Modeling and Analysis of 5G Full Duplex Wireless Radios

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***Abstract*—In this paper, we propose an analytical Markovian model to compute the performance of a network composed by four radios in a line wireless multihop configuration, with data in only one way, considering four operation modes, with half duplex and full duplex communications and omnidirectional and directional antennas. This kind of network was previously presented in the literature, but its performance has been analyzed only based on simulation. We use the proposed Markovian model to compute the performance of the system considering that no buffer is available on the servers, based on the following performance metrics: throughput, capacity, block probability, drop probability, and the average number of packets in the network. We showed that in a system without buffer the performance of half duplex operation can be better than the performance of full duplex operation in terms of capacity and throughput.**

***Keywords*–5G; full duplex communications; performance analysis; Markovian models.**

I. Introduction

With the rapid growth of traffic demand in mobile communication networks, the future fifth generation (5G) mobile network is facing considerable challenges in spectral efficiency. 5G is expected to provide 1000-fold throughput of today's 4G [1].

To deal with it, several techniques have been recently developed. Among them, In-Band Full Duplex (IBFD) communications, which enable a device to transmit and receive simultaneously at the same frequency, can potentially double the spectral efficiency [1]. Until very recently, the concept of transmission and reception at the same time and frequency domain IBFD did not seem to be very promising, because of the Self-Interference (SI), which is generated by the transmitter on its own receiver [2]. Fortunately, with the recent advances in interference cancellation techniques [3]–[7], SI can be reduced to acceptable levels.

In order to perform IBFD, a new radio design has been developed. The new radio design differs mostly in the way the SI cancellation is implemented, and also in the number and types of antennas. For example, [8] proposed a radio design with two omnidirectional antennas and [9] proposed a radio design with two directional antennas and one omnidirectional antenna. In [9], Miura and Bandai analyzed the performance of the proposed scheme based only on simulation.

In this paper, we propose a first approximate Markovian analytical model to investigate the performance of the system proposed in [9], considering the same line wireless multihop network with data in only one way.

The remainder of this paper is organized as follows. Section II describes the considered radio design and the network. Section III presents the proposed Markovian model of the network. Section IV derives the performance metrics of interest. Section V presents the numerical results. Finally, the paper concludes in Section VI.

II. Network Scenario and Assumptions

We use the proposed network shown in Figure 1, reproduced from [9], to evaluate the radio design in a multihop network. In this network, each node can communicate with its neighbor node and can not do carrier sense from two separated nodes, such as Node S and Node 2 in the figure.

Half duplex nodes cannot transmit and receive simultaneously, while full duplex nodes can.

Omnidirectional antennas transmissions interfere with the anterior neighbor node; for example, Node 2 transmission interferes with Node 1 reception. In this case, only one operation is allowed for a successful transmission. Directional antennas do not have this problem.

We defined the following representations of the transmission possibilities, called operation modes:

- A[Half,Omni]: representation of a conventional node using one omnidirectional antenna to transmit and receive in a half duplex mode.
- B[Full,Omni]: representation of an IBFD node using two omnidirectional antennas, one to transmit and one to receive, as proposed in [8].
- D[Full,Direc]: representation of an IBFD node using two directional Transmission Antennas (TX), TX1 to transmit from 0 to π and TX2 from π to 2π, and one omnidirectional Reception Antenna (RX). TX1 and TX2 cannot be used simultaneously. Therefore, the node can operate in two modes: TX1-RX and TX2-RX. This mode was proposed in [9].
- C[Half,Direc]: representation of the same radio design as proposed in D[Full,Direc], but operating in a half duplex mode.

In Figure 1, we have the transmission processes in the network for each operation mode. The network operation

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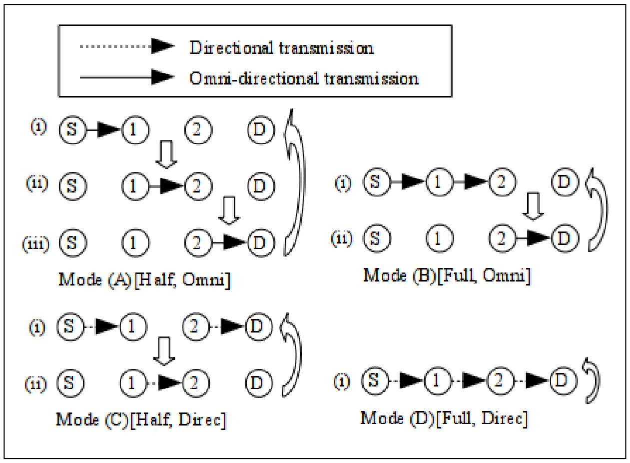

Figure 1. Transmission process for each operation mode [9].

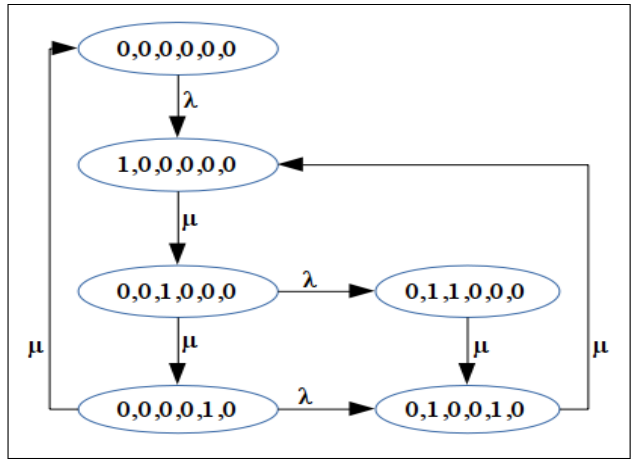

Figure 2. Mode A[Half,Omni] State Diagram.

depends on the type of nodes that it uses, so each network operates differently according to the type of nodes used.

The representation shows how each network should operate in order to achieve the maximum end-to-end throughput.

Figure 1 Mode A[Half,Omni]. In this mode, a transmission from S to D needs three steps to be completed: (i) transmission from S to 1; (ii) transmission from 1 to 2; and (iii) transmission from 2 to D. This is necessary to obtain the maximum end-to-end throughput, because only one node can transmit at a time to avoid interferences since they are not full duplex capable.

Figure 1 Mode B[Full,Omni]. In this case, nodes S and 1 can transmit simultaneously. However, the full duplex operation in node 2 can not be used, because a transmission from node 2 will interfere with the reception of node 1. Thus, in order to obtain the maximum throughput, the pattern (i) and (ii) must be repeated.

Figure 1 Mode C[Half,Direc]. Here, node 2 can transmit simultaneously with node S. However, node 1 can not transmit and receive at the same time, because of the half duplex operation. Thus, in order to obtain the maximum throughput, the pattern (i) and (ii) must be repeated.

Finally, Figure 1 Mode D[Full,Direc]. Here, nodes S, 1 and 2 can transmit simultaneously, due to the full duplex operation and the use of directional antennas.

For each one of these four operation modes, [9] has computed the maximum throughput and, based only on simulation, the throughput and the number of retransmissions as a function of the number of nodes.

The main contribution of this paper is to propose a Markovian model to investigate the performance of the system proposed in [9] in terms of throughput and other performance metrics.

III. MARKOVIAN MODEL

In this section, multidimensional Continuous-Time Markovian Chains (CTMCs) are used to model the system, one for each operation mode. The network consist of 4 nodes and three hops. The last node is the destination, so it does not transmit. Figure 2 shows the state diagram for mode A[Half, Omni]. The same approach is applied to the other modes in order to compute the desired performance metrics.

The transitions in the Markovian model occur due to arrival or departure of a packet in a given node. The arrival processes follow a Poisson distribution with average value λ packets/s; the service time follows an exponential distribution with mean value $1/\mu$ seconds, resulting in a maximum departure rate or service rate equal to μ packets/s.

Finding and solving a Markovian model to evaluate the performance of the presented systems is a complex task. Thus, in order to simplify the model, we considered a system without queue. This assumption could be unrealistic for most applications. However, the results and conclusions obtained using this simplified model is useful to give us some insights about the comparative performance of the systems. A new model, considering a more realistic system, is under construction.

Let $x = \{i, wi, j, wj, k, wk\}$ be the general state representation of the system, where i indicates a transmission in the first hop, wi indicates a packet waiting in the first node, j indicates a transmission in the second hop, wj indicates a packet waiting in the second node, k indicates a transmission in the third hop, and wk indicates a packet waiting in the third node. For example, $x = \{0, 0, 1, 0, 0, 0\}$ represents a state where there is a transmission in the second hop and no packets waiting in the nodes.

Only one packet can be on a server at any given moment. The packet can be in transmission in the proper hop or waiting for transmission. Thus, we have: $i + wi \leq 1; j + wj \leq 1$; and $k + wk \leq 1$. The set of generic feasible states is denoted as $S = \{x|0 \leq i, wi, j, wj, k, wk \leq 1; 0 \leq i + wi \leq 1; 0 \leq j + wj \leq 1; 0 \leq k + wk \leq 1\}$. More specific sets of feasible states for each mode are presented in Tables I to IV.

To simplify the notation, we considered that the subset $\{$hop, node$\}$ denotes a server, so we have three servers: server i $\{i, wi\}$, server j $\{j, wj\}$ and server k $\{k, wk\}$. Only one packet can be in a server at a moment, the packet can be in a state of being transmitted $\{1, 0\}$ or waiting for transmission $\{0, 1\}$; i.e., if $i = 1, wi = 0$ and if $wi = 1, i = 0$, meaning $i + wi$ will never be greater than 1. The same is valid for all other servers.

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

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which are given as

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

where π is the steady state probability vector and Q denotes the transition rate matrix. The detailed transition rates and conditions for each mode can be found in Tables I to IV below.

The total transition rate from state i to state j, namely q_{ij} is the summation of transition rates from state i to state j considering all possible transitions. Once we determine the q_{ij} for all $i, j(i \neq j) \in S$, the diagonal elements in Q, i.e., q_{ii} $i \in S$ are found as

$$q_{ii} = - \sum_{j \in S, j \neq i} q_{ij}. \quad (2)$$

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

IV. Performance Metrics

To analyze the performance of the system we considered the following metrics: blocking probability, drop probability, capacity, throughput and the average number of packets in the network.

A. Blocking Probability

The blocking probability, denoted by P, is defined as the probability of the network being in a state where there is a transmission or a packet waiting in the server i and, therefore, no packet can enter the network. This is computed by:

$$P = \sum_{x \in S} \pi(x), \; if \;\; i + wi = 1. \quad (3)$$

where P is equal to the summation of all states probabilities where $i + wi = 1$; i.e., there is a packet being transmitted or waiting in the server i.

B. Capacity

The capacity, denoted by C, is defined as the average number of successful transmissions per time unit. This is computed by:

$$C = \sum_{x \in S} \pi(x)\mu, \; if \;\; k = 1. \quad (4)$$

where $k = 1$ represents a transmission from server k to destination node, that is a successful transmission, and μ represents the maximum departure rate in server k.

C. Drop Probability

The drop probability, denoted by D, is defined as the probability that once a packet enters the network, it doesn't complete the transmission with success, meaning it is dropped. This is computed by:

$$D = 1 - ST. \quad (5)$$

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

$$ST = \frac{C}{\lambda(1 - P)}. \quad (6)$$

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

D. Throughput

The throughput, denoted by Th, is defined as the relation between the successful transmission rate by the total arrival rate in the network and can be computed by:

$$Th = \frac{C}{\lambda}. \quad (7)$$

E. Average Number of Packets in the System

Let $N(x)$ represent the sum $i + wi + j + wj + k + wk$ in each state. The average number of packets in the system can be computed by:

$$Eq = \sum_{x \in S} \pi(x) N(x). \quad (8)$$

V. Numerical Results

In this section, we present the performance analysis of the four modes described in Section II. All computation was done in MatLab using the analytical model proposed in this paper. To compute the performance metrics, we set the arrival rate λ varying from 1 to 10 packets/s and the maximum departure rate μ equal to 10 packets/s.

The goal of this paper is to compare the performance of half and full duplex systems. Thus, the channel is considered error free. In addition, it is important to note that the performance parameters used in the paper are normalized and, therefore, depend only on the utilization factor (λ/μ) and not on the actual data rate in the channel.

Figure 3 illustrates that the mode A[Half,Omni] has the greater blocking probability because only one server can transmit at a time and also because, while a packet does not reach the end of the network, no other packet can enter the network. The mode D[Full,Direc] has the lowest block probability due to the fact that a new packet can enter into the network at any moment (if server i is empty). The B[Full,Omni] and C[Half,Direc] modes have almost the same blocking probability.

In Figure 4, we can observe that the mode A[Half,Omni] has no drop probability. This is because only one packet can be transmitted in the network at a time. The B[Full,Omni] and D[Full,Direc] modes have the greater drop probability because they use full duplex transmission, meaning a server can receive and transmit at the same time, but a packet is dropped if it is received when the server is still transmitting, due to the absence of queue positions in the servers.

Figure 5 and Figure 6 show that mode C[Half,Direc] has the best performance in terms of capacity and throughput. This result is due to the high drop probability of mode D, compared with mode C. Finally, Figure 7 shows the average number of packets in the system. Again, in this case, mode D[Full,Direc] has the best performance.

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TABLE I. TRANSITION RATES AND CONDITIONS FOR MODE A[HALF, OMNI]
$S = \{x|0 \le i, wi, j, k \le 1; wj = 0; wk = 0; 0 \le i + wi \le 1; 0 \le i + j + k \le 1; \}$

Activity	Dest. State	Trans. Rate	Condition
Packet arrival (PA). No transmission in all network.	$i+1, wi, j, wj, k, wk$	λ	$i = 0; wi = 0; j = 0; wj = 0; k = 0; wk = 0.$
Transmission in server j or k. PA and goes to Server i waiting position.	$i, wi+1, j, wj, k, wk$	λ	$i = 0; bi = 0; j + k = 1; bj = 0; wk = 0$.
Transmission from server i to j.	$i-1, wi, j+1, wj, k, wk$	μ	$i = 1; wi = 0; j = 0; wj = 0; k = 0, wk = 0.$
Transmission from server j to k.	$i, wi, j-1, wj, k+1, wk$	μ	$i = 0; 0 \le wi \le 1; j = 1; wj = 0; k = 0; wk = 0$.
Transmission from server k to destination.	$i, wi, j, wj, k-1, wk$	μ	$i = 0; wi = 0; j = 0; wj = 0; k = 1; wk = 0$.
Transmission from server k to destination. Packet in server i waiting position is moved to transmission position.	$i+1, wi-1, j, wj, k-1, wk$	μ	$i = 0; wi = 1; j = 0; wj = 0; k = 1; wk = 0$.

TABLE II. TRANSITION RATES AND CONDITIONS FOR MODE B[FULL, OMNI]
$S = \{x|0 \le i, wi, j, k, wk \le 1; wj = 0; 0 \le i + wi \le 1; 0 \le k + wk \le 1; 0 \le i + j + k \le 2; 0 \le wi + wk \le 1\}$

Activity	Dest. State	Trans. Rate	Condition
Packet arrival (PA).	$i+1, wi, j, wj, k, wk$	λ	$i = 0; wi = 0; 0 \le j \le 1; wj = 0; k = 0; wk = 0$
Transmission in server k. PA and goes to Server i waiting position.	$i, wi+1, j, wj, k, wk$	λ	$i = 0; wi = 0; 0 \le j \le 1; wj = 0; k = 1; wk = 0$
Transmission from server i to j.	$i-1, wi, j+1, wj, k, wk$	μ	$i = 1; wi = 0; j = 0; wj = 0; k = 0; wk = 0$
Transmission from server j to k.	$i, wi, j-1, wj, k+1, wk$	μ	$i = 0; wi = 0; j = 1; wj = 0; k = 0; wk = 0$
Transmission from server k to destination.	$i, wi, j, wj, k-1, wk$	μ	$i = 0; wi = 0; 0 \le j \le 1; wj = 0; k = 1; wk = 0$
Transmission from server j to server k waiting position, because server i is also transmitting.	$i, wi, j-1, wj, k, wk+1$	μ	$i = 1; wi = 0; j = 1; wj = 0; k = 0; wk = 0$
Blocked transmission from server i to j, when both servers are transmitting and server i is the first to finish.	$i-1, wi, j, wj, k, wk$	μ	$i = 1; wi = 0; j = 1; wj = 0; k = 0; wk = 0$
Transmission from server k to destination. Packet in server i waiting position is moved to transmission position.	$i+1, wi-1, j, wj, k-1, wk$	μ	$i = 0; wi = 1; 0 \le j \le 1; wj = 0; k = 1; wk = 0$
Transmission from server i to j. Packet in server k waiting position is moved to transmission position.	$i-1, wi, j+1, wj, k+1, wk-1$	μ	$i = 1; wi = 0; j = 0; wj = 0; k = 0; wk = 1$
Blocked transmission from server j to k, when both servers are transmitting and server j is the first to finish.	$i, wi, j-1, wj, k, wk$	μ	$i = 0; 0 \le wi \le 1; j = 1; wj = 0; k = 1; wk = 0$

TABLE III. TRANSITION RATES AND CONDITIONS FOR MODE C[HALF, DIREC]
$S = \{x|0 \le i, wi, j, wj, k \le 1; wk = 0; 0 \le i + wi \le 1; 0 \le j + wj \le 1; 0 \le i + j + k \le 2; 0 \le wi + wj \le 1\}$

Activity	Dest. State	Trans. Rate	Condition
Packet arrival (PA).	$i+1, wi, j, wj, k, wk$	λ	$i = 0; wi = 0; j = 0; 0 \le wj, k \le 1; wk = 0$
Transmission in server j. PA and goes to Server i waiting position.	$i, wi+1, j, wj, k, wk$	λ	$i = 0; wi = 0; j = 1; wj = 0; k = 0; wk = 0$
Transmission from server i to j.	$i-1, wi, j+1, wj, k, wk$	μ	$i = 1; wi = 0; j = 0; wj = 0; k = 0; wk = 0$
Transmission from server j to k.	$i, wi, j-1, wj, k+1, wk$	μ	$i = 0; wi = 0; j = 1; wj = 0; k = 0; wk = 0$
Transmission from server j to k. Packet in server i waiting position is moved to transmission position.	$i+1, wi-1, j-1, wj, k+1, wk$	μ	$i = 0; wi = 1; j = 1; wj = 0; k = 0; wk = 0$
Blocked transmission from server i to j, because server j waiting position is occupied.	$i-1, wi, j, wj, k, wk$	μ	$i = 1; wi = 0; j = 0; wj = 1; k = 1; wk = 0$
Transmission from server k to destination.	$i, wi, j, wj, k-1, wk$	μ	$0 \le i \le 1; wi = 0; j = 0; wj = 0; k = 1; wk = 0$
Transmission from server k to destination. Server j has a packet waiting but can not transmit because server i is also transmitting.	$i, wi, j, wj, k-1, wk$	μ	$i = 1; wi = 0; j = 0; wj = 1; k = 1; wk = 0$
Transmission from server i to server j waiting position, because server k is also transmitting.	$i-1, wi, j, wj+1, k, wk$	μ	$i = 1; wi = 0; j = 0; wj = 0; k = 1; wk = 0$
Transmission from server k to destination. Packet in server j waiting position is moved to transmission position.	$i, wi, j+1, wj-1, k-1, wk$	μ	$i = 0; wi = 0; j = 0; wj = 1; k = 1; wk = 0$
Blocked transmission from server i to j, because server j waiting position is occupied. Packet on server j waiting position is moved to transmission position.	$i-1, wi, j+1, wj-1, k, wk$	μ	$i = 1; wi = 0; j = 0; wj = 1; k = 0; wk = 0$

TABLE IV. TRANSITION RATES AND CONDITIONS FOR MODE D[FULL, DIREC]
$S = \{x|0 \le i, j, k \le 1; wi = 0; wj = 0; wk = 0; 0 \le i + j + k \le 3\}$

Activity	Dest. State	Trans. Rate	Condition
Packet arrival (PA).	$i+1, wi, j, wj, k, wk$	λ	$i = 0; wi = 0; 0 \le j \le 1; wj = 0; 0 \le k \le 1; wk = 0$
Transmission from server i to j.	$i-1, wi, j+1, wj, k, wk$	μ	$i = 1; wi = 0; j = 0; wj = 0; 0 \le k \le 1; wk = 0$
Transmission from server j to k.	$i, wi, j-1, wj, k+1, wk$	μ	$0 \le i \le 1; wi = 0; j = 1; wj = 0; k = 0; wk = 0$
Blocked transmission from server i to j, when both servers are transmitting and server i is the first to finish.	$i-1, wi, j, wj, k, wk$	μ	$i = 1; wi = 0; j = 1; wj = 0; 0 \le k \le 1; wk = 0$
Transmission from server k to destination.	$i, wi, j, wj, k-1, wk$	μ	$0 \le i \le 1; wi = 0; 0 \le j \le 1; wj = 0; k = 1; wk = 0$
Blocked transmission from server j to k, when both servers are transmitting and server j is the first to finish.	$i, wi, j-1, wj, k, wk$	μ	$0 \le i \le 1; wi = 0; j = 1; wj = 0; k = 1; wk = 0$

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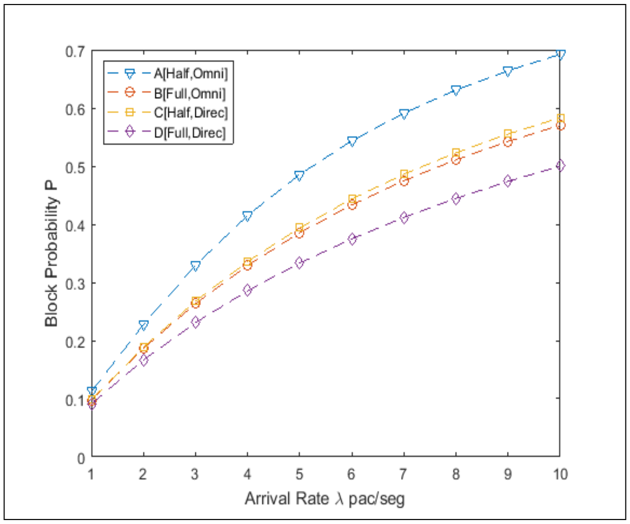

Figure 3. Blocking Probability.

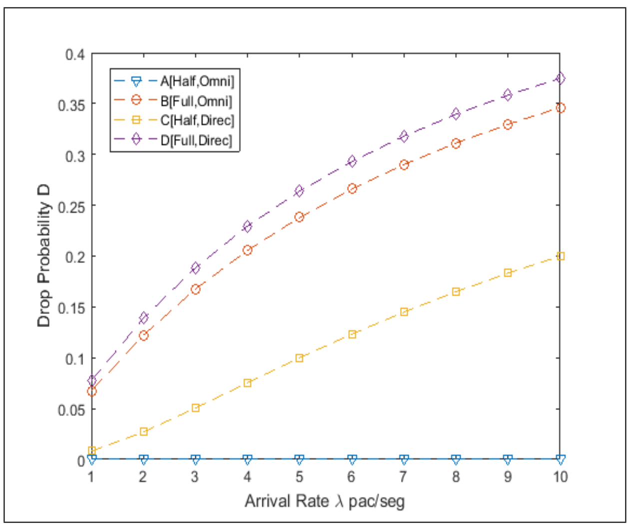

Figure 4. Drop Probability.

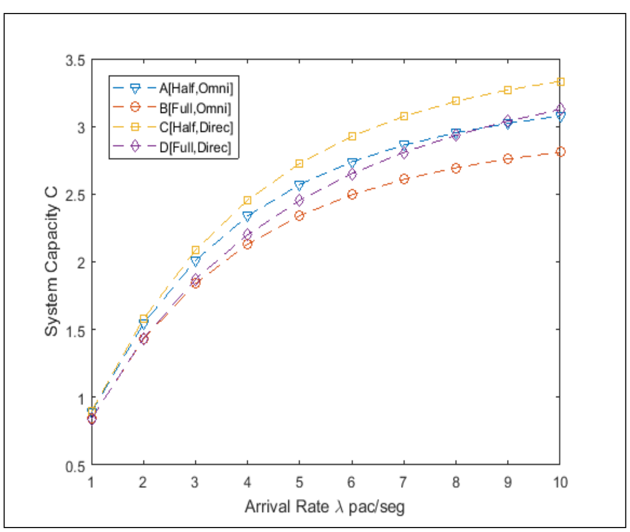

Figure 5. Capacity.

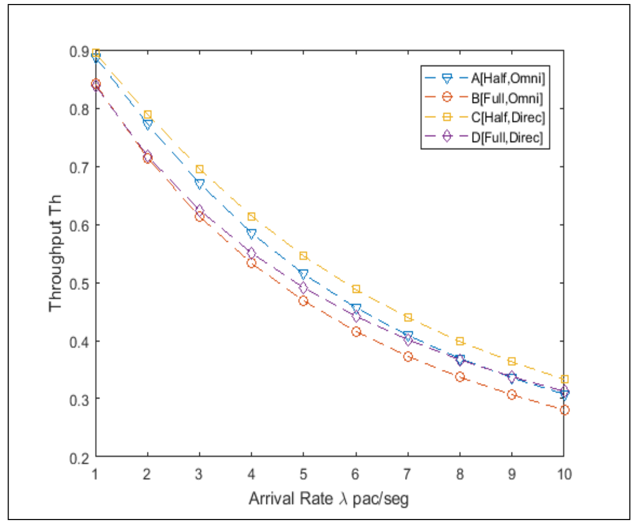

Figure 6. Throughput.

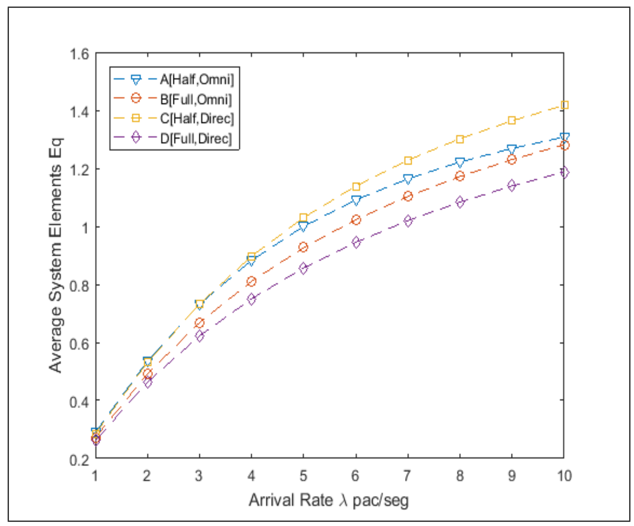

Figure 7. Average Number of packets in the System.

VI. CONCLUSION

In this paper, we presented a first approximate Markovian analytical model to evaluate the performance of four operation modes in a line wireless multihop network, considering half and full duplex operations and omnidirectional and directional antennas, including a new IBFD mode proposed in [9], where this mode was analyzed based only on simulation.

We considered a scenario with no buffer (no queue in the servers). In this scenario, we conclude that the use of full duplex operation with directional antennas mode has the best performance in terms of blocking probability and the average number of packets in the system and the mode using half duplex operation with directional antennas has the best performance in terms of capacity and throughput.

For future works, we intend to analyze the performance of a system considering buffer (queues) in the servers.

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