Performance Analysis of Full Duplex Wireless Multi-hop Networks

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Abstract. The Fifth Generation (5G) mobile communication standard is expected to come on-line in 2020. Among the performance requirements of 5G, stands out the capacity, that is expected to be 1000-fold of the Fourth Generation (4G). Several technologies have been considered to achieve this goal, among them Full Duplex communications. This paper analyzes the performance of a Full Duplex multi-hop wireless network combined with directional and omnidirectional antennas. Several performance metrics were considered to evaluate the performance of the network: throughput, capacity, block and drop probability. The Markovian model presented here considers buffers in the network nodes and is an extension of a simpler model previously presented in [14], in which no buffer was considered.

Keywords: 5G · Multi-hop network · Full Duplex communications · Performance analysis · Markovian models · Directional antennas · Omni-directional Antennas

1 Introduction

The Fifth Generation (5G) of mobile communication networks is currently under standardization. Several performance requirements are defined for 5G networks. One challenging requirement is the capacity, which is expected to be 1000 times greater than the capacity of the Fourth Generation (4G) networks [1]. Several new technologies have been proposed to 5G networks in order to achieve the performance requirements of that network. Cognitive Radio is an important technology to improve the spectral efficiency and capacity of the network. Another important technology that can be used in conjunction with cognitive radio to increase the capacity of the network is In-Band Full Duplex (IBFD) or simply Full Duplex (FD) communication.

FD communication technology enables a device to transmit and receive simultaneously at the same frequency band; thus, this technology can potentially double the spectral efficiency and, consequently, the network capacity [1]. Some important issues about FD communication are Self-Interference (SI) [2–6], the need of new radios [7,8], the need of new Medium Access Control (MAC) Protocols [8–12] and the transmission modes [13].

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The performance analysis of FD wireless networks is important to define the best configuration and transmission mode of the network. In general, the performance analysis of FD networks is based on simulations only [7,8,8–13]. In [14], the authors proposed an analytical Markovian model to analyze the performance of a multi-hop wireless FD network. However, that model considered that the nodes of the network had no buffer. The results presented in [14] showed that the performance of FD networks are very limited if the nodes do not have a buffer. Thus, an analytical model considering buffer in the nodes is important to understand the real benefit of full-duplex networks and the best configuration of these networks.

In this paper, we propose an analytical Markovian model to analyze the performance of a full duplex multi-hop wireless network (and also a half duplex network) combined with directional and omnidirectional antennas considering buffer in the nodes. The size of the buffer is defined by the parameter b. The performance metrics are the same previously discussed in [14]: throughput, capacity, block, and drop probability.

The remainder of this paper is organized as follows: Sect. 2 describes the network scenario considered; Sect. 3 presents the proposed Markovian model; in Sect. 4 we define and compute the performance metrics; Sect. 5 shows the numerical results and, finally, Sect. 6 presents the conclusion and future works.

2 Network Scenario and Assumptions

The network considered in this paper is the same proposed in [8]: a wireless multi-hop network, with data in only one way, composed of 4 nodes (Source, 1, 2, Destination), as illustrated in Fig. 1. Each node can communicate only with its neighbor (for example, node S can communicate only with node 1 and node 1 can communicate only with nodes S and 2).

Following [8], the network nodes can be configured with two parameters: the communication type (HD-Half Duplex or FD-Full Duplex) and the antenna type (DA-Directional Antennas or ODA-Omni-directional Antennas). HD nodes can only transmit or receive at a given time, and FD nodes can transmit and receive simultaneously. When an ODA node transmits, the transmission interferes with the reception of the previous neighbor reception (for example, a transmission of node 2 can interfere with the reception of node 1); DA nodes do not have this problem. Thus, it is possible to have four types of nodes:

- ⋆ A[Half,Omni]: This type of node is configured with HD communication and one ODA to transmit and receive, just like a conventional node.
- ⋆ B[Full,Omni]: This type of node is configured with FD communication and two ODAs, one to transmit and one to receive, as proposed in [7].
- ⋆ D[Full,Direc]: This type of node is configured with FD communication and two DA for Transmission (TX), TX1 to transmit from 0 to π, TX2 from π to 2π and one ODA for Reception (RX) (TX1 and TX2 cannot be used simultaneously), as proposed in [8].

⋆ C[Half,Direc]: This type of node is configured with HD communication and the same antenna configuration used in D[Full,Direc].

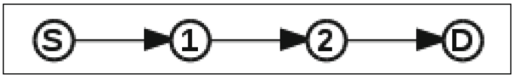

Fig. 1. Network scenario [8].

We suppose that the network is composed only by one type of node (A, B, C or D). Thus, we have four different operation modes, denoted by mode A[Half,Omni], when the nodes are type A; mode B[Full,Omni], when the nodes are type B; mode C[Half,Direc], when the nodes are type C; and mode D[Full,Direc], when the nodes are type D. These modes operate differently, as illustrated in Fig. 2.

For Mode A[Half,Omni], the network needs three steps to complete a transmission: (i) transmission from S to 1; (ii) transmission from 1 to 2; and (iii) transmission from 2 to D. In this mode, nodes cannot transmit and receive at the same time because they are HD and node 2 cannot transmit while node 1 is receiving because they use ODA. So, in this mode, only one node can transmit at a given time, and the packet is transmitted until the destination without stops.

For Mode B[Full,Omni], the network needs two steps to complete a transmission: (i) transmission from S to 1 and from 1 to 2; (ii) transmission from 2 to D. In this mode, nodes are FD, so, in step (i), node 1 can receive and transmit at the same time; however, because the nodes use ODA, node 2 cannot transmit in step (i), because its transmission would interfere with the reception of node 1.

For Mode C[Half,Direc], the network needs two steps to complete a transmission: (i) transmission from S to 1 and from 2 to D; (ii) transmission from 1 to 2. In this mode, DA is used, so, nodes S and 2 can transmit at the same time without interference, but, because all nodes are HD, no node can transmit and receive at the same time.

For Mode D[Full,Direc], the network needs only one step to complete a transmission: (i) transmission from S to 1, 1 to 2 and 2 to D. In this mode, all nodes can transmit simultaneously, because they are FD and use DA.

3 Markovian Model

In this section, we propose a multidimensional Continuous-Time Markovian Chain (CTMCs) to model each operation modes. Transitions in the chain occur due to arrival or transmission of a packet. The arrival processes follow a Poisson distribution with average value λ packets/s, the service time follows an exponential distribution with mean value $1/\mu$ s, resulting in a service rate equal to μ packets/s.

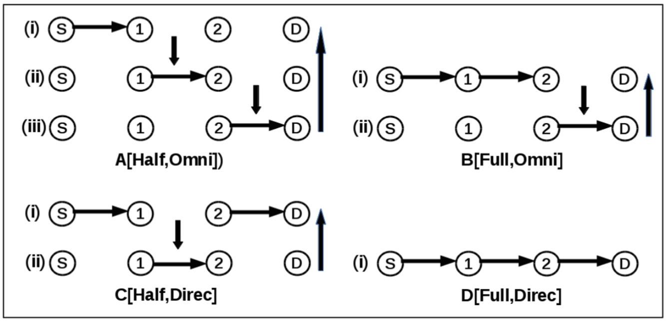

Fig. 2. Transmission process for each operation mode [8].

Each state in the chain is defined by six variables and is represented by dimensions $x = \{i(wi), j(wj), k(wk)\}$, where i represents the existence (1) or not (0) of a transmission from node S to 1; wi represents the number of packets waiting in node S; j represents the existence (1) or not (0) of a transmission from node 1 to 2; wj represents the number of packets waiting in node 1; k represents the existence (1) or not (0) of a transmission from node 2 to D; wk represents the number of packets waiting in node 2.

To simplify the notation the subset $\{hop, node\}$ will be denoted as a server, so $\{i, wi\}$ is defined as server i, $\{j, wj\}$ is defined as server j, and $\{k, wk\}$ is defined as server k. For example, $x = \{0(2), 1(0), 0(0)\}$ represents a state where server i has two packets in the buffer and server j is transmitting. As an example, Fig. 3 illustrates the state transition diagram of mode A[Half,Omni] with buffer size (b) equal to 1. In this mode, the packet is transmitted to the destination without stops; thus, only node S needs a buffer to queue incoming packets. The others transition state diagrams will not be presented due to the complexity, but all the possible state transitions for all modes are explained in Tables 1, 2, 3 and 4, where is also given the set of possible states.

The stationary probabilities, $\pi(x)$ can be calculated from the global balance equations and the normalization equation, which are given by:

$$\pi Q = 0, \sum_{x \in S} \pi(x) = 1. \tag{1}$$

where π is the steady-state probability vector, Q is the transition rate matrix, and S is the set of all possible states. S and Q can be constructed using the transition patterns explained in Tables 1, 2, 3 and 4, where PA means Packet Arrival and TX_a_b means transmission from the server a to b.

When the steady-state probabilities are determined from (1), the performance of the system can be evaluated for different metrics. The derivations of mathematical expressions for these metrics are presented in the following section.

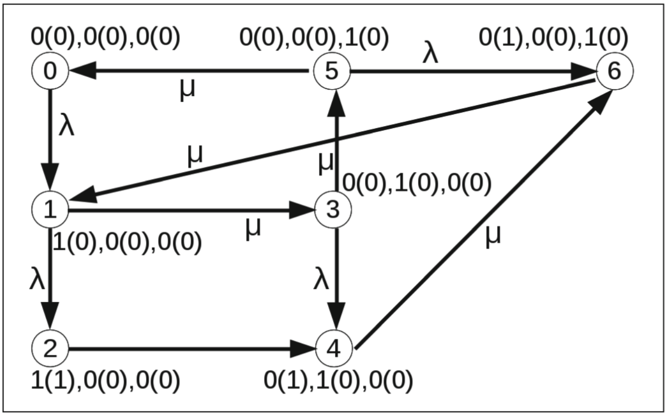

Fig. 3. State diagram of mode A[Half,Omni] with buffer 1.

4 Performance Metrics

In this section the following performance metrics are defined: blocking probability, drop probability, capacity, throughput and the average number of packets in the network.

4.1 Blocking Probability

The blocking probability, P, is the summation of steady-state probabilities for all state where the buffer of the server i is full and, therefore, no packet can enter the network. This parameter is calculated by:

$$P = \sum_{x \in S} \pi(x), \; if \quad wi = b. \tag{2}$$

4.2 Capacity

The capacity C, is the average number of successful transmissions per time unit. This metric is calculated by:

$$C = \sum_{x \in S} \pi(x)\mu, \; if \quad k = 1. \tag{3}$$

4.3 Drop Probability

The drop probability D, is the probability that, once a packet enters the network, it does not complete the transmission with success, meaning it is dropped. This parameter is calculated by:

$$D = 1 - ST. \tag{4}$$

Table 1. Mode A[Half,Omni] $S = \{x|0 \leq i,j,k \leq 1; 0 \leq wi \leq b; wj = 0; wk = 0; i+wi \leq b+1; i+j+k \leq 1\}$

Event	Destination state	Rate	Condition
PA	$i+1$	λ	$i = wi = j = wj = k = wk = 0$
PA	$wi+1$	λ	$i = 1; wi < b; j = wj = k = wk = 0$
PA	$wi+1$	λ	$i = 0; wi < b; j = 1; wj = k = wk = 0$
PA	$wi+1$	λ	$i = 0; wi < b; j = wj = 0; k = 1; wk = 0$
TX_i_j	$i-1, j+1$	μ	$i = 1; wi \leq b; j = wj = k = wk = 0$
TX_j_k	$j-1, k+1$	μ	$i = 0; wi \leq b; j = 1; wj = k = wk = 0$
TX_k_d	$k-1$	μ	$i = wi = j = wj = 0; k = 1; wk = 0$
TX_k_d	$i+1, wi-1, k-1$	μ	$i = 0; wi > 0; j = wj = 0; k = 1; wk = 0$

Table 2. Mode B[Full, Omni] $S = \{x|0 \leq i,j,k \leq 1; 0 \leq wi, wj, wk \leq b; i+wi \leq b+1; j+wj \leq b+1; k+wk \leq b+1; i+j+k \leq 2;\}$

Event	Destination state	Rate	Condition
PA	$i+1$	λ	$i = wi = 0; j \leq 1; wj = k = wk = 0$
PA	$wi+1$	λ	$i = 1; wi < b; j \leq 1; wj \leq b; k = 0; wk \leq b$
PA	$wi+1$	λ	$i = 0; wi < b; j \leq 1; wj \leq b; k = 1; wk \leq b$
TX_i_j	$i-1, j+1$	μ	$i = 1; wi = j = wj = k = wk = 0$
TX_i_j	$wi-1, j+1$	μ	$i = 1; wi > 0; j = wj = k = wk = 0$
TX_i_j	$i-1, wj+1$	μ	$i = 1; wi = 0; j = 1; wj < b; k = wk = 0$
TX_i_j	$wi-1, wj+1$	μ	$i = 1; wi > 0; j = 1; wj < b; k = wk = 0$
TX_i_j	$i-1, j+1, k+1, wk-1$	μ	$i = 1; wi \leq b; j = wj = k = 0; wk > 0$
TX_i_j	$i-1, wj+1, k+1, wk-1$	μ	$i = 1; wi \leq b; j = 1; wj < b; k = 0; wk > 0$
TX_i_j dropped	$i-1$	μ	$i = 1; wi = 0; j = 1; wj = b; k = wk = 0$
TX_i_j dropped	$wi-1$	μ	$i = 1; wi > 0; j = 1; wj = b; k = wk = 0$
TX_i_j dropped	$i-1, k+1, wk-1$	μ	$i = 1; wi > 0; j = 1; wj = b; k = 0; wk > 0$
TX_j_k	$j-1, k+1$	μ	$i = wi = 0; j = 1; wj = k = wk = 0$
TX_j_k	$j-1, wk+1$	μ	$i = 1; wi \leq b; j = 1; wj = k = 0; wk < b$
TX_j_k	$j-1, wk+1$	μ	$i = 0; wi \leq b; j = 1; wj = 0; k = 1; wk < b$
TX_j_k	$wj-1, k+1$	μ	$i = wi = 0; j = 1; wj > 0; k = wk = 0$
TX_j_k	$wj-1, wk+1$	μ	$i = 1; wi \leq b; j = 1; wj > 0; k = 0; wk < b$
TX_j_k	$wj-1, wk+1$	μ	$i = 0; wi \leq b; j = 1; wj > 0; k = 1; wk < b$
TX_j_k dropped	$j-1$	μ	$i = 1; wi \leq b; j = 1; wj = k = 0; wk = b$
TX_j_k dropped	$j-1$	μ	$i = 0; wi \leq b; j = 1; wj = 0; k = 1; wk = b$
TX_j_k dropped	$wj-1$	μ	$i = 1; wi \leq b; j = 1; wj > 0; k = 0; wk = b$
TX_j_k dropped	$wj-1$	μ	$i = 0; wi \leq b; j = 1; wj > 0; k = 1; wk = b$
TX_k_d	$k-1$	μ	$i = wi = 0; j \leq 1; wj \leq b; k = 1; wk = 0$
TX_k_d	$i+1, wi-1, k-1$	μ	$i = 0; wi > 0; j \leq 1; wj \leq b; k = 1; wk \leq b$
TX_k_d	$wk-1$	μ	$i = wi = 0; j \leq 1; wj \leq b; k = 1; wk > 0$

Table 3. Mode C[Half, Direc] $S = \{x | 0 \le i, j, k \le 1; 0 \le wi, wj \le b; wk = 0; i + wi \le b + 1; j + wj \le b + 1; i + j + k \le 2\}$

Event	Destination state	Rate	Condition
PA	$i + 1$	λ	$i = wi = j = wj = k = wk = 0$
PA	$i + 1$	λ	$i = wi = j = 0; wj \le b; k = 1; wk = 0$
PA	$wi + 1$	λ	$i = 1; wi < b; j = 0; wj \le b; k \le 1; wk = 0$
PA	$wi + 1$	λ	$i = 0; wi < b; j = 1; wj \le b; k = wk = 0$
TX_i_j	$i - 1, j + 1$	μ	$i = 1; wi \le b; j = 0; wj \le b; k = wk = 0$
TX_i_j	$i - 1, wj + 1$	μ	$i = 1; wi = j = 0; wj < b; k = 1; wk = 0$
TX_i_j	$wi - 1, wj + 1$	μ	$i = 1; wi > 0; j = 0; wj < b; k = 1; wk = 0$
TX_i_j dropped	$i - 1$	μ	$i = 1; wi = j = 0; wj = b; k = 1; wk = 0$
TX_i_j dropped	$wi - 1$	μ	$i = 1; wi > 0; j = 0; wj = b; k = 1; wk = 0$
TX_j_k	$j - 1, k + 1$	μ	$i = wi = 0; j = 1; wj \le b; k = wk = 0$
TX_j_k	$i + 1, wi - 1, j - 1, k + 1$	μ	$i = 0; wi > 0; j = 1; wj \le b; k = wk = 0$
TX_k_d	$k - 1$	μ	$i \le 1; wi \le b; j = wj = 0; k = 1; wk = 0$
TX_k_d	$k - 1$	μ	$i = 1; wi \le b; j = 0; wj > 0; k = 1; wk = 0$
TX_k_d	$j + 1, wj - 1, k - 1$	μ	$i = wi = j = 0; wj > 0; k = 1; wk = 0$

Table 4. Mode D[Full, Direc] $S = \{x | 0 \le i, j, k \le 1; 0 \le wi, wj, wk \le b; i + wi \le b + 1; j + wj \le b + 1; k + wk \le b + 1; i + j + k \le 3\}$

Event	Destination state	Rate	Condition
PA	$i + 1$	λ	$i = wi = 0; j \le 1; wj \le b; k \le 1; wk \le b$
PA	$wi + 1$	λ	$i = 1; wi < b; j \le 1; wj \le b; k \le 1; wk \le b$
TX_i_j	$i - 1, j + 1$	μ	$i = 1; wi = j = wj = 0; k \le 1; wk \le b$
TX_i_j	$wi - 1, j + 1$	μ	$i = 1; wi > 0; j = wj = 0; k \le 1; wk \le b$
TX_i_j	$i - 1, wj + 1$	μ	$i = 1; wi = 0; j = 1; wj < b; k \le 1; wk \le b$
TX_i_j	$wi - 1, wj + 1$	μ	$i = 1; wi > 0; j = 1; wj < b; k \le 1; wk \le b$
TX_i_j dropped	$i - 1$	μ	$i = 1; wi = 0; j = 1; wj = b; k \le 1; wk \le b$
TX_i_j dropped	$wi - 1$	μ	$i = 1; wi > 0; j = 1; wj = b; k \le 1; wk \le b$
TX_j_k	$j - 1, k + 1$	μ	$i \le 1; wi \le b; j = 1; wj = k = wk = 0$
TX_j_k	$j - 1, wk + 1$	μ	$i \le 1; wi \le b; j = 1; wj = 0; k = 1; wk < b$
TX_j_k	$wj - 1, k + 1$	μ	$i \le 1; wi \le b; j = 1; wj > 0; k = wk = 0$
TX_j_k	$wj - 1, wk + 1$	μ	$i \le 1; wi \le b; j = 1; wj > 0; k = 1; wk < b$
TX_j_k dropped	$j - 1$	μ	$i \le 1; wi \le b; j = 1; wj = 0; k = 1; wk = b$
TX_j_k dropped	$wj - 1$	μ	$i \le 1; wi \le b; j = 1; wj > 0; k = 1; wk = b$
TX_k_d	$k - 1$	μ	$i \le 1; wi \le b; j \le 1; wj \le b; k = 1; wk = 0$
TX_k_d	$wk - 1$	μ	$i \le 1; wi \le b; j \le 1; wj \le b; k = 1; wk > 0$

Where Successful Transmission (ST) is the probability that, once a packet enters the network, it completes the transmission with success. Calculated by:

$$ST = \frac{C}{\lambda(1-P)}. \tag{5}$$

Where C is the capacity, and $\lambda(1-P)$ represents the average number of packets that enter the network.

4.4 Throughput

The throughput, denoted by Th, is defined as the ratio between the capacity and the total arrival rate of packets in the network. This metric is computed by:

$$Th = \frac{C}{\lambda}. \tag{6}$$

With all performance metrics defined, we can now investigate the performance of the network. The results are presented in the next section.

5 Numerical Results

All calculations were done using MatLab, with the following parameters: arrival rate, λ, varying from 1 to 10 packets/s, departure rate, μ, equal to 10 packets/s and two buffer sizes: 5 and 20. The channel is considered error free. The performance metrics depend only on the normalized traffic in the network, or utilization factor, (λ/μ).

Figures 4 and 5 show the blocking probability, it is possible to observe that for modes A[Half,Omni] and B[Full,Omni] the blocking probability remain practically the same for buffer size equal or greater than 5, but for modes C[Half,Direc] and D[Full,Direc] the blocking probability continues to decrease while the buffer size is increased, mode D[Full,Direc] has the lower block probability, followed by mode C[Half,Direc], next is mode B[Full,Omni] and then mode A[Half,Omni]. It is clear that directional antennas have a significant impact on decreasing the blocking probability.

The drop probability is shown in Figs. 6 and 7. It is possible to observe that:

- ⋆ Mode A[Half,Omni] has no drop because only one packet can be transmitted at a given time in the network.
- ⋆ Mode B[Full,Omni] has a drop probability about zero even with a buffer size equal to 5.
- ⋆ Mode D[Full,Omni] get close to zero drop probability only with buffer size equal to 20.

- ⋆ For mode C[Half,Direc], the drop probability increase when the buffer size increases; for buffer size equal to 20, the drop probability tends to 1/2 when the utilization factor tends to 1 ($\lambda = 10$). This occurs because, in this mode, when node 1 finish to send a packet to node 2, it must wait till node 2 send this packet to the destination to be able to send another packet to node 2; meanwhile, node S can transmit to node 1 while node 2 is transmitting, causing, when the utilization factor tends to 1, the node 1 buffer to become full and drop packets. This problem gets worse when the buffer size is increased because node S will always have packets to transmit when node 2 is transmitting, and thus, more packets will be dropped in node 1.
- ⋆ It is clear that full duplex communication has a lower drop probability.

Figures 8, 9, 10 and 11 show the System Capacity and Throughput. It is possible to observe that for modes A[half,Omni] and B[Full,Omni] the Throughput and Capacity remain practically the same for buffer size equal or greater than 5, mode C[Half,Direc] have a degradation on the performance while the buffer size is increased due to drop probability explained above, and mode D[Full,Omni] get to a Throughput greater than 0.9 with buffer size equal to 20 when the utilization factor tends to 1 ($\lambda = 10$).

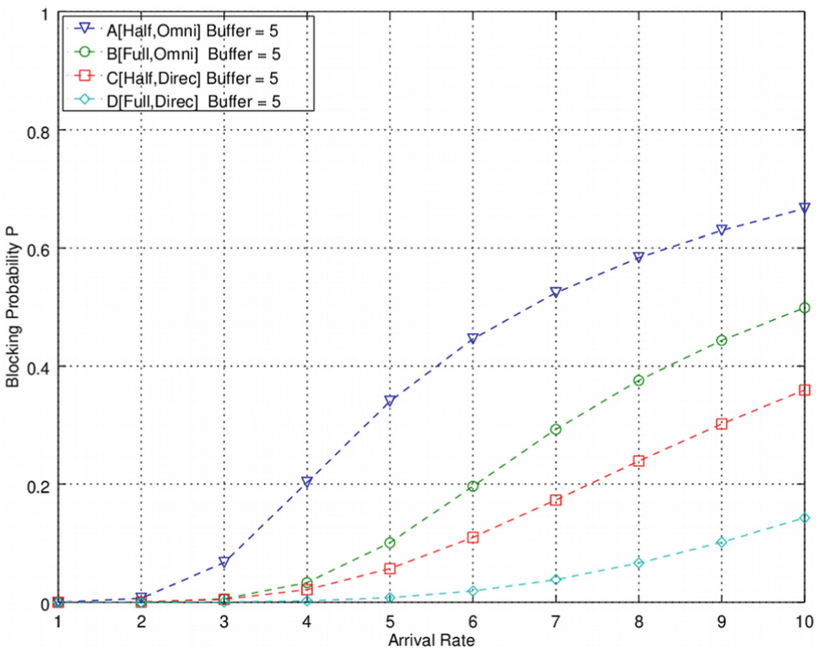

Fig. 4. Blocking probability with buffer 5.

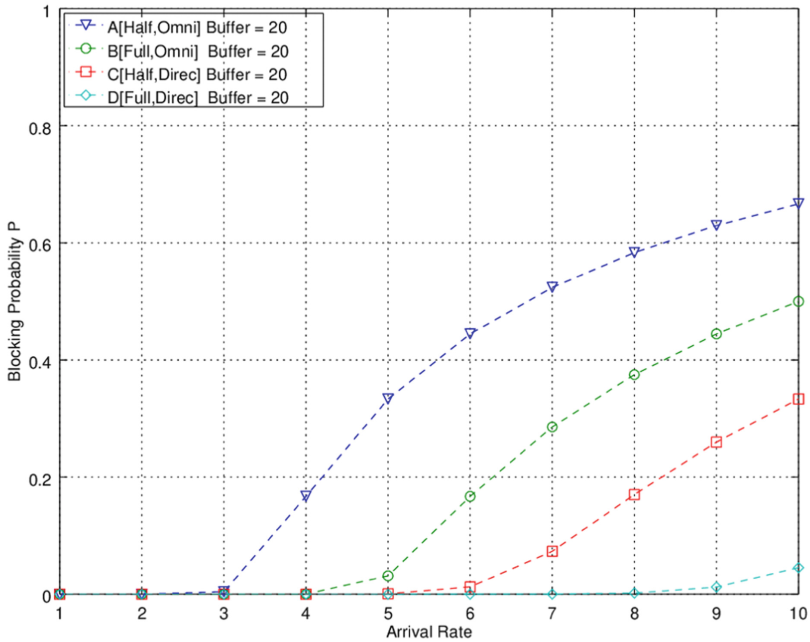

Fig. 5. Blocking probability with buffer 20.

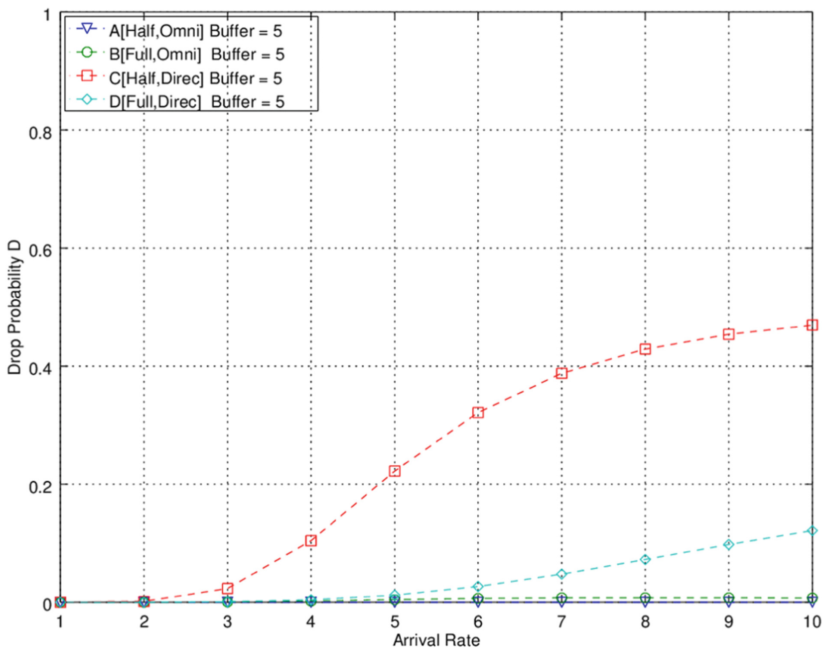

Fig. 6. Drop probability with buffer 5.

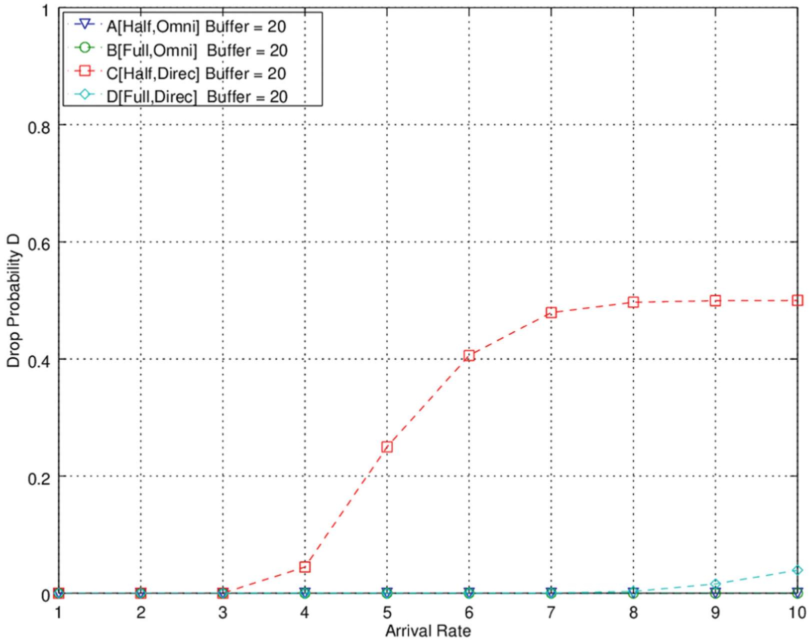

Fig. 7. Drop probability with buffer 20.

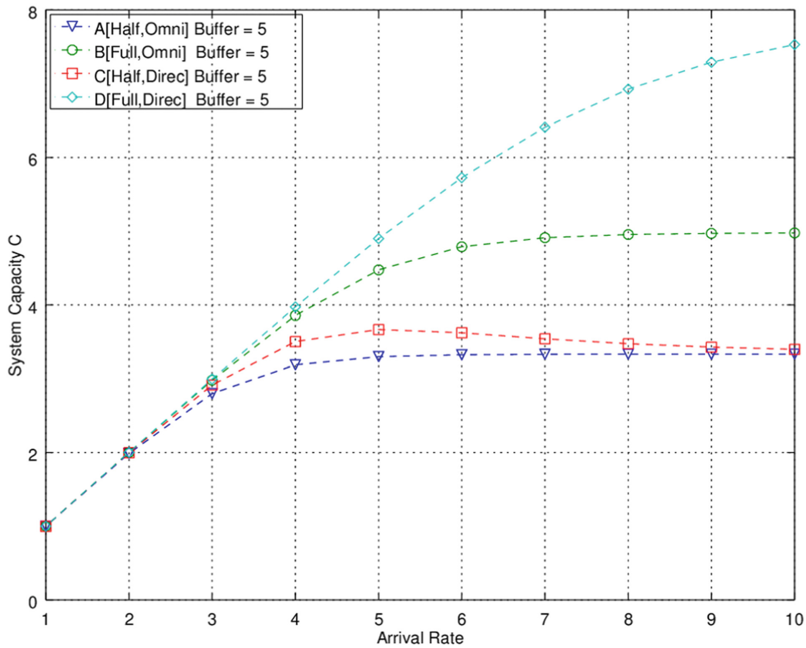

Fig. 8. Capacity with buffer 5.

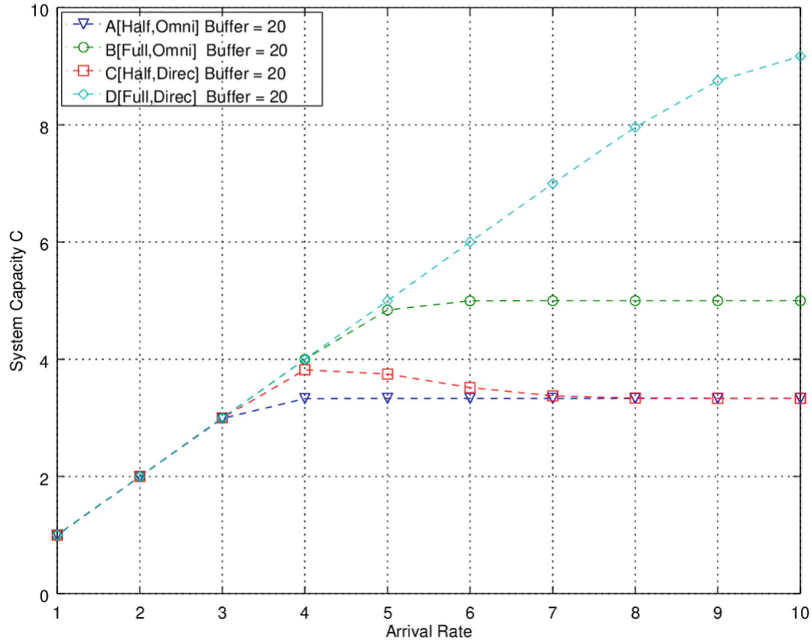

Fig. 9. Capacity with buffer 20.

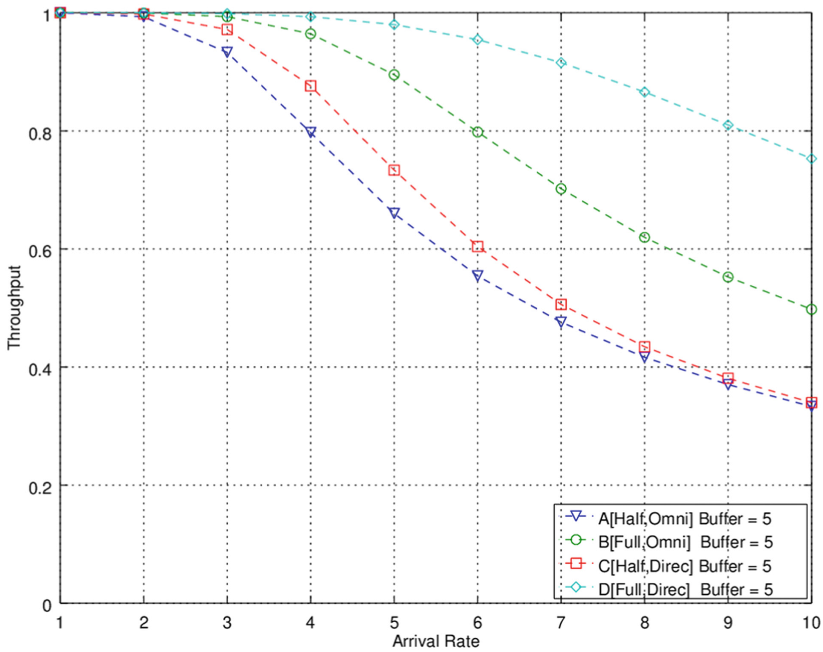

Fig. 10. Throughput with buffer 5.

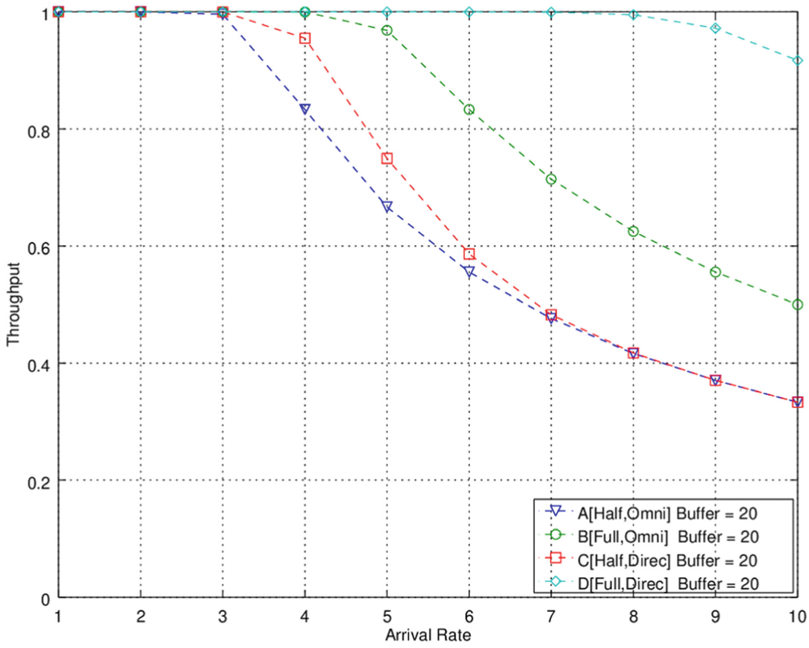

Fig. 11. Throughput with buffer 20.

6 Conclusion

In this paper, a Markovian analytical model to analyze the performance of a full-duplex wireless multi-hop network, combined with directional and omnidirectional antennas, was proposed. The model presented considered buffer in the nodes and is an extension of the model previously shown in [14], in which no buffer was considered in the nodes.

Several performance metrics were computed: blocking probability, capacity, drop probability and throughput. The influence of the buffer size in these parameters was investigated. With the addition of buffer, the blocking probability decrease for all modes, particularly for full duplex modes and modes with directional antennas; also, the drop probability off full duplex modes decrease significantly improving the capacity and throughput, for example, in mode D[Full,Direc] the block and drop probability decrease to almost 0, and the capacity and throughput improve to more than 300% of half duplex modes. In mode B[Full,Omni] the capacity and throughput improve up to 160% of half duplex modes.

When the utilization factor tends to 1 ($\lambda = 10$) modes A[Half,Omni] and B[Full,Omni] achieve a throughput of 1/3 and 1/2 indicated in [8] with only 5 buffer positions, but modes C[Half,Direc] and D[Full,Direc] did not achieve the throughput indicated in [8]. For mode C[half,Direc] the addition off buffer degrades its performance tending to a throughput of 1/3 when the utilization factor tends to 1 ($\lambda = 10$) and mode D[Full,Direc] achieve a throughput higher than 0.9 with 20 buffer positions when the utilization factor tends to 1 ($\lambda = 10$).

Based on the presented analysis it is possible to say that the performance of full duplex communication on the presented network, is at least 166% greater than half duplex communication and can get to more than 300% if used with directional antennas.

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