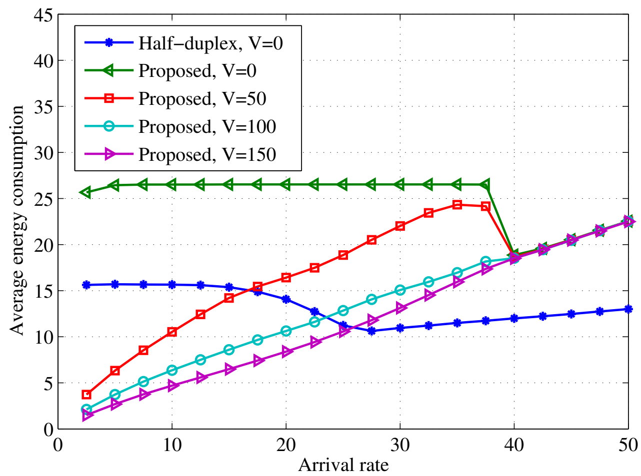

Fig. 2. Average energy consumptions achieved by the proposed algorithm: half-duplex with V=0, full-duplex with V=0, full-duplex with V=50, full-duplex with V=100, and full-duplex with V=150.

5 Conclusion

In this paper, we proposed an online scheduling algorithm to jointly decide the channel assignment, transmission scheduling, half- or full-duplex transmission mode selection for each UE in a multi-channel ful-duplex WLAN. The proposed scheme was based on Lyapunov optimization. We also proved the optimality of the proposed algorithm and derived upper bounds for the average queue length and energy consumption under the proposed algorithm. We evaluated the performance of the proposed algorithm with simulations. We showed that under the proposed algorithm, there was a trade-off between the average queue length and energy consumption under different V values.

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