IET Communications

Research Article

Adaptive protocol for full-duplex two-way systems with the buffer-aided relaying

ISSN 1751-8628
Received on 29th March 2018
Accepted on 11th September 2018
E-First on 5th November 2018
doi: 10.1049/iet-com.2018.5155
www.ietdl.org

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Abstract: In this study, the authors explore two-way relaying having a full-duplex decode-and-forward relay with two finite buffers. Chiefly, they propose a novel adaptive protocol (that maximises the cumulative network throughput) based on the combination of the buffer states, lossy link, and the outage probability; a decision is generated as to whether it can transmit, receive or even simultaneously receive and transmit information. Towards this objective, first, based on the queue state transition and the outage probability, an analytic Markov chain model is proposed to analyse this scheme, and the throughput and queueing delay are derived. Second, they evaluate the performance of the throughput according to the variation of the self-interference. The authors' numerical results reveal exciting insights. First, the adaptive protocol is optimal when the length of the buffer is superior to a certain threshold. Second, they demonstrate that the adaptive protocol can boost the transmission efficiency and prevent buffer overflow.

1 Introduction

Two-way relaying systems communication, which was first studied by Shannon *et al.* in [1], adding with the relay to support the exchange of information between the two nodes has been dramatically analysed and implemented to overcome the incessant demand of speed. In [2–4], the capacity of the traditional two-way relay channel (TWRC) in half-duplex has been extensively investigated. With the benefit of the buffer, for cooperative wireless networks, in half-duplex relays. Buffer-aided relaying enables the relays to adaptively choose whether to receive or transmit a packet in a given time slot based on the instantaneous quality of the receiving and transmitting channels. In [5], the authors enabled the buffering capability of relay nodes and proposed a framework for joint scheduling and relay selection. The goal is to maximise the long-term system throughput by fully exploiting multi-user diversity in the network. Nevertheless, the delay performance of the network, which is very crucial to evaluate the system network was not investigated. Whereas in [6], the authors investigated the sum-rate maximisation problem in the time division broadcast (TDBC), i.e. the users send signals to the relay station (RS) in different time slots, and the RS decodes and stores messages in the buffers. For downlink transmission, the RS re-encodes and sends using the optimal broadcast strategy. Regrettably, the whole system processes in three time slots, namely, one time slot for broadcasting and two time slots for multicast. To tackle this issue in [7], the authors renounced the restriction of having a fixed and predefined schedule and considered the selection of the states of the nodes as a degree of freedom that can be exploited for performance optimisation. Moreover, they assumed that two users always have enough information to send to the relay in all time slots. Nevertheless, they ignored the signalling overhead caused by the feedback of the channel state information (CSI). Consequently, in [8], the authors investigated two-way practical relay protocol with an enhanced transmission scheduling, which takes a joint consideration of the finite relay buffers, signalling overheads, and lossy links. In this regard, to enhance the performance of the system, full-duplex relay with buffer is proposed due to its throughput merits. Thus, optimal full-duplex buffer-aided relaying schemes were used in [9, 10]. However, the authors in [9] assumed that the self-interference (SI) at the full-duplex (FD) relay is negligible, which may not be a realistic model in practice. Similarly, the work in [10] investigates a FD relay channel, where the SI channel is not impaired by fading, and this may not be an accurate model of the SI channel either. In [11], they proposed optimal FD buffer-aided relaying schemes for the case when both the source and the relay select their transmission rates from sets of discrete rates. They also proposed a novel buffer-aided relaying scheme for the two-hop FD relay channel with SI and fading enable the FD relay to adaptively select either to receive, transmit, or simultaneously receive and transmit in a given time slot based on the qualities of the receiving, transmitting, and SI channels, such that the achievable data rate/throughput is maximised. The assumption that the buffer is so large seems not realistic in practice. Instead, in this paper, we work with two finite buffers and propose a protocol which not only considers the instantaneous qualities of the involved links for adaptive mode selection but also takes into account the states of the queues at the buffers to reduce the wastage of spectrum when it is not used. From the available literature, we are the first and the only one to have proposed a concept of FD two-way relay (FD-TWR), such that the achievable data rate/throughput is maximised.

The contribution of this paper can be summarised as follows:

- We propose an adaptive protocol for FD-TWR. Contrary to other adaptive protocols, we not only take into consideration the instantaneous qualities of the involved links but also consider the states of the queues at the buffers for FD-TWR.
- The transition matrix is so huge and almost impossible to compute. There is not much literature to solve these kinds of equations. To overcome it, we combine two methods, namely, the quotient matrix and the successive substitution. After that, we present a general framework for obtaining the average throughput and delay of information flows based on Markov chain analysis of the queue states at the buffers.
- Comparisons between our adaptive scheme and the bidirectional buffer-aided relay networks with the half-duplex relay in [8] reveal that our scheme can achieve a higher throughput even when the FD relay suffers from a huge residual self-interference.

2 System model

2.1 Channel models

In this paper, we investigate the average rate and the end-to-end delay of three-node model based FD-TWR with finite buffers in the decode-and-forward mode, denoted as Q_a of maximum length K at node A and Q_b of maximum length L at node B. There is no direct

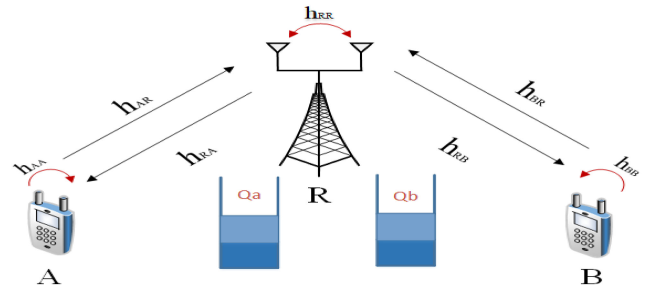

Fig. 1 *System model*

link between node A and node B. We consider the FD-TWR with finite buffer-aided where two users named A and B exchange data via the relay (R), which is equipped with two finite buffers, see Fig. 1.

Namely, the relay can transmit and receive data at the same time. Moreover, due to the co-channel transmission and imperfect interference cancellation, we assume that the FD-TWR would undergo more severe self-interference. Thus, in essence, one of the by-products of this work is to, unlike in [7], assume that user A and user B have enough information to send to the relay in some time slots, and do not have enough information in other time slots. Especially, we assume that the state of buffers can also be empty or full in all time slots. Illustratively, we choose the state $(0, 1)$ for instance. It has different state transitions, such as $(1, K)$, $(0, K)$, $(1, 1)$, $(1, 0)$, $(0, 0)$, and $(0, 1)$, and the transition probabilities can be represented in (1). By setting $j, k \in \{\mathrm{A}, \mathrm{B}, \mathrm{R}\}$, we denote the probability of successful transmission from node j to node k as P_{jk} with $0 < P_{jk} < 1$, and $1 - P_{jk}$ the probability to fail from node j to node k (the outage probability of the whole system). After that, with the state of the buffer known, we model the system to obtain the transition matrix. Before all else, we present the behaviour of the buffer state at each node. (see (1)) .

2.2 Adaptive link protocol

In this section, we analyse the state of the buffers, i.e. Q_a and Q_b. The adaptive link algorithm achieves momentous throughput gains compared to conventional relaying protocols with and without buffers. Throughout this paper, we denote the state of the two buffers as '0' and '*K, L*' for empty and full buffers, respectively, as shown in Table 1.

In this table, '*a*' and '*b*' represent the state of the buffers when they are neither full nor empty in Q_a and Q_b, respectively. Our main goal through this algorithm is to facilitate the buffer-aided relay to queue or dequeue faster by either paying on the state of the buffers or checking the lossy link and the outage probability.

Based on the link selection, the states of buffers, and the assumption that the relay in some time slots can be silent, we develop our algorithm as shown in Algorithm 1 (see Fig. 2).

2.3 Outage probability

In this section, we express the channel state information. We denote the channel coefficients as h_{AR}, h_{RB}, representing the

Table 1 States of buffers

	State of the buffers		
	Q_a	Q_b	
buffers are full or empty	0	0	state 1
	0	*L*	state 2
	K	0	state 3
	K	*L*	state 4
buffers are neither full nor empty	*a*	*b*	state 5
combined states	0	*b*	state 6
	a	0	state 7
	K	*b*	state 8
	a	*L*	state 9

while $CSI_{ar} > CSI_{br}$ **do**
  if state1 || Combined states **then**
    A receive data and B is silent.
  else if state2 **then**
    A is silent and B is silent as well.
  else if state3 **then**
    A is silent and B is silent.
  else if state4 **then**
    A receives data and B is silent.
  end if
end while
while $CSI_{ar} < CSI_{br}$ **do**
  if state1 || Combined states **then**
    A is silent and B receives data.
  else if state2 **then**
    A is silent and B is silent as well.
  else if state3 **then**
    A is silent and B is silent.
  else if state4 **then**
    A is silent and B receives data.
  end if
end while
while $CSI_{ar} = CSI_{br}$ **do**
  if state1 || Combined states **then**
    A receives data and B receives data.
  else if state2 **then**
    A receives and B transmits.
  else if state3 **then**
    A transmits and B receives.
  else if state4 **then**
    A transmits data and B transmits.
  else if state5 **then**
    A and B receive and send information.
  end if
end while

Fig. 2 *Algorithm 1: Adaptive algorithm*

$$\begin{cases} (0,1) \rightarrow (1,1): & P_{\mathrm{AR}}(1-P_{\mathrm{RB}})(1-P_{\mathrm{BR}})(1-P_{\mathrm{RA}}) + P_{\mathrm{AR}}P_{\mathrm{RA}}P_{\mathrm{BR}}(1-P_{\mathrm{RB}}), \\ (0,1) \rightarrow (1,K): & P_{\mathrm{AR}}P_{\mathrm{BR}}(1-P_{\mathrm{RB}})(1-P_{\mathrm{RA}}), \\ (0,1) \rightarrow (0,K): & P_{\mathrm{AR}}P_{\mathrm{RB}}(1-P_{\mathrm{RA}})P_{\mathrm{BR}} + P_{\mathrm{BR}}(1-P_{\mathrm{AR}})(1-P_{\mathrm{RB}})(1-P_{\mathrm{RA}}), \\ (0,1) \rightarrow (1,0): & (1-P_{\mathrm{RB}})P_{\mathrm{AR}}(1-P_{\mathrm{BR}})P_{\mathrm{RA}}, \\ (0,1) \rightarrow (0,0): & (1-P_{\mathrm{AR}})(1-P_{\mathrm{RB}})(1-P_{\mathrm{BR}})P_{\mathrm{RA}} + P_{\mathrm{RA}}P_{\mathrm{RB}}(1-P_{\mathrm{BR}})P_{\mathrm{RA}}, \\ (0,1) \rightarrow (0,1): & (1-P_{\mathrm{AR}})(1-P_{\mathrm{RB}})(1-P_{\mathrm{BR}})(1-P_{\mathrm{RA}}) + P_{\mathrm{AR}}P_{\mathrm{RB}}P_{\mathrm{BR}}P_{\mathrm{RA}} + P_{\mathrm{AR}}P_{\mathrm{RB}}(1-P_{\mathrm{BR}})(1-P_{\mathrm{RA}}) \\ & +(1-P_{\mathrm{AR}})(1-P_{\mathrm{RB}})P_{\mathrm{BR}}P_{\mathrm{RA}}. \end{cases} \quad (1)$$

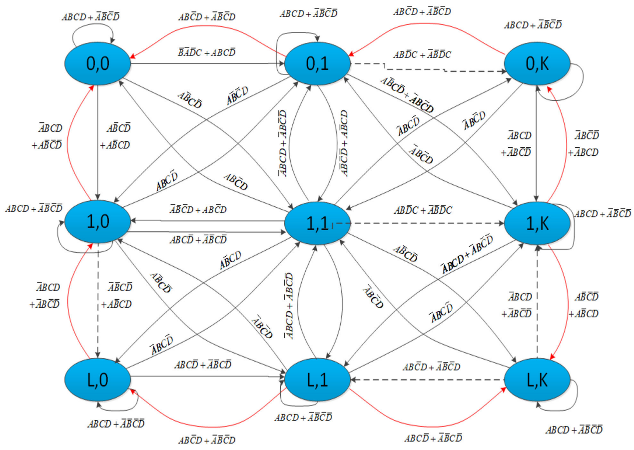

Fig. 3 *Transition diagram with an adaptive link protocol*

channels from the source A to the relay R and from the source B to the relay R, respectively. Moreover, we denote h_{AA}, h_{RR} and h_{BB} as the residual self-interference channels from user A, B, and the relay (R), respectively. Here h_{AR} and h_{BR} are independent, and the incoming and outgoing channels are reciprocal, i.e. $h_{\mathrm{AR}} \doteq h_{\mathrm{RA}}$ and $h_{\mathrm{BR}} \doteq h_{\mathrm{RB}}$. Y_{li} is the residual self-interference. Thus, the instantaneous signal-to-noise ratio (SNR) of the decode-and-forward (DF) based on FD-TWR at the nodes B and A can be, respectively, expressed as Y_{br} and Y_{ar}. For two-way relaying, both data streams must be successfully decoded at the destination nodes or else. Let $Y^{\mathrm{th}} = 2^{R_{\mathrm{th}}} - 1$, where Y^{th} and R_{th} are the outage SNR and rate thresholds, respectively. The outage probabilities of the FD two-way under Rayleigh fading channels has been well-studied in [12] and be written as (3). Furthermore, we associate the lossy links as the outage probability of the whole system. The queue at the buffer A is described as (2).

$$Q_a = \begin{cases} \text{Case 1}: Q_a = +1, \text{ if we have } P_{\mathrm{AR}}; \\ \text{Case 2}: Q_a = 0, \text{ if we have } 1 - P_{\mathrm{AR}}; \\ \text{Case 3}: Q_a = -1, \text{ if we have } P_{\mathrm{RA}}; \\ \text{Case 4}: Q_a = 0, \text{ if we have } 1 - P_{\mathrm{RA}}. \end{cases} \quad (2)$$

Finally, we annotate some alphabetical letters to the link qualities from the sources (A and B) to the relay (R) and from the relay to sources, i.e. $P_{\mathrm{AR}} = A$, $P_{\mathrm{BR}} = C$, $P_{\mathrm{RA}} = D$, and $P_{\mathrm{RB}} = B$ are the links qualities from the sources (A and B) to the relay and the links qualities from the relay to sources, respectively. And as fallout from that, $1 - P_{\mathrm{AR}} = \bar{A}$, $1 - P_{\mathrm{BR}} = \bar{C}$, $1 - P_{\mathrm{RA}} = \bar{D}$, and $1 - P_{\mathrm{RB}} = \bar{B}$ are their inverse link qualities from the sources (A and B) to the relay (R) and the links qualities from the relay to sources, respectively. The adaptive protocol applied with the link probability on the state $(0, 1)$ is represented in (1), and the transition diagram is represented in Fig. 3.

(see (3))

(see (4))

3 Throughput-delay analysis

In this section, we present a general framework for the throughput-delay analysis. The Markov process is irreducible since there is no isolated state in the Markov chain, and the aperiodic character holds true because every state can transit to itself immediately with non-zero probabilities. As a result, there exists a unique stationary distribution for this Markov process. Let $\boldsymbol{\pi}_{a,b} \in \mathbb{R}^2(a+b)$ be the steady-state probability vector of **S**, where the matrix **R** is called the geometric coefficient. Fig. 3 is sufficient to construct a transition matrix (denoted as **P**). $\boldsymbol{\pi}_{a,b}$ can be derived by solving the equations:

$$\boldsymbol{\pi}_{a,b} = \boldsymbol{\pi}_{a,b}\mathbf{P}, \quad \boldsymbol{\pi}_{a,b}\,\mathbf{e} = 1, \quad \boldsymbol{\pi}_{a,b} \geq 0, \quad (5)$$

where $\mathbf{e}$ is a column vector with all elements being 1. The transition matrix **P** is represented by (6) as

$$\mathbf{P} = \begin{bmatrix} \mathbf{D}_0 & \mathbf{D}_1 & 0 & 0 & 0 & 0 & \dots \\ \mathbf{D}_2 & \mathbf{A}_0 & \mathbf{A}_1 & 0 & 0 & 0 & \dots \\ 0 & \mathbf{A}_2 & \mathbf{A}_0 & \mathbf{A}_1 & 0 & 0 & \dots \\ 0 & 0 & \mathbf{A}_2 & \mathbf{A}_0 & \mathbf{A}_1 & 0 & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \end{bmatrix} \quad (6)$$

where $\mathbf{D}_0, \mathbf{D}_1, \mathbf{A}_0, \mathbf{A}_1$, and $\mathbf{A}_2$ are square matrices of the order $m \leq \infty$. The stationary probability distribution, when it exists, is of the form $\pi_n = \pi_0 R^n$, where the matrix **R** is called the geometric coefficient, and $s \in \{(i, j) | 0 \leq i \leq L, 0 \leq j \leq K\}$ are the states of the queues at the buffer relay. Therefore, we use an iterative method to solve these quadratic matrix equations and present the closed-form expression of $\boldsymbol{\pi}_{a,b}$.

The steady state is represented as

$$\pi_n = \pi_0 R^n, \quad n \geq 2, \quad \pi_n = \boldsymbol{\pi}_{a,b}, \quad (7)$$

and the normalisation equation based on [13], is

$$\sum_{K=0}^{\infty} \boldsymbol{\pi}_k \boldsymbol{\Omega} = \pi_0 \sum_{k=0}^{\infty} R^k \boldsymbol{\Omega} = \pi_0 [I - \mathbf{R}]^{-1} \boldsymbol{\Omega} = 1,$$

where $\boldsymbol{\Omega}$ is the column vector $\boldsymbol{\Omega} = [1\,1]^T$. Thus, when the matrix does not exist, it is a common practice to use the iterative procedure that is derived from the equations:

$$[\pi_0\, \pi_1] \begin{bmatrix} \mathbf{D}_0 & \mathbf{D}_1 \\ \mathbf{A}_2 & \mathbf{A}_0 + \mathbf{R}A_2 \end{bmatrix} = 0,$$

$$\pi_0 \mathbf{A}_1 + \pi_1 \mathbf{A}_0 + \pi_2 \mathbf{A}_2 = \pi_0 [\mathbf{A}_1 + \mathbf{R}\mathbf{A}_0 + R^2 \mathbf{A}_2] = 0,$$

where

$$\mathbf{R} = -[\mathbf{A}_1 + R^2 \mathbf{A}_2] \mathbf{A}_0^{-1}. \quad (8)$$

Thus, the recursive solution is given by

$$P_{\mathrm{out}} = \begin{cases} 1 - \dfrac{\gamma\mathrm{AR}}{\gamma\mathrm{AR} + \gamma\mathrm{BR}\gamma\mathrm{th}} e^{-[(\gamma\mathrm{th}(\gamma II + 1)(\gamma\mathrm{AR} + \gamma\mathrm{BR} + \gamma\mathrm{BR}\gamma\mathrm{th}))/\gamma\mathrm{AR}\gamma\mathrm{BR}]} - \dfrac{\gamma\mathrm{BR}}{\gamma\mathrm{BR} + \gamma\mathrm{AR}\gamma\mathrm{th}} e^{-[(\gamma\mathrm{th}(\gamma\mathrm{LI} + 1)(\gamma\mathrm{AR} + \gamma\mathrm{BR} + \gamma\mathrm{AR}\gamma\mathrm{th}))/\gamma\mathrm{AR}\gamma\mathrm{BR}]}, & \gamma\mathrm{th} \geq 1 \\ 1 - \dfrac{\gamma\mathrm{AR}}{\gamma\mathrm{AR} + \gamma\mathrm{BR}\gamma\mathrm{th}} e^{-[(\gamma\mathrm{th}(\gamma II + 1)(\gamma\mathrm{AR} + \gamma\mathrm{BR} + \gamma\mathrm{BR}\gamma\mathrm{th}))/\gamma\mathrm{AR}\gamma\mathrm{BR}]} - \dfrac{\gamma\mathrm{BR}}{\gamma\mathrm{BR} + \gamma\mathrm{AR}\gamma\mathrm{th}} e^{-[(\gamma\mathrm{th}(\gamma\mathrm{LI} + 1)(\gamma\mathrm{AR} + \gamma\mathrm{BR} + \gamma\mathrm{AR}\gamma\mathrm{th}))/\gamma\mathrm{AR}\gamma\mathrm{BR}]} & \\ + \dfrac{(1 - \gamma\mathrm{th}^2)\gamma\mathrm{AR}\gamma\mathrm{BR}}{(\gamma\mathrm{th}\gamma\mathrm{AR})(\gamma\mathrm{AR} + \gamma\mathrm{th}\gamma\mathrm{BR})} e^{-[(\gamma\mathrm{th}(\gamma\mathrm{LI} + 1)(\gamma\mathrm{AR} + \gamma\mathrm{BR}))/((1 - \gamma\mathrm{th})\gamma\mathrm{AR}\gamma\mathrm{BR})]}, & \gamma\mathrm{th} \in [0, 1) \end{cases} \quad (3)$$

$$\boldsymbol{\pi}_{a,b} = \left(1 - \frac{\sum_1^4 \mathrm{Pr}a^2(1 - \mathrm{Pr}b)^2 + \mathrm{Pr}a(1 - \mathrm{Pr}b^3) + (1 - \mathrm{Pr}a)^2 \mathrm{Pr}b^2 + (1 - \mathrm{Pr}a)\mathrm{Pr}b^3}{\sum_1^2 (1 - \mathrm{Pr}a)\mathrm{Pr}b^3 + \sum_1^3 (1 - \mathrm{Pr}a)^2 (\mathrm{Pr}b)^2 + \mathrm{Pr}a^2 \mathrm{Pr}b(1 - \mathrm{Pr}a)}\right) \left(\frac{\sum_1^4 \mathrm{Pr}a^2(1 - \mathrm{Pr}b)^2 + \mathrm{Pr}a(1 - \mathrm{Pr}b^3) + (1 - \mathrm{Par})^2 \mathrm{Pr}b^2 + (1 - \mathrm{Pr}a)\mathrm{Pr}b^3}{\sum_1^2 (1 - \mathrm{Pr}a)\mathrm{Pr}b^3 + \sum_1^3 (1 - \mathrm{Pr}a)^2 (\mathrm{Pr}b)^2 + \mathrm{Pr}a^2 \mathrm{Pr}b(1 - \mathrm{Pr}a)}\right)^2 \quad (4)$$

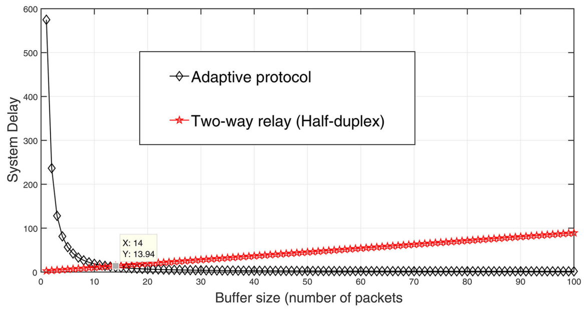

Fig. 4 *Comparison of the delay performance*

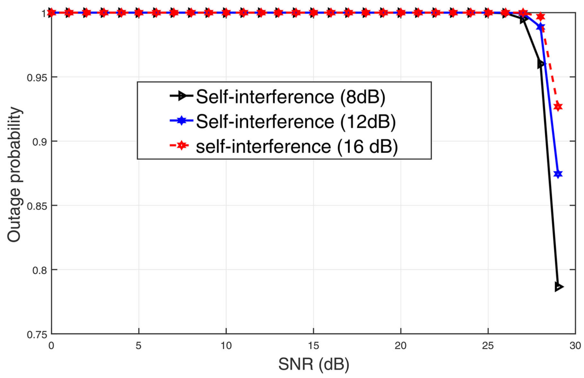

Fig. 5 *Outage probability versus the residual self-interference*

$$\mathbf{R}(0) = 0 \tag{9}$$

$$\mathbf{R}(k+1) = -[\mathbf{A}_1 + R^2(k)\mathbf{A}_2]\mathbf{A}_0^{-1} \tag{10}$$

$$\| \mathbf{R}(k+1) - \mathbf{R}(k) \| < \Theta . \tag{11}$$

The iteration is remade until the results of two successive iterations diverge by less than a predefined parameter Θ. The average arrival rate is given by $r_0 = 1$ Mbit/s, where $\mathbf{R}$ is equal to the expected number of visits to n between two successive visits. In [14], the quotient matrix corresponding to the partition specified by $\{C_1, C_2, \ldots, C_K\}$ is defined as the $K \times K$ matrix and we have

$$A^{\pi} = \left(S^T\mathbf{S}\right)^{-1} S^T(A)\mathbf{S} . \tag{12}$$

The quotient matrix allows us to transform the matrices $\mathbf{A}_2$, $\mathbf{A}_1$, and $\mathbf{A}_0$ from three dimensions to two dimensions by conserving the matrix $\mathbf{P}$ properly. Then, based on the quotient matrix, $\mathbf{A}_0$, $\mathbf{A}_1$, and $\mathbf{A}_2$ can be rewritten as

$$\mathbf{A}_0 = \begin{bmatrix} A\bar{B}C\bar{D} & A\bar{B}C\bar{D} \\ A\bar{B}\bar{C}D & A\bar{B}\bar{C}\bar{D} \end{bmatrix}, \tag{13}$$

$$\mathbf{A}_2 = \begin{bmatrix} \bar{A}BCD & ABC\bar{D} \\ \bar{A}B\bar{C}D & \bar{A}BCD \end{bmatrix}, \tag{14}$$

$$\mathbf{A}_1 = \begin{bmatrix} A\bar{B}\bar{C}\bar{D} & A\bar{B}C\bar{D} \\ A\bar{B}CD & 0 \end{bmatrix}. \tag{15}$$

An approximate closed-form of the steady-state probability based on the quotient matrix can be shown as (4).

We define the throughput ϕ as the amount of successfully delivered data of both A and B per second, which can be given by

$$\phi = \sum_{1}^{Q_a} \sum_{1}^{Q_b} (P_{\mathrm{RA}} + P_{\mathrm{RB}})\pi_0 R_b^a . \tag{16}$$

We denote Q as the average length of buffers. Then we have

$$\begin{aligned} Q &= \sum_{a=1}^{a} \sum_{b=1}^{b} n_{a,b}\boldsymbol{\pi}_{a,b} = \sum_{k=1}^{n} kp^k \\ &= \frac{p(np^{(n+1)} - (n+1)p^n + 1)}{(p-1)^2} . \end{aligned} \tag{17}$$

The last equation in (17) can be proved by induction as follows. When $n = 1$, we have

$$p = \frac{p(p^{1+1} - (1+1)p + 1)}{(p-1)^2} = \frac{p(p^2 - 2p + 1)}{(p-1)^2} .$$

Assume it holds for $n, n \geq 2$, then for $n+1$, we have

$$\begin{aligned} Q &= (n+1)P^{n+1} + \frac{p(np^{n+1} - (n+1)p^n + 1)}{(p-1)^2} \\ &= \frac{(n+1)p^{n+1}(p-1)^2 + p(np^{n+1} - (n+1)p^n + 1)}{(p-1)^2} \\ &= \frac{p((n+1)p^{n+2} - (n+1+1)p^{n+1} + 1)}{(p+1)^2} \\ &= \sum_{k=1}^{n+1} kp^k . \end{aligned} \tag{18}$$

Then (17) has been proved.

Finally, the average packet delay T can be properly defined according to the Little's law in [15], i.e.

$$T = \frac{Q}{\phi} . \tag{19}$$

4 Numerical results

In this section, we evaluate the performance of the FD-TWR aided buffer in terms of the throughput and the system delay according to the formulas derived in the above section. For the simulations, the size of the buffers (N) is finite, and we adopt $N = 100$ in all simulations. The residual self-interference is severe, i.e. $R_{\mathrm{th}} = 1$ b/s/Hz, $Y_{li} = 15$, $Y_{ar} = 50$, $Y_{br} = 10$, and $Y_{\mathrm{th}} = 1$ dB is the outage SNR.

Fig. 4 compares the system delay among FD-TWR aided buffer with an adaptive protocol and bidirectional buffer aided in the half-duplex relay over Rayleigh fading channels versus the size of the buffers. It reveals that when the size of the buffers increases, the system delay is reduced, and the average packet delay of the FD buffering relay model is smaller than the half-duplex one.

Fig. 5 depicts the outage probability of the DF based on FD-TWR with threshold rate under the outage $R_{\mathrm{th}} = 1$ b/s/Hz. The results compare that the outage probability while the relay suffers from a huge self-interference (16, 12, and 8 dB). The results show that there is a correlation between the outage probability and the self-interference. While the self-interference increases the outage probability decreases.

Fig. 6 compares the throughput between FD-TWR aided buffer with adaptive protocol and bidirectional buffer aided in the half-duplex relay over Rayleigh fading channels (residual self-interference: 15, 16, and 17 dB) versus the number of the buffers. The results show that there is a cross point between the three curves. We observe that there is a correlation between the buffer size and the residual self-interference. When the residual self-interference decreases and the buffer size increase, the throughput increases exponentially due to the ability of the adaptive protocol. The reason is that the adaptive protocol can reduce the probability of the queue empty. In this case, when the number of the buffers is $N > 28$, the throughput of the FD with the adaptive protocol (residual self-interference: 15 dB) is superior to the one in half-duplex. This result is due to the capability of the adaptive protocol with the residual self-interference 15 dB to queue and dequeue rapidly compared to others.

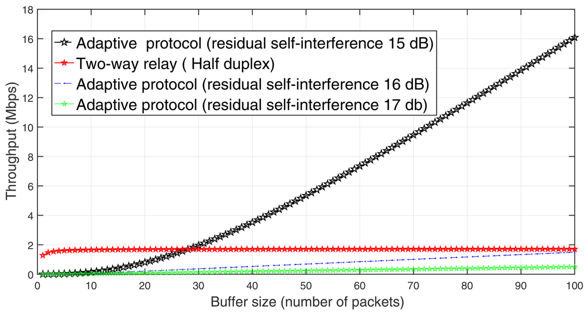

Fig. 6 *Comparison of the delay performance*

5 Conclusion

In this paper, we studied the throughput and the system delay in FD-TWR networks using an adaptive scheme. Specifically, we considered a buffer-aided-relay which has a finite length buffer. Based on the Markov Chain, we characterised an adaptive protocol that can maximise the aggregate network throughput by taking into consideration the constraint of the outage probability. Moreover, we compared the performance of the proposed transmission policy to the two-way relay with the half-duplex scheme, especially when our FD relay suffers from a colossal self-interference. The numerical results showed that buffering relay techniques improve the capacity of relay networks in slow fading environments, and the adaptive link protocol significantly improves the throughput of the system by queuing or dequeuing the buffers rapidly according to the buffer states, lossy link, and the outage probability. Furthermore, the adaptive protocol can remedy the bottleneck problem of residual self-interference; and outperform the two-way half-duplex network even when the FD relay suffers from a huge residual self-interference.

6 Acknowledgment

This research was supported by Project 123613020889 supported by the CSC (China Scholarship Council).

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