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Throughput Analysis of Secondary Full Duplex Multi-User Scheduling System in Underlay Cognitive Radio Environment

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Abstract:

Cognitive radio (CR) is a promising technique which is able to improve the spectrum utilization by dynamically adjusting the radio parameters based on the recognition results on the radio environment. Moreover, full duplex (FD) transmission is also a key technique for future wireless communication systems which enhances spectral efficiency by transmitting and receiving simultaneously in the same frequency band. In this paper, we analyze the throughput performance of the secondary FD multi-user scheduling system in underlay CR environment. For this goal, we first formulate scheduling rule for FD system which maximizes the throughput of the secondary system while protecting the primary system. Then, we evaluate the throughput performance of the considered system by using computer simulations. Through the simulation results, we show that the FD system outperforms the conventional systems. Moreover, we also show the functional relationship among the various parameters and throughput performance.

Keywords: Cognitive radio, full duplex, scheduling, power allocation, interference temperature.

INTRODUCTION

Recently, various efforts for developing future wireless communication systems or 5th generation (5G) communication systems have been made in many directions [1]. Among them, two main approaches have attracted many researchers' attention: 1) broader spectrum band and 2) higher transmission rate [2, 3]. For the broader spectrum band, most of the microwave band is already allocated to specific applications in exclusive manner. Hence, it is very difficult to secure new spectrum band for future communications. One possible solution is cognitive radio (CR) technique, which allows a communication system (secondary system) to access a band that is already allocated to the other system (primary system) dynamically such that the secondary system does not bother the primary system's communications. By this operation, CR is possible to improve the spectrum utilization efficiency [4-6].

For the higher transmission rate, various techniques such as massive multi-input multi-output (MIMO), enhanced interference management, and complex coding techniques have been studied [1-3]. Among the various techniques, full duplex (FD) communication is also an important technique which can improve the spectral efficiency, i.e. transmission rate [7]. FD is a technique in which a single device receives from one transmitter and transmits to the other receiver simultaneously in the same frequency band [7, 8]. Due to the basic nature of wireless channel, the transmitted signal can be fed back to its receiving antenna such that the transmitting part of the device becomes an interferer to the receiving part of itself. Therefore, while the FD may improve the spectral efficiency by increasing transmission and reception chances, it also suffers from the self-interference problem [8].

In this paper, we analyze the throughput performance of the secondary FD multi-user scheduling system in underlay CR environment. For this goal, we first formulate scheduling rule for FD system which maximizes the throughput of the secondary system while protecting the primary system. Then, we evaluate the throughput performance of the considered system by using computer simulations.

The rest of this paper is organized as follows. In Section 2, we first present the system model considered in this work and formulate scheduling rule for the conventional half duplex (HD) communication systems as a reference for performance comparison. In Section 3, we develop power allocation criterion and scheduling rule of the proposed secondary FD system which maximizes the throughput while protecting the primary system. Section 4 provides intensive simulation results which evaluate the performance of the FD system by comparing to the HD system. Finally, conclusions are presented in Section 6.

SECONDARY FULL DUPLEX MULTI-USER SCHEDULING SYSTEM

System Model

Fig. 1 illustrates the system model considered in this work, in which the primary system and the secondary system co-exist in the same frequency band. In the figure, solid lines denote desired signals for each system and dotted lines are interferences. Considered secondary system is a FD multi-user scheduling system, where a NodeB operated in FD mode and it selects one uplink UE and one downlink UE to serve at each time slot. We assume that there are M uplink UEs and N downlink UEs in the secondary system. Since the NodeB operates in FD mode, two types of interferences occur: cross UE interference and self-interference, which are denoted by h_{jk} and g in the figure, respectively. Please note the self-interference g is a main factor which limits the transmission performance of FD communications [8].

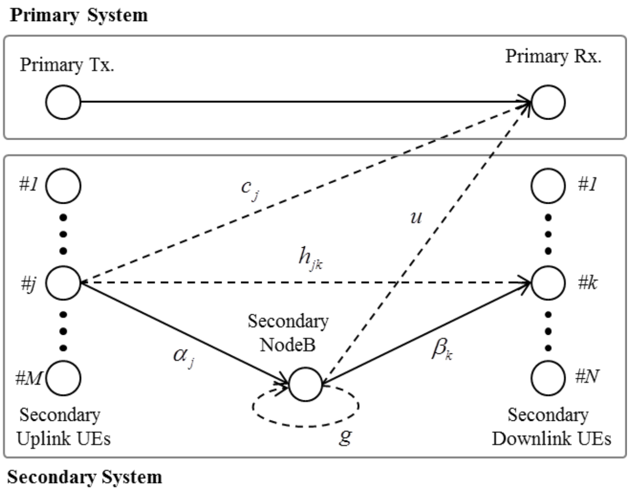

Figure 1: System model.

Therefore, most research works on FD technique are focusing on how to mitigate the impact of the self-interference [8].

For the primary system protection, underlay cognitive radio technique is utilized, where the primary system allows up to a constant limit of interference from the secondary system and the secondary system accesses the spectrum band by controlling its transmit power to keep its interference to the primary system under the allowed limit [6]. The allowed interference limit is called as interference temperature [6]. Due to the underlay CR, the secondary system induces two kinds of interferences in the system model: c_j and u generated by uplink UE j and NodeB, respectively. Hence, in each time slot, the secondary NodeB selects one uplink UE and one downlink UE first, then it adjusts transmit powers of the uplink UE and the NodeB to protect the primary system and to maximize the throughput of the secondary system.

For further formulation in this work, we assume all the wireless channels follow independent Rayleigh fading channel model, i.e. $|\alpha_j|^2 \sim Exp(\rho_\alpha)$, $|\beta_k|^2 \sim Exp(\rho_\beta)$, $|h_{jk}|^2 \sim Exp(\rho_h)$, $|c_j|^2 \sim Exp(\rho_c)$, $|u|^2 \sim Exp(\rho_u)$, $|g|^2 \sim Exp(\rho_g)$, where $Exp(\cdot)$ represents the Exponential distribution and ρ_α, ρ_β, ρ_h, ρ_c, ρ_u, and ρ_g denote average channel gains for each channel shown in Fig. 1.

Scheduling for Conventional Half Duplex System

In this subsection, we formulate the scheduling rule when the secondary system in Fig. 1 operates in conventional HD mode for comparison. Objective of this scheduling is to maximize the throughput of the secondary system while protecting the primary system by using underlay CR strategy.

For HD operation, the NodeB selects and serves one uplink UE in the first half of a time slot and, in the next half of the time slot, the NodeB schedules one downlink UE alternatively. Let phase 1 and phase 2 denote the first and the second half of the time slot. In phase 1, because only the selected UE j transmits, the interference to the primary receiver becomes

$$|c_j|^2 \rho_j^{UP}, \tag{1}$$

where ρ_j^{UP} denotes the transmit power of the uplink UE j normalized by noise power. By the underlay CR constraint, (1) should satisfy

$$|c_j|^2 \rho_j^{UP} \le Q, \tag{2}$$

where Q is the interference temperature. From (2), the uplink UE j can transmit with power of $Q/|c_j|^2$. In phase 2, the NodeB selects a downlink UE k and transmits with power of ρ_k^{DN}. Then, the interference at the primary receiver can be formulated as

$$|u|^2 \rho_k^{DN}. \tag{3}$$

Similar to (2), the transmission power of NodeB should be $Q/|u|^2$. Therefore, transmit power of the uplink UE j and the NodeB when the downlink UE k is selected can be written as

$$\begin{aligned} &\text{In phase1,} \quad \rho_j^{UP} = \min\left(\frac{Q}{|c_j|^2}, \rho_0\right), \\ &\text{In phase2,} \quad \rho_k^{DN} = \min\left(\frac{Q}{|u|^2}, \rho_0\right) \end{aligned} \tag{4}$$

where ρ_0 denotes the maximum transmit power of the secondary system. When uplink UE j and downlink UE k are selected in each phase and transmit powers are allocated by (4), then received signal to noise ratios (SNRs) from the uplink and the downlink transmissions become

$$\gamma_j^{UP} = \left|\alpha_j\right|^2 \rho_j^{UP} \text{ , and } \gamma_k^{DN} = \left|\beta_k\right|^2 \rho_k^{DN} \text{ ,} \qquad (5)$$

where γ_j^{UP} and γ_k^{DN} represent the SNRs of the uplink and downlink transmissions. From (5), it is possible to formulate the throughput of the secondary system with selected UEs j and k such as

$$R_{jk}^{HD} = \frac{1}{2}\log_2\left(1+\gamma_j^{UP}\right) + \frac{1}{2}\log_2\left(1+\gamma_k^{DN}\right). \qquad (6)$$

It is worth to note that $1/2$ in (6) is induced by time slot divide into the two phases for HD operation. Finally, the scheduler can select one uplink and one downlink UEs which maximize (6) according to

$$\left(j^*, k^*\right) = \arg \max_{\substack{j\in\{1,\cdots,M\} \\ k\in\{1,\cdots,N\}}} R_{jk}^{HD}, \qquad (7)$$

where j^* and k^* denote the selected uplink and downlink UEs, respectively.

SCHEDULING FOR SECONDARY FULL DUPLEX SYSTEM

Unlike HD operation in Section 2.2, the NodeB in FD operation serves both the uplink and downlink UEs simultaneously in spite of the interferences h_{jk} and g in Fig. 1 to overcome performance degradation factor of $1/2$ in (6) of HD operation. Total interference caused by the secondary system to the primary receiver should not be exceed the allowed interference temperature, then

$$\left|c_j\right|^2 \rho_j^{UP} + \left|u\right|^2 \rho_k^{DN} \le Q. \qquad (8)$$

Another constraint should be considered is that total transmit power should be constant regardless of scheduling method such as

$$\rho_j^{UP} + \rho_k^{DN} = \rho_0. \qquad (9)$$

From (8) and (9), we can formulate following expressions such as

$$\rho_j^{UP} \le -\frac{\left|u\right|^2}{\left|c_j\right|^2}\rho_k^{DN} + \frac{Q}{\left|c_j\right|^2}, \qquad (10)$$
$$\rho_j^{UP} = -\rho_k^{DN} + \rho_0.$$

From (10), it is straightforward to expect that best values of ρ_j^{UP} and ρ_k^{DN} are determined at the intersection point of two lines. However, because ρ_j^{UP} and ρ_k^{DN} should be greater than or equal to zero, if we let $\hat{\rho}_j^{UP}$ and $\hat{\rho}_k^{DN}$ denote the values at the intersection point then it is possible to formulate the power allocation rule as in Table. 1.

Table 1: Power allocation rule.

Case	Condition	Allocation power	
		ρ_j^{UP}	ρ_k^{DN}
1	$0 < \hat{\rho}_j^{UP} \le \rho_0$, $0 < \hat{\rho}_k^{DN} \le \rho_0$	$\frac{Q - \left|u\right|^2 \rho_0}{\left|c_j\right|^2 - \left|u\right|^2}$	$\frac{\left|c_j\right|^2 \rho_0 - Q}{\left|c_j\right|^2 - \left|u\right|^2}$
2	$\hat{\rho}_j^{UP} < 0$, $\hat{\rho}_k^{DN} > \rho_0$	0	$\min\left(\frac{Q}{\left|u\right|^2}, \rho_0\right)$
3	$\hat{\rho}_j^{UP} > \rho_0$, $\hat{\rho}_k^{DN} < 0$	$\min\left(\frac{Q}{\left|c_j\right|^2}, \rho_0\right)$	0

Please note that the power allocation rule in Table. 1 is formulated with two constraints based on (10): 1) total power cannot exceed ρ_0 , 2) transmit power cannot be less than 0.

Once the transmit powers of uplink UE j and NodeB to downlink UE k for all combinations of j and k are calculated according to the rule in Table. 1, then the scheduler can also compute the received SINRs of the uplink and the downlink transmissions such as

$$\gamma_j^{UP} = \frac{\left|\alpha_j\right|^2 \rho_j^{UP}}{1+\left|g\right|^2 \rho_k^{DN}} \text{, and } \gamma_{jk}^{DN} = \frac{\left|\beta_k\right|^2 \rho_k^{DN}}{1+\left|h_{jk}\right|^2 \rho_j^{UP}}. \qquad (11)$$

Comparing (11) with (5), the interference terms induced by FD operation can be observed. The instantaneous throughput with uplink UE j and downlink UE k can be written as

$$R_{jk}^{FD} = \log_2\left(1+\gamma_j^{UP}\right) + \log_2\left(1+\gamma_{jk}^{DN}\right). \qquad (12)$$

Then, in each time slot, the scheduler can select uplink and downlink UEs which maximize (12) such as

$$\left(j^*, k^*\right) = \arg \max_{\substack{j\in\{1,\cdots,M\} \\ k\in\{1,\cdots,N\}}} R_{jk}^{FD}. \qquad (13)$$

NUMERICAL EVALUATION

Comparison with HD System

Fig. 2 compares the performance of the FD system based on (13) with the HD system based on (7) when $\rho_c = \rho_u = 0$ dB,

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$\rho_h = 0$ dB, $\rho_g = 3$ dB, $\rho_\alpha = \rho_\beta = 0$ dB, $\rho_0 = 3$ dB, and $M = 5$. In the figure, solid lines represent the performance of FD system and dotted lines denote the performance of HD system. Moreover, circle marker denotes the case when interference temperature is -3dB and square marker presents the case when interference temperature is 3dB. From the figure, it can be seen that the FD system overwhelms the HD system regardless of the interference temperature. This means that the gain obtained by the simultaneous transmission of HD operation is greater than the degradation in SINR due to the interferences as in (11). By comparing (11) with (5) and (12) with (6), it is clear that there is trade-off relation between SINR and transmission time.

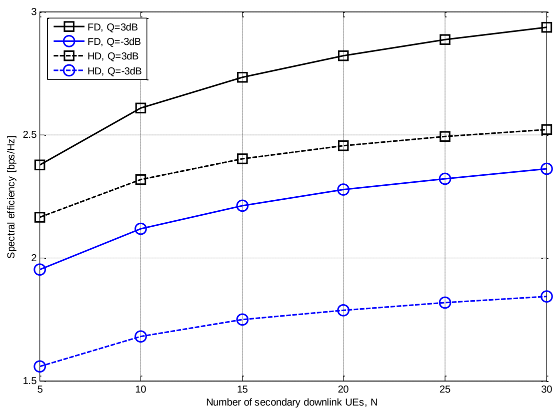


Figure 2: Comparison with HD system.

Impact of Self-Interference

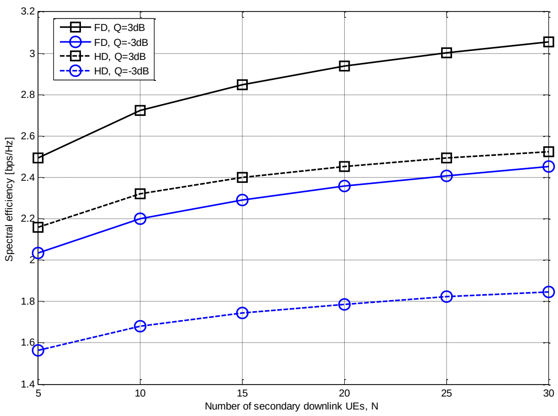
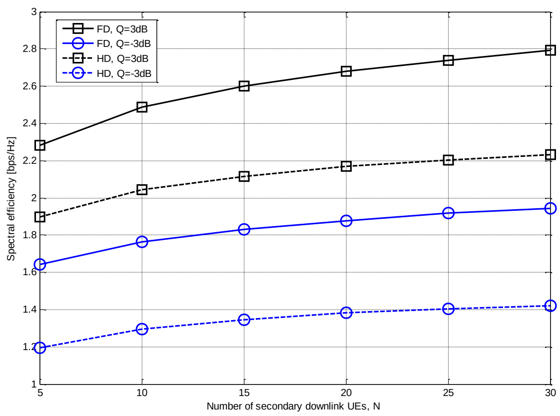


Figure 3: Throughput with $\rho_g = -3$dB.

Fig. 3 compares the performance of the FD system and HD system with the same parameters as in Fig. 2 except for $\rho_g = -3$ dB, which evaluates the case of lower self-interference g of FD operation to evaluate the impact of the self-interference. Comparing Figs. 2 and 3, the throughput of FD system is improved as ρ_g is reduced from 3dB to -3dB.

Impact of Coupling with Primary System

Fig. 4 shows the throughput performance of FD and HD systems when $\rho_c = \rho_u = 3$ dB, and other parameters are same as those in Fig. 2, to evaluate how much the level of coupling with the primary system affects the performance of the secondary system. As seen in Fig. 1, as ρ_c and ρ_u have higher values, the secondary system more easily interfere with the primary system. By comparing Figs. 2 and 4, it can be seen that both the FD and the HD systems are degraded in their throughput performance because the secondary system should lower their transmit powers to protect the primary system with the constant level of interference.



Fiigure 4: Throughput with $\rho_c = \rho_u = 3$ dB.

Impact of Interference Temperature

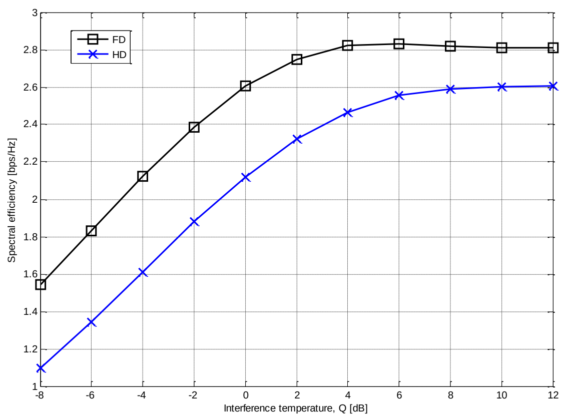


Figure 5: Throughput performance vs. Q.

Fig. 5 shows the throughput performance according to the interference temperature Q when $\rho_c = \rho_u = 0$ dB, $\rho_h = 0$ dB, $\rho_g = 0$ dB, $\rho_\alpha = \rho_\beta = 0$ dB, $\rho_0 = 3$ dB, $M = 5$, and $N = 15$. In the figure, solid line with 'x' marker represents the throughput of the HD system and solid line with square marker denotes the performance of the FD system. As shown in the figure, the FD system outperforms the HD system in wide range of Q. Moreover, when Q is large enough, i.e. the primary system allows large amount of interference, the throughput of the both systems saturates because the transmit power of the secondary system is dominated by the total power limit ρ_0. This region can be identified as *power-limited region*. On the other hand, when the value of Q is very small, the transmit power of the secondary system is severely limited by the value of Q. Hence, this region can be defined as *interference-limited region*.

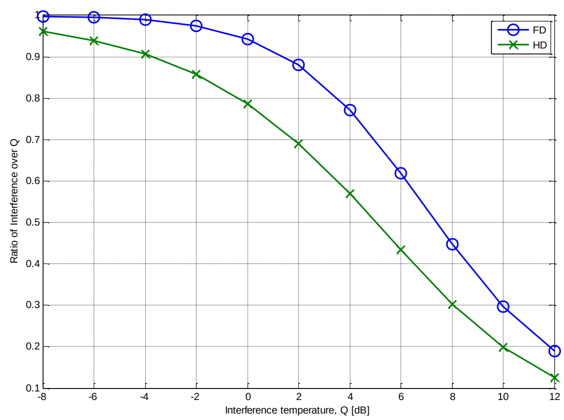


Figure 6: Ratio of total amount of the interference to the primary receiver over the interference temperature Q.

In Fig. 6, we can show the region change clearly. Fig. 6 presents the ratio of total amount of the interference at the primary receiver over interference temperature Q. When Q is small, i.e. the secondary system is mainly limited by Q, the FD system utilizes most of the allowed interference. However, as the value of Q grows, the ratio gradually decreases to 20% in the figure. This means the secondary system is limited by its total power constraint, so it cannot cause enough interference to fill the allowed interference temperature.

CONCLUSION

In this paper, we analyze the throughput performance of the secondary FD multi-user scheduling system in underlay CR environment. First, we formulate power allocation criteria and scheduling strategy for FD system which maximizes the throughput of the secondary system while protecting the primary system. Moreover, we also formulate the power allocation and scheduling rule for the conventional HD systems in underlay CR scenario as a reference. To evaluate the performance of the considered system, we perform intensive simulations. From the numerical results, it has been shown that the FD system outperforms the HD system in spite of its self-interference problem. Furthermore, we also evaluate the functional relationship among various parameters and the throughput performance.

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