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FDDS-MAC: Enhancing spectrum usage on full-duplex communications in 5G mobile wireless networks

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***Abstract*—Full-duplex communications emerged as an alternative to improve throughput and spectrum usage on the forthcoming fifth-generation (5G) mobile networks. However, the existing medium access control schemes for full-duplex lack mechanisms designed to enhance spectrum usage. In this context, this work proposes FDDS-MAC, which is a full-duplex communication scheme tailored to improve spectrum usage. FDDS-MAC introduces a decision phase where the receiver with a higher probability of having data back to the sender is prioritized in the sender's packet queue. Thus, FDDS-MAC is able to perform packet rescheduling to boost throughput and spectrum usage. Numerical results show that FDDS-MAC has a positive impact over full-duplex communications, achieving throughput up to 40% higher than a state-of-art full-duplex scheme.**

***Index Terms*—5G mobile wireless networks, Medium access control, Full-duplex communications, Spectrum usage.**

I. Introduction

Recent innovations in the field of communication are designed to cope with growing bandwidth demand and with the high density of devices on a mobile network [1]. The fifth-generation (5G) mobile wireless networks are target of many studies in a wide range of areas to support the higher data rates and user mobility with reduced latency [2]. Also, 5G is designed to be able to deal with 1000-fold increase of capacity [1]. Furthermore, 5G networks are expected to address heterogeneous devices such as vehicles, machines and sensors, which is paramount in the context of internet of things and vehicular networks [1]. As the requirements regarding to density of devices and bandwidth for 5G networks are rigorous, the development of techniques that enhance spectrum usage to meet those demands is mandatory.

Full-duplex communication, that is, transmitting and receiving simultaneously over the same frequency band were considered to be infeasible due to the harmful effects of self-interference [3]. Recently, many self-interference cancellation techniques arose and claim to be able to mitigate self-interference almost totally [3] [4] [5]. Therefore, the development of these self-interference cancelling techniques turned full-duplex communication feasible. Moreover, full-duplex antennas have theoretical advantages over its half-duplex counter parts regarding to throughput and spectrum usage [6]. To exploit these advantages, efficient medium access control (MAC) schemes are needed. These MAC schemes may be designed considering the characteristics of a full-duplex communication, once MAC protocols are necessary to provide an efficient use of the network resources.

Recently, the FD-MAC [5] was proposed as an alternative to support requests to be processed in full-duplex communication. FD-MAC relies on some of the basic mechanisms of the IEEE 802.11 [7] standard, such as the use of exponential backoff algorithm, virtual carrier sensing and the use of handshake frames to realize channel reservation. FD-MAC is able to provide throughput gain over IEEE 802.11 half-duplex version (HD-MAC), however, it does not introduces any mechanism to enhance spectrum usage. In fact, FD-MAC throughput gain comes primarily from its power allocation policy and the use of full-duplex communication. However, FD-MAC does not have any mechanism to enhance spectrum usage, such as packet aggregation or a packet rescheduling policy, for example.

The main contribution of our work is Full-Duplex Dynamic Scheduling MAC (FDDS-MAC) scheme that is tailored for full-duplex communication with the aim of improving spectrum usage. To this end, FDDS-MAC introduces a prior decision phase before channel reservation to select a destination node that will improve spectrum usage. Note that a proper packet rescheduling policy may enhance spectrum usage by increasing the probability of a communication where the sender and the receiver have data payload to transmit each other. FDDS-MAC decision phase is done in an efficient way, once it does not constitute a severe overhead to network latency as further discussed. Therefore, FDDS-MAC can provide a higher throughput and a better spectrum usage than FD-MAC and the traditional schemes. The results point that this improvement surpasses 40%.

The rest of this paper is organized as follows: Section II presents an overview about related works on full-duplex communications and describes some important characteristics of these communication; Section III explains FDDS-MAC thus showing its phases and the theoretical background that makes FDDS-MAC to enhance spectrum usage; Section IV presents the evaluations held in this work that compare FDDS-MAC with traditional schemes; Section V concludes this work and points directions to further investigation.

II. Related Work

One of the great challenges to overcome when using full-duplex antennas is the self-interference. In this way, several techniques were designed to almost cancel self-interference losses as presented by [3] and [5]. In this context, FD-MAC [5] arose proposing a MAC scheme to support full-duplex communications. FD-MAC considers the use of a three-way handshake with the aid of Request to Send (RTS) and Full-duplex Clear to Send (FCTS) frames to reserve the channel and avoid collisions to be caused by neighbor nodes. Thus, FD-MAC is able to realize full-duplex communications properly, providing gains when compared with half-duplex MAC scheme of IEEE 802.11 [7].

A cooperative communication approach is proposed by Janus protocol [8]. This protocol is a centralized receiver-initiated protocol that aims to maximize throughput of full-duplex communications by performing a scheduling that leverage simultaneous transmissions. The protocol presented in [8] is tailored for Access Points (AP) architecture since it is a centralized protocol that takes advantage from the traffic characteristics of this architecture. Also, this protocol reschedules ACK packets and adapts data rate transmission in order to maximize simultaneous transmissions [8]. Packet rescheduling is also employed by several works in many other contexts and is possible to realize on MAC layer, as described in [9]. Janus resorts to pulse and tone signals to collect information of neighbor nodes. Pulse and tone signals are commonly used to point particular network conditions [9]. Moreover, pulse and tone signals are a fast alternative to frames, since those signals can be decoded in 5μs [10]. Thus, our work terms the time elapsed to decode a tone signal as T_{sync} and considers it to be equal to 5μs. Although pulse and tone signals have no MAC header, some information can be encoded in these signals with a negligible probability of failure. It is possible to decode from a signal the source of it and its destination as described in [9]. Also, the transmission duration of this signal may encode the duration of the whole communication as pointed in [9]. So, our work considers these characteristics as valid in the presented evaluations. Also, it is considered that packet rescheduling on MAC layer is feasible and that the communication are done in omnidirectional mode, since this is the model commonly addressed in related works such as [5] and [8]. Ended the related work explanation, the proposed MAC scheme for full-duplex communications will be presented next.

III. MAC for enhancing spectrum usage in full-duplex communications

This section presents the proposed MAC scheme tailored for full-duplex communications. This MAC scheme is named Full-Duplex Dynamic Scheduling MAC (FDDS-MAC) and aims to maximize the usage of the channel for full-duplex communications. To this end, FDDS-MAC uses pulse/tone signals to query neighbor nodes to find out which of them has data packets bounded to the sender. Based on this information, FDDS-MAC chooses the neighbor that maximizes the usage of the channel for full-duplex communications. In this way, FDDS-MAC is expected to enhance network throughput and improve spectrum usage with a proper scheduling of the communications. FDDS-MAC is composed by three phases: decision, synchronization and transmission. These phases will be described in detail next.

A. Decision

The first phase of FDDS-MAC consists of choosing which of the sender's neighbor will be the destination node. This choice relies on criteria that maximize the spectrum usage. Let S be the sender node. Also, let $\mathcal{X} = \{B, C, D, E\}$ denotes the candidate destination nodes to which S has packets in its queue to send. Clearly, if $|\mathcal{X}| = 1$, node S has packets only to a single destination and the decision phase becomes trivial. Suppose that $|\mathcal{X}| > 1$. In this case, node S may select the destination node R ($R \in \mathcal{X}$) that maximizes channel usage. To that end, it is considered that a rescheduling of the packets in node S's queue uses an approach similar to that reported in [9], where multiple frames can be handled at MAC layer. The main difference from FDDS-MAC to that approach is related to the criteria used to reschedule the frames. That approach seeks on spacial reuse for directional antennas. In turn, FDDS-MAC aims to boost full-duplex communications. FDDS-MAC's decision phase is based on the fact that a node that has data packets bounded to the sender is more interesting to establish a communication with than a node that does not have. In this way, it is possible to better take advantage from the full-duplex communications because when both source and destination nodes have data packets one to another, a better spectrum usage is achieved. Note that the referred rescheduling does not lead to starvation, since every node contends to be the sender through exponential backoff algorithm in a similar way to the proposed by IEEE 802.11 [7].

As an example of the decision phase, consider the scenario depicted in Figure 1. At the beginning, node A has packets to send to nodes B, C, D and E ordered in node A's MAC queue, as illustrated in Figure 1. So, node A send an RTSM (Request to Send Multi) to t ($1 \leq t \leq |\mathcal{X}|$) of the nodes. In this example, consider that $t = 3$, so that node A sent an RTSM packet to nodes B, C and D. RTSM packet has the same MAC header than RTS with the addition of $t - 1$ destination fields. As nodes B, C and D receive RTSM, they will answer to node A with a tone-d (tone decision) signal if they have data to send to node A. In this example, nodes C and D have data to node A, thus, they will reply with a tone-d signal to node A. Then, node A decides to transmit to one of the nodes that replied to it. In this case, it is considered that node C was chosen since it was higher ranked in the node A's MAC queue, as depicted in Figure 1. Some considerations about tone-d (td) are needed to a better explanation of FDDS-MAC. The reply sent from nodes C and D has duration of T_{sync} and are not overlapped, as presented in Figure 1. Hence,

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if the t-th destination node in RTSM will transmit a tone-d, it needs to wait for $(t-1)\cdot T_{sync}$ time to start transmitting tone-d. Node A will move to next phase (synchronization phase) when it identifies a tone-d signal, that is, node A does not need to wait to know the reply of all the t nodes. It is required only one reply with a tone-d to proceed to the next phase. Otherwise, if none of the nodes reply, node A would choose the first node of the MAC queue as its destination and proceed to next phase. Also, if a node receives a pulse signal which is used on the the next phase (synchronization phase) of the scheme, it immediately stops its decision phase, since it knows another node was already chosen in this case. Note that this overlap between pulse and tone-d is possible since these signals are sent in the same mini-slot, as depicted in Figure 1. Therefore, the total time elapsed sending tone-d signals in decision phase (T_{td}) can be defined as:

$$T_{td} = (1-p)^{t-1} \cdot t \cdot T_{sync} + \sum_{i=1}^{t-1} (1-p)^{i-1} \cdot p \cdot i \cdot T_{sync}, \quad (1)$$

where p is the probability p of a node has data packet bounded to the sender node and T_{sync} denotes the time elapsed to decode a tone signal.

B. Synchronization

The synchronization phase consists of performing the channel reservation for a communication between sender node (S) and receiver node (R). This channel reservation mainly relies on advertising the potential contending nodes about the communication that is about to be initiated. Channel reservation causes the neighbors of nodes S and R to update their network allocation vector (NAV), thus preventing collisions. FDDS-MAC performs channel reservation in an innovative way using pulse and tone signals instead of the frames RTS/FCTS used by FD-MAC. The information necessary to realize a successful channel reservation with proper NAV update are: Duration of the communication and identification of the communication pair (S, R). Regarding to node S's identification, it is explicitly defined in RTSM packet sent previously in decision phase. RTSM packet also contains duration information. In turn, node R's identification is done in synchronization phase with the aid of the pulse signal sent from S and bounded to R. A tone confirm (tone-c) with the communication duration encoded is replied by R towards S. Any neighbor of node S can update its NAV with the duration contained in RTSM packet. The only neighbor of node S that engages in communication is node R which is alerted by pulse signal that he was the chosen destination. In a similar way, any neighbor of node R is aware of the duration communication encoded in tone-c signal, that is, every neighbor of node R can update its NAV properly by overhearing tone-c signal. For more information about the encoding of duration and destination on pulse and tone signals, readers are directed to [9] and the references therein, since FDDS-MAC assumes the employment of a similar pulse/tone encoding mechanism.

Let P_{sz}^{IJ} denotes the payload size of the data transmitted from node I to J. In FDDS-MAC operation, $P_{sz}^{SR} \geq P_{sz}^{RS}$

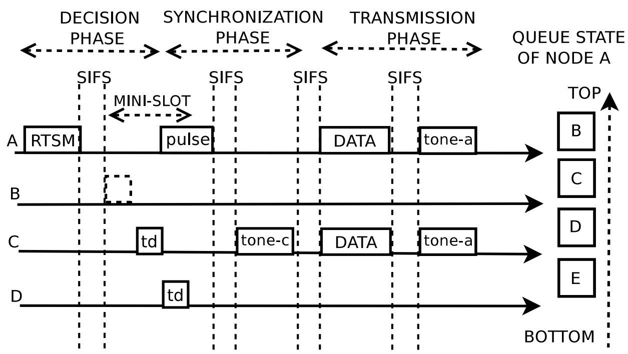

Figure 1. Example of FDDS-MAC operation.

always holds. That is, FDDS-MAC requires that the packet from R to S must be at most of the size of the packet from S to R, where S is the sender that initiates the communication sending an RTSM.

An instance of synchronization phase is depicted in Figure 1. In this case, the sender is node A and the selected destination was node C in the previous phase of FDDS-MAC. Hence, node A sends pulse signal to node C that replies with a tone-c (tone confirm) to node A confirming the duration of this communication. Neighboring nodes (*i.e.*, B, D, E) that overhear pulse and tone-c signals set its NAV properly and defer its communications in order to prevent collisions.

C. Transmission

This is the last phase of the proposed scheme. In this phase, both sender and receiver exchange DATA packets and tone-a (Tone Acknowledgment) signals. Tone-a signals replace ACK packets to confirm the receipt of DATA packets. This replacement is motivated by the fact that tone-a signal can be transmitted in a fraction of time wasted with ACK packet. Also, tone-a provides the necessary information to a proper acknowledgment operation. It is important to highlight that the proposed MAC scheme is able to identify if a signal is a pulse, tone-a, tone-c or tone-d, once these signals can be differentiated either by phase, amplitude or signal [11].

To exemplify this phase, in Figure 1, node A sends DATA packet to node C that replies with tone-a signal. As in this case node C also sends DATA to node A, node A also replies to node C with tone-a signal. After the transmission, the communication ends, and the nodes may random generate its backoff time for the next communication. This concludes the explanation of FDDS-MAC operation. Next, it will be presented the theoretical background of FDDS-MAC performance when compared with a state of art full-duplex protocol, that is, FD-MAC [5].

D. Theoretical Background

In order to achieve a more accurate estimation of throughput under heavy traffic conditions, many analytical models aroused [12] [13]. These models address the backoff time

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growth due to collisions, since these models consider that the network is saturated, that is, every node always has packets to transmit, thus contending for the channel. When this condition is considered, the throughput will be referred as "channel throughput". The Bianchi's model [12] is a building block of many other network analytical models [13] and widely used to assess protocols. Many other authors resort to this model to do their analytical performance evaluations [14] [15] [16] in half-duplex communications. Simple modifications to the model can be done to extend it to the full-duplex communication scenario, as further discussed. Therefore, Bianchi's model can be used to compare network performance under saturated traffic addressing MAC techniques tailored for half-duplex or full-duplex communications. The Bianchi's model mathematical definition of channel throughput (S) is [12]:

$$S = \frac{(p_s \cdot p_{tr} \cdot P_{sz})}{\overline{T}_{slot}}, \tag{2}$$

where

$$\overline{T}_{slot} = T_{slot} \cdot (1 - p_{tr}) + p_{tr} \cdot p_s \cdot T_s + p_{tr} \cdot (1 - p_s) \cdot T_c,$$

T_{slot} denotes the size of the time slot, T_s denotes the total transmission time elapsed in a successful communication, T_c denotes the time elapsed in an RTS collision, p_s denotes the probability of a transmission during a time slot be successful and p_{tr} denotes the probability of at least one station transmit during a time slot. These probabilities are related to the parameters of exponential backoff algorithm, such as minimum and maximum backoff window size. For more details on the calculations of p_s and p_{tr}, the readers are directed to [12]. There is only a change needed to Eq. (2) to address full-duplex antennas communication. When a successful communication occurs, the total payload (P_{sz}) must be the sum of the payloads of both directions of a bidirectional data communication. This change is due to the fact that data can be send from A to B and from B to A simultaneously in a same successful communication, as depicted in Figure 1. Therefore, for all results presented in this paper the channel throughput is considered as follows:

$$S = (p_s \cdot p_{tr} \cdot \overline{P}_{sz})/\overline{T}_{slot}, \tag{3}$$

$$\overline{P}_{sz} = P_{sz}^{AB} + P_{sz}^{BA}. \tag{4}$$

For this analysis, it will be considered that node A always has data to send to B, once node A starts the communication (Figure 1). Moreover, it will be considered that node B has data to send to A with probability p. Also, it is considered that the packet size is equal for both payloads if a bidirectional communication occurs ($P_{sz}^{AB} = P_{sz}^{BA}$). Therefore, for traditional full-duplex schemes:

$$\overline{P}_{sz} = P_{sz}^{AB} + p \cdot P_{sz}^{BA} = (1 + p) \cdot P_{sz}^{AB}. \tag{5}$$

In turn, the proposed scheme has a different $\overline{P}_{sz}$ value since it tries to establish a bidirectional link with one of the t nodes targeted by RTSM packet. So, for the proposed scheme:

$$\overline{P}_{sz} = P_{sz}^{AB} + (1-(1-p)^t) \cdot P_{sz}^{BA} = (2-(1-p)^t) \cdot P_{sz}^{AB}. \tag{6}$$

In order to provide a comparison of proposed scheme against FD-MAC, the quotient $\eta = S_m/S$ needs to be evaluated. For this quotient, S_m denotes the channel throughput calculated with the proposed technique parameters and S is calculated with FD-MAC parameters. In our analysis we consider $t = 3$, that is, RTSM is targeted to three nodes. Moreover, it will be investigated the ideal value of p to maximize η, since as $\eta > 1$ rises, the gain of the proposed technique improves. Let $\overline{T}'_{slot}$ denotes the average time slot for the proposed technique and $\overline{P}'_{sz}$ denotes the expected payload size for the proposed technique. Therefore, η is defined as follows:

$$\eta = \frac{\overline{P}'_{sz}}{\overline{T}'_{slot}} \cdot \frac{\overline{T}_{slot}}{\overline{P}_{sz}}. \tag{7}$$

Next, the calculation of the value of p that maximizes η will be shown. This value of p shall imply that $\eta > 1$. So:

$$\eta > 1 \leftrightarrow \frac{\overline{P}'_{sz}}{\overline{T}'_{slot}} > \frac{\overline{P}_{sz}}{\overline{T}_{slot}} \leftrightarrow$$
$$\frac{(2-(1-p)^3) \cdot P_{sz}^{AB}}{\overline{T}'_{slot}} > \frac{(1+p) \cdot P_{sz}^{AB}}{\overline{T}_{slot}} \leftrightarrow$$
$$(2-(1-p)^3) \cdot \overline{T}_{slot} - \overline{T}'_{slot} \cdot (1+p) > 0. \tag{8}$$

In this calculation, it is considered that $\overline{T}_{slot}$ and $\overline{T}'_{slot}$ are independent of p. To achieve this, T_{td} is set to the upper bound such as $T_{td} = t \cdot T_{sync} = 15\mu s$. Thus, Eq. (7) was differentiated with respect to p and the derivative was set to 0 to find p ($0 < p < 1$) value that maximizes η. The resulting equation of the differentiation is the following:

$$p^3 - 3p + 1 = 0. \tag{9}$$

The value of $p = 0.3473$ satisfies Eq. (9) for $0 \leq p \leq 1$. This behavior about p value was somehow expected. In case the value of p was close to 1, the increased size to address t destinations in RTSM becomes more expensive as compared to traditional RTS. For a high p value, a bidirectional communication would be established with high probability even though traditional RTS is used. For p value close to 0, a similar argument holds, that is, a bidirectional communication would hardly be established. In such case, the RTS time is increased and the gain of adoption of proposed scheme may be limited. It is worth mentioning that for $t = 3$, the p value that maximizes η is independent of the number of neighboring nodes, data rate and packet size. This argument ends the analysis about the p value that maximizes η. Next, it will be presented the results obtained at this work.

IV. Numerical Results

This section describes the evaluations held in this work. These evaluations aim to point the positive impact of FDDS-MAC over network performance regarding to full-duplex communications. To this end, FDDS-MAC was evaluated in terms of channel throughput. Recall that channel throughput relies on Bianchi's model [12] which is widely employed in the related literature when medium access control (MAC)

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schemes are being evaluated in terms of throughput over networks with intensive traffic as previously discussed. The presented evaluation compares FDDS-MAC with state of art MAC scheme (FD-MAC [5]) in terms of channel throughput. The evaluation addresses the quotient between FDDS-MAC channel throughput and FD-MAC channel throughput. This quotient is termed η. If $\eta > 1$, the use of the FDDS-MAC is recommended. For the referred evaluation, the payload packet size was varied among the values of 256, 512 and 1024 bytes. Also, the number of neighbor nodes was varied among the values of 10, 25, 50, 75 and 100. The probability p is varied among the values of $0.1 \cdot x$, where $1 \leq x \leq 9$. Similar to other works that consider full-duplex communication in 5G networks (e.g. [5]), the FDDS-MAC physical and MAC layers parameters used in this evaluation are those of the IEEE 802.11 standard [7]. More precisely, the physical and MAC layers parameters are considered to have the values described in IEEE 802.11a [7] with a data rate equal to 6 Mbps.

For FDDS-MAC and FD-MAC, the channel throughput will be calculated according to Eq. (3). Regarding to FDDS-MAC, the number of queried nodes will be considered equal to three ($t = 3$) and T_{td} will be considered as defined in Eq. (1). The comparison between FDDS-MAC and FD-MAC in terms of η for packet size of 256, 512 and 1024 bytes is depicted in Figures 2, 3 and 4, respectively. For packet size of 256 bytes, FDDS-MAC provided a channel throughput improvement over FD-MAC up to 40%, that is, η reached up to 1.40 for $p = 0.4$ and $n = 10$. In this case ($P_{sz} = 256$), η averaged 1.28. It is noticeable that FDDS-MAC outperformed FD-MAC for all cases in at least 9%. Similar behavior is observed when $P_{sz} = 512$ as depicted in Figure 3. In this case, η reaches up to 1.36 ($p = 0.4, n = 10$) and averages 1.25. Again, FDDS-MAC outperformed FD-MAC for all cases, by at least 8%. When $P_{sz} = 1024$, the same tendency of behavior can be noted. Once more, $\eta > 1$ in all cases, that is, FDDS-MAC outperforms FD-MAC for all evaluated cases by at least 7%. In this situation, η was up to 1.32 ($p = 0.4, n = 10$) and averaged 1.23. Some trends occurred for the three scenarios. As n rises, η decreases what can be explained by the fact that when n rises, T_c tends to be more significant to $\overline{T}_{slot}$. Moreover, T_c for FD-MAC is lower than for FDDS-MAC, once RTS is smaller than RTSM. This occurs, since RTSM has more $t-1$ destination fields than RTS in order to leverage the probability of the two sides of the communication be transmitting data simultaneously. Besides, it is remarkable that for $p = 0.4$, η achieved its higher values in all evaluated cases. When $p = 0.4$, η averaged 1.34. This result is consistent with the expected behavior of η in terms of p. Recall that expected p value to maximize η was close to 0.35 as discussed previously.

Aiming to investigate different scenarios than the one with 6 Mbps, the same evaluation was held considering a data rate equal to 54 Mbps. Due to lack of space, it will be presented only the case where $P_{sz} = 1024$ bytes. The results obtained for this case are depicted in Figure 5. Although the change of data rate, a similar behavior occurs to the described for data rate of 6 Mbps. η reached up to 1.35 when

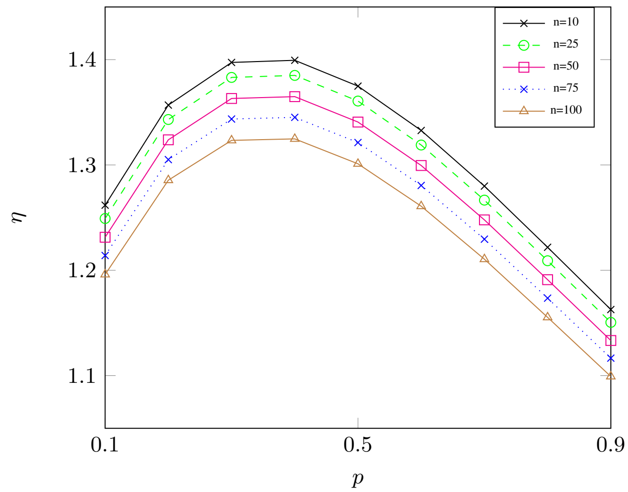

Figure 2. η values for various probabilities of successful bidirectional communication for $P_{sz} = 256$ and data rate equal to 6 Mbps.

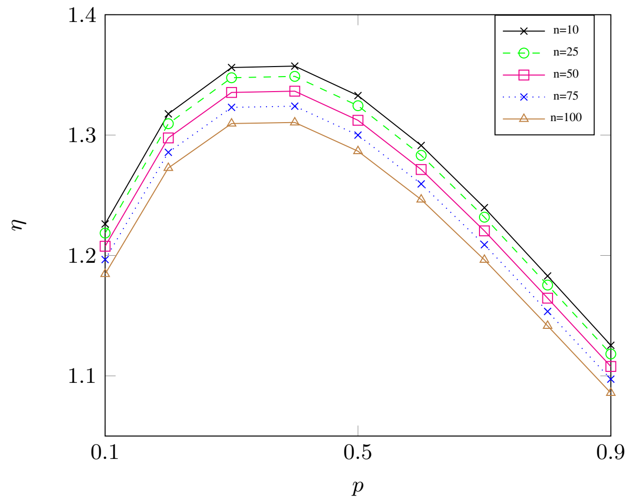

Figure 3. η values for various probabilities of successful bidirectional communication for $P_{sz} = 512$ and data rate equal to 6 Mbps.

$p = 0.4$ and $n = 10$. Moreover, η averaged 1.24. Also, FDDS-MAC outperforms FD-MAC at least by 9%. The presented results reinforced the expectation of the positive impact of the adoption of FDDS-MAC on full-duplex communications, once FDDS-MAC provided throughput improvement up to 40% when compared with FD-MAC.

V. Conclusion

Efficient spectral use is paramount in the context of 5G generation networks. In this way, this paper proposed FDDS-MAC which as MAC scheme tailored for full-duplex communications that is able to enhance spectrum usage. Moreover, FDDS-MAC improved throughput up to 40% when compared to traditional full-duplex schemes. Regarding to future works,

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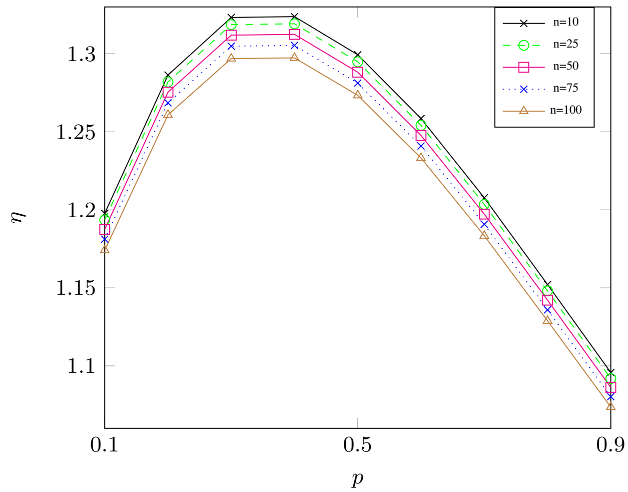

Figure 4. η values for various probabilities of successful bidirectional communication for $P_{sz} = 1024$ and data rate equal to 6 Mbps.

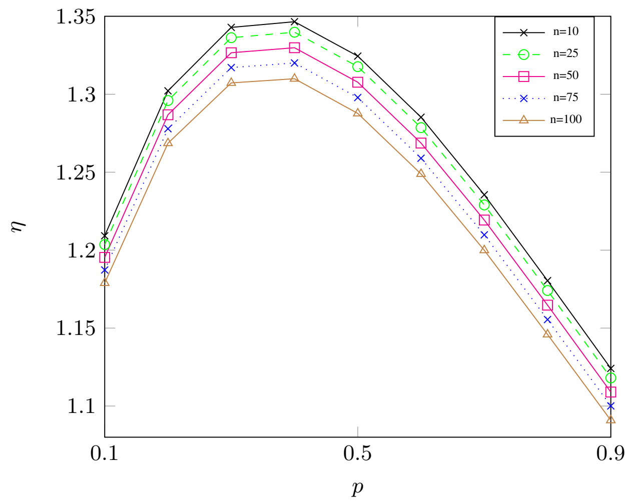

Figure 5. η values for various probabilities of successful bidirectional communication for $P_{sz} = 1024$ and data rate equal to 54 Mbps.

it would be interesting to incorporate to FDDS-MAC some artificial intelligence mechanism able to accurately estimate the values of n and p. Although FDDS-MAC provided remarkable channel throughput improvement in all evaluated cases, it would be of great interest to dynamically preview the values of P_{sz}, p and n. If these values were known with high accuracy, a node could decide properly if it is worthy to use FDDS-MAC and the best value of t to use. These values (P_{sz}, p and n) could be estimated based on cross-layer information such as routing knowledge about active and inactive routes of the network. In some cases, a node could even decide if it is worthy in terms of throughput to realize or not the decision phase of FDDS-MAC.

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References

[1] G. D. Swetha and G. R. Murthy, "Selective overlay mode operation for d2d communication in dense 5g cellular networks," in *Computers and Communications (ISCC), 2017 IEEE Symposium on*. IEEE, 2017, pp. 704–709.

[2] R. Tang, J. Zhao, H. Qu, and Z. Zhang, "Energy-efficient resource allocation for 5g full-duplex enabled device-to-device communication," in *Globecom Workshops (GC Wkshps), 2016 IEEE*. IEEE, 2016, pp. 1–7.

[3] N. H. Mahmood, M. G. Sarret, G. Berardinelli, and P. Mogensen, "Full duplex communications in 5g small cells," in *Wireless Communications and Mobile Computing Conference (IWCMC), 2017 13th International*. IEEE, 2017, pp. 1665–1670.

[4] M. Murad and A. M. Eltawil, "A simple full-duplex mac protocol exploiting asymmetric traffic loads in wifi systems," in *Wireless Communications and Networking Conference (WCNC), 2017 IEEE*. IEEE, 2017, pp. 1–6.

[5] X. Zhang, W. Cheng, and H. Zhang, "Full-duplex transmission in PHY and MAC layers for 5G mobile wireless networks," *IEEE Wireless Communications*, vol. 22, no. 5, pp. 112–121, 2015.

[6] Z. Zhang, K. Long, A. V. Vasilakos, and L. Hanzo, "Full-duplex wireless communications: challenges, solutions, and future research directions," *Proceedings of the IEEE*, vol. 104, no. 7, pp. 1369–1409, 2016.

[7] IEEE, "IEEE Standard for information technology-telecommunications and information exchange between systems-local and metropolitan area networks - specific requirements - part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications," Institute of Electrical and Electronics Engineers, IEEE Standard 802.11, December 2007.

[8] J. Y. Kim, O. Mashayekhi, H. Qu, M. Kazandjieva, and P. Levis, "Janus: A novel MAC protocol for full duplex radio," Stanford University, Tech. Rep., 2013.

[9] L. D. M. Guimaraes, J. L. Bordim, and K. Nakano, "Using pulse/tone signals as an alternative to boost channel reservation on directional communications," *IEICE TRANSACTIONS on Fundamentals of Electronics, Communications and Computer Sciences*, vol. 98, no. 8, pp. 1647–1656, 2015.

[10] K. Shih, W. Liao, H. Chen, and C. Chou, "On avoiding RTS collisions for IEEE 802.11-based wireless ad hoc networks," *Computer Communications*, vol. 32, no. 1, pp. 69–77, 2009.

[11] J. Liberti and T. Rappaport, *Smart antennas for wireless communications*. Prentice Hall PTR, 1999.

[12] G. Bianchi, "Performance analysis of the ieee 802.11 distributed coordination function," *IEEE Journal on selected areas in communications*, vol. 18, no. 3, pp. 535–547, 2000.

[13] I. Tinnirello, G. Bianchi, and Y. Xiao, "Refinements on IEEE 802.11 distributed coordination function modeling approaches," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 3, pp. 1055–1067, 2010.

[14] S. Sagari, S. Baysting, D. Saha, I. Seskar, W. Trappe, and D. Raychaudhuri, "Coordinated dynamic spectrum management of LTE-U and Wi-Fi networks," in *Dynamic Spectrum Access Networks (DySPAN), 2015 IEEE International Symposium on*. IEEE, 2015, pp. 209–220.

[15] Y. Yao, L. Rao, and X. Liu, "Performance and reliability analysis of IEEE 802.11p safety communication in a highway environment," *IEEE transactions on vehicular technology*, vol. 62, no. 9, pp. 4198–4212, 2013.

[16] P. Nayak, M. Garetto, and E. W. Knightly, "Multi-user downlink with single-user uplink can starve TCP," in *INFOCOM 2017-IEEE Conference on Computer Communications, IEEE*. IEEE, 2017, pp. 1–9.

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