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Optimal Power Adjustment Algorithm for Buffer-Aided Full Duplex Relay with Cognitive Radio Technique

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Abstract: Full Duplex Relaying (FDR) is a promising wireless relaying technique which extends system throughput considerably by transmitting data while receiving at the same time. However, the performance of FDR system is limited by the self-interference induced from the transmitting part in the same device. Hence, Kim *et al.* proposed buffer-aided FDR system based on Cognitive Radio (CR) technique which can minimize the self-interference using underlay CR technique. It has been shown that the proposed FDR scheme based on CR technique can overwhelm the conventional FDR systems in terms of system throughput. In this study, we first investigate the optimal performance of the FDR system proposed and show how optimal value of interference temperature which is a tuning parameter of the underlay CR technique, maximizes the system throughput. Further, we propose a practical adaptive interference temperature adjustment algorithm which achieves near-optimal throughput performance.

Key words: Full Duplex relaying, cognitive radio, interference temperature, power control, system throughput

INTRODUCTION

Recently, many communication engineers focus on developing 5th generation (5G) communication techniques. To achieve the performance goal for 5G communication system, transmission efficiency should be extremely improved (Osseiran *et al*., 2014; Mitra and Agrawal, 2015). Among various wireless communication techniques, full duplex transmission has gained a lot of interests due to its theoretical possibility to double the transmission efficiency.

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The fundamental concept of full duplex is that transmission and reception of different wireless signal occur in a single device at the same time (Korpi *et al*., 2016). Meanwhile, by the nature of wireless propagation, the transmitted signal can arrive at the receiver part of the same device, i.e., the transmitted signal becomes the interference to itself. This self-interference problem severely limits the transmission performance of the full duplex system. Therefore, half duplex technique which strictly divides the transmission and the reception of the same device in time or frequency domain has been usually used despite of the sacrifice of transmission efficiency. However, many efforts have been made to resolve the self-interference problem of the full duplex system. Moreover, some recent research results have shown significant improvement that full duplex technique can be used in practical systems in near future.

Another important keyword for 5G wireless communications is cooperative relaying technique which improves wireless transmission coverage and reliability by relaying data from source to destination (Jung and Kim, 2016). Moreover, cooperative relaying with buffer enhances temporal diversity to improve system capacity. However, conventional relaying system operates in half duplex mode, i.e., relay node stops transmitting to destination while receiving data from source node and vice versa to avoid self-interference. Because of this half duplex relaying, transmission efficiency is reduced.

To overcome the limitation caused by the half duplex relaying, buffer-aided Full Duplex Relaying (FDR) based on Cognitive Radio (CR) technique has been proposed (Kim *et al*., 2016). This scheme uses CR technique to manage the self-interference which is induced by full duplex operation of the relay node. Kim *et al.* (2016) showed that the CR technique is very effective to improve the throughput performance of the buffer-aided FDR system. In this study, we further investigate the optimal performance of the buffer-aided FDR system based on CR technique. Moreover, a practical algorithm to achieve the optimal performance in real system is developed and we justify its performance by using numerical results.

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MATERIALS AND METHODS

Problem statement

Buffer-aided FDR based on CR technique (B-FDR-CR): We first introduce the buffer-aided FDR system based on CR technique (B-FDR-CR) (Kim *et al*., 2016). Figure 1 shows the system model of the buffer-aided FDR system which consists of single source, single relay with buffer and single destination. Please note that the buffer in the relay is assumed to have infinite length. Since, the relay works as FDR which forwards to the destination while it receives from the source at the same time, three different channels are established at time slot, n such as g[n] h[n] and $\alpha[n]$, i.e., the source-relay channel, the relay-destination channel and the self-interference channel, respectively. These three channels are assumed to be independent Rayleigh channels. Average power gains of each channel are represented as ρ_{SR}, ρ_{RD} and ρ_{RR}, respectively.

The proposed system applies underlay CR technique, in which the primary system allows the secondary system's communication while the interference to the primary system is kept under the pre-defined threshold called as interference temperature (Lameiro *et al*., 2014; Pang *et al*., 2010). Hence, the secondary transmitter should control its transmit power not to interfere the primary system over the interference temperature. To apply this technique to the system in Fig. 1, the proposed system regards the source to the receiver of the relay as the primary system and the transmitter of the relay to the destination as the secondary system. Therefore, the transmitter of the relay controls the transmit power such that the caused interference to the receiver of the relay is maintained under the interference temperature.

Formulation and Power Control Rule: Let $\gamma_R[n]$ and $\gamma_D[n]$denote the received Signal-to-Interference and Noise Ratio (SINR) of the relay and the Signal-to-Noise Ratio (SNR) of the destination at time slot n, respectively. Then, they can be formulated as:

$$\gamma_R[n]=\frac{|g[n]|^2\rho_S}{1+|\alpha[n]|^2\rho_R[n]} \tag{1}$$

$$\gamma_D[n]=|h[n]|^2\rho_R[n] \tag{2}$$

Where:

ρ_S = The transmit power of the source normalized by noise power

$\rho_R[n]$ = The transmit power of the relay over noise power at time slot n

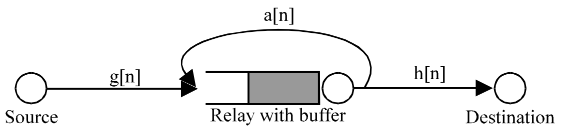

Fig. 1: System model

Note that ρ_S is a constant while $\rho_R[n]$ varies at every time slot because the proposed system controls the transmit power of the relay using CR technique. Then, the arrival traffic amount at the buffer and the departure traffic amount from the buffer are in bits:

$$A[n]=\tau B\log_2(1+\gamma_R[n]) \tag{3}$$

$$D[n]=\tau B\log_2(1+\gamma_D[n]) \tag{4}$$

Where:

τ = A time slot length (sec)

B = Bandwidth (Hz)

The queue length at time slot n becomes:

$$Q[n]=Q[n\text{-}1]+A[n]\text{-}\min\{Q[n\text{-}1],D[n]\} \tag{5}$$

in bits. Finally, the traffic rate delivered to the destination, which is the system throughput R[n] in bps/Hz is formulated as:

$$R[n]=\frac{1}{\tau}\min\{Q[n\text{-}1],D[n]\} \tag{6}$$

By Kim *et al.* (2016), we proposed power control rule for relay node based on underlay CR technique such that the self-interference is kept under the interference temperature I, i.e., $|\alpha[n]|_2\,\rho_R[n]\leq I$. Therefore, the transmit power of the relay at every time slot should follow the rule:

$$\rho_R[n]=\min\left\{\frac{I}{|\alpha[n]|^2},\rho_S\right\} \tag{7}$$

where, ρ_S is a constant transmit power of source. According to Eq. 7, if the self-interference channel is strong, then the relay should control its transmit power to make the self-interference to be I. Otherwise, the relay can use the maximum power ρ_S.

Optimality of B-FDR-CR: In this study, investigate the optimality of the proposed scheme which is B-FDR-CR in terms of system throughput. Figure 2 compares the system throughput of the proposed FDR system with various values of with that of the conventional FDR

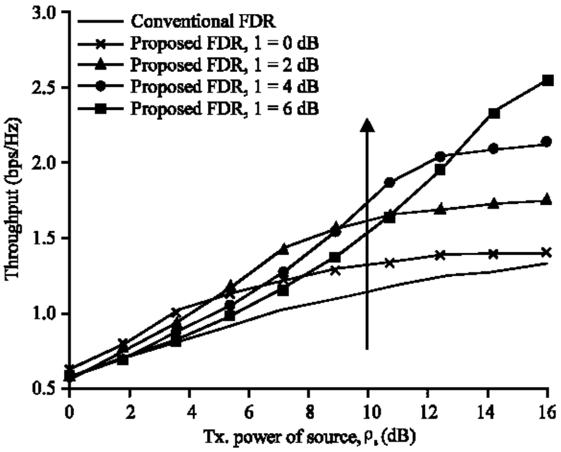

Fig. 2: Throughput comparison when $\rho_{SR} = \rho_{RD} = 0$ dB

system. First, it can be shown that the proposed system overwhelms the conventional FDR system in wide range of which is already presented by Kim *et al.* (2016).

Second, for a given value of ρ_S, throughput performance of the proposed system depends on the value of interference temperature I. In general as I increases, the relay transmission power may also increase. This yields two different results. Increased relay transmission power increases in Eq. 2 while decreases in Eq. 1. Therefore, increased I causes the increase of the departure traffic amount in Eq. 4 and the decrease of the arrival traffic in Eq. 3. For example when ρ_S = 10 dB in Fig. 2, if we increase interference temperature 1 from 0-4 dB, then the throughput also increases because the departure rate from the buffer increases. However, if we allow more interference as I = 6 dB in the Fig. 2, the throughput decreases because the arrival rate to the buffer is reduced due to the high interference. This trade-off relation makes the optimal value of I.

Then what is the optimal value of I? in Fig. 3 we can clearly show the existence and the location of the optimal value of I. In this case, the optimal I is 3.36 dB where the arrival rate and the departure rate is exactly balanced. If I <3.36 dB where the arrival is larger than the departure, then the queue length increases rapidly. On the other hand, if I>3.36 dB, the queue is almost empty, i.e., no traffic to forward. This can be confirmed in Fig. 4 which shows the average queue length for different values of I.

Adaptive interference temperature adjustment algorithm: **Optimal interference temperature:** In section 3, we proved that there exists an optimal value of I which maximizes the system throughput. Moreover, the optimal I occurs when the arrival and departure rates are equal. If

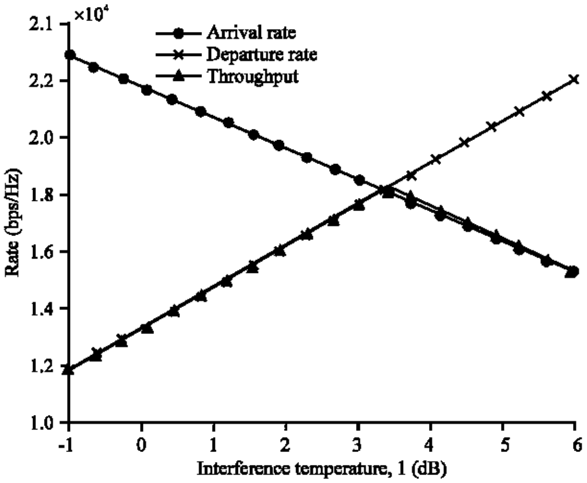

Fig. 3: Optimal value of l when $\rho_{SR} = \rho_{RD} = \rho_{RR} = 0$ dB and $\rho_S = 10$ dB

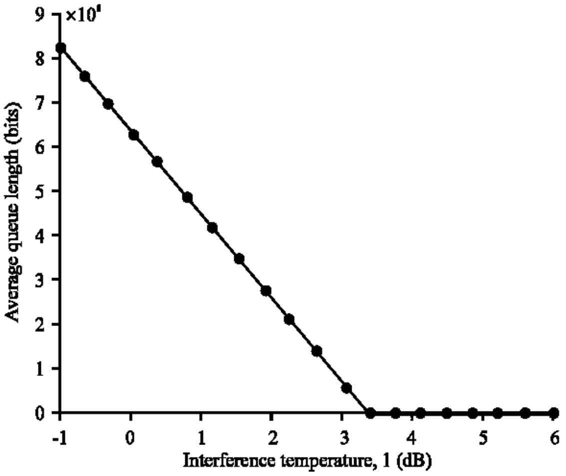

Fig. 4: Queue length versus l when $\rho_{SR} = \rho_{RD} = \rho_{RR} = 0$dB and $\rho_S = 10$ dB

we assume the self-interference channel is strong enough, then the transmit power of the relay is controlled to be $\rho_R[n] = I/|\alpha[n]|^2$ from Eq. 7 in most cases. Then, Eq. 1 and 2 can be rewritten as $3\gamma_R[n] = |g[n]|^2 \rho_S/1+I$ and $\gamma_D[n] = |h[n]|^2/|\alpha[n]|^2$. Hence, from the intuition obtained in study, the optimal should satisfy the condition $\gamma_R[n] = \gamma_D[n]$ and it can be formulated as:

$$I_{opt} = -1+\sqrt{1+\frac{4|\alpha[n]|^2|g[n]|^2}{|h[n]|^2}\rho_S} \tag{8}$$

However, Eq. 8 contains inverse exponential random variable, i.e., $I/|h[n]|^2$ and very complex random structure, it is almost impossible to obtain a long-term average expression of I_{opt} which is required for the best operation of the proposed system, B-FDR-CR.

Adaptive adjustment algorithm: Because we could not obtain a closed form expression of the optimal l, we need to design a practical algorithm to find the optimal value heuristically. One clue for this algorithm can be found in Fig. 5. The optimal value is the minimum value of l among the various values which make the queue empty in long term average sense. Hence, if the current queue length is increasing, then the current interference temperature is less than the optimal value. Based on this, we developed simple adaptive adjustment algorithm.

Figure 5 shows the adaptive adjustment algorithm. Our algorithm groups Win denotes an window size which is an interference temperature adjustment period. Win time slots into one block to adjust interference temperature. First, we set the slot length of a block denotes an window size which is an interference temperature adjustment period, initial interference temperature I_{init} and adjustment step size ΔI_{dB} and initialize such as. After waiting for time slots which consist one block, we measure the slope the slope s implies the growing rate of queue length in a block using the queue lengths at the first slot and the last slot of the block. If the queue is growing, then s will possibly be positive which means current I is less than the optimum. Hence, the adjustment procedure increase the current I as $I+\Delta I_{dB}$. Otherwise, it is reasonable to decrease the current I as $I-\Delta I_{dB}$. This update goes on every time slots.

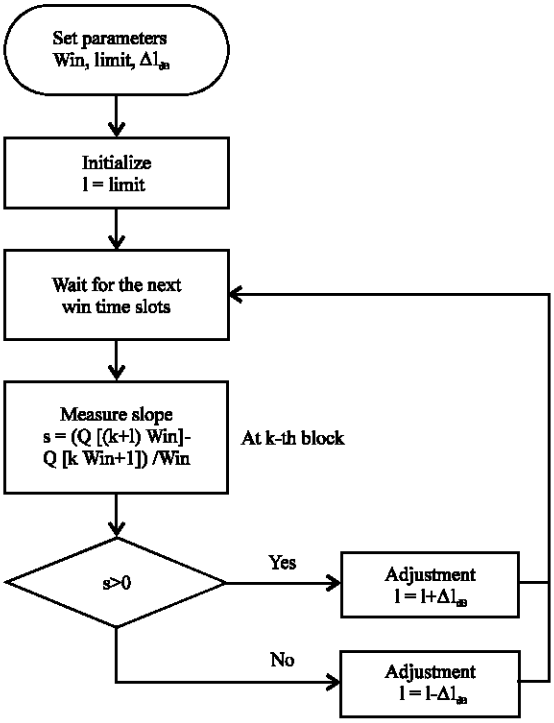

Fig. 5: Flow chart of the adaptive adjustment algorithm

RESUTLS AND DISCUSSION

Numerical evaluation: To evaluate the impact of various parameters shown in Fig. 5, we set 4 simulation scenarios as shown. In all scenarios, we use Win = 5000 slots and $\rho_{SR} = \rho_{RD} = \rho_{RR} = 0$ dB and $P_s = 10$ dB which are the same configurations with Fig. 3 and 4.

Figure 6 shows an interference temperature adjustment according to time slots for scenarios 1 and 2. Note that because we have the same configuration with Fig. 3, the optimal l is 3.36 dB. Although some fluctuations are observed in Fig. 6, the adjusted I converges to the optimal value after about 15, 000 slots in scenario 1. If we consider a few dozen microseconds for single slot length, then the adaptive algorithm converges in a few milliseconds. In scenario 2, we set the initial l as 2 dB, which is closer to the optimal value. It can be seen that the convergence latency is much less than that of scenario 1.

Figure 7 illustrates the adjusted interference temperature in scenarios 3 and 4. Comparing with Fig. 6, convergence delay decreases because the adjustment step size becomes larger. However, it is hard to achieve the exact optimal interference temperature due to the large step size.

In Fig. 8, we compare system throughput among different schemes. Conv.FDR denotes the conventional FDR system, Prop.FDR represents B-FDR-CR without adaptive adjustment algorithm. And 1, 2, 3 and 4 denote the B-FDR-CR with adaptive adjustment algorithm in 4 scenarios.

Table 1: Evaluation scenario

Scenario	l_{init} (dB)	ΔL_{dB} (dB)
1	2	0.1
2	0	0.1
3	2	0.5
4	0	0.5

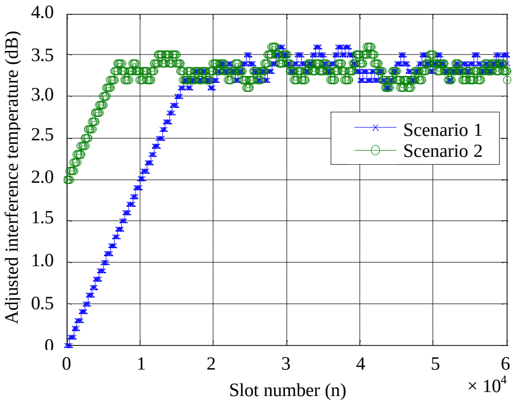

Fig. 6: Adjusted interference temperature in scenario 1, 2

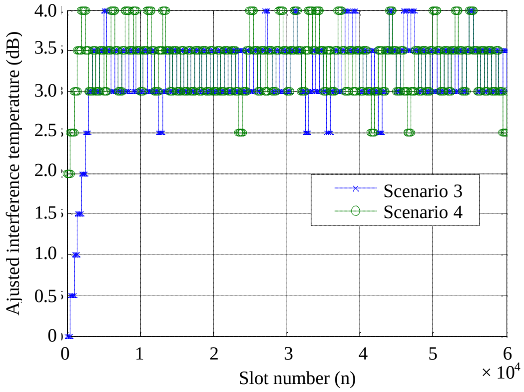

Fig. 7: Adjusted interference temperature in scenario 3, 4

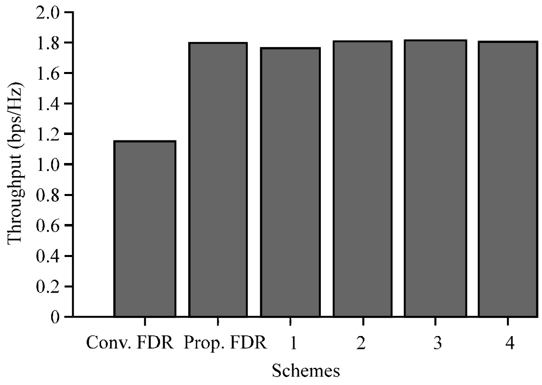

Fig. 8: System throughput comparison

found. Because the Prop.FDR uses fixed optimal l of 3.36 dB obtained from Fig. 3, it has the maximum throughput. Figure 8 justifies that the adaptive adjustment algorithm in Fig. 5 obtains near-optimal throughput.

CONCLUSION

Main contribution of this study can be summarized in two aspects. First, we investigated the impact of interference temperature on the throughput performance of the buffer-aided FDR system based on underlay CR technique. From this study, we showed the throughput performance severely depends on the value of interference temperature. The interference temperature affects both the arrival rate and the departure rate at the relay in opposite direction. Because of this trade-off relation, there exists an optimal interference temperature which maximizes the system throughput.

Second, we developed an adaptive interference temperature adjustment algorithm to practically find the optimal interference temperature. As shown in Eq. 8, analytical expression for the optimal interference temperature cannot be formulated due to its inherent random variables. Therefore, the adaptive adjustment algorithm is required to operate the proposed buffer-aided FDR system properly. From the numerical evaluation we verified the performance of our adaptive adjustment algorithm and finally, we could conclude that the proposed buffer-aided FDR system can achieve near-optimal throughput performance with our adaptive interference temperature adjustment algorithm.

RECOMMENDATIONS

For future reserach, we need to evaluate the impact of the parameters on the convergence performance of the adaptive algorithm in various environments. Moreover, sophisticated algorithm design is required to improve the convergence latency and accuracy.

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