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MARIANO EDUARDO BURICH

A CROSS LAYER ANALYSIS OF HARQ PROTOCOLS IN WIRELESS NETWORKS

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A CROSS LAYER ANALYSIS OF HARQ PROTOCOLS IN WIRELESS NETWORKS

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Título da Dissertação Nº. ____

Uma Análise Entre-Camadas de Protocolos HARQ em Redes Sem Fio

por

Mariano Eduardo Burich

Orientador: Prof. Dr. Richard Demo Souza (UFSC)
Coorientador: Prof. Dr. Glauber Gomes de Oliveira Brante (UTFPR)

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”The absence of evidence is not the evidence of absence.”

(Carl Sagan)

RESUMO

BURICH, Mariano E.. UMA ANÁLISE ENTRE-CAMADAS DE PROTOCOLOS HARQ EM REDES SEM FIO. 43 f. Dissertação – Programa de Pós-graduação em Engenharia Elétrica e Informática Industrial, Universidade Tecnológica Federal do Paraná. Curitiba, 2017.

Este trabalho estuda as potenciais melhorias na eficiência energética e vazão do método híbrido de requisição automática de retransmissão (*Hybrid Automatic Retransmission Request*, HARQ). A análise inclui as camadas física (PHY) e de acesso ao meio (MAC). É investigada a relação de compromisso gerada pelo HARQ, o qual demanda uma menor potência de transmissão para uma certa probabilidade de falha alvo ao custo de mais acessos ao canal. Uma vez que a competição para acesso ao canal na camada MAC é bastante custosa em termos de energia e atraso, os resultados mostram que a utilização do HARQ leva a uma grande melhoria de performance devido ao menor número de nós competidores – uma consequência da redução na potência de transmissão necessária. Contra-intuitivamente, esta análise leva à conclusão que retransmissões podem diminuir o atraso, melhorando a performance do sistema. Finalmente, são também investigados valores ótimos para o número de retransmissões permitidas, visando maximizar vazão ou/e eficiência energética.

Palavras-chave: Híbrido de Requisição Automática de Retransmissão, Análise Entre-Camadas, Eficiência Energética, IEEE 802.11

ABSTRACT

BURICH, Mariano E.. A CROSS LAYER ANALYSIS OF HARQ PROTOCOLS IN WIRELESS NETWORKS. 43 f. Dissertação – Programa de Pós-graduação em Engenharia Elétrica e Informática Industrial, Universidade Tecnológica Federal do Paraná. Curitiba, 2017.

This work studies the potential improvements in terms of energy efficiency and throughput of a hybrid automatic retransmission request (HARQ) mechanism. The analysis includes both the physical (PHY) and medium access (MAC) layers. We investigate the trade-off provided by HARQ, which demands reduced transmit power for a given target outage probability at the cost of more accesses to the channel. Since the competition for channel access at the MAC layer is very expensive in terms of energy and delay, our results show that HARQ leads to great performance improvements due to the decrease in the number of contending nodes – a consequence of the reduced required transmit power. Counter-intuitively, our analysis leads to the conclusion that retransmissions may decrease the delay, improving the system performance. Finally, we investigate the optimum values for the number of allowed retransmissions in order to maximize either the throughput or the energy efficiency.

Keywords: Hybrid Automatic Repeat Request, Cross-Layer Analysis, Energy Efficiency, IEEE 802.11

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LIST OF ACRONYMS

ACK	Acknowledge
ARQ	Automatic Repeat Request
AWGN	Additive White Gaussian Noise
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
CTS	Clear To Send
DCF	Distributed Coordinated Function
DIFS	DCF interframe space
FEC	Forward Error Correction
HARQ	Hybrid Automatic Repeat Request
HCF	Hybrid Coordination Function
IEEE	Institute of Electrical and Electronics Engineers
MAC	Medium Access Control
MCF	Mesh Coordination Function
MRC	Maximum Ratio Combining
NAV	Network Allocation Vector
OSI	Open Systems Interconnection
PCF	Point Coordination Function
PHY	Physical
QoS	Quality of Service
RTS	Request To Send
SIFS	Short Interframe Space
SNR	Signal-to-Noise Ratio
VoIP	Voice over IP
WLAN	Wireless Local Area Networks
WSN	Wireless Sensor Networks

LIST OF SYMBOLS

B	Bandwidth
C	Channel capacity
CW	Contention window size
CW_{max}	Maximum contention window size
CW_{min}	Minimum contention window size
$E[L]$	Average time for the backoff counter to decrement
$E[X]$	Average number of backoff counts for successful channel access
G_{η}	Energy efficiency gain
$G_{\mathcal{P}}$	Transmit power gain
$G_{\mathcal{T}}$	Throughput gain
H	Header size
I	Payload size
M	Maximum number of transmission allowed
N	Average number of required transmissions per data packet
N_0	Noise power spectral density
P_{rx}	Receiver power consumption
P_{r}	Average received power
P_{sp}	Power consumed by signal processing
P_{tx}	Total power consumption at the source node
P_{t}	Transmit power
P_{th}	Receiver sensitivity
Q	Total packet size
R	Data transmission rate
R_c	Control transmission rate
T_D	Time consumed by data transmission
T_H	Time consumed by header transmission
T_{ACK}	Time consumed by ACK message
T_{CTS}	Time consumed by CTS message
T_{DIFS}	Distributed Coordinated Function interframe time
T_{MAC}	Overhead of the MAC protocol
T_{RTS}	Time consumed by RTS message
T_{SIFS}	Short interframe space time
T_{c}	Time the medium is sensed busy by nearby nodes in case of collisions
T_s	Time the medium is sensed busy by nearby nodes in case of a successful transmission
α	Path loss exponent
$\mathcal{O}$	System outage probability
$\mathcal{T}$	System throughput
δ	Propagation delay
η	Energy efficiency
γ	Instantaneous receiver SNR
γ_0	Minimum necessary SNR at the receiver

λ	Wavelength
$\bar{R}(M)$	Average transmission rate
$\bar{\gamma}$	Average received SNR
$\mathbf{n_g}$	Additive white Gaussian noise
$\mathbf{x}$	Transmitted packet
$\mathbf{y}$	Received packet
μ	Transmitter power efficiency
ρ	Network node density
σ	Time slot
τ	Probability that a station transmits in a randomly chosen time slot
c	Propagation speed
d	Distance between source and destination nodes
f	Frequency
h	Channel fading
n	Number of contending nodes
p	Probability that a transmitted packet collides
p_{s}	Probability that a transmission occupying the channel is successful (no collisions)
p_{tr}	Probability of at least one node transmitting at a random slot
p_{out}	Single transmission outage probability
$\mathcal{O}^*$	Target outage probability
$\mathcal{D}_{\mathrm{MAC}}$	MAC layer delay
$\mathcal{D}_{\mathrm{PHY}}$	PHY layer delay
$\mathcal{D}_{\mathrm{total}}$	Total delay
$\mathcal{E}_{\mathrm{MAC}}$	MAC layer energy consumption
$\mathcal{E}_{\mathrm{PHY}}$	PHY layer energy consumption
$\mathcal{E}_{\mathrm{access}}$	Energy consumption by channel access attempts
$\mathcal{E}_{\mathrm{total}}$	Total energy consumption
$\mathcal{E}_{\mathrm{wait}}$	Energy consumption while waiting for the backoff counter to expire
$\mathcal{T}_{\mathrm{MAC}}$	MAC layer throughput
$\mathcal{T}_{\mathrm{PHY}}$	PHY layer throughput
η_{MAC}	MAC layer energy efficiency
η_{PHY}	PHY layer energy efficiency

SUMÁRIO

1 INTRODUCTION

Wireless communications have been continuously growing for the past years, with mobile data traffic increasing eighteen times on the last five years and 63% between 2015 and 2016, reaching 7.2 exabytes per month. Future prospects are very positive for this segment, indicating that the mobile data traffic compound annual growth rate will be 47% until 2021, reaching 49 exabytes per month on that year (CISCO, 2017). While estimates point to a significant increase of data traffic demand, technological challenges also arise due to the need of providing faster and sustainable wireless networks. If present paradigms are used in order to provide the expected level of device connectivity, it will be inevitable to cause an energy crunch with severe economic and environmental concerns (BUZZI et al., 2016). Furthermore, energy consumption is also important in battery-powered applications, such as Wireless Sensor Networks (WSN), which consequently demand energy-efficient protocols. Energy consumption of a network architecture depends on several factors, such as transmit power, circuitry consumption, data rate and transmission scheme, which can all be grouped into the energy efficiency metric, defined as the ratio between the amount of bits correctly decoded and the total energy expenditure (CHEN et al., 2011; LI et al., 2011).

Communication networks have focused on performance parameters such as throughput for over a century, however, due to the previously presented facts, penalizing throughput in order to achieve a better energy efficiency is acceptable (BUZZI et al., 2016). Nevertheless, delay and throughput analysis are still important in order to achieve a certain Quality of Service (QoS), as demanded by time constrained applications such as voice over IP (VoIP), multimedia streaming and interactive video (OZMEN; GURSOY, 2016).

The interest in Wireless Local Area Networks (WLAN) led the IEEE to create a study group to standardize a protocol for this type of application (BIANCHI, 2000), which later resulted in one of the most well known wireless protocols: the IEEE 802.11 standard (IEEE, 2012), also known as Wi-Fi. This protocol embraces rate adaptation, optional Request To Send (RTS) and Clear To Send (CTS) packets (solve hidden node problem), centralized and ad-hoc capabilities, and a contention based channel access which relies on exponential backoffs upon packet collision. Due to its simplicity and popularity, it later became subject of study of several works, which include throughput and energy analysis, such as (BIANCHI, 2000; XU; SAADAWI, 2001; CARVALHO; GARCIA-LUNA-ACEVES, 2003; CHATZIMISIOS et al., 2003; CARVALHO et al., 2004; SERRANO et al., 2010; KIM; STARK, 2012, 2014; PERON et al., 2016).

The IEEE 802.11 specification uses the OSI (Open Systems Interconnection) model as a basis to organize its protocol structure and preserve compatibility. The OSI model is composed by seven layers with defined roles, providing a way to organize the function of each protocol and how they should be grouped to provide a certain communication. The IEEE 802.11 specifies the Physical (PHY) and the Medium Access Control (MAC) layers, which respectively correspond to the first and half of the second layer of the OSI model. While the PHY layer is in charge of defining the modulation, bit rate, bandwidth and transmit power, the MAC layer controls the access to the communication medium.

The first work to present a throughput model that embraces all backoff characteristics of the IEEE 802.11 MAC Distributed Coordinated Function (DCF) was (BIANCHI, 2000). The protocol's accurate modeling allowed works to consider joint PHY and MAC characteristics, including the relation between transmit power and MAC throughput (KIM; STARK, 2014), leading to the name "Cross-layer" in this context and a more accurate system model.

Energy consumption measurements of 802.11 network cards in ad-hoc mode were performed by (FEENEY; NILSSON, 2001; EBERT et al., 2002a) and (EBERT et al., 2002b), nevertheless, none of these works evaluated the energy spent in channel contention. An analytical model which characterizes 802.11 node service time is presented in (CARVALHO; GARCIA-LUNA-ACEVES, 2003), whereupon an energy model which embraces MAC operations was constructed (CARVALHO et al., 2004), however, neglecting throughput performance. In (KIM; STARK, 2014) an energy and throughput analysis based on (BIANCHI, 2000) and (CHATZIMISIOS et al., 2003) was presented for the IEEE 802.11 in a fast fading Rayleigh channel, concluding that the DCF caused a major impact on energy and throughput as the transmit power was increased. For a constant distance, in order to improve the PHY characteristics, the transmit power was increased, leading to a higher channel capacity. However, an increased transmit power had negative effects on the MAC layer because now the network nodes presented a higher communication range, increasing channel access time and energy consumption. In that same paper, benefits of using a relay node were also explored. When considering a relay node, one more transmission round needs to be performed for both MAC and PHY layers. Since the relay node is between source and destination nodes, the distance for each hop is decreased, leading to a lowered transmit power, achieving gains in the PHY and MAC layers for certain conditions.

Retransmissions provided by Hybrid Automatic Repeat Request (HARQ) protocols may improve the system performance similarly to the use of relay nodes. By allowing retransmissions in a slow-fading channel, the required SNR (Signal-to-Noise Ratio) to obtain a certain outage probability is decreased, which can have positive effects in the MAC layer. However, retransmissions also require an increased amount of channel accesses per information bit, leading to a relation worth exploring, thus, motivating the study of HARQ in the 802.11 energy and throughput environment. In the literature, optimum power allocation for HARQ was considered in (CHAITANYA; LARSSON, 2013) and (SU et al., 2011), minimizing the necessary transmit power in quasi-static fading scenarios. HARQ trade-off between spectral and energy efficiency was analyzed by (WU et al., 2014) while a closed-form expression for energy efficiency was provided by (GE et al., 2015). Nevertheless, the effect of retransmissions in MAC layer contention was not explored by these papers. Moreover, (PERON et al., 2016) expands the 802.11 cross-layer energy framework provided by (KIM; STARK, 2014) into a multiple antenna scenario, however, HARQ is not considered.

Differently from previous work, we assume single-hop links using HARQ within a wireless network where multiple nodes contend for channel access. Moreover, we consider quasi-static Rayleigh fading where a target outage probability must be ensured at the receiver, which is common in practice.We perform a cross-layer analysis, including the PHY and MAC layers, in terms of two metrics: system throughput and energy efficiency. In a preliminary intuitive analysis, HARQ should decrease energy consumption because it enables the use of a lower transmit power for a fixed target outage probability. Moreover, the use of HARQ should also increase the number of channel access attempts, which for a contention based MAC protocol may lead to negative effects, increasing the delay and thus decreasing the throughput. However, as a matter of fact, our results show that despite the need for more channel accesses, HARQ provides simultaneous benefits on throughput and energy efficiency because the contending radius is decreased. The great improvements in the MAC layer are mainly due to the reduced required transmit power, which decreases the communication radius, and thus, the number of contending nodes per area, providing major benefits in terms of throughput and delay. Moreover, we also investigate the optimum number of retransmissions in order to maximize either the system throughput or the energy efficiency. Finally, it is worth mentioning that this work was partially presented in the 2017 Wireless Days Conference (BURICH et al., 2017).

1.1 OBJECTIVES

The main goal of this work is to perform a PHY/MAC cross-layer analysis of the impact of retransmissions in energy and throughput on a single-hop IEEE 802.11 environment. Differently from previous literature, the framework presented by (KIM; STARK, 2014) is expanded to support Chase Combining HARQ in a quasi static Rayleigh fading channel with fixed bit rate.

More specifically, we aim at evaluating if retransmissions can provide energy and throughput benefits, and if so, analyze how they change according to the number of allowed retransmissions.

1.2 DOCUMENT ORGANIZATION

Theoretical contextualization regarding outage probability, IEEE 802.11 MAC, and HARQ protocols are discussed in Chapter 2. The proposed scheme is introduced in Chapter 3. Numerical results and conclusions are respectively presented in Chapters 4 and 5.

2 THEORETICAL CONTEXTUALIZATION

2.1 OUTAGE PROBABILITY

The data packets sent by the source to the destination node suffer degradation provoked by the wireless channel, which can be modeled in several ways depending on the environment and transmission parameters and also separated into two different types: small-scale fading and large-scale fading. While the latter is caused by path loss and shadowing by objects, affecting the average received power, the former is caused by constructive and destructive addition of multipath signals, affecting the instantaneous received power (GOLDSMITH, 2005). Among the diverse models which exist for each type of fading, we consider a quasi-static Rayleigh channel due to the assumption of a small node mobility, with a path loss expressed by

$$P_{\mathrm{r}} = \frac{P_{\mathrm{t}}\lambda^2}{16\pi^2 d^{\alpha}}, \tag{11}$$

where P_{t} is the transmit power, P_{r} is the average received power, α is the path loss exponent and λ the wavelength.

In order to properly understand the characteristics which affect the decoding capabilities of a given packet, the received symbols must be modeled from the receiver's point of view after channel degradation and additive reception noise, leading to the following relationship

$$\mathbf{y} = \sqrt{P_{\mathrm{r}}}h\mathbf{x} + \mathbf{n_g}, \tag{12}$$

where h is the channel fading, $\mathbf{x}$ is the transmitted packet and $\mathbf{n_g}$ is the additive white Gaussian noise (AWGN) with power spectral density $N_0/2$ per dimension.

A quasi-static channel implies that the channel coefficient h is constant throughout the transmission of a certain packet, while changing in an independent way from packet to packet. We assume the channel as quasi-static because in our particular scenario mobility is supposed to be very small. The performance of communications in slow-fading channels is mainly defined by the outage probability, which can be interpreted as the probability that a certain received packet cannot be decoded.

In order to evaluate the outage probability, it is necessary to define the minimum required SNR for a certain packet to be decoded. In (SHANNON, 1948), Claude Shannon introduces the idea of channel capacity, which corresponds to the maximum amount of mutual information that can be reliably transmitted from a node to another, which for an AWGN channel is defined as

$$C = B\log(1+\gamma), \tag{13}$$

where C is the channel capacity in bits/s, B is the bandwidth and γ is the instantaneous SNR.

According to Shannon, there exists a code which achieves data rates arbitrarily close to channel capacity with negligible bit error rate. Thus, if we assume that our scenario uses such code and that transmission occurs at a bit rate R, then the channel capacity relation can be adapted to

$$R = B\log(1+\gamma_0), \tag{14}$$

where γ_0 is the minimum necessary SNR at the receiver for correct packet decoding.

Instantaneous receiver SNR is defined by the ratio between signal and noise power (N_0B),

$$\gamma = |h|^2 \frac{P_\mathrm{r}}{N_0 B}. \tag{15}$$

Since the channel coefficient affects the magnitude and power of the received symbols, the SNR is affected by small-scale fading, resulting in an exponential-distributed SNR for a Rayleigh channel, the average received SNR $\bar{\gamma}$ is then P_r/N_0B.

Moreover, outage probability for a single transmission, p_{out}, is defined as the chance of incorrect packet decoding, or in other words, the probability that γ is less than γ_0, which when considering h as a Rayleigh random variable leads to

$$p_{out} = p(\gamma < \gamma_0) = p\left(|h|^2 < \frac{\gamma_0}{\bar{\gamma}}\right) = 1 - e^{-\gamma_0/\bar{\gamma}}. \tag{16}$$

In the following sections, (16) will be revisited and adapted to consider benefits provided by retransmissions (HARQ) on the outage probability. Nonetheless, the concept expressed by outage probability is still the same.

2.2 IEEE 802.11

When considering an ad-hoc network with nodes that may transmit at any instant, a MAC layer is necessary in order to coordinate which node has the turn to access the shared medium. If all nodes transmit whenever they have new packets, there would be an excessive interference between nearby nodes at the same frequency, jeopardizing an effective communication. The MAC layer specified by the IEEE 802.11 is in charge of several tasks, among which the most relevant to this work are: packet size, packet collision avoidance, actions to be taken in case of an unsuccessful transmission, and the use of RTS/CTS packets.

The IEEE standard specifies the DCF, Hybrid Coordination Function (HCF), Point Coordination Function (PCF) and Mesh Coordination Function (MCF) to access the wireless channel, among which DCF is the fundamental method and of mandatory implementation. HCF provides QoS functionalities specified by IEEE 802.11e, however, this function is not considered because QoS is not the focus on this work. The PCF is less used and of optional implementation, depending on a centralized network infrastructure, nevertheless, our scenario characterizes an ad-hoc network, thus, this function is not considered as well. Moreover, even though mesh networks are related to ad-hoc infrastructures, they depend on multi-hop and routing protocols, which are also not the focus of this analysis. Based on the above, the DCF is chosen as the access method to be considered in this scenario.

2.2.1 DISTRIBUTED COORDINATION FUNCTION

According to the IEEE 802.11 specification, all stations must implement the DCF in both ad-hoc and infrastructure modes. The DCF access method is known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), which consists on waiting for the medium to be free in order to transmit its packet. Different from wired Ethernet (IEEE 802.3), which uses Collision Detection (CSMA/CD) instead of Avoidance, the stations must transmit their whole data packet (or RTS packet) before sensing if another station was simultaneously transmitting. This occurs because full-duplex radios were not widely commercially available when the specification was designed, thus, resulting in a MAC for half-duplex communications. Furthermore, even if the source station were able to sense a collision during its own transmission, that would not necessarily lead to a packet collision at the receiver, requiring another approach to solve this problem. In order to solve these issues, and verify if there was a packet collision or any other communication problem, an Acknowledgment (ACK) from the destination is expected to be received by the packet sender.

The DCF protocol specifies an exponential backoff mechanism to manage channel access. Each station implements an internal counter that upon zero indicates that the node can send their packet, or in other words, occupy the wireless medium. The counter's initial value is randomly drawn from an uniform distribution over the interval $[0, CW-1]$, where CW is defined as the Contention Window Size, ranging from CW_{min} up to CW_{max}. Once an initial value is randomly drawn, the counter decrements until it reaches zero, signalizing to the node that its data transmission is now allowed. The counter is decremented when the node detects that the medium is not being occupied by any transmissions for the duration of a time slot, denoted by σ. When the counter reaches zero and the medium has been idle for a time longer than a DIFS time (DCF interframe space, denoted by T_{DIFS}), the node transmits its packet. As stated before, since the node is not able to directly detect a collision at the receiver, the protocol specifies that an ACK packet must be sent from destination to source in order to indicate a successful transmission. If the ACK is not received by the source within a SIFS time (short interframe space, depicted as T_{SIFS}), that packet is scheduled for retransmission. Moreover, upon each transmission failure the value of CW is successively doubled until it reaches CW_{max}. When the packet is successfully transmitted CW returns to CW_{min}.

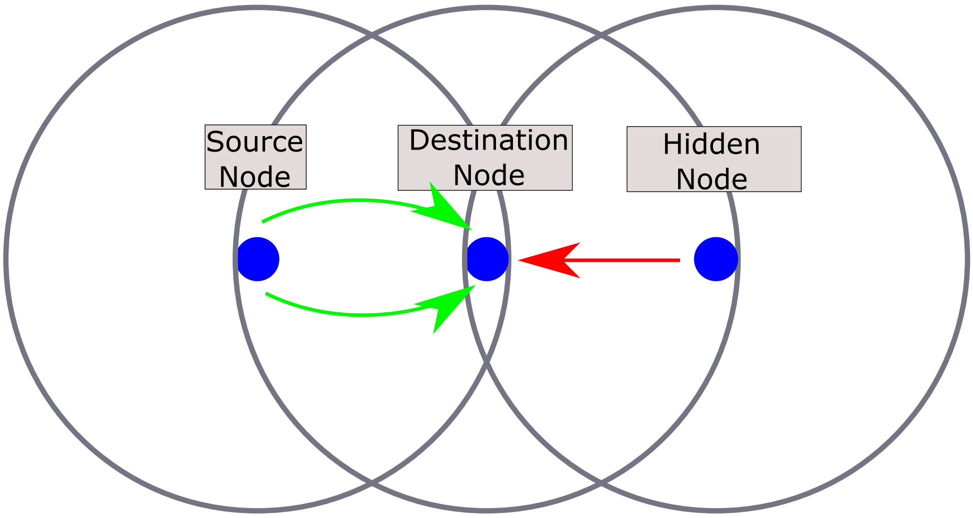

Figure 1: Hidden Node Problem

The IEEE 802.11 also specifies the use of RTS/CTS packet to mitigate the hidden node problem, illustrated by Figure 1. In that scenario, the hidden node can send a packet to the destination node even if the source node is already transmitting to the destination, leading to a packet collision. This happens because the hidden node is not within the source node range, consequently not being able to sense that the wireless medium is already busy for the destination node. In order to avoid this undesired situation, a RTS packet is previously sent from the source to destination, which in sequence answers with a CTS packet, informing the source node that it may send its data. The RTS and CTS packets tell nodes within source and destination ranges that a transmission will be initiated, allowing the hidden node to know that the destination node will be busy. The RTS and CTS packets contain a Network Allocation Vector (NAV) field, which is an indicator of how long the medium will be busy for a certain transmission. In order not to enable the counter decrement of the nearby nodes, the time between control and data packets within a transmission must be of a SIFS (less than of a DIFS). One more advantage of using the RTS/CTS mechanism is that collisions now occur between RTS instead of data packets, which result in a smaller time for collision resolution because RTS packets are smaller than data packets. A successful IEEE 802.11 RTS/CTS communication from the MAC perspective is illustrated in Figure 2.

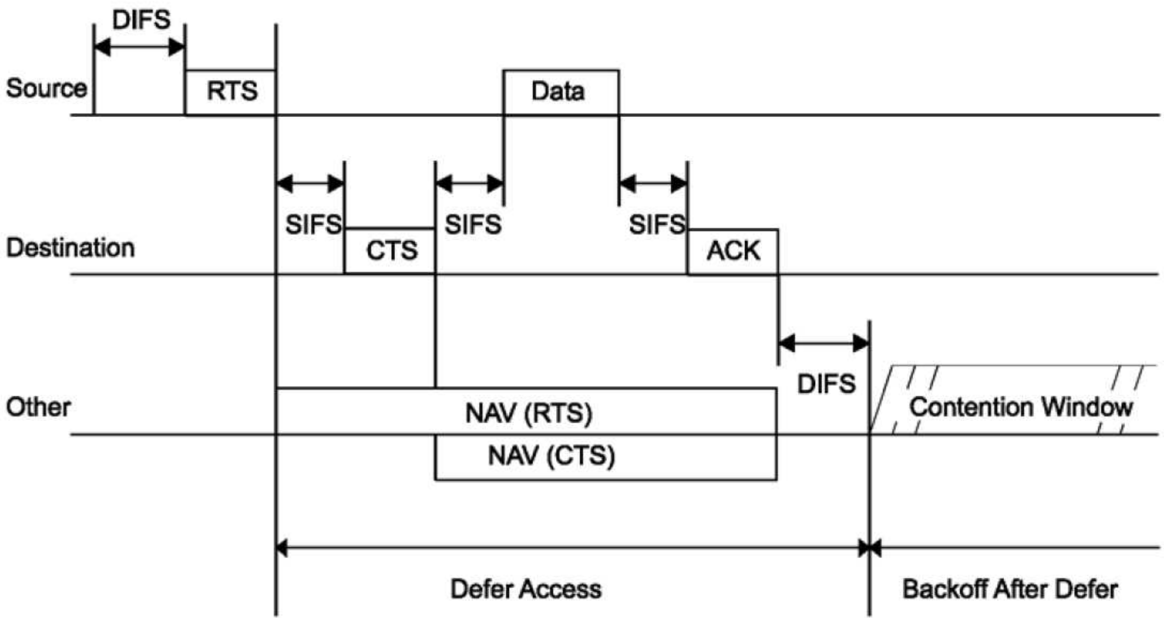

Figure 2: RTS/CTS Channel Access and Data Transmission (IEEE, 2012)

2.3 RETRANSMISSIONS

Retransmissions are a method used to recover from packet errors. In general retransmissions depend on feedback packets (ACK) sent by the receiver, informing the transmitter that the previous packet was received correctly or not. Therefore, error detecting codes are employed. The IEEE 802.11 standard specifies that packets should be retransmitted when the ACK is not received by the source, indicating an error condition. If erroneous reception happens even after the packet is retransmitted a predefined amount of times (retransmissions trials), that packet is discarded by the source node. Moreover, retransmissions are also named as Automatic Repeat reQuest (ARQ), and when ARQ is improved by Forward

Error Correction (FEC), they are named as Hybrid Automatic Repeat reQuest (HARQ). In HARQ schemes first the receiver tries to correct errors using the FEC scheme before detecting remaining errors and sending or not a retransmission request.

There are several types of retransmissions methods, which differ on the type of redundant data to be retransmitted and how the feedback path to the source is implemented. Three basic types of feedback are discussed by the literature (COMROE; COSTELLO, 1984; CHUANG, 1990):

- Stop-And-Wait → The source node stops after transmission and waits for the ACK, which if not received, triggers a timeout at the source node indicating packet failure.
- Go-Back-N → Up to N data packets are allowed to be transmitted by the source node before an ACK. Every packet is numbered and the destination must discard all out-of-order packets. In case of receiving an out-of-order packet, the destination must notify the sender, which in turn retransmits the desired packet and the following $(N-1)$ packets, leading to the name Go-Back-N. A timer is also associated with the next expected ACK, resulting in a retransmission of that packet if the timeout is reached.
- Selective Repeating → Similar to Go-Back-N, up to N data packets are allowed to be simultaneously sent to the destination, however, each transmitted packet is related to its own timer at the source. If the ACK for a packet does not happen, a timeout occurs and only that packet is retransmitted, regardless of the order it arrived at the receiver.

The use of FEC along with ARQ allows different types of data combination at the receiver, which may improve data reliability and throughput (COMROE; COSTELLO, 1984; COSTELLO; MILLER, 1984; QIAN et al., 2013). Below follows some basic types of retransmissions with different ways of combining data at the receiver:

- ARQ → Retransmits the exact same packet that was received with error at the destination. No use of FEC.
- Type I HARQ → Similar to ARQ, however, all packets are encoded by a error correction code (FEC). The same packet is transmitted at all transmission trials.
- Type I HARQ with Chase Combining → Each packet received in the Type I HARQ method is soft combined with the previous packets before decoding, leading to an improved performance (CHASE, 1985).

- Type II HARQ $\rightarrow$ Aspects from ARQ and Type I HARQ are merged. The first packet to be transmitted is the same as in ARQ (no FEC), however, in case that decoding fails, the following packet to be transmitted includes solely parity bits. This method is also called incremental redundancy.

- Type III HARQ $\rightarrow$ All transmitted packets contain redundancy and data bits, similarly to Type I HARQ. Nevertheless, the parity bits sent at each retransmission trial are different. Each received packet is self decodable and is also able to be combined with previously received packets.

The framework considered in this work adopts a Stop-And-Wait Type I Chase Combining HARQ, because it is relatively easy to implement when compared to incremental redundancy protocols, possesses a simple mathematical model, and also presents lower outage probability than a scenario without Chase Combining.

3 PROPOSED SCHEME

3.1 SYSTEM MODEL

This section presents the basic mathematical model adopted for PHY and MAC layers, which enable the development of mathematical models for throughput and energy efficiency.

We consider the communication between two nodes, source and destination, within a network containing several other nodes communicating among themselves and contending for channel access, as illustrated in Figure 3. The distance between source and destination,

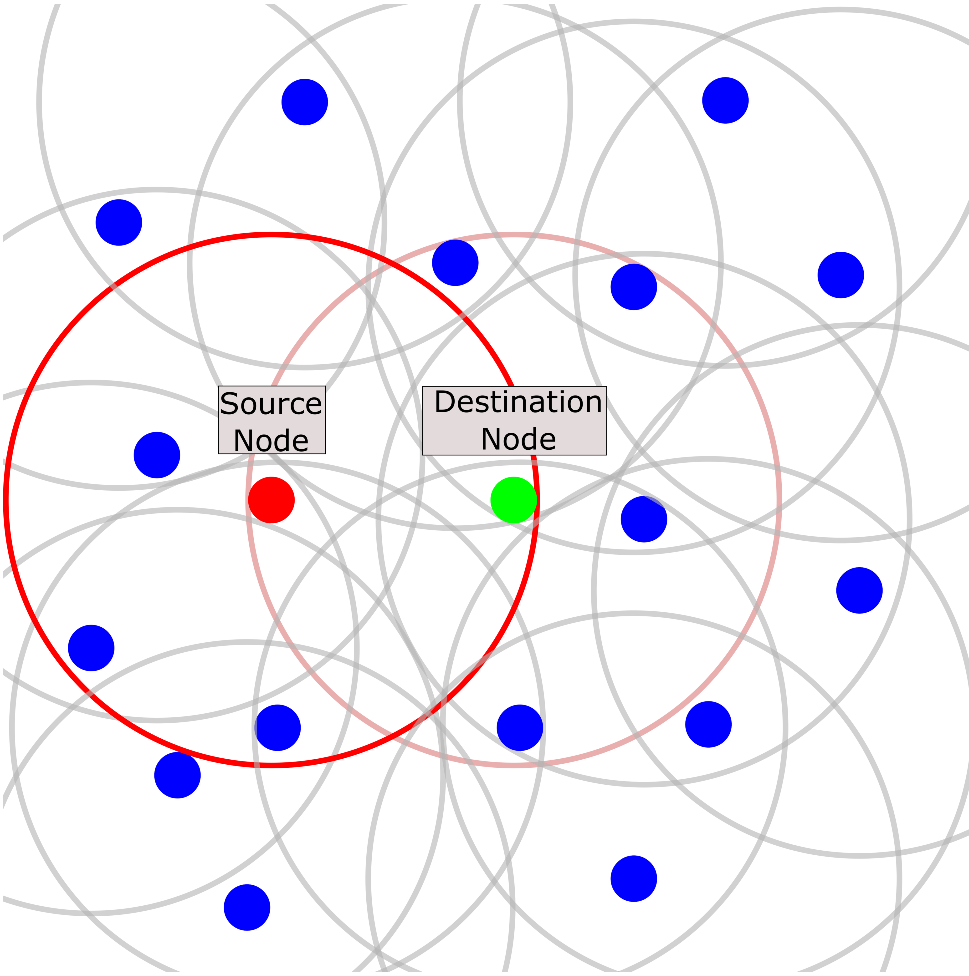

Figure 3: Disposition of the considered network

the length of the hop between them, is denoted as d. A node density ρ per square meter is considered, as well as a quasi-static Rayleigh fading setup with additive white Gaussian noise (AWGN), where each transmission trial is affected by a different and independent channel gain. Packets transmitted by all nodes are constituted of header and payload, which respectively contain H and I bits, and lead to a total of $Q = H + I$ bits per packet. Data and control bit rates are constant and identical for all nodes, respectively denoted as R and R_c.

3.1.1 PHYSICAL LAYER

The outage probability for a single transmission was presented in Section 2.1, however, HARQ with Chase Combining merges the received packets through Maximum-Ratio-Combining (MRC), decreasing the error probability and demanding adaptations of the previously presented equations. If same transmission rate and SNR are considered, the outage probability for each transmission is also expressed by (16), even for a HARQ with Chase Combining. Nevertheless, since the same packet is transmitted more times and then merged at the receiver, the system outage probability, defined as $\mathcal{O}$, is improved and expressed by (GE et al., 2015; GOLDSMITH, 2005)

$$\mathcal{O}(M) = 1 - e^{-\gamma_0/\bar{\gamma}} \sum_{k=1}^{M} \frac{(\gamma_0/\bar{\gamma})^{k-1}}{(k-1)!}, \tag{18}$$

where M is the maximum number of transmissions allowed for the same packet due to successive outage.

For all considered scenarios in this work, the transmission power P_t is adapted to guarantee a sufficient SNR so that $\mathcal{O}(M) = \mathcal{O}^*$, where $\mathcal{O}^*$ is the target outage probability, for each distance between source and destination, thus, since P_t depends on M, it can be interpreted as its function, allowing us to rewrite it as $P_\mathrm{t}(M)$. Due to a target outage probability, HARQ with Chase Combining allows a continuously decreasing SNR as M increases, allowing improvements on MAC contention.Furthermore, in order to evaluate the transmit power reductions provided by HARQ, we define the transmit power gain as

$$G_{\mathcal{P}}(M) = 10\log_{10}\left(\frac{P_\mathrm{t}(M)}{P_\mathrm{t}(1)}\right), \tag{19}$$

where $P_\mathrm{t}(M)$ is the demanded transmit power by allowing up to M transmissions, and $P_\mathrm{t}(1)$ is the demanded transmit power by a non-HARQ scenario.

HARQ may demand a number of transmission trials for the same packet, so this must be taken into account in energy and throughput calculations. Since the number of required transmissions is not deterministic (depends if the packet was received with error), the metric used to incorporate the effect of increased transmissions is the average number of required transmission trials per data packet, depicted as N, and expressed by (LAGRANGE, 2010)

$$N(M) = \sum_{k=0}^{M-1} \mathcal{O}(k). \tag{20}$$

Moreover, the transmission rate is also affected by HARQ due to its increased amount of required transmission trials. For a certain number of allowed transmissions M, the average transmission rate, $\bar{R}(M)$, can be shown to be

$$\begin{aligned}\bar{R}(M) &= R\sum_{k=1}^{M} \frac{\mathcal{O}(k-1) - \mathcal{O}(k)}{k} \\ &= R\frac{\bar{\gamma}}{\gamma_0}\left(\mathcal{O}(1) - \mathcal{O}(M+1)\right) < R.\end{aligned} \tag{21}$$

3.1.2 MEDIUM ACCESS CONTROL LAYER

As stated previously, the considered MAC layer is the IEEE 802.11 (IEEE, 2012), described with further details in the Section 2.2. The exponential backoff mechanism was modeled by (BIANCHI, 2000) through a Markov-Chain analysis, providing probabilities related to channel access that are essential to this analysis, leading to the following probabilities: $p_{\text{tr}} \rightarrow$ probability of at least one node transmitting at a random slot; $p_{\text{s}} \rightarrow$ probability that a transmission occupying the channel is successful (no collisions); $\tau \rightarrow$ probability that a station transmits in a randomly chosen time slot; $p \rightarrow$ probability that a transmitted packet collides.

The transmit power is related to these probabilities because as the range increases (higher transmit power), more packet collisions happen due to the increased channel contention. Nodes contenting for channel access in a certain area are called contending nodes, represented by n, and expressed by

$$n = \rho\pi\left(\frac{P_{\text{t}}}{P_{\text{th}}}\frac{\lambda^2}{16\pi^2}\right)^{\frac{2}{\alpha}}, \tag{22}$$

where ρ is the network node density (nodes per square meter) and P_{th} is the receiver sensitivity.

Collision and transmission probability, respectively p and τ, constitute the following nonlinear equation system (BIANCHI, 2000)

$$p = 1 - (1-\tau)^{n-1}, \tag{23}$$

$$\tau = \frac{2(1-2p)}{(1-2p)(CW_{\min}+1) + CW_{\min}p(1-(2p)^m)}, \tag{24}$$

where n is the number of nodes contending for channel access and m is the maximum amount of times the contention window can be doubled, or in other words, $CW_{\max} = 2^m CW_{\min}$. Recall that $CW_{\min}$ and $CW_{\max}$ are respectively the minimum and maximum contention window size.

Furthermore, the transmission probability of some node in a random slot and the probability of successful communication of an ongoing transmission, respectively p_{tr} and p_{s}, are expressed as (BIANCHI, 2000)

$$p_{\text{tr}} = 1 - (1-\tau)^n, \tag{25}$$

$$p_{\text{s}} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}. \tag{26}$$

3.2 SYSTEM THROUGHPUT

The system throughput is a performance metric which provides the average time necessary for the transmission of a certain quantity of information bits. In this work, it takes into account the number of information bits within a packet and the total delay for their successful transmission; the latter consists of two parts: *i.)* the delay at the PHY layer, for packet transmission; and *ii.)* the delay at the MAC layer, for channel access and control packet transmissions.

3.2.1 PHYSICAL LAYER DELAY

At the PHY layer, the transmission delay $\mathcal{D}_{\text{PHY}}$ depends on the average effective data rate $\bar{R}$ and on the overall number of bits Q per packet, so that

$$\mathcal{D}_{\text{PHY}}(M) = \frac{Q}{\bar{R}(M)}. \tag{27}$$

Throughput of the PHY layer is defined as the ratio between the number of useful bits transmitted and the amount of time taken for their transmission with an outage probability $\mathcal{O}$, leading to

$$\mathcal{T}_{\text{PHY}}(M) = \frac{I}{\mathcal{D}_{\text{PHY}}(M)}. \tag{28}$$

3.2.2 MAC LAYER DELAY

At the MAC layer, we build upon (BIANCHI, 2000; KIM; STARK, 2012, 2014), which model the MAC average delay $\mathcal{D}_{\text{MAC}}$ as the sum of the time spent on backoff count, the time consumed by collisions, and the protocol overhead. As in (KIM; STARK, 2014), $\mathcal{D}_{\text{MAC}}$ can be written as

$$\mathcal{D}_{\text{MAC}} = E[X]E[L] + \frac{pT_c}{1-p} + T_{\text{MAC}}, \tag{29}$$

where $E[X]$ is the average number of backoff counts needed for successful channel access, $E[L]$ is the average time for the backoff counter to decrement, T_{c} is time the medium is sensed busy by nearby nodes in case of collisions, and T_{MAC} is the overhead of the MAC protocol given by

$$T_{\text{MAC}} = T_{\text{RTS}} + T_{\text{CTS}} + 4\delta + T_{\text{ACK}} + 3T_{\text{SIFS}} + T_{\text{DIFS}}, \tag{30}$$

with T_{RTS} and T_{CTS} being the time consumed by RTS and CTS messages, respectively, and δ is the propagation delay (the ratio between distance and speed of light).

The time spent on backoff count depends on τ and p in (24)-(23), and according to (CHATZIMISIOS et al., 2003) can be calculated by

$$E[X] \quad = \frac{(1-2p)(CW_{\min}+1) + pCW_{\min}(1-(2p)^m)}{2(1-2p)(1-p)}, \tag{31}$$

$$E[L] \quad = (1-p_{\text{tr}})\sigma + p_{\text{tr}}p_{\text{s}}T_{\text{s}} + p_{\text{tr}}(1-p_{\text{s}})T_{\text{c}}, \tag{32}$$

where the amount of time the medium is sensed busy by nearby nodes in case of a successful transmission (T_s) and in case of collision (T_c) are respectively evaluated by (KIM; STARK, 2014)

$$T_{\text{s}} \quad = T_H + T_D + T_{\text{MAC}}, \tag{34}$$

$$T_c \quad = T_{\text{RTS}} + \delta + T_{\text{DIFS}}, \tag{35}$$

where $T_H = H/\bar{R}$ and $T_D = I/\bar{R}$ are the time consumed by the header and data packets transmission, respectively.

Throughput of the MAC layer is defined similarly as for the PHY layer, however, due to the use of retransmissions, it is necessary to take into account the increased number of channel accesses, leading to

$$\mathcal{T}_{\text{MAC}}(M) = \frac{I}{N(M)\cdot\mathcal{D}_{\text{MAC}}}. \tag{37}$$

3.2.3 CROSS-LAYER DELAY AND THROUGHPUT

When both PHY and MAC layer delays are combined, we notice that $\mathcal{D}_{\text{PHY}}$ is independent of $\mathcal{D}_{\text{MAC}}$, since it is a direct function of the average number of transmission attempts N per packet. Nevertheless, the delay at the MAC layer also depends on N, since every retransmission restarts the process for channel access. Therefore, we can write the total delay as

$$\mathcal{D}_{\text{total}}(M) = \mathcal{D}_{\text{PHY}}(M) + N(M) \cdot \mathcal{D}_{\text{MAC}}. \tag{38}$$

Since the overall number of bits Q per packet and of allowed retransmissions M are fixed for a given scenario, if the transmit power is adapted to keep a fixed outage probability at the destination (21) with the increase of the distance d, then $\mathcal{D}_{\text{PHY}}$ is constant over distance (27). However, in the same conditions, $\mathcal{D}_{\text{MAC}}$ is monotonically decreasing over distance because as the transmit power increases, so does the delay due to the increase in the number of contending nodes (22). This causes $\mathcal{D}_{\text{total}}$ to eventually get very dependent on $\mathcal{D}_{\text{MAC}}$ as the distance increases (38).

Moreover, the system throughput $\mathcal{T}$ is defined as the ratio between the number of payload bits and the time taken for their transmission, yielding

$$\mathcal{T}(M) = \frac{I}{\mathcal{D}_{\text{total}}(M)}. \tag{39}$$

Finally, as our goal is to analyze the possible benefits of using retransmissions, we define a throughput gain denoted by $G_{\mathcal{T}}(M)$, which consists on the ratio between a scenario allowing M transmission trials per packet and a scenario with only one transmission trial ($M = 1$), as

$$G_{\mathcal{T}}(M) = 10 \log_{10}\left(\frac{\mathcal{T}(M)}{\mathcal{T}(1)}\right). \tag{40}$$

3.3 SYSTEM ENERGY CONSUMPTION

Similarly to the system throughput, the energy consumption is also linked to the transmission delay so that we split the following analysis to tackle each layer separately. But first, let us define the total power consumption at the source node P_{tx} as (KIM; STARK, 2014)

$$P_{\text{tx}} = \frac{P_{\text{t}}}{\mu} + P_{\text{sp}}, \tag{41}$$

where μ is the transmitter power efficiency and P_{sp} denotes the power consumed by signal processing baseband operations. Moreover, at the receiver the power consumption is fixed and denoted by P_{rx}.

3.3.1 PHYSICAL LAYER ENERGY CONSUMPTION

PHY energy consumption, $\mathcal{E}_{\text{PHY}}$, is modeled as the energy spent for payload transmission and reception with a target outage probability $\mathcal{O}^*$, not considering any energy spent on channel access. The energy consumption at the PHY layer mainly depends on the delay for data transmission, which takes into account the bits transmitted during the successful channel access attempts. Thus,

$$\mathcal{E}_{\text{PHY}}(M) = (P_{\text{tx}} + P_{\text{rx}})\,\mathcal{D}_{\text{PHY}}(M), \tag{42}$$

which already encompasses the retransmission attempts due to possible outages.In addition, the PHY layer energy efficiency is defined as

$$\eta_{\text{PHY}}(M) = \frac{I}{\mathcal{E}_{\text{PHY}}(M)}. \tag{43}$$

3.3.2 MAC LAYER ENERGY CONSUMPTION

At the MAC layer, the energy consumption must take into account the fraction of time spent waiting for the backoff counter to expire, and the fraction of time spent attempting to access the channel. Thus, $\mathcal{E}_{\text{MAC}}$ can be written as

$$\mathcal{E}_{\text{MAC}} = \mathcal{E}_{\text{wait}} + \mathcal{E}_{\text{access}}, \tag{44}$$

and the energy efficiency of that same layer is defined as

$$\eta_{\text{MAC}}(M) = \frac{I}{N(M)\cdot\mathcal{E}_{\text{MAC}}(M)}. \tag{45}$$

While waiting for the backoff counter to expire, three different cases are possible for the neighboring nodes: successful, unsuccessful and no transmission, yielding (KIM; STARK, 2014)

$$\mathcal{E}_{\text{wait}} = E[X](p_{\text{tr}}p_{\text{s}}P_{\text{rx}}T_{\text{RTS}} + p_{\text{tr}}(1-p_{\text{s}})P_{\text{rx}}T_{\text{RTS}} + (1-p_{\text{tr}})P_{\text{rx}}\sigma), \tag{46}$$

where the terms in the summation correspond to, respectively, the contribution of each mentioned case.

On the other hand, if there is no packet collision and channel access was successful, MAC energy is spent only on flow control. Otherwise, energy is spent on RTS collision and retrial attempts, leading to (KIM; STARK, 2014)

$$\mathcal{E}_{\text{access}} = \frac{p}{1-p} P_{\text{tx}} T_{\text{RTS}} + (P_{\text{tx}} + P_{\text{rx}})(T_{\text{RTS}} + T_{\text{CTS}} + T_{\text{ACK}}), \tag{47}$$

where the first term denotes the energy spent on RTS collisions and the second term represents energy consumption of a successful channel access.

3.3.3 CROSS-LAYER ENERGY EFFICIENCY

The total energy consumption combines (42) and (44) as

$$\mathcal{E}_{\text{total}}(M) = \mathcal{E}_{\text{PHY}}(M) + N(M) \cdot \mathcal{E}_{\text{MAC}}, \tag{48}$$

while the energy efficiency is defined as the ratio

$$\eta(M) = \frac{I}{\mathcal{E}_{\text{total}}(M)}, \tag{49}$$

representing the amount of bits successfully transmitted per Joule of energy. Finally, we define the energy efficiency gain in a way similar to the throughput gain as

$$G_{\eta}(M) = 10 \log_{10} \left(\frac{\eta(M)}{\eta(1)} \right). \tag{50}$$

4 NUMERICAL RESULTS

In this section results for transmit power, throughput, and energy, with different numbers of transmission trials M in the PHY and MAC layers, are explored according to the numerical parameters in Table 1, based on (KIM; STARK, 2014, 2012). The node density ρ is relatively small, but we consider that nodes are always ready for transmission, and therefore competition for channel access is high even with small ρ. The target outage probability, $\mathcal{O}^*$, is the same for all scenarios (except for Figure 5), and consequently for different M, which according to (18) results in a decrease on the demanded SNR as M increases.

4.1 TRANSMIT POWER ANALYSIS

Retransmissions are expected to provide enhancements due to the decreased necessary transmit power for the same target outage probability $\mathcal{O}^*$, parameters which are related by equations (11) and (18). This relation can be observed in Figure 4, where the transmit power for several distances can be analyzed as a function of M. As M increases the necessary transmit power monotonically decreases, possibly leading to MAC improvements depending on the chosen M, as a small one demands relatively high transmit power at moderate distances and a large one requires excessive channel attempts. If a scenario with limited transmit power is considered, it can be noted in Figure 4 that HARQ allows the source node to reach a greater distance while maintaining the same outage probability.

Moreover, it can be observed that the power reduction provided by HARQ is exactly the same for all distances. As for instance, P_t at $d = 5$m and 200m with $M = 10$ are, respectively -70.33dB and -6.25dB, which when subtracted from their values at $M = 1$ (respectively, -35.62dB and 28.46dB) lead to the conclusion that $M = 10$ allowed a decrease of 34.71dB in P_t. This same benefit can be expanded to all distances for a certain M because $\mathcal{O}^*$ is fixed, also leading to a constant P_r, and consequently to the same HARQ benefits in P_t. This conclusion leads us to analyze the power gain G_P, which is defined by equation (19) and shown in Figure 5, representing the amount of power saved by HARQ as the target outage probability changes.

Table 1: Simulation Parameters

Parameter	**Value**
Payload (I) / Header (H)	2000 / 36 bytes
RTS / CTS / ACK	20 / 16 / 15 bytes
Slot time (σ) / T_{DIFS} / T_{SIFS}	20 / 50 / 10 μs
CW_{min} / CW_{max}	32 / 1024 slots
α (Path loss exponent)	4
R_c / R	6 Mbps / 48 Mbps
ρ (Node Density)	0.00001 nodes/m^2
μ (RF power efficiency)	50%
P_{sp} / P_{rx} / P_{th}	140 mW / 150 mW / -110 dBm
Frequency (f) / Bandwidth (B)	2.4 GHz / 20 MHz
Propagation Speed (c)	3.10^8 m/s
Target Outage Probability ($\mathcal{O}^*$)	10^{-3}

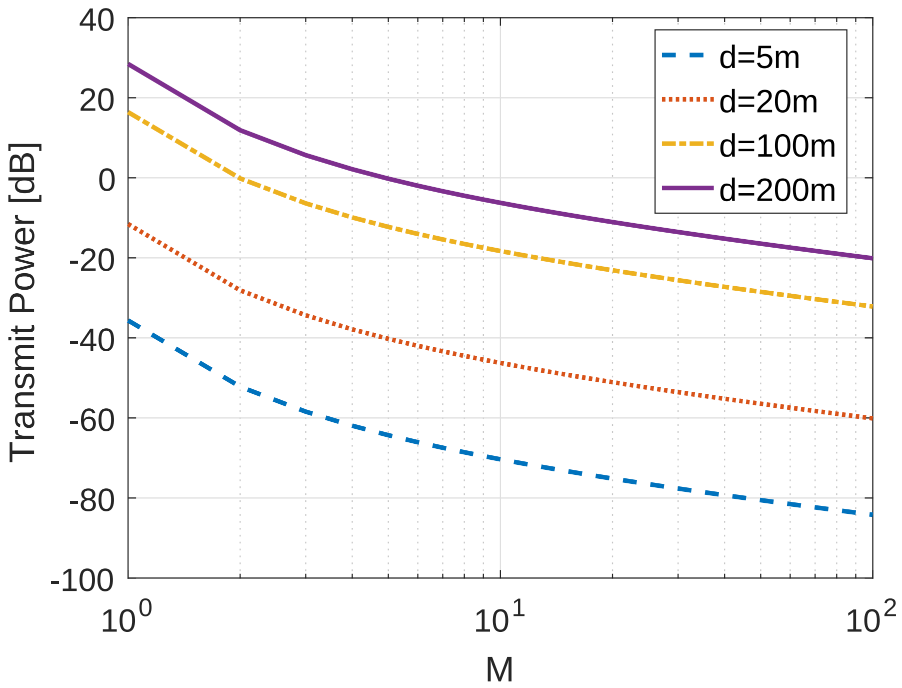

Figure 4: Necessary P_t to achieve the target outage probability as a function of allowed transmission attempts.

In Figure 5 it can be observed that as M increases the necessary transmit power for a certain outage decreases, which is corroborated by the previous analysis of Figure 4. Furthermore, as the target outage probability increases the gains provided by HARQ reduce, showing that HARQ may be a valuable method to provide reliable communications without demanding an excessively high SNR at the receiver.

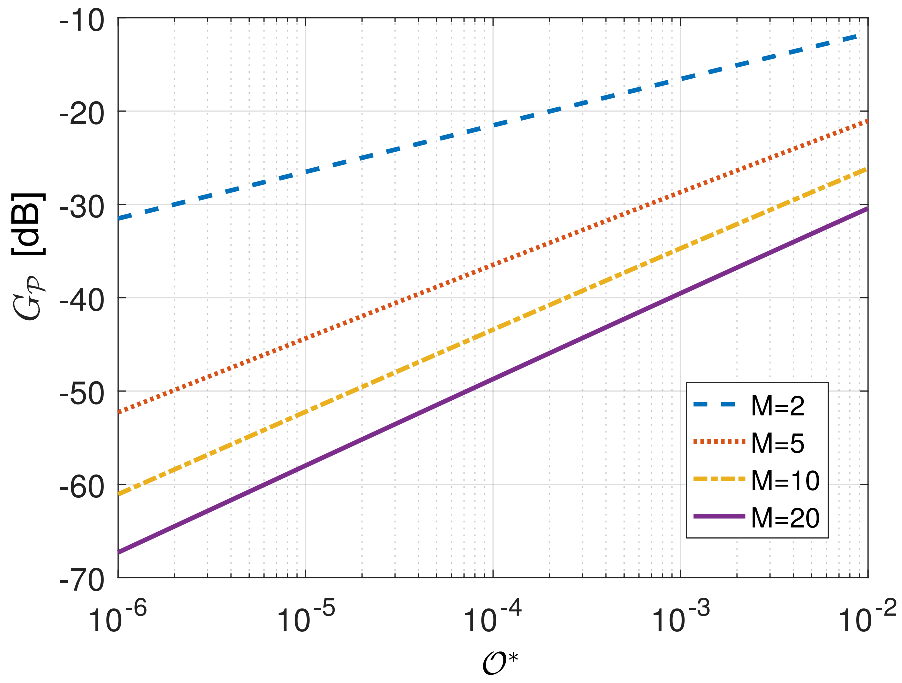

Figure 5: Power gain provided by HARQ for several M as a function of target outage probability $\mathcal{O}^*$.

4.2 THROUGHPUT ANALYSIS

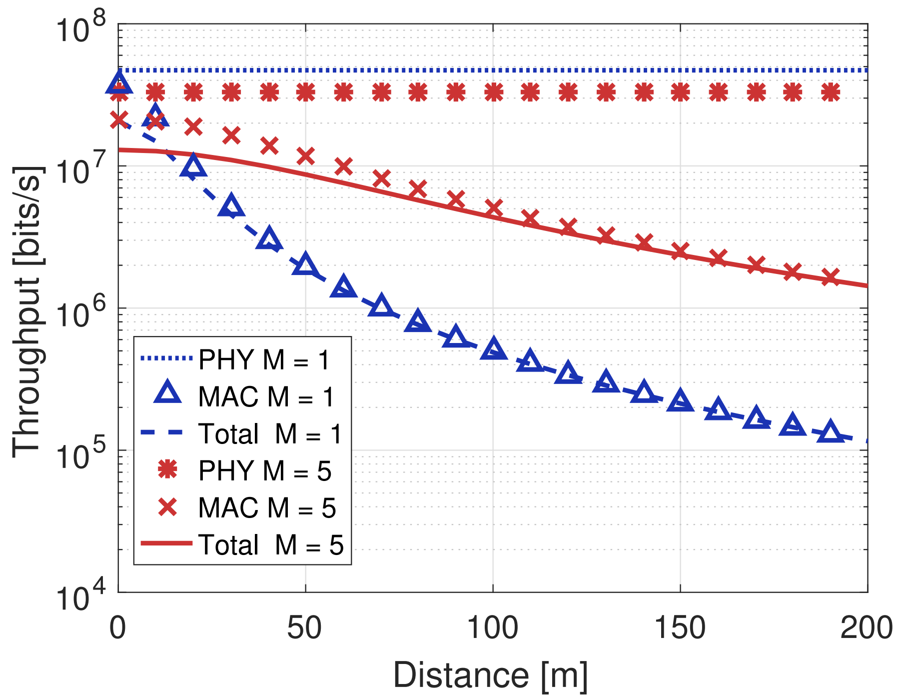

Figure 6: Throughput in the PHY and MAC layers, as well as the total throughput, as a function of the distance for $M = 1$ and 5.

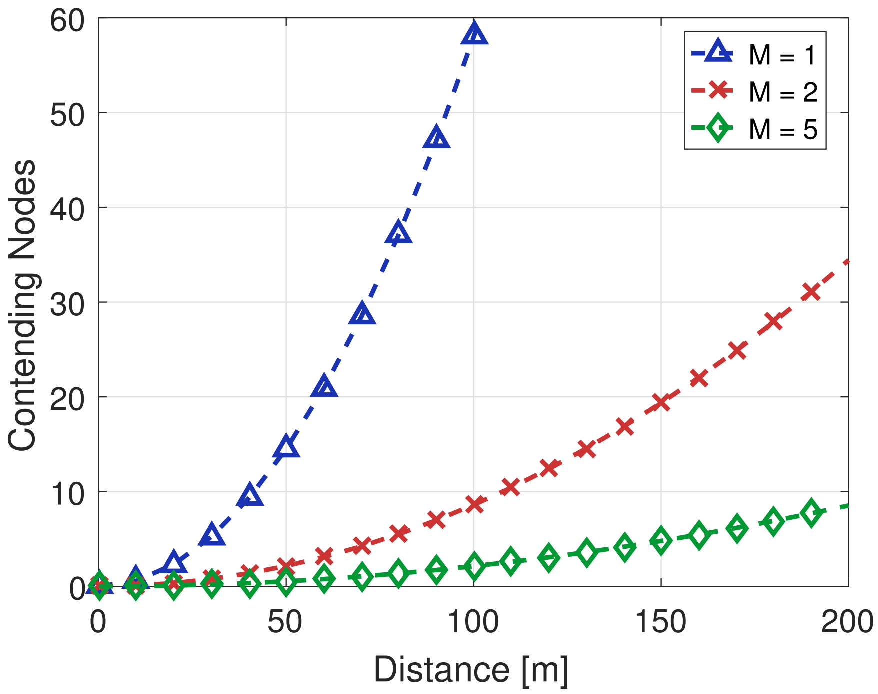

Figure 7: Number of nodes contending for channel access as a function of the distance for $M = 1$, 2 and 5.

As distance increases, each layer contributes differently to $\mathcal{D}_{\text{total}}$ as shown in Fig. 6. The average PHY throughput for a given fixed target outage probability $\mathcal{O}^*$, as given in (21), is a decreasing function of M, but constant over distance. For a fixed M, with the increase in distance and consequent increase in the required transmit power to meet the target outage probability, so does the number of contending nodes (22), negatively affecting the throughput at the MAC layer.

However, differently from the PHY layer, in the MAC layer the throughput does not necessarily decreases with M. That is because when retransmissions are allowed the required transmit power to meet a given target outage probability is reduced, and therefore the number of contending nodes is also reduced, as illustrated in Fig. 7. As the delay in the MAC layer is heavily dependent on the number of contending nodes, allowing for retransmissions in the PHY layer has a very positive impact in the MAC layer throughput. Moreover, as with the increase in distance – and therefore in the required transmit power – the delay in the MAC layer dominates over the delay in the PHY layer, and therefore improving the performance of the MAC layer significantly affects the overall system throughput as shown in Fig. 6. For very short distances retransmissions at the PHY layer do not provide sufficiently low power to overcome the increased number of average transmissions, but for sufficiently large distances the advantages in terms of throughput are very clear.

4.3 ENERGY EFFICIENCY ANALYSIS

The energy efficiency of the PHY and MAC layers is shown in Fig. 8 as a function of the distance for different M. Clearly, η is a decreasing function with d in both layers. In the PHY layer, we observe that the energy consumption in (42) depends on transmit and receive powers, as well as on the PHY delay. Thus, an increasing transmit power is needed to maintain the SNR constant at the receiver with the increase of distance, in order to meet the target outage probability $\mathcal{O}^*$. Therefore, η decreases with d due to the higher required transmit power, but increases with M since then the required transmit power is reduced. At the MAC layer the effects are very similar, with η decreasing with the increase of the transmit power, but increasing with the number of allowed transmission trials M.

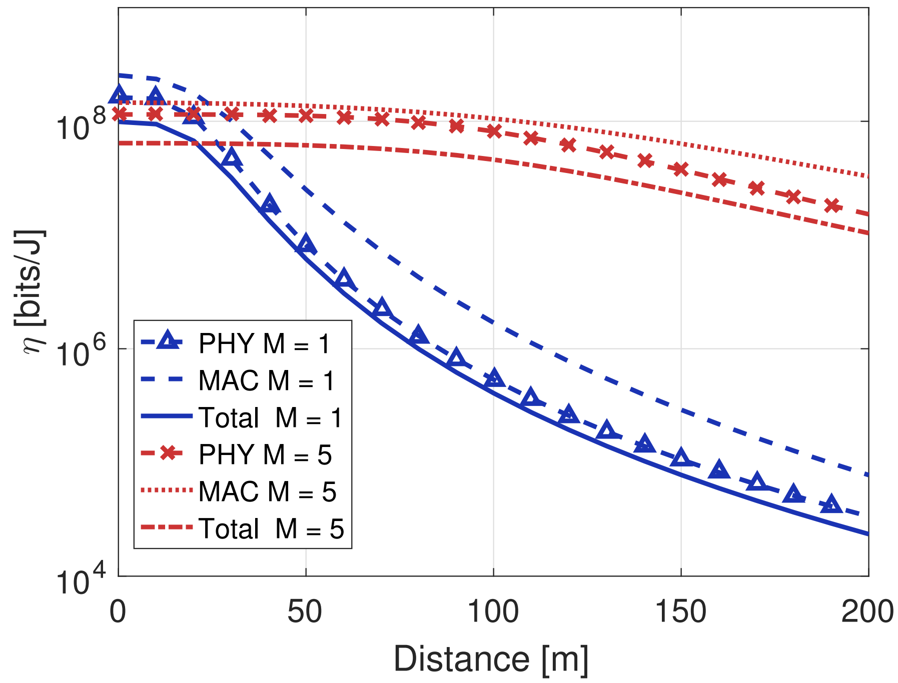

Figure 8: Energy efficiency in the PHY and MAC layers as a function of the distance for $M = 1$ and 5.

Moreover, Fig. 8 shows an interesting behavior at very short distances. In that case, the fixed power consumption related to P_{rx} and P_{sp} becomes very relevant in the energy consumption, as can be observed in (42), (46) and (47). Therefore, at small transmit ranges (smaller than 25 m in this particular example), Fig. 8 also shows that it is better to avoid retransmissions (imposing $M = 1$), slightly increasing P_{t} to meet the outage probability target, achieving better energy efficiency.

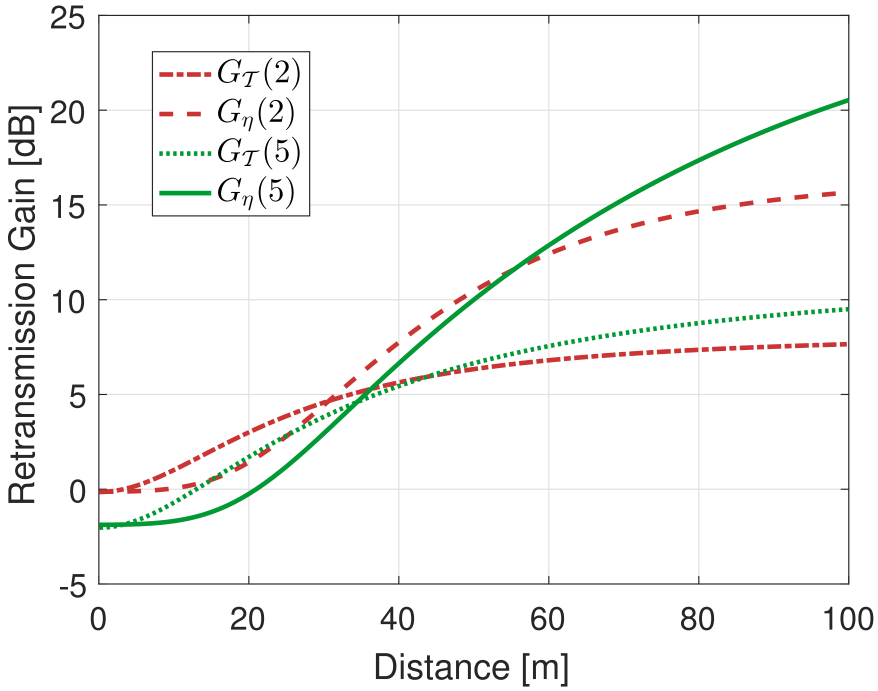

Figure 9: Throughput and energy efficiency gains, $G_{\mathcal{T}}$ and G_{η}, as a function of the distance for $M=2$ and $M=5$.

Fig. 9 plots the throughput and energy efficiency gains, $G_{\mathcal{T}}(M)$ and $G_{\eta}(M)$, respectively, for $M=2$ and $M=5$ as a function of the distance between source and destination. Notice that gains above 0 dB imply in an improvement when compared to the case without retransmissions ($M=1$). As we can observe from Fig. 9, there are no throughput improvements for very short distances, as $G_{\mathcal{T}}(M)$ and $G_{\eta}(M)$ are below the 0 dB margin in this range, what is in accordance with Fig. 6. However, $M=2$ quickly surpasses the 0 dB margin. As M increases the starting gain decreases due to the increased average number of transmission trials, however, the reduced amount of contending nodes provides a larger gain with M over distance. As for throughput, energy efficiency also benefits from the decreased number of contending nodes that is a consequence of allowing multiple transmission trials and reducing the required transmit power. The starting gain in terms of energy efficiency is mainly defined by the fixed energy consumption of some components, such as P_{rx} and P_{sp} pondered by the average number of transmissions, resulting in a successive decrease with M.

It is interesting to notice in Fig. 9 that optimum values of M for energy efficiency and throughput are not necessarily the same, due to the difference on switching points (change of optimal M) for energy and delay. Fig. 10 presents the optimum M for the considered scenario, illustrating that the difference on switching points for energy and throughput leads to different

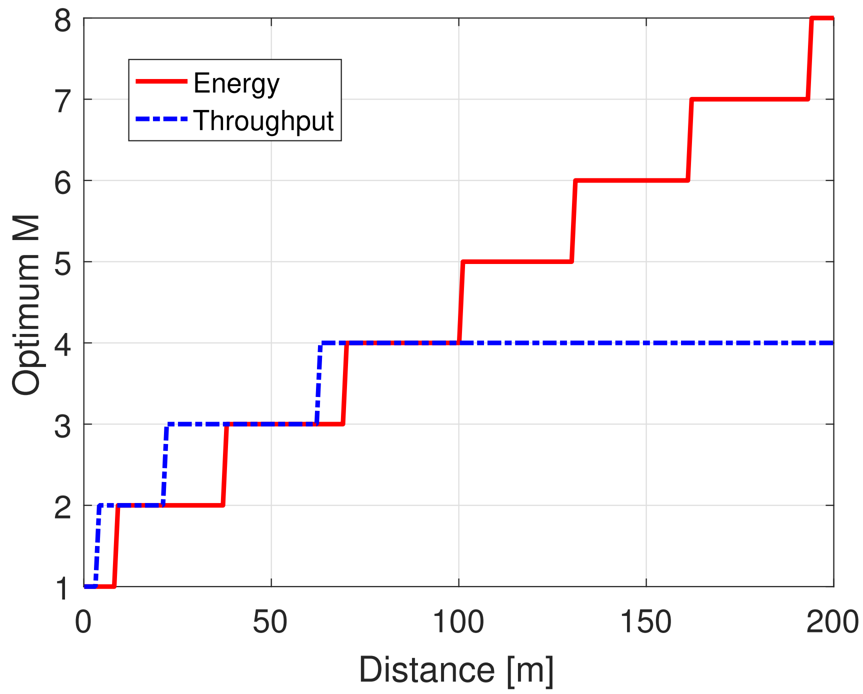

Figure 10: Optimal number of allowed transmission trials (M), that maximizes either the throughput or the energy efficiency, as a function of the distance.

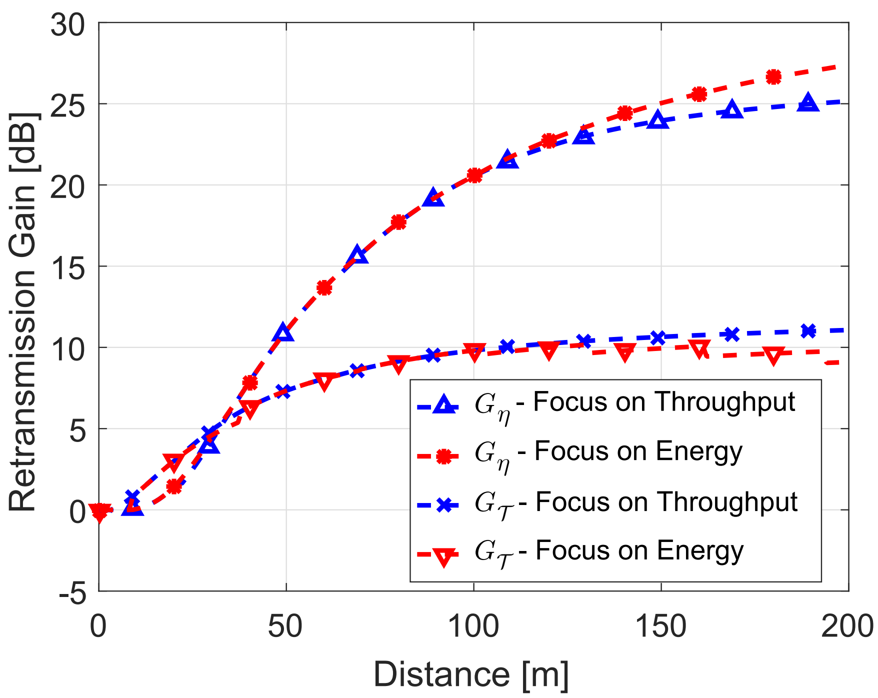

Figure 11: Throughput and energy efficiency gains, $G_\mathcal{T}$ and G_η, when the optimal M for either throughput or energy efficiency is applied.

optimum M, and also that this value changes with distance due to different starting gains and growth rates for each M, as illustrated in Fig. 9.

Two possible optimization scenarios with respect to M arise from Fig. 9, one which focuses on energy efficiency, and the other focused on throughput. Fig. 11 presents the behavior of $G_{\eta}(M)$ and $G_{\mathcal{T}}(M)$ for both scenarios. It can be noticed that for up to a distance the performance is very similar for both energy efficiency and throughput scenarios, because the optimum M is very similar in both cases. However, as the distance increases, the difference on the optimum M for each case starts to grow. When considering an optimization focused on throughput, the energy gain ever grows with distance, even though at a decreasing rate. On the other hand, if the optimization is focused on energy efficiency, the throughput gain starts to decrease over distance because the optimum M for energy efficiency is larger than that for throughput, excessively penalizing the PHY layer delay. Therefore, for maximum energy efficiency it may not be possible to achieve the best performance in terms of data throughput.

5 CONCLUSIONS

In this work, a PHY/MAC cross-layer analysis was applied to a scenario considering multiple transmission trials in the PHY layer, under the effect of quasi-static Rayleigh fading. The use of retransmissions lead to an increased amount of channel accesses and a decreased transmit power, resulting on system enhancements for some scenarios, which pointed towards possible future works that could take advantage of the HARQ benefits described in this work. The main conclusions of this work can be summarized as follows: *i.*) Despite the need for more channel access attempts, retransmissions may provide higher throughput and decreased MAC delay. That is because with HARQ less transmit power is required for achieving the target outage probability, leading to a reduced number of potential contending nodes and of collisions in the channel access attempts; *ii.*) HARQ may provide simultaneous energy efficiency and throughput improvements, while there are different optimum numbers of maximum transmission trials for energy efficiency or throughput.

5.1 FUTURE WORK

The framework presented may be expanded by several different techniques and scenarios in order to seek for performance improvements, such as:

1. Considering relay nodes along with retransmissions. Since retransmissions and relay nodes (KIM; STARK, 2014) may provide benefits due to a lowered transmit power, it is possible to merge them both and also compare their behavior regarding throughput and energy efficiency.

2. The use of multiple antennas, which may lead to performance enhancements (PERON et al., 2016), thus it would be interesting to evaluate its use along with retransmissions.

3. More efficient and complex HARQ protocols, as the ones which consider incremental redundancy and power allocation schemes, may provide enhancements.

4. An IEEE 802.11 MAC model that does not assume the nodes are always ready for transmission.

5. Different MAC protocols which also rely on channel contention.

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