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A Cooperative MAC Protocol to Improve the Performance of In-Home Broadband PLC Systems

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"You never change things by fighting the existing reality. To change something, build a new model that makes the existing model obsolete."

(Buckminster Fuller)

RESUMO

Nesse trabalho, discutimos o uso de protocolos de cooperação na subcamada de controle de acesso ao meio (CMAC) para reduzir a taxa de perda de pacote e aumentar o *goodput* em um sistema de comunicação banda larga via rede elétrica (PLC) de ambientes residenciais. Para apoiar essa discussão, nós, pela primeira vez, apresentamos uma análise estatística da taxa de erro de pacote (PER) de canais PLC residenciais a partir de dados medidos em um modelo com um único *relay*. Adicionalmente, nós esboçamos um simples protocolo CMAC capaz de explorar a diversidade oferecida por uma rede elétrica doméstica. Usando esse protocolo, nosso objetivo é mostrar o impacto da variação da largura de banda, da variação da PER e da posição relativa do *relay* no desempenho do sistema. Sendo assim, nós mostramos que a taxa de perda de pacote e o *goodput* melhoram quando a largura de banda de frequência aumenta. Além disso, resultados mostram que a cooperação na camada de enlace não oferece vantagens caso os valores de PER do enlace direto e do enlace intermediado pelo *relay* sejam muito altos ou muito baixos. Nós também notamos que as melhorias estudadas dependem da posição do nó *relay* em relação ao nó fonte e ao nó destino (i.e., notamos melhoras na rede nos casos em que o *relay* estava situado próximo à fonte e no meio do caminho entre a fonte e o destino). Finalmente, uma comparação entre os esquemas de acesso múltiplo por divisão de frequências ortogonais - acesso múltiplo por divisão de tempo (OFDMA-TDMA) e acesso múltiplo por divisão de tempo - multiplexação por divisão ortogonal de frequência (TDMA-OFDM) mostra que o simples protocolo CMAC é mais eficaz quando usado juntamente com o primeiro esquema do que com o último. Em suma, a nossa contribuição é dividida em duas etapas: primeiramente, desenvolvemos um simples protocolo MAC de cooperação que traz melhorias de desempenho na rede quando comparado com um sistema sem a cooperação; em segundo lugar, nós realizamos uma análise sistemática de diferentes cenários, mostrando os benefícios e limitações da cooperação na camada de enlace de redes PLC.

Palavras-chave: PLC. Protocolo CMAC. OFDMA-TDMA. TDMA-OFDM. Taxa de perda de pacotes. *Goodput*.

ABSTRACT

In this work, we discuss the use of cooperative medium access control (CMAC) protocols to reduce packet loss rate and to improve goodput of in-home broadband power line communication (PLC) systems. To support this discussion, we, for the first time, present a statistical packet error rate (PER) analysis of measured in-home PLC channels by adopting a single relay model. Additionally, we outline a simple CMAC protocol that is capable of exploiting the diversity offered by in-home electric power grids. Using this protocol, we aim to show the impact of bandwidth variation, PER variation and of relative relay location on system performance. Thus, we show that packet loss rate and goodput improve when frequency bandwidth increases. Also, results show that cooperation at the link layer does not offer advantages if the PER values of direct and relayed links are very high or very low. Furthermore, we note that the improvements depend on the location of the node relay in relation to the nodes source and the destination (i.e., network improves if the relay is located near the source or in the midway between the source and the destination). Finally, a comparison between orthogonal frequency division multiple access - time division multiple access (OFDMA-TDMA) and time division multiple access - orthogonal frequency division multiplexing (TDMA-OFDM) schemes show that the simple CMAC protocol is more effective when it is used together with the former scheme than the latter.

Keywords: PLC. CMAC protocol. OFDMA-TDMA. TDMA-OFDM. Packet Loss rate. Goodput.

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LIST OF SYMBOLS

α	Packet loss rate
β	Goodput
γ	Packet loss rate reduction
η	Goodput improvement
N_{ACK}	Number of successful receptions
N_i	Packet length in terms of number of bits
N_{PL}	Number of packets lost
N_{PS}	Number of packets sent from node source to node destination
P	Total power
P_0	Power allocated to node source
P_1	Power allocated to node relay
T	Number of Frames

LIST OF ACRONYMS

ACK	Acknowledge
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CD	Cooperative Diversity
CDF	Cummulative Distribuition Function
CMAC	Cooperative Medium Access Control
D	Destination
DP	Data Period
DSAC	Dynamic Slot Assignment Cooperative
HS-OFDM	Hermitian symmetric - Orthogonal Frequency Division Multiplexing
NACK	Negative-acknowledge
MAC	Medium Access Control
MIMO	multiple-input multiple-output
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Multiple Access
PER	Packet Error Rate
PKT	Packet
PLC	Power Line Communication
PSD	Power Spectrum Density
R	Relay
S	Source
SP	Signaling Period
SFO	Sample Frequency Offset
TDMA	Time Division Multiple Access
W/O COOP	Without Cooperation
WTC	Want To Cooperate

CONTENTS

1 INTRODUCTION

Cooperative communication is a promising technique for performance enhancing on many kinds of networks, such as wireless, ad-hoc, mesh and power line communication (PLC) (CIPRIANO et al., 2012; ZHAO et al., 2013; LEE et al., 2014). In short, cooperation can reduce packet loss, perform spatial reuse, improve system throughput, reduce network delay, act on energy efficiency problems and explore network diversity advantages. Despite these benefits, appropriate medium access control (MAC) protocols are required in order to exploit advantages provided by cooperative communications at the link layer level (FITZEK; KATZ, 2006).

In PLC systems, it is well-known that distance between nodes source and destination, impedance mismatching, frequency selectivity of PLC channels and high power impulsive noise affect the data communication quality (ZIMMERMANN; DOSTERT, 2002; GALLI et al., 2010). Because of these problems, the use of a node relay for cooperation is an attractive approach to enhance the communication (NOORI; LAMPE, 2013; BILBAO et al., 2014). However, there is a lack of studies about cooperation at the link layer of PLC systems. Therefore, it is an important issue to investigate in which conditions and what kind of benefits a cooperative MAC protocol can offer to PLC networks.

In this work, we perform a comprehensive analysis to highlight in which circumstances cooperation benefits in-home broadband power line communication (PLC) networks. To do so, we, for the first time, present a statistical analysis of packet error rate (PER) of measured in-home PLC channels when we adopt a single relay model (GOLDFISHER; TANABE, 2010) and a hermitian-symmetric orthogonal frequency division multiplexing scheme (RIBEIRO et al., 2014) for data communication. Additionally, we outline a simple CMAC protocol that is capable of exploiting the diversity offered by in-home electric power grids. We use the proposed protocol results of packet loss rate and goodput in order to answer the following questions related to the studied scenario:

- What are the best relative relay positions for cooperation?
- Which frequency band is more adequate: 1.7-30 MHz, 1.7-50 MHz or 1.7-100 MHz?
- Which PER values are more suitable for cooperation: low values, intermediate values

or high values?

- Which scheme present the best cooperation results: OFDMA-TDMA or TDMA-OFDM?

We show that there are communication improvements if the node relay is located near the node source or in the midway between the nodes source and destination. On the other hand, we cannot observe improvements if the relay is located far from nodes source and destination or near the node destination. It occurs due to the fact that, when the node relay is far from node source, the link source-relay PER increases and, so, the cooperation is compromised.

In terms of frequency band, the improvements increase as the frequency bandwidth increases. The CMAC protocol results of goodput improvement compared with a system without cooperation, for example, were up to 30%, 33% and 35% in the frequency bands of 1.7-30 MHz, 1.7-50 MHz and of 1.7-100 MHz, respectively, for 90% of the measured samples.

Finally, we have compared the CMAC protocol improvements obtained in PLC systems based on orthogonal frequency division multiple access - time division multiple access (OFDMA-TDMA) scheme with the ones based on time division multiple access - orthogonal frequency division multiplexing (TDMA-OFDM) scheme. This analysis shows that goodput results for OFDMA-TDMA scheme are up to 70% for 90% of the measured in-home and cooperative PLC channels. On the other hand, the goodput results for TDMA-OFDM scheme are up to 54% at the same conditions.

The reminder of this work is organized as follows. In Chapter 2, we make some assumptions and definitions and calculate the packet error rates based on measurements. In Chapter 3, we describe our proposed protocol. In Chapter 4, we show some numeric results and discussions. In Chapter 5, we compare the proposed protocol results in PLC systems based on uncoded OFDMA-TDMA scheme with the ones based on TDMA-OFDM scheme. In 6, we discuss about related work. Finally, in Chapter 7, we conclude the work.

2 PROBLEM FORMULATION

In this work, we consider a cooperative in-home broadband PLC network at the link layer. Figure 2.1 shows a graphic representation of this network, in this case, using a single relay. Note that the letters S, R and D represents the nodes source, relay and destination, respectively. In this scenario, there are three links: the source-destination (SD), the source-relay (SR) and the relay-destination (RD). Moreover, each link has an independent packet error rate named as PER_i, where $i \in \{SD, SR, RD\}$.

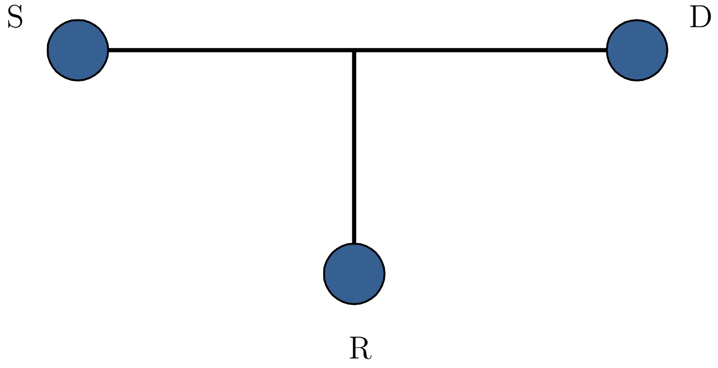


Figure 2.1: Single relay cooperative model for PLC channels.

We obtain the PER_i values from the physical layer through the bit error rate (BER) related to the ith link. It is calculated as $PER_i = 1 - (1 - BER_i)^{N_i}$, where N_i is the packet length in terms of number of bits. However, the lack of information based on real systems is a problem related to this model. To overcome this issue, we have performed a measurement campaign in order to estimate the PER_i in a real scenario.

This campaign was carried out in seven residences in a typical Brazilian urban area of Juiz de Fora city, as shown in Table 2.1. We performed our channel error rate characterization, for the most part, by estimating channel frequency response and noise power spectrum density (PSD). We have employed the same measurement setup as Colen et al. (COLEN et al., 2013). As shown in Figure 2.2, we used three main components: a PLC coupler, a waveform signal generator and a digitizer. Additionally, we have used the discrete-time version of both generated and measured signals in order to apply the channel-estimation methodology, as in Oliveira et al. (OLIVEIRA et al., 2014), encompassing the following stages: (i) input-output timing synchronization; (ii) initial channel estimation; (iii) sample frequency offset (SFO) correction; (iv) channel estimation; (v) channel estimation enhancement, which mitigates noise effects. According to this method, the transmitted signal is composed of hermitian symmetric - orthogonal frequency division multiplexing (HS-OFDM) symbols (RIBEIRO et al., 2014), using a 200 MHz sampling frequency, with frequency resolution around 48.83 kHz. For the measurement of the noise PSD, we have used the data digitizer when no sounding signal was being transmitted.

Table 2.1: Main features of the measured places.

Construction Type	Age (years)	Constructed Area (m^2)
House #1	30	78
House #2	10	69
Apartment #1	9	54
Apartment #2	9	42
Apartment #3	18	65
Apartment #4	3	62
Apartment #5	2	54

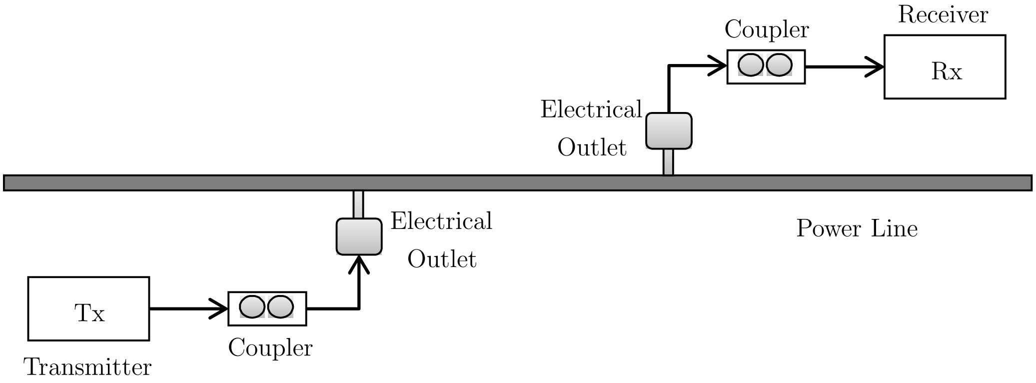


Figure 2.2: The measurement setup.

Over this campaign, we have calculated a total of 35040 estimates of PER, which are equally divided among the links SR, RD and SD, resulting in 11680 estimates of PER for each link of the single relay model. As mentioned before, each PER_i estimation uses a BER obtained from in-home PLC channels information. These estimates cover the frequency bands of 1.7-30 MHz, 1.7-50 MHz and of 1.7-100 MHz. First and second frequency bands refer to PLC system regulated frequency bands in some European countries (GALLI; LOGVINOV, 2008) and in Brazil (ANATEL, 2009), respectively. The 1.7-100 MHz band is a new alternative under study to considerable increase on data rate in PLC systems (TONELLO et al., 2014; TLICH et al., 2008).

Finally, our characterization includes relative locations of node R, in relation to nodes S and D, as shown in Figure 2.3. Intuitively, we have covered the most common node R positions (equidistant from nodes S and D, near node S, near node D and far from nodes S and D).

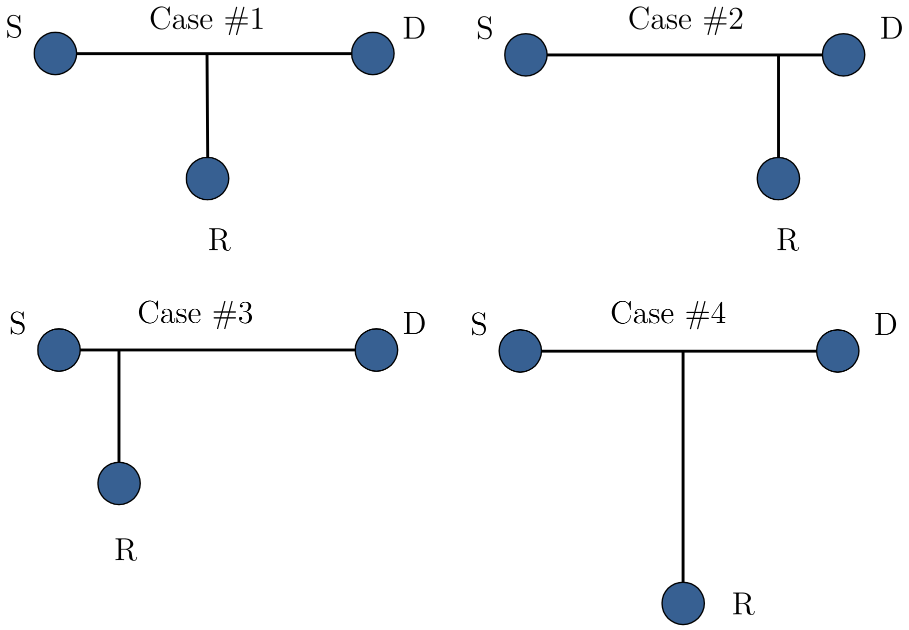
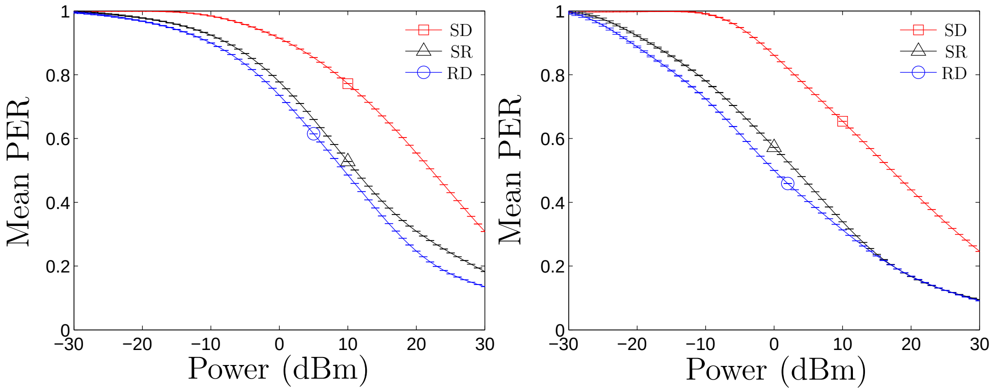


Figure 2.3: Relative location of the node R addressed in the measurement campaign.

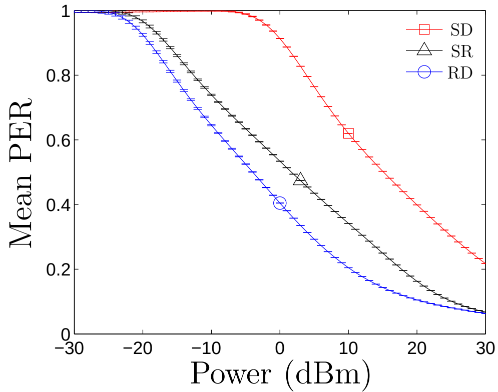
In order to estimate the PER_i, we considered an uncoded HS-OFDM scheme together with Binary Phase Shift Keying (BPSK) modulation, perfect synchronization and complete channel state information available at the receiver side. The total power is $P = P_0 + P_1$, where P_0 and P_1 are allocated to nodes S and R, in this order. These powers are equally distributed among N subcarriers of the HS-OFDM symbol (P_0/N and P_1/N for nodes S and R, respectively) during a data communication cycle (the first time slot is allocated to the node S and the second one to the node R) associated with the single relay model. Note that $N = 4096$, $N = 2048$ and $N = 1228$ for frequency bands of 1.7-100 MHz, 1.7-50 MHz and of 1.7-30 MHz, respectively. We also chose the length of the cyclic prefix to deal with delay spread of the measured in-home PLC channels.

Figure 2.4 shows mean PER values calculated from the 11680 estimates of PER of each link (SD, SR, and RD) for each frequency band, while we vary the system total power from -30 dBm to 30 dBm. We present confidence intervals, considering a 99% confidence. According to these figures, all PERs tends to 1 as the total power decreases and to 0 as the total power increases.

Moreover, for all range of total power and frequency band, we observed that the PER associated with SD is higher than those ones related to links SR and RD. For 10 dBm and a frequency band of 1.7-100 MHz, e.g., we noted that the link SD mean PER value is of 62%, while for links SR and RD it is of 34% and of 21%, respectively. Therefore, the use of the relay to assist the node S at the link layer and to improve the system performance is an important issue that is addressed in this work.



(a) Frequency band 1.7-30 MHz. (b) Frequency band 1.7-50 MHz.



(c) Frequency band 1.7-100 MHz.

Figure 2.4: PER for each link when the total power varies considering a 99% confidence interval.

Additionally, we observe higher packet error rates for narrower frequency bands. For example, Figure 2.4.a shows that the mean PER value of link SD is of 77% in 1.7-30 MHz. On the other hand, Figure 2.4.c reveals a mean PER_{SD} of 62% in 1.7-100 MHz. Also these plots show lower differences between the PER_{SR}, PER_{RD} and PER_{SD} for narrower frequency bands since the curves are closer in 1.7-30 MHz. Hence, the relay exploitation may be less attractive in this case.

Finally, we point out that Figure 2.4 curves would shift to the left if we adopted a coded HS-OFDM due to the performance advantages attained to this scheme (JOSHI; SAINI, 2010; SARI et al., 2002).

3 COOPERATIVE PLC MAC PROTOCOL

As we previously show on Figure 2.1, the electric power grid acts as a bus for data communication purposes. More precisely, if node S sends a packet, both nodes R and D will receive a copy (corrupted or not) of it. We also assume that nodes S and R make use of ideal buffers with sufficient space to ensure that no packet is lost once it is received. Thus, in case of negative-acknowledge (NACK) message reception from node D, the nodes S and R can use their own network resources to retransmit the packet. Note that node D is responsible for detecting errors and missing packets. If one occurs, node D broadcasts a NACK requesting the retransmission of the packet.

In this work, we assume that users access electric power grid communication system using a OFDMA-TDMA scheme. Moreover, we assume that frame is divided into signaling (SP) and data (DP) periods. Signaling period SP is used for control message exchanges, which adjust transmission and cooperation details. Data period DP is used to transfer data frames, as expected. Additionally, nodes S, R and D, in this order, have their time-slots successively allocated.

The proposed cooperative MAC protocol (PLC-CMAC) exploits the relay availability for retransmitting data. It aims to efficiently use the network resources and to enhance the communication of an in-home PLC environment. Figure 3.1 shows the algorithm of the proposed protocol. The process starts in DP, when node S sends a data packet (PKT) to node D, which is also received by node R. So, nodes S and R store this data temporarily. If there is a positive acknowledgement (ACK) from node D, both nodes S and R clear the stored packet. Then, node S is able to send a new data during its next time-slot to node D. Otherwise, in case of a negative acknowledgement (NACK) from node D, if node R is idle (it does not have packets for transmission during the next DP), it sends a Want To Cooperate (WTC) message to node S offering its own time-slot for cooperation. Thus, we note that if node S receives a WTC message, we apply a technique dependent of relay idleness, which was proposed in (LEE et al., 2013), for performing the packet retransmission. This technique was discussed for wireless networks and is named Dynamic Slot Assignment Cooperation (DSAC) protocol.

Figure 3.2 shows the operation of the DSAC technique. This figure shows two con-

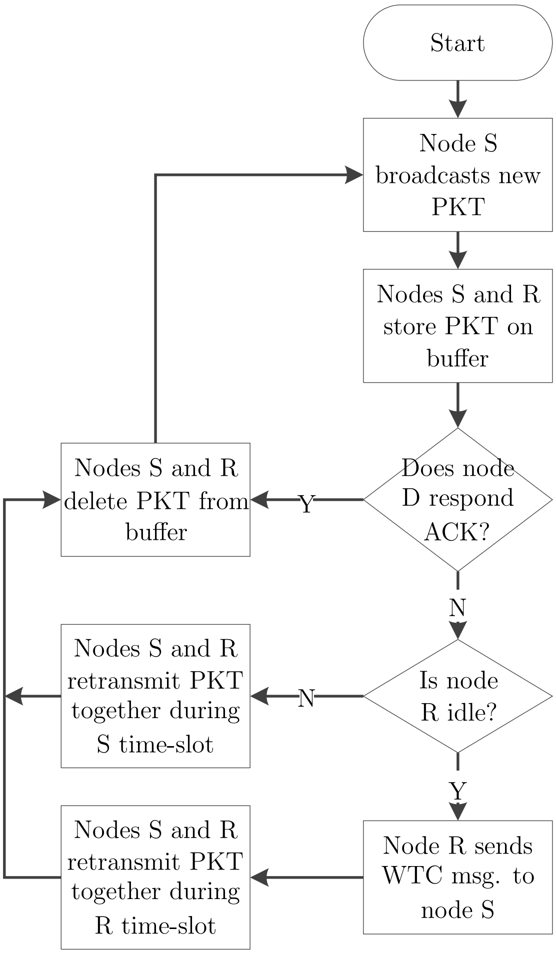


Figure 3.1: The proposed cooperative MAC protocol for in-home PLC systems based on TDMA.

secutive frames. During the first one, in DP, node S sends a data message (PKT1) to node D that is also received by node R, as mentioned before. Lastly, node D detects a packet error and broadcasts a NACK message to nodes S and R. Hence, during the next frame, in SP, node R sends a WTC message offering its time-slot for cooperation to node S. Then, in DP, node S will send a new packet to node D (PKT2) in its time-slot. Then, during node R time-slot, nodes S and R will retransmit the PKT1 stored in their buffers. This retransmission through two different links (SD and RD) exploits system diversity advantage improving the performance in terms of packet loss rate reduction. Moreover, as the node S does not use its own time-slot for retransmitting packets, we may obtain a goodput gain.

On the other hand, if node R is not idle to offer its own time-slot for retransmission, the DSAC protocol works without cooperation. Thus, it loses communication diversity, the packet loss rate increases and the system goodput is lost. In order to avoid this prob-

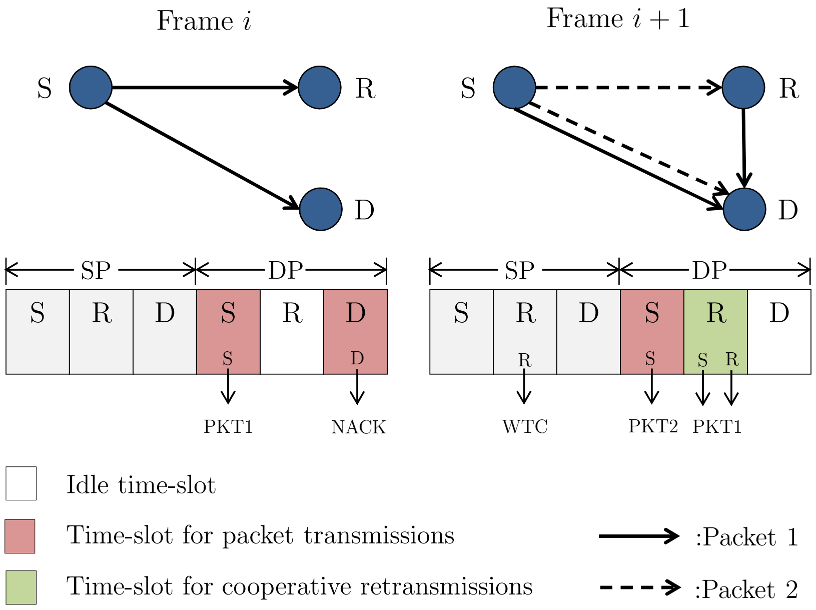


Figure 3.2: The Cooperative MAC protocol operation when the node R is idle.

lem, PLC-CMAC protocol uses a protocol independent of relay idleness, which performs the cooperation during the node S time-slot. This technique, shown in Figure 3.3, was discussed in (YANG et al., 2010) for wireless networks and is named Cooperative Diversity (CD) protocol.

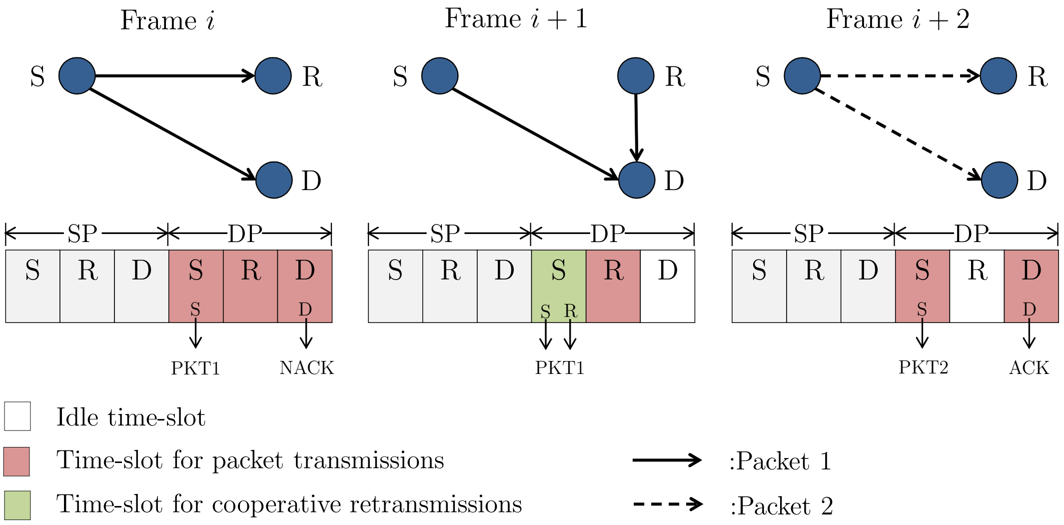


Figure 3.3: The Cooperative MAC protocol operation when the node R is not idle.

In Figure 3.3 we observe that the node R does not send a WTC message to the node S during the second frame SP. It informs that node R will not be able to offer its own time-slot for retransmission. Thus, node S will not be able to transmit a new packet (PKT2) because the first one (PKT1) need to be retransmitted together with the packet stored in node R, during the node S time-slot. Hence, CD protocol may not show the same goodput gain as DSAC protocol when the relay is idle, since, in DSAC protocol, the node S will be able to send a new packet regardless of the retransmission. Thus, in case of NACK, in DSAC two packets are sent during two frames, while CD protocol needs three frames for achieving the same purpose. However, the use of the CD protocol can maintain the diversity gain keeping the retransmission through two different paths (SD and RD) and, thus, reducing the packet loss rate.

Based on the aforementioned description of the PLC-CMAC protocol, it is clear that it is a merge of two cooperative MAC protocols designed for wireless networks. This merge improves the PLC network performance as discussed in Sec. 4. This fusion means that the node R is, opportunistically, used for cooperating with the node S. As a result, the proposed protocol offers the following advantages:

- Case node R is idle and a retransmission is needed, it will be executed during the relay time-slot. Hence, the network goodput will be improved, since the source will be able to transmit a new packet in the next time-slot and the packet loss rate will decrease because of the use of two paths with different PER (PER_{SD} and PER_{RD}) for retransmission.

- Case node R is busy and a retransmission is needed, it will be performed during the source time-slot. Therefore, the network goodput will not be improved as in the idle relay case, since the source will need to spend its own time-slot for retransmitting packets. So, new transmissions will not be possible. However, this technique will be able to keep a good packet loss rate reduction in cases of retransmissions. It is due to the cooperative diversity attained when the same packet is retransmitted by nodes S and R through two different links (links SD and RD, respectively).

4 COOPERATION PERFORMANCE EVALUATION

4.1 SIMULATION METHODOLOGY

As we present in section 3, we have analyzed an uncoded OFDMA-TDMA based PLC system. In such system, we have allocated half of the numbers of the subcarriers ($N/2$) to nodes S and R (even and odd subcarriers, respectively). This subcarriers division is a fair assumption due to the fact that we are not applying any bit loading technique. Moreover, this scheme allows both nodes transmitting concurrently (HAO et al., 2009) during the same time-slot.

We use a BPSK (binary phase shift keying) digital modulation with total power P, where $P \in \{-20, -10, 0, 10, 20, 30\}$ dBm. We also assume that link power is equally distributed among each link subcarrier. Finally, we have evaluated PLC system using the following frequency bands: 1.7-30 MHz, 1.7-50 MHz and 1.7-100 MHz.

To evaluate the performance of PLC system, we analyze packet loss rate and goodput through simulations. The former is defined as the number of losses per number of packets sent by node S and the latter is the number of successful receptions by node D in a given time period.

In each simulation, node S sends 100 packets to node D. In case of a NACK from D, we allow only one retransmission attempt. In other words, we consider as a packet loss if S receives a NACK from a retransmission. Moreover, unless we say otherwise, we assume that relay is idle in 50% of time. In this case, relay idleness is an intermediate value which illustrates the cooperation process in a common situation. Nevertheless, in section 4.1.2, we vary relay idleness to further investigate the impact of relay activity in our cooperation protocol. Furthermore, we consider that control messages (ACK, NACK and WTC) are error-immune in order to simplify the protocols analysis and focus on cooperation proposals.

Finally, after each simulation, we store information about the number of packets sent, the number of packets lost, the number of successful receptions by node D and the number of frames required for the transmission of all 100 packets. After the last simulation, we use this data to calculate packet loss rate and goodput.

In order to carry out the experiments, we divided them in two different scenarios. In the first one, described in section 4.1.1.1, we considered all relay positions of the measurements shown in Figure 2.3 grouped in a single case. In this general case, we vary the total power to verify the impact on the proposed protocol and to choose the most appropriate power value for cooperation in the studied system. As shown in section 3, we performed 35040 measurements among different relay positions. From this measurements, we extracted 11680 sets of PER. Para simular a transmissão de dados, consideramos apenas a PER values of the links SR, RD and SD. In other words, we implemented 11680 different simulations for each considered power variation. It is important to emphasize that the protocols were reproduced and simulated on the software MATLAB[1]. Thus, we did not use any preexistent simulator.

In the second scenario, described in section 4.1.1.2, we use the total power defined in section 4.1.1.1 to evaluate which relay positions show the best results. Also, we analyze the impact of relay idleness variation on the proposed protocol.

4.1.1 NUMERICAL RESULTS

4.1.1.1 General case analysis

As described in section 4.1, in this section we do not distinguish relay position. In this general case, we compare packet loss rate reduction and goodput improvement due to the use of the proposed protocol. To do so, we vary the total system power in order to observe which power value corresponds to the best cooperation results.

Figure4.1 presents cumulative distribution functions (CDFs) of PLC-CMAC protocol packet loss rate reduction, compared to a system without any cooperation technique. For each frequency band, we have varied total power from -20 dbm to 30 dbm. According to this figure, packet loss reduction varies depending on the total power applied. In fact, for all frequency bands, we note that packet loss rate reduction is lower to the lowest total power (i.e., -20 dBm). It is due to the fact that low power levels result in high PER values on the communication links. Thus, in this case, the cooperation path through node R is not more appropriate for transmissions than the direct link from node S to node D.

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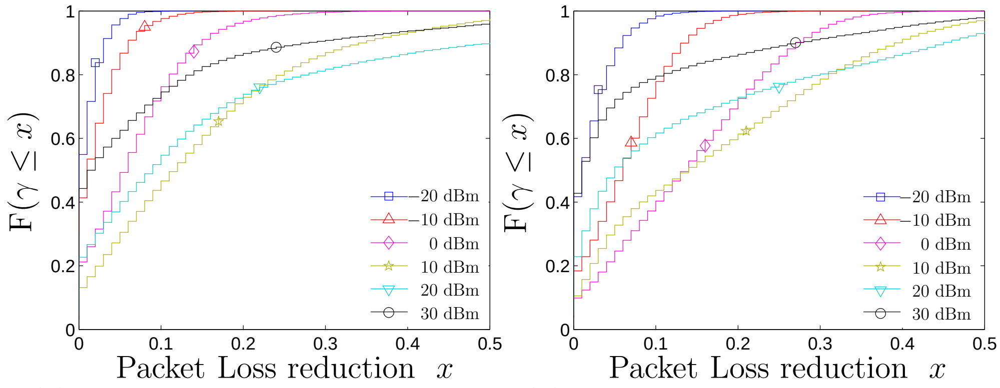
[1] The simulation algorithms and the PER samples are available on http://netlab.ice.ufjf.br/plc/.

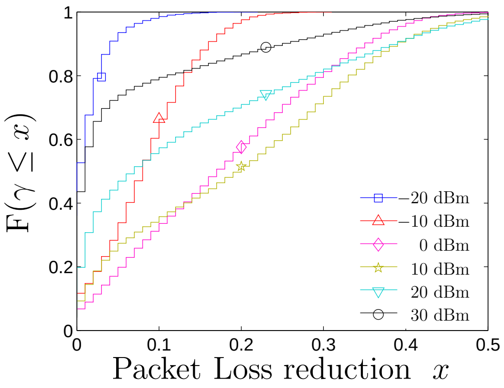
To higher power values, as 30 dBm, we observe just the opposite. Links presents very low error ratios. As consequence, direct transmission between source and destiny occurs practically without retransmission cases, which denies opportunity to relay cooperation.

Therefore, we conclude that intermediate power values, which correspond to intermediate PER values on communication links, are more appropriate for cooperation. In fact, we observe in Figure 4.1 that the curves of intermediate power values (e.g. 0 dBm and 10 dBm) tends to be shifted to the right, achieving the highest packet loss reduction values.

Moreover, we observe how the frequency band variation also interferes in cooperation results. In Figure 4.1.a, the packet loss rate reduction, in comparison with a system working without cooperation, is up to 35% for 90% of the measured in-home PLC channels covering 1.7-30 MHz when we use the PLC-CMAC protocol in a total power of 10 dBm. Figures 4.1.b and 4.1.c show a packet loss rate reduction up to 39% for 90% of the cases for the same total power in the frequency bands of 1.7-50 MHz and of 1.7-100 MHz, respectively.



(a) Frequency band 1.7-30 MHz. (b) Frequency band 1.7-50 MHz.

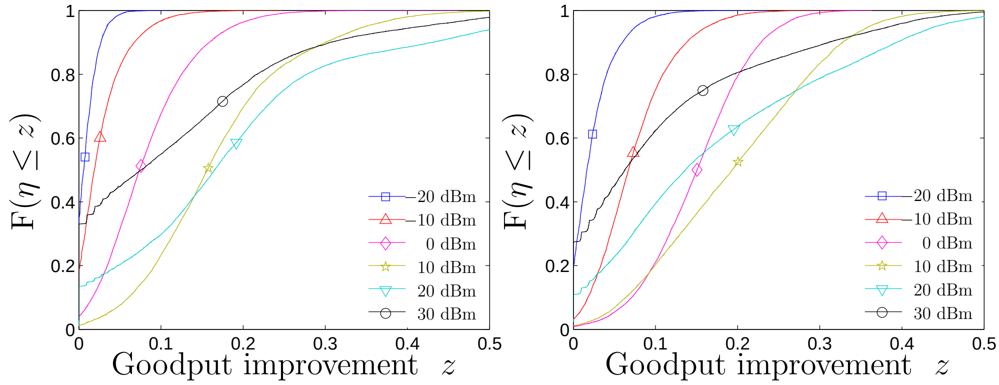


(c) Frequency band 1.7-100 MHz.

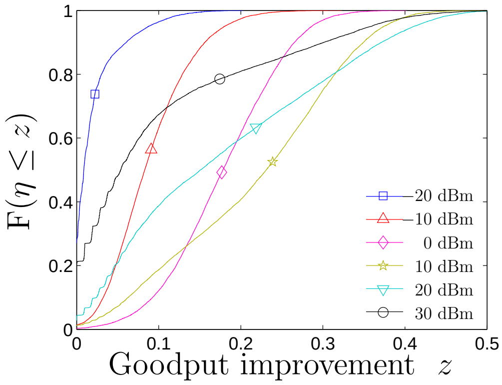
Figure 4.1: CDFs for packet loss rate reduction when the total power changes.

Figure 4.2 shows the CDFs for the goodput improvement comparing a system using PLC-CMAC protocol with a system working without cooperation. According to this figure, we verify the highest probability of goodput improvement when the total power assume intermediate values (see the curves associated with 0 dBm and 10 dBm). Therefore, the behavior of goodput improvement totally agrees with the packet loss rate reduction highlighted in Figure 4.1. Hence, the situation in which the PER of the link SD assume intermediate values, which corresponds to intermediate total power values, configures the best scenario for applying cooperative protocols at the link layer.

Additionally, to verify the impact of the frequency bands variation in terms of goodput improvement, Figures 4.2.a, 4.2.b and 4.2.c show results up to 30%, 33% and 35%, respectively, for 90% of the measured in-home PLC channels when we apply the proposed protocol considering a total power of 10 dBm in the frequency bands of 1.7-30 MHz, 1.7-50 MHz and of 1.7-100 MHz, respectively.



(a) Frequency band 1.7-30 MHz. (b) Frequency band 1.7-50 MHz.



(c) Frequency band 1.7-100 MHz.

Figure 4.2: CDFs for goodput improvement when the total power changes.

In sum, as we show in Figures 4.1 and 4.2, for the analyzed in-home broadband PLC environment, adoption of average system power values is the most suitable scenario to cooperation regardless of the used frequency band. For example, for a total power of 10 dBm we notice results up to 39% of packet loss rate reduction and up to 35% of goodput improvement. For this reason, in the following experiments, we present results from a PLC system using the total power of 10 dBm.

4.1.1.2 Specific cases analysis

In this section, we analyze the proposed cooperation protocol considering the specific cases showed in Figure 2.3.

According to Zimmerman et al. and Galli et al. (ZIMMERMANN; DOSTERT, 2002; GALLI et al., 2010), power strength of a signal transmitted across a PLC channel tends to degrade exponentially within the distance. Therefore, case #1, where relay is equidistant from source and destiny, and case #3, where relay is closer to source than to destination, may represent the best cooperation scenario in PLC systems. In these cases, the packet reception from R for cooperation depends on the communication through a shorter link SR than in case #2, in which node R is far from node S and near to node D, and than in case #4, in which node R is distant from nodes S and D.

Thus, in the following analysis, for the sake of simplicity, we will present the results of cases #1 and #3 together, as well as cases #2 and #4 (see details in Appendixes A, B and C).

Figure 4.3 shows the CDFs for packet loss rate of a system using PLC-CMAC, CD, and DSAC protocols and of a system without cooperation in the frequency bands of 1.7-30 MHz, 1.7-50 MHz and of 1.7-100 MHz. We note that, for any case, the packet loss rate results from PLC-CMAC and CD protocols are equivalent. This occurs because both protocols apply the same diversity cooperating regardless of the state of the relay (idle or busy), which implies on the lowest packet loss rate. However, the DSAC protocol does not cooperate when the node R is not idle. So, it offers the cooperation diversity only in 50% of the node R time-slots, presenting intermediate results. Finally, the system without cooperation represents the worst scenario, since it does not exploit network diversity.

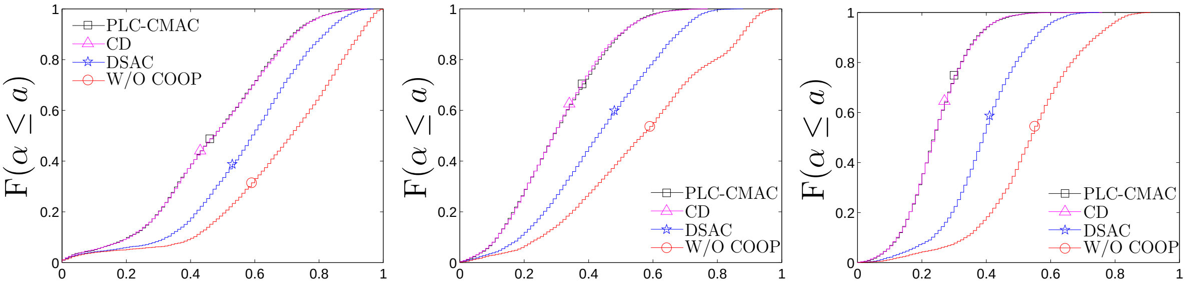
We use Figure 4.3 to confirm the most appropriate relative relay positions for cooperation at the link layer of the studied PLC system. Figure 4.3.a shows packet loss rate results up to 73% to systems using PLC-CMAC and CD protocols. These values are up to 82% and 93% to DSAC protocol and to a system without cooperation, respectively, for

90% of the measured samples of the cases #1 and #3. Figure 4.3.d shows results up to 49% to PLC-CMAC and CD protocols, 53% to DSAC protocol and up to 58% to a system without cooperation for 90% of the measured samples of cases #2 and #4. According to these values, while a system using PLC-CMAC protocol presents a packet loss rate up to 73%, the system without cooperation has values up to 93% in cases #1 and #3. Thus, we note that the cooperation can improve the network performance on these cases. On the other hand, cases #2 and #4 tends to be unfavorable for cooperating, since the system without cooperation results are similar to the ones attained by systems using other protocols (e.g., PLC-CMAC packet loss rate is up to 49% and system without cooperation packet loss is up to 58%, which is as small difference compared to the mentioned results of cases #1 and #3).

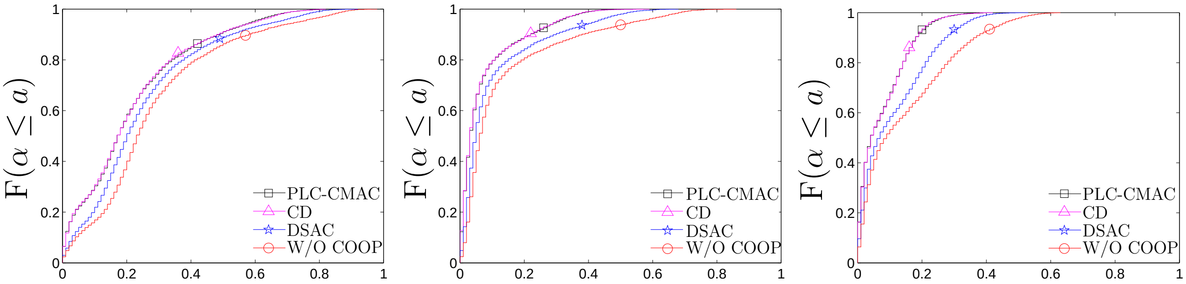
Figures 4.3.b and 4.3.e show the packet loss rate results for each technique in frequency band of 1.7-50 MHz. Specifically, Figure 4.3.b shows packet loss rate results up to 50% for PLC-CMAC and CD protocols, 67% for DSAC protocol and up to 87% for a system without cooperation for 90% of the measured samples of cases #1 and #3. Additionally, Figure 4.3.e shows packet loss results up to 22% for PLC-CMAC and CD protocols, 30% for DSAC protocol and up to 38% for a system without cooperation for 90% of the measured samples of the cases #2 and #4. Therefore, we note that the results follow the same behavior explained for the previous frequency band. Also, the packet loss rates are the smallest for PLC-CMAC and CD protocols.

Finally, Figures 4.3.c and 4.3.f show the CDFs of packet loss rate for each analysed protocol in the frequency band of 1.7-100 MHz. Figure 4.3.c shows packet loss rate results up to 38% for PLC-CMAC and CD protocols, 55% for DSAC protocol and up to 74% for a system without cooperation for 90% of the measured samples of the cases #1 and #3. For the cases #2 and #4, Figure 4.3.f shows results up to 19% for PLC-CMAC and CD protocols, 27% for DSAC protocol and up to 36% for a system without cooperation for 90% of the measured samples. Once more, we note that the proposed protocol presents the best results of packet loss rate and that cases #1 and #3 are more suitable for cooperation.

Furthermore, Figure 4.3 shows that the best cooperation results, in terms of packet loss rate, correspond to the frequency band of 1.7-100 MHz (see Figures 4.3.c and 4.3.e.). To show it, we observe packet loss rate results of PLC-CMAC up to 73%, 50% and 38% in the frequency bands of 1.7-30 MHz, 1.7-50 MHz and of 1.7-100 MHz, respectively, in cases #1 and #3.



(a)Cases #1 and #3 in 1.7-30 MHz.
(b)Cases #1 and #3 in 1.7-50 MHz.
(c)Cases #1 and #3 in 1.7-100 MHz.



(d) Cases #2 and #4 in 1.7-30 MHz.
(e) Cases #2 and #4 in 1.7-50 MHz.
(f) Cases #2 and #4 in 1.7-100 MHz.

Figure 4.3: CDFs for packet loss rate when the total power is equal to 10 dBm.

In terms of goodput, Figure 4.4 shows that the proposed protocol has the best results for any case. This occurs because PLC-CMAC protocol works as DSAC protocol in 50% of time cooperating during the node R time-slot. As discussed in section 3, this behavior provides a goodput improvement. Also, while DSAC protocol works without cooperation, when the node R is idle, PLC-CMAC protocol works as CD protocol, keeping the cooperation advantages on goodput. The system without cooperation presents the worst results, since the node S always need to use its own time-slot for retransmissions.

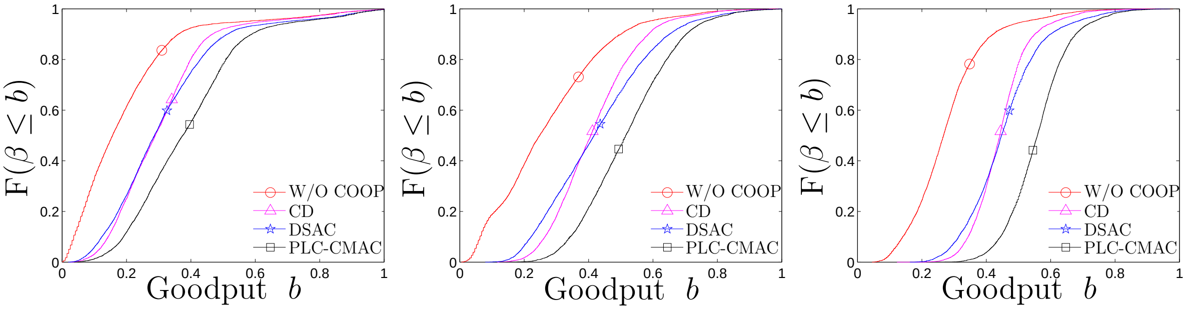
In order to analyze the relative relay positions, Figure 4.4.a shows CDFs for goodput of the cases #1 and #3. These results are up to 36% for a system without cooperation and up to 47%, 52% and 60% for systems using CD, DSAC and PLC-CMAC protocols, respectively, for 90% of the measured samples in 1.7-30 MHz. Otherwise, Figure 4.4.d shows goodput results of cases #2 and #4 in the same frequency band. These results are up to 80% for systems without cooperation and for systems using CD protocol, 88% for DSAC protocol and up to 89% for PLC-CMAC protocol for 90% of the measured samples. Then, we observe, once more, that the last cases tends to be unfavorable for cooperation, since the system without cooperation goodput results are closer to the ones from the systems using cooperative protocols.

In the same way, Figures 4.4.b and 4.4.e present CDFs of goodput for each analysed protocol in the frequency band of 1.7-50 MHz. Thus, Figure 4.4.b shows goodput results up to 42% for a system without cooperation, 55% for CD protocol, 58% for DSAC protocol and up to 68% for PLC-CMAC protocol for 90% of the measured samples of the cases #1 and #3. Otherwise, for the cases #2 and #4, Figure 4.4.e shows goodput results up to 85% for a system without cooperation, 86% for CD protocol, 93% for DSAC protocol and up to 94% for PLC-CMAC protocol for 90% of the measured samples. We note that the PLC-CMAC protocol offers the best results, but the cooperation is less effective for the cases #2 and #4 as mentioned before.

Figures 4.4.c and 4.4.f represent the goodput values in 1.7-100 MHz. Figure 4.4.c shows goodput values up to 49% for a system without cooperation and up to 55%, 64% and 70% for CD, DSAC and PLC-CMAC protocols, respectively, for 90% of the measured samples of the cases #1 and #3. Figure 4.4.f shows goodput results up to 89% for a system without cooperation and for CD protocol and up to 90% for DSAC and PLC-CMAC protocols for 90% of the measured samples of the cases #2 and #4. These results also shows the PLC-CMAC advantages, in terms of goodput, when compared with the other analyzed protocols. Furthermore, cases #1 and #3, once more, show the best results compared with cases #2 and #4.

Additionally, through Figure 4.4 we can note that the frequency band of 1.7-100 MHz also show the best results in terms of goodput. We observe it on PLC-CMAC goodput results up to 60%, 68% and 70% for the frequency bands of 1.7-30 MHz, 1.7-50 MHz and of 1.7-100 MHz, respectively, in cases #1 and #3.

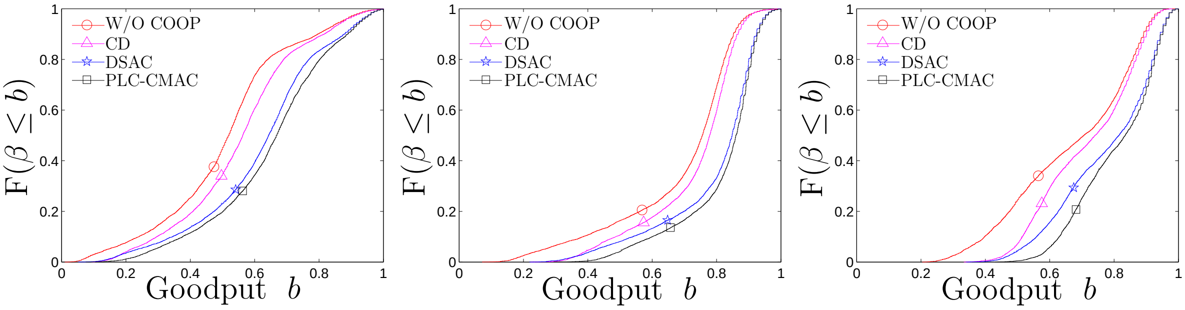
In short, we observe in Figures 4.3 and 4.4, for all frequency bands, that the cases #1 and #3 tends to be more attractive for cooperative protocols. Also, we note that, even unfavorable for cooperation, the cases #2 and #4, according to the measurement campaign, present shorter distance between nodes S and D than #1 and #3. In 1.7-100 MHz, e.g., the packet loss rate of the system without cooperation was up to 74% in the cases #1 and #3 while it was up to 37% in the cases #2 and #4. It reveals that, despite the node R was far from node S in case #2 and far from nodes S and D in case #4%, the distance between nodes S and D was smaller in cases #2 and #4 than in cases #1 and #3 of the measurement campaign. As we mentioned before, the lower packet loss



(a)Cases #1 and #3 in 1.7-30 MHz.

(b)Cases #1 and #3 in 1.7-50 MHz.

(c)Cases #1 and #3 in 1.7-100 MHz.



(d) Cases #2 and #4 in 1.7-30 MHz.

(e) Cases #2 and #4 in 1.7-50 MHz.

(f) Cases #2 and #4 in 1.7-100 MHz.

Figure 4.4: CDFs for packet loss rate when the total power is equal to 10 dBm.

rate is due to the fact that PLC channel attenuation increase with distance.

Moreover, we show that the best results are from the frequency band of 1.7-100 MHz and the worst ones are from 1.7-30 MHz. Furthermore, we observe that the frequency bands affect more the packet loss rate than the goodput. In fact, there is a gap from 73% to 34% on packet loss rate results of PLC-CMAC on frequency bands of 1.7-30 MHz and of 1.7-100 MHz, respectively, in cases #1 and #3. In terms of goodput this gap is only from 60% to 70% on frequency bands of 1.7-30 MHz and of 1.7-100 MHz, respectively, in the same cases.

4.1.2 VARIATION OF RELAY IDLENESS

In the following analysis, we vary the node R idleness in order to evaluate its impact on PLC-CMAC results of packet loss rate and goodput. To do so, we consider only the cases #1 and #3 as they are the most suitable cases for cooperation. Also, for the same reason, we consider the frequency band of 1.7-100 MHz.

Figure 4.5 shows the relation among mean packet loss rate, total power and relay idleness (defined as the state of the node R, in which its time-slot is available for cooperations) and how they affect PLC-CMAC protocol. We note that the relay idleness variation (from 0, when the relay is always busy, to 1, when the relay is always available) does not change the packet loss rate results. As PLC-CMAC protocol always work as a cooperative protocol, it does not have any diversity change regardless of the relay availability. However, the packet loss rate increases as the total power values decreases because of higher PER on every link of the single relay model for low power levels (e.g., −20 dBm).

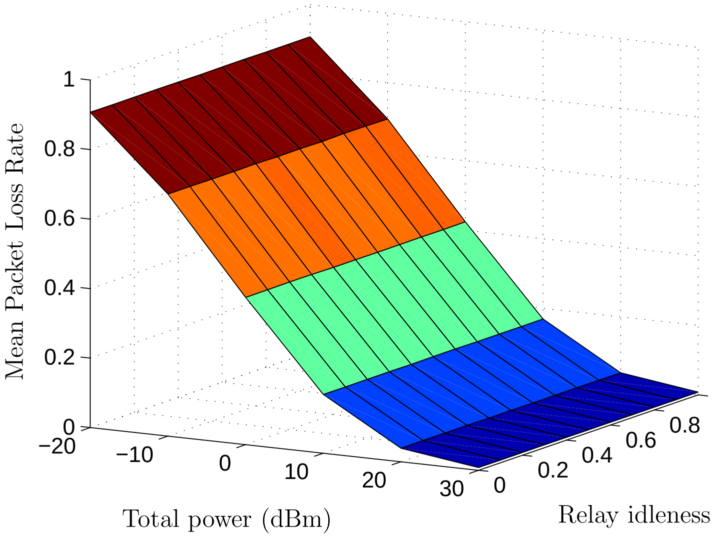


Figure 4.5: Mean values of packet loss rate when the relay idleness and the power vary

In terms of goodput, Figure 4.6 shows that the relay idleness affect the PLC-CMAC protocol performance results. When the relay is idle, the proposed protocol work as DSAC protocol and cooperate during the node R time-slot. It means that, as higher is the relay idleness, more the PLC-CMAC protocol will use the node R time-slot for retransmissions and, thus, higher will be the goodput results. Also, as in the packet loss rate analysis, the goodput results are worse for low total power values (e.g., −20 dBm).

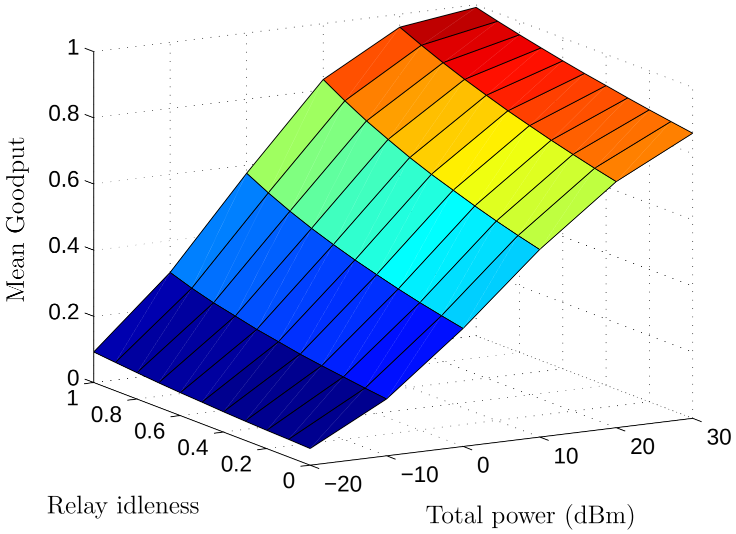


Figure 4.6: Mean values of goodput when the relay idleness and the power vary

5 COMPARISON BETWEEN OFDMA-TDMA AND TDMA-OFDM SCHEMES

OFDM scheme is also often used on PLC systems (REN et al., 2013; DAI et al., 2012; PICORONE et al., 2014). Despite the differences between OFDM and OFDMA, our MAC layer cooperation protocol can be used transparently on both. In fact, to work on TDMA-OFDM scheme, we just have to take into account that two nodes are not able to transmit data concurrently.

More precisely, Figure 5.1 shows our PLC-CMAC protocol working on a TDMA-OFDM environment. We note that, if nodes R and S receive a NACK from D, relay node R will send a want to cooperate (WTC) message to node S offering its own time-slot for retransmitting *PKT1*. In this case, we have a goodput improvement, since R will perform retransmission during its own time-slot. As consequence, S will be able to send a new packet (PKT2) during its next time-slot.

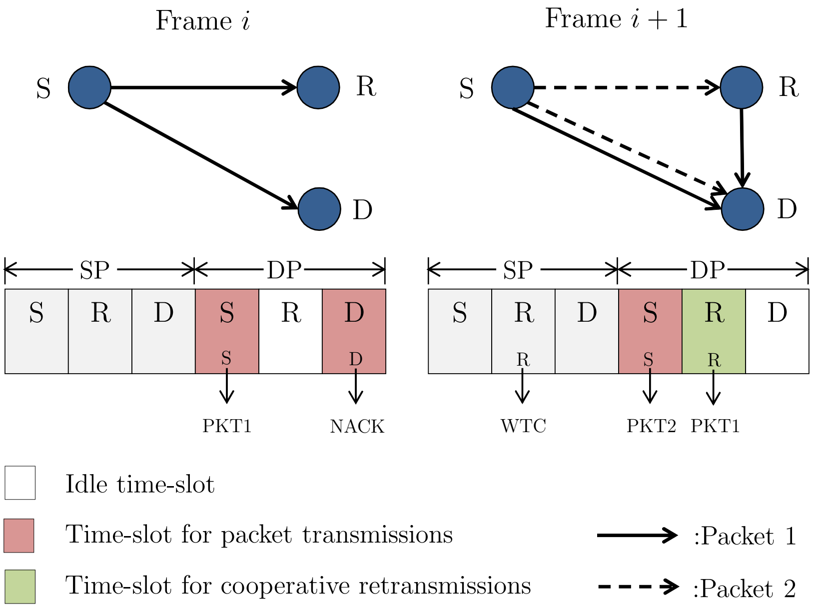


Figure 5.1: PLC-CMAC operation in the TDMA-OFDM scheme when the node R is idle.

Case relay R is busy, as show in Figure 5.2, it will not send WTC message to S. In this case, R will be able to retransmit data package during S time-slot. As consequence, data will be transmitted trough two distinct links (transmission through link SD and retransmission through link RD) and in this case, we might have a path diversity related gain. Nevertheless, this situation does not represent a goodput improvement, since node R will spend node S time-slot and, thus, node S will not be able to send a new packet in this case.

In sum, as we show in Figure 5.1 and 5.2, case node R is idle, node S will be able to send two new packets (PKT1 and PKT2) to D during two time-slots. Case node R is busy, S will need at least three time-slots to send the same amount of packets. Moreover, we note that the process showed in Figure 5.1 and 5.2 differ from the ones showed in Figures 3.2 and 3.3, in which nodes S and R were able to retransmit together due to the inherent characteristic of OFDMA-TDMA scheme.

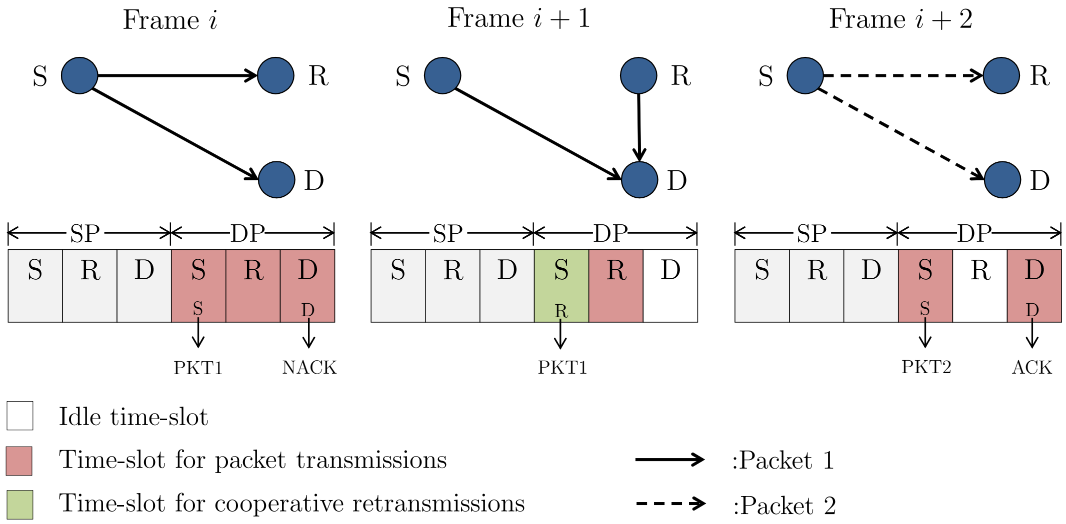


Figure 5.2: PLC-CMAC operation in the TDMA-OFDM scheme when the node R is not idle.

We have compared PLC-CMAC performance on both scenarios: a PLC system using OFDMA-TDMA and TDMA-OFDM. In the following analysis, we also consider the total power of 10 dBm. Moreover, we consider the best scenario to cooperation we previously analyzed (cases #1 and #3 from Figure 2.3 and frequency band of 1.7-100 MHz, see details of all cases in Appendixes D, E and F)). Finally, we consider all references to the OFDMA-TDMA as an uncoded scheme.

According to Figure 5.3, PLC-CMAC packet loss rate results in OFDMA-TDMA and in TDMA-OFDMA schemes and in scenario without cooperation are up to 37%, 54% and 74%, respectively, for 90% of the measured in-home PLC channels. Therefore, this figure show that OFDMA-TDMA scheme presents lower packet loss rate results than the TDMA-OFDM scheme. Furthermore, we can observe that both schemes present better results than the scenario without cooperation.

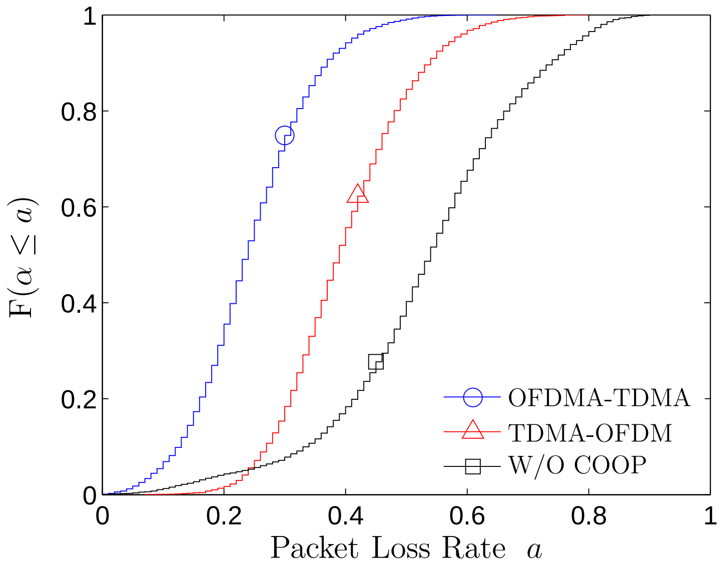


Figure 5.3: CDFs of packet loss rate results of PLC-CMAC using OFDMA-TDMA and TDMA-OFDM schemes.

In terms of goodput, Figure 5.4 shows results of PLC-CMAC in OFDMA-TDMA and in TDMA-OFDMA schemes and in scenario without cooperation are up to 70%, 54% and 42%, respectively, for 90% of the measured in-home PLC channels. Hence, the OFDMA-TDMA scheme also presents higher goodput results than TDMA-OFDM scheme. Additionally, as well as packet loss rate results, goodput results of the scenario without cooperation represent the worst case.

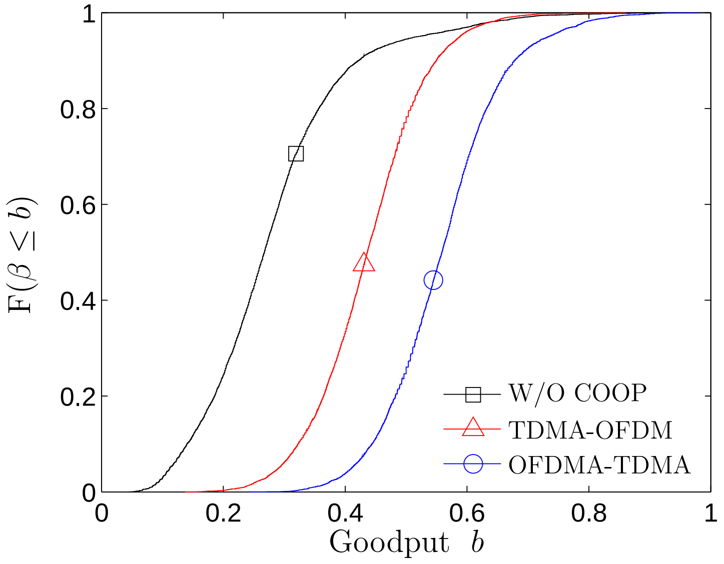


Figure 5.4: CDFs of goodput results of PLC-CMAC using OFDMA-TDMA and TDMA-OFDM schemes.

Overall, our results indicates that OFDMA-TDMA scheme, in the studied scenario, shows the best performance improvements. This occurs because, in OFDMA-TDMA scheme, it is possible to share the subcarriers between nodes S and R. Thus, these nodes can retransmit data together during the same time-slot. Otherwise, in TDMA-OFDM scheme, the node R must perform the retransmission alone, since there is not a sharing of subcarriers.

6 RELATED WORK

PLC networks are similar to wireless networks in many aspects, such as broadcast transmissions profile, adoption of multi-carrier modulation, frequency selective channel. Thus, it is not rare to find, in PLC systems, techniques adapted from wireless systems (e.g, signal processing techniques like multiple-input multiple-output (MIMO) (SCHNEIDER et al., 2008) and cognitive detection of radio frequencies (PRAHO et al., 2010)).

There is a lack of works on CMAC protocols for PLC systems in the literature. In fact, cooperation studies on PLC are focused on physical layer (LAMPE; VINK, 2012; SUNG; BOJANCZYK, 2010). For this reason, our study is based on wireless protocols to perform cooperation at the link layer of PLC systems.

Zhao et al. (2013), developed a CMAC protocol for wireless networks that works proactively. It means that the network is monitored and, if there is a parameter that indicates a possible communication problem, the cooperation process will start before the occurrence of this problem. In this protocol, a node offers its own time-slot for cooperation if its traffic queue length is less than a defined threshold. It improves the system performance reducing the number of retransmissions. However, high traffic loads nullify the cooperation, since, in this case, the traffic queue threshold may not be reached.

Lee et al. (2014), proposed a proactive cooperation which starts when a node, between S and D nodes position, correctly decodes a packet from S node. In this case, this node forwards the packet to the next node on the path to D node. This protocol does not have signaling overhead, since the relays are self-selected. However, the packets forwarding have priority in relation to R node own packets, which can generate a resource starvation problem.

Differently than (ZHAO et al., 2013) and (LEE et al., 2014), in most of the studied CMAC protocols the cooperation starts reactively. A reactive approach is simpler than the proactive one, since it does not need the use of algorithms to decide when to cooperate. The cooperation simply starts when D node responds a NACK after a packet reception failure. For this reason, we used the reactive cooperation strategy on PLC-CMAC protocol.

Lee et al. (2013), developed a CMAC protocol that works reactively on wireless networks. In this protocol, when R node receives a NACK message broadcasted by D node, if it is idle, it offers its own time-slot for cooperation. Otherwise, Yang et al. (2010) proposed a protocol that, in case of a NACK message from D node, S and R nodes retransmit the lost packet together during the S node next time-slot. We mentioned (LEE et al., 2013) and (YANG et al., 2010) advantages and disadvantages on Chapter 3.

Kong et al. (2010) proposed a CMAC protocol for wireless networks which considers that, if a packet transmission fails, R node will use its own time-slot for retransmitting this packet. However, in order to do this, R node sacrifices its time-slot. As a compensation, if the cooperative retransmission succeeds, S node will concede its next time-slot to R node. The main advantage of this protocol is that the cooperation does not depend on R node idleness. Nevertheless, if the cooperative retransmission fails, there will not be a compensation from S node and, them, the system fairness is compromised. In order to solve this problem Zheng and Kong (2010) proposed a new compensation method regardless of the retransmission failure, but it is more complex compared with (KONG et al., 2010). On the other hand, the protocol that we have developed does not need compensation methods and it is capable of perform cooperation regardless of the relay idleness without affecting system fairness.

For Sadek et al. (2006) CMAC protocol, in case of a NACK from D node, R node searches an idle time-slot belonging to any node of the network. If there is an idle time-slot, R node uses it to retransmit the packet. This protocol has the advantage of full utilizing idle time-slots of network scenario. However, if there is not at least an idle time-slot, there is not cooperation. Nevertheless, PLC-CMAC protocol does not depend on idle time-slots to perform cooperation.

Murad et al. (2011), proposed a cooperation protocol divided in two steps. The first step is a proactive process in which the S node monitors the network storing information about each network node in a local table. Then, S node chooses the best two relays from table according to their stored information: the first relay and the backup relay. The cooperation starts when S node sends a packet that is received by the first relay and the backup relay. So, the first relay forward this packet to D node. In case of a NACK from D node, the reactive process starts and the backup relay performs the second retransmission to D node. The use of this protocol can enhance the system reliability. Nevertheless, S node needs to store a table of all network neighbors and calculate which ones are the best relay candidates. However, PLC-CMAC protocol does not need to involve more than one relay in the cooperation process and to spend resources storing network information.

Overall, we described CMAC protocols for wireless networks due to the lack of works on CMAC protocols for PLC networks. Additionally, most of the studied protocols use the reactive approach, which is simpler than the proactive one. Thus, we developed a CMAC protocol for PLC systems taking into account the simplest wireless approach capable of exploit the diversity offered by a PLC network, considering a single relay model.

7 CONCLUSION

In this work, we have addressed a comprehensive analysis of cooperative communication at link layer to reveal under which circumstances the use of a cooperative MAC protocol may improve in-home broadband PLC systems. To support this discussion, we presented a statistical packet error rate analysis of measured in-home PLC channels by adopting a single relay model. Additionally, we outlined a simple cooperative MAC protocol that was capable of exploiting the diversity offered by in-home electric power grids. Our cooperation protocol can reduce packet loss rate up to 39% in 1.7-100 MHz for 90% of the measured samples, compared with a system without cooperation. In terms of goodput, our cooperation protocol, compared with the system without cooperation, can improve system performance up to 35% in 1.7-100 MHz for 90% of the measured samples.

Furthermore, results showed that values of packet error rate of link source-destination, in most of cases, were higher than the packet error rate of link source-relay and the packet error rate of link relay-destination. As a consequence, cooperation at the link layer improves system performance. Also, we show that cooperative protocols at the link layer are more effective if packet error rate assumes intermediate values (between 0 and 1). Moreover, we conclude that the frequency band of 1.7-100 MHz tends to be more appropriate for cooperation. In the other hand, the frequency band of 1.7-30 MHz offers the lowest improvement. Therefore, cooperation may present better system performance to higher frequency bands. Additionally, we note that the cases in which node relay is equidistant from nodes source and destination or closer to node source (cases #1 and #3) offer the best performance improvement results. It is justified by the node R position, which is closer to node S in the cases #1 and #3 than in the cases #3 and #4, in which node relay is closer to node destination or far from nodes source and destination. Because of it, the link source-relay presents smaller packet error rates in the former cases.

Finally, we compared PLC-CMAC protocol results working in OFDMA-TDMA and TDMA-OFDM schemes, separately. For OFDMA-TDMA scheme, the packet loss rate results are up to 37% in the frequency band of 1.7-100 MHz for 90% of the measured in-home and cooperative PLC channels. For TDMA-OFDM scheme in the same frequency band, the results are up to 54%. In terms of goodput, the OFDMA-TDMA scheme results are up to 70% in the frequency band of 1.7-100 MHz for 90% of the measured in-home and cooperative PLC channels. Lastly, the results for TDMA-OFDM scheme are up to 54% at the same conditions. Thus, we conclude that, for the analysed factors, the OFDMA-TDMA scheme presents the best results of network performance improvement, when we adopt the PLC-CMAC protocol. Nevertheless, the TDMA-OFDM scheme is, also, better than the system without cooperation in terms of packet loss rate and goodput improvement.

As future work, we intend to evaluate our cooperative MAC protocol under the presence of multiple relays and take into account network delay and transmission rate.

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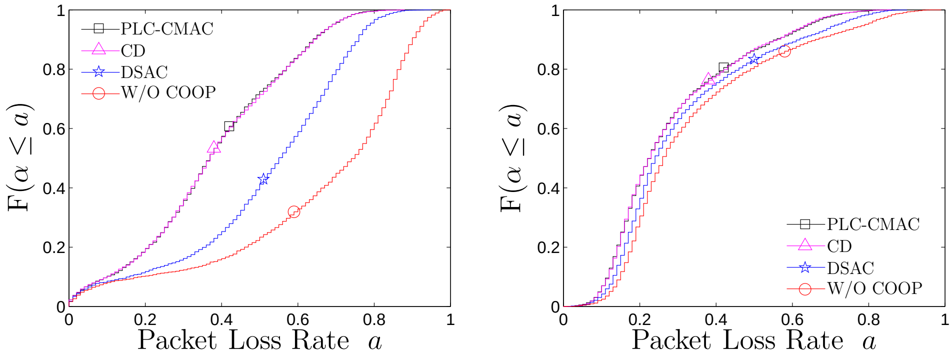
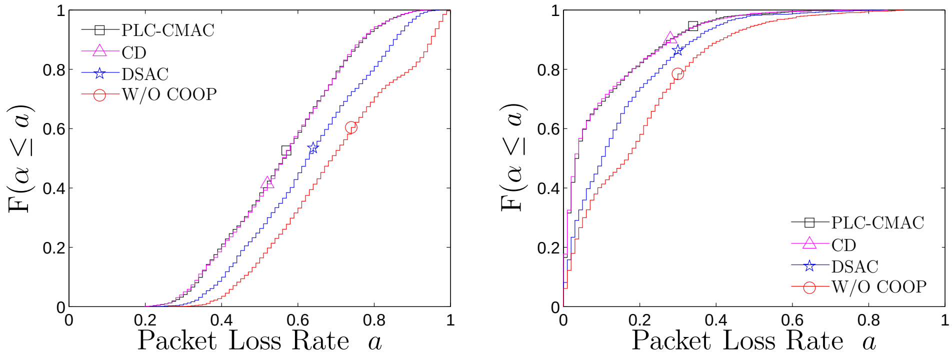
Appendix A - CASES #1 TO #4 IN FREQUENCY BAND OF 1.7-30 MHZ

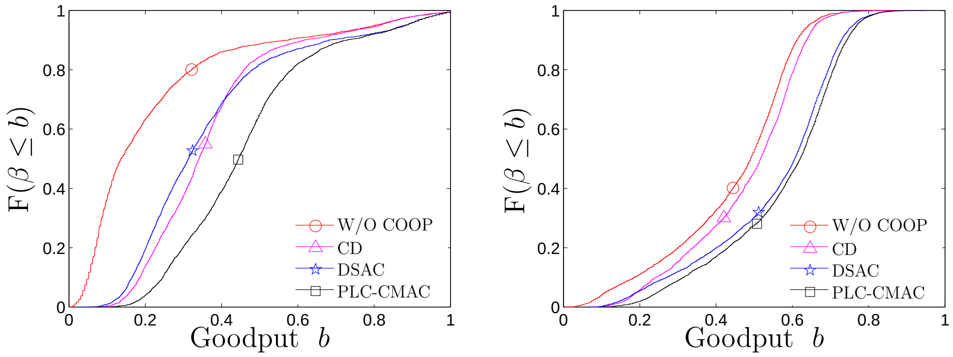


(a) Case #1. (b) Case #2.

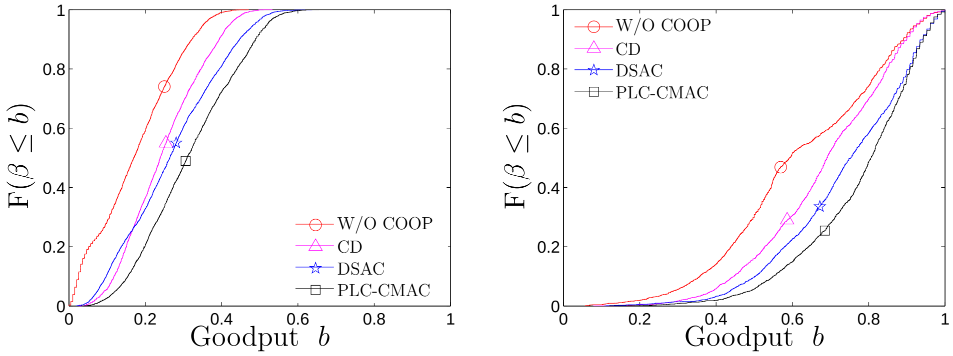


(c) Case #3. (d) Case #4.

Figure A.1: CDFs for packet loss rate in the frequency band of 1.7-30 MHz.



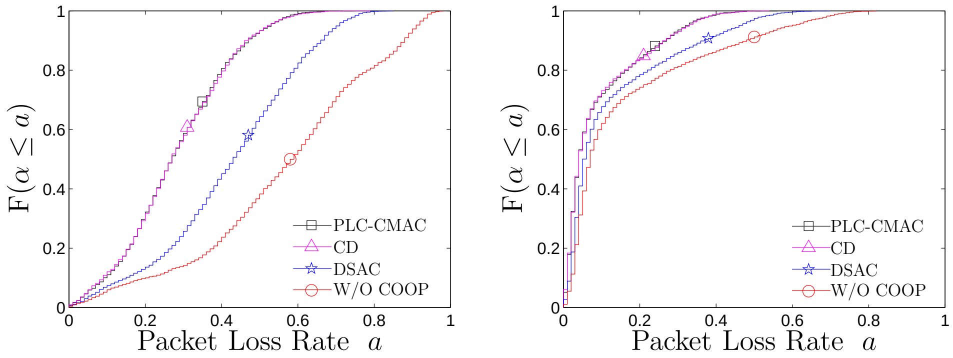
(a) Case #1. (b) Case #2.



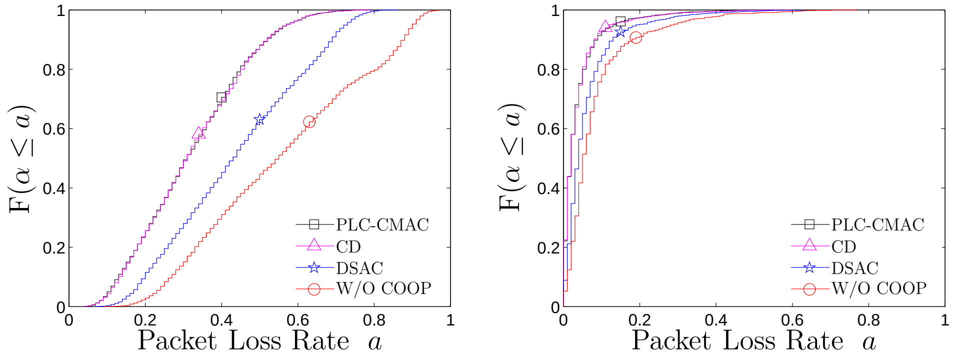
(c) Case #3. (d) Case #4.

Figure A.2: CDFs for goodput in the frequency band of 1.7-30 MHz.

Appendix B - CASES #1 TO #4 IN FREQUENCY BAND OF 1.7-50 MHZ

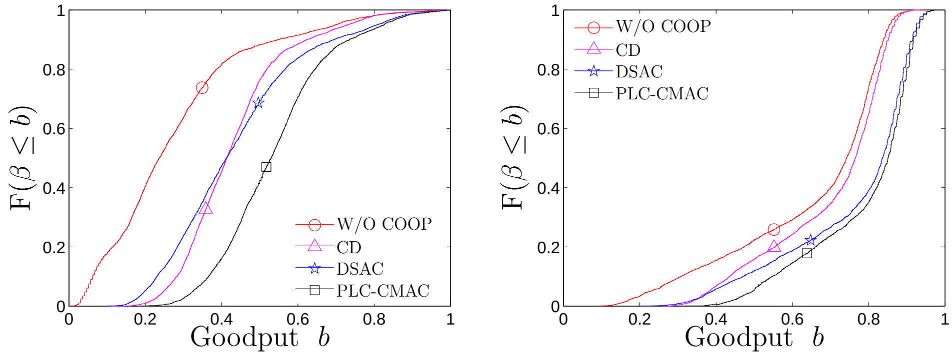


(a) Case #1. (b) Case #2.



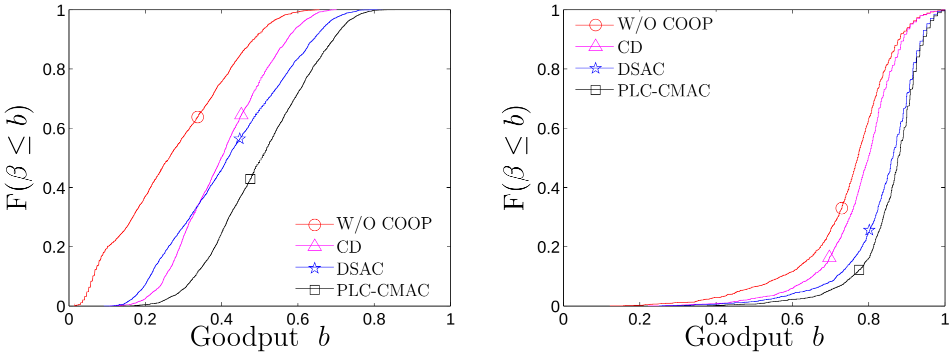
(c) Case #3. (d) Case #4.

Figure B.1: CDFs for packet loss rate in the frequency band of 1.7-50 MHz.



(a) Case #1.

(b) Case #2.

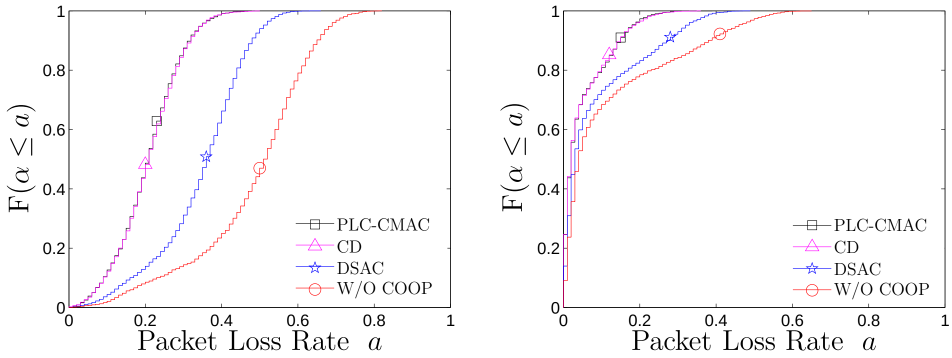


(c) Case #3.

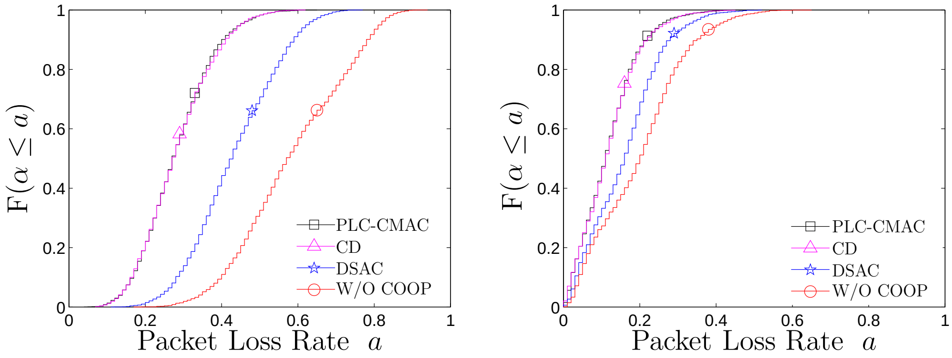
(d) Case #4.

Figure B.2: CDFs for goodput in the frequency band of 1.7-50 MHz.

Appendix C - CASES #1 TO #4 IN FREQUENCY BAND OF 1.7-100 MHZ

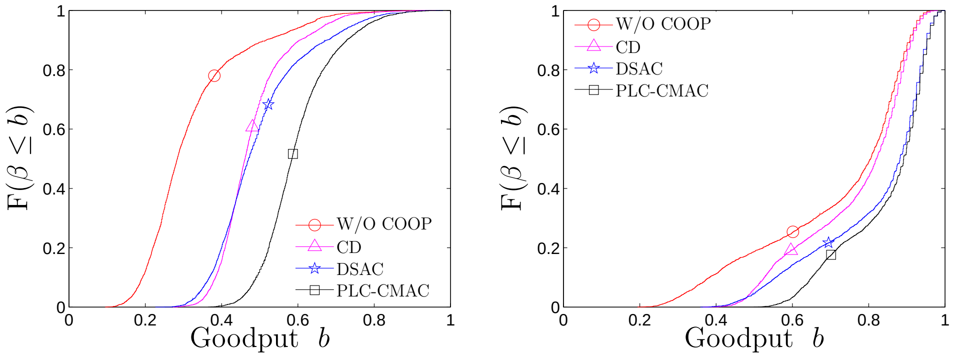


(a) Case #1. (b) Case #2.



(c) Case #3. (d) Case #4.

Figure C.1: CDFs for packet loss rate in the frequency band of 1.7-100 MHz.



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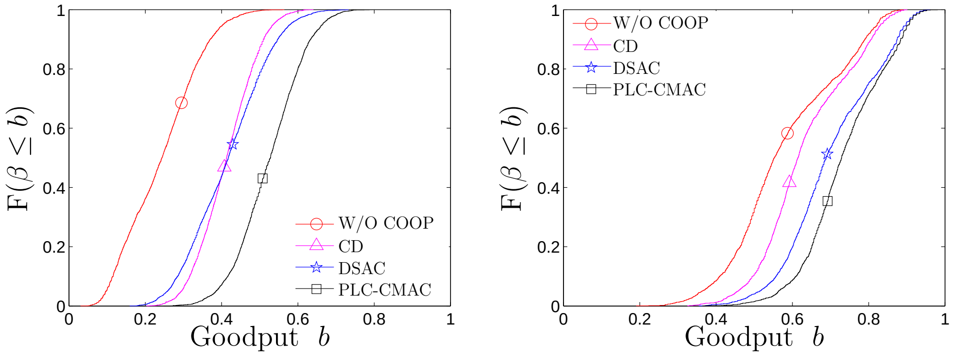
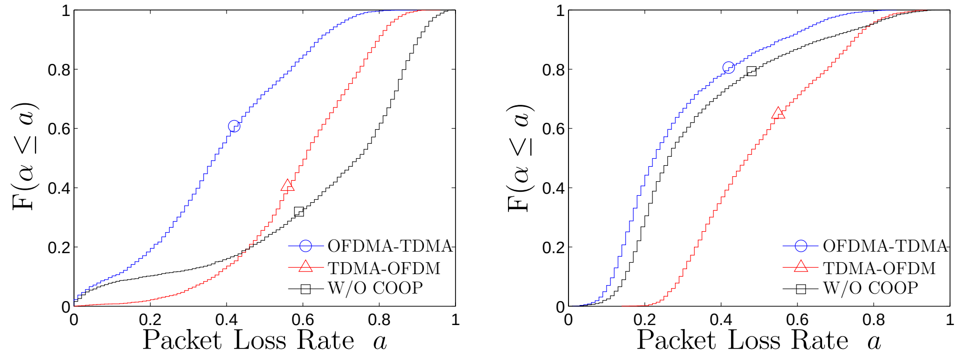


(c) Case #3. (d) Case #4.

Figure C.2: CDFs for goodput in the frequency band of 1.7-100 MHz.

Appendix D - COMPARISON BETWEEN OFDMA-TDMA AND TDMA-OFDM: CASES #1 TO #4 IN FREQUENCY BAND OF 1.7-30 MHZ



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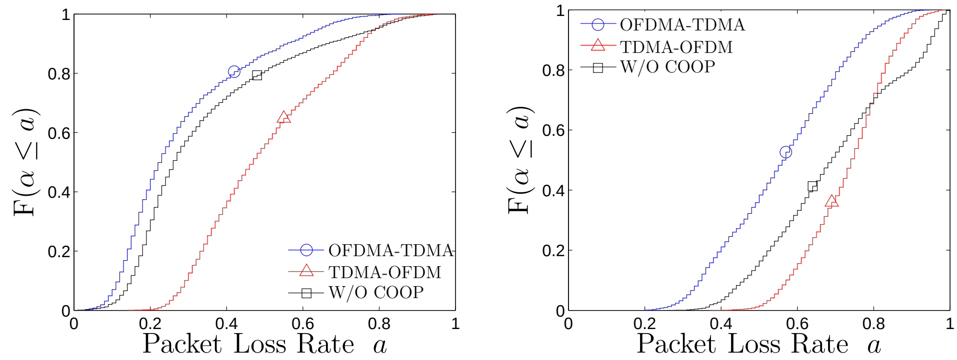
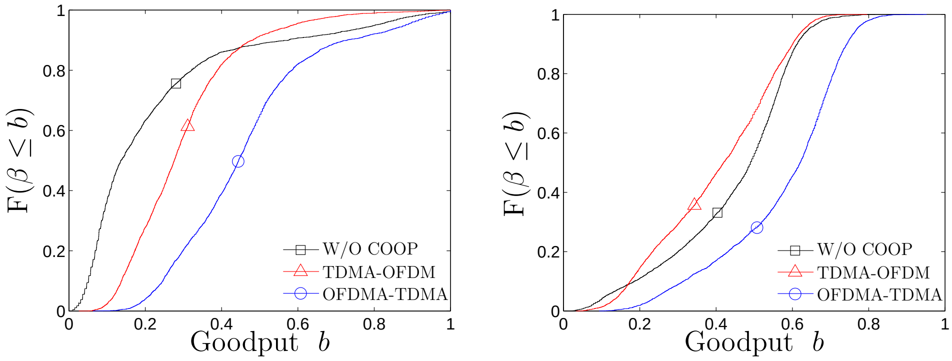


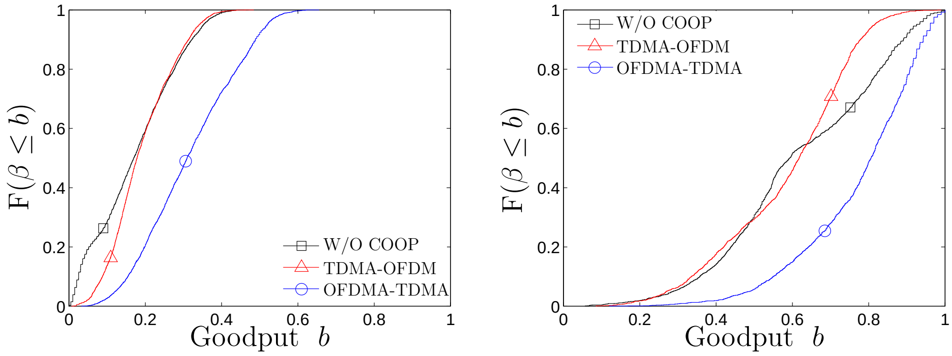
(c) Case #3. (d) Case #4.

Figure D.1: CDFs of PLC-CMAC packet loss rate results using OFDMA-TDMA and TDMA-OFDM schemes in 1.7-30 MHz.



(a) Case #1.

(b) Case #2.

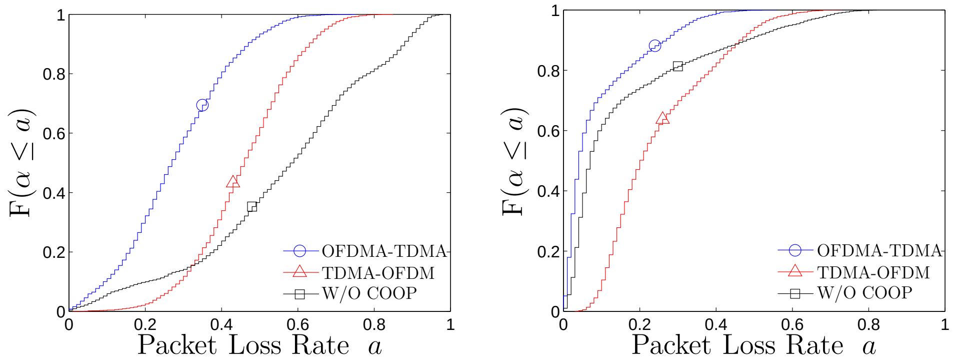


(c) Case #3.

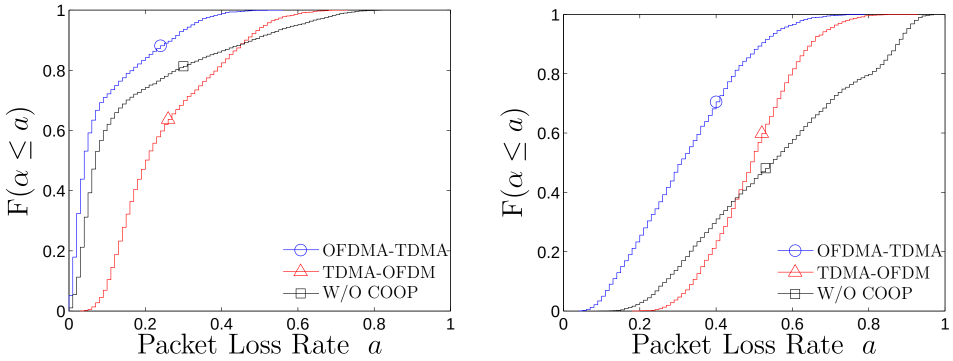
(d) Case #4.

Figure D.2: CDFs of PLC-CMAC goodput results using OFDMA-TDMA and TDMA-OFDM schemes in 1.7-30 MHz.

Appendix E - COMPARISON BETWEEN OFDMA-TDMA AND TDMA-OFDM: CASES #1 TO #4 IN FREQUENCY BAND OF 1.7-50 MHZ

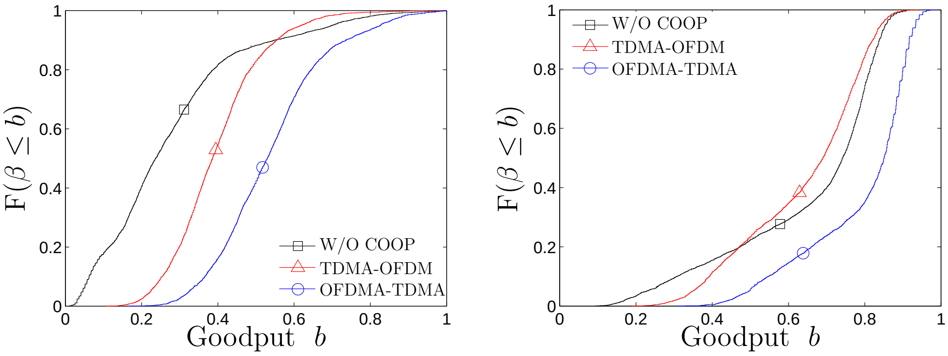


(a) Case #1. (b) Case #2.

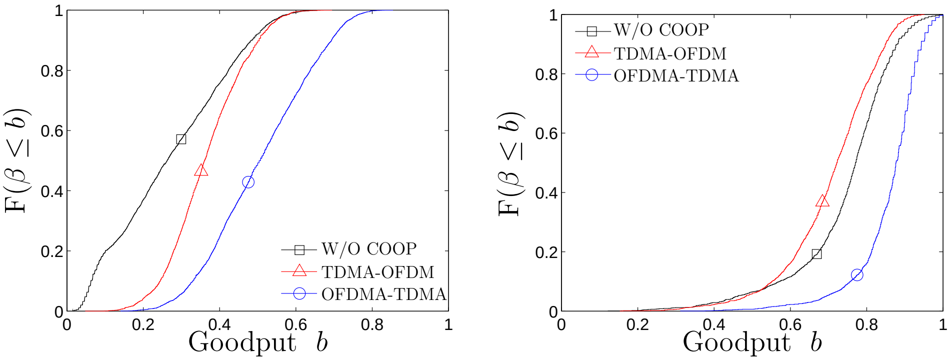


(c) Case #3. (d) Case #4.

Figure E.1: CDFs of PLC-CMAC packet loss rate results using OFDMA-TDMA and TDMA-OFDM schemes in 1.7-50 MHz.



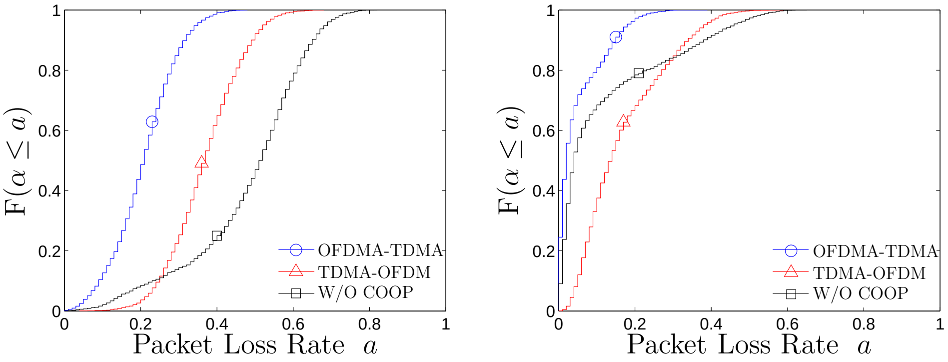
(a) Case #1.　(b) Case #2.



(c) Case #3.　(d) Case #4.

Figure E.2: CDFs of PLC-CMAC goodput results using OFDMA-TDMA and TDMA-OFDM schemes in 1.7-50 MHz.

Appendix F - COMPARISON BETWEEN OFDMA-TDMA AND TDMA-OFDM: CASES #1 TO #4 IN FREQUENCY BAND OF 1.7-100 MHZ



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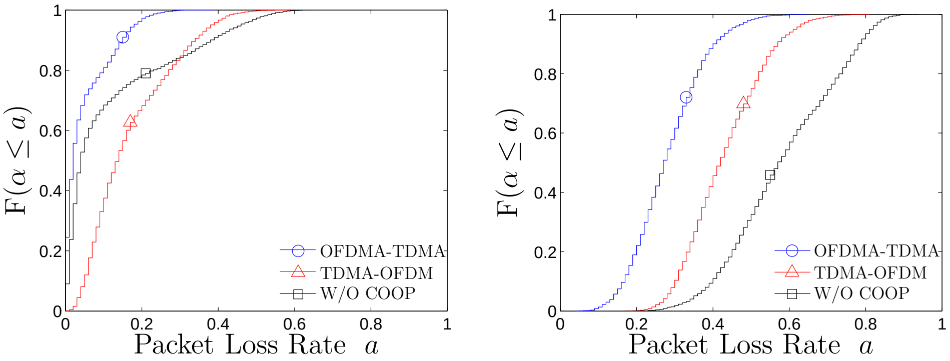
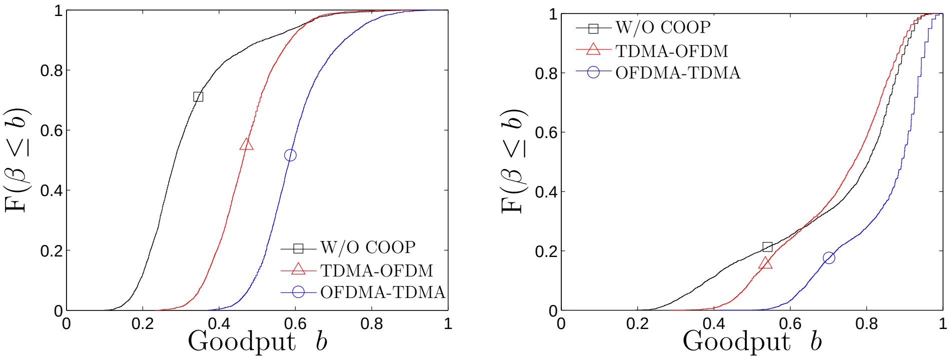
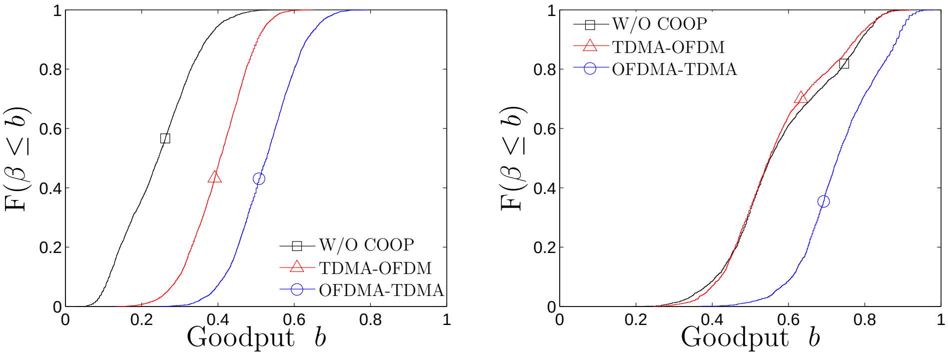


(c) Case #3. (d) Case #4.

Figure F.1: CDFs of PLC-CMAC packet loss rate results using OFDMA-TDMA and TDMA-OFDM schemes in 1.7-100 MHz.



(a) Case #1. (b) Case #2.



(c) Case #3. (d) Case #4.

Figure F.2: CDFs of PLC-CMAC goodput results using OFDMA-TDMA and TDMA-OFDM schemes in 1.7-100 MHz.