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2017

Citation for published version (APA):
Franco, A. (2017). *Improving Throughput and Minimizing Age of Information in dense WLANs, Using Cooperative Techniques*. [Licentiate Thesis, Lund University].

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Lund 2017

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This thesis is set in Computer Modern 10pt
with the LaTeX Documentation System

Series of licentiate and doctoral theses
No. 112
ISSN 1654-790X
ISBN 978-91-7753-551-5 (print)
ISBN 978-91-7753-552-2 (pdf)

Printed in Sweden by *Tryckeriet i E-huset*, Lund.
December 2017.

Front cover illustration:
Original work by the author.
Uses the following third party image:
“Router Emoticon ”Happy! Happy!””
by Yudha Agung Pribadi
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> [The] chief [of the gods of Cimmeria] is Crom. He dwells on a great mountain. What use to call on him? Little he cares if men live or die. Better to be silent than to call his attention to you; he will send you dooms, not fortune! He is grim and loveless, but at birth he breathes power to strive and slay into a man's soul. What else shall men ask of the gods?
>
> Robert E. Howard

Abstract

Mobile and wireless data are in increasing demand worldwide. New trends such as the Internet of Things paradigm and the Smart City paradigm describe scenarios comprising thousands of devices all exchanging information amongst themselves wirelessly — or through the WAN to another device, possibly connected to another WLAN. Operators and radio engineers are faced with the problem of designing efficient ways to share the electromagnetic spectrum — a scarce and expensive resource — between thousands of devices.

In this context, operators look at the unlicensed spectrum as a possible solution to complement the existing infrastructure. Unfortunately, the IEEE 802.11 MAC family, the most widespread MAC protocol in the unlicensed portion of the spectrum, still suffers when managing a large number of interconnected devices. In this thesis we are both addressing the open problems in the IEEE 802.11 MAC scheme and our contributions on their solution.

Specifically, in the first part of the thesis we will present the IEEE 802.11 MAC scheme and the challenges it faces, along with solutions already present in literature. We will also show a new metric recently defined in the literature called the Age of Information (AoI). This new metric is a measure of how fresh the piece of information stored in a remote receiver is. Age of Information attracted interest in the literature, but little is known about how it behaves in a IEEE 802.11 WLAN.

In the second part of the thesis we present two papers and an appendix that address the problem of designing new protocols that let the devices cooperate in order to achieve a common goal. Specifically, these papers focus on two metrics. The first paper addresses collision reduction and throughput via a new MAC scheme that uses RSSI to identify other devices in a WLAN, and uses a priority based access system in order to act cooperatively. We show, through simulation, that this scheme outperforms the classical IEEE 802.11 DCF mode of operation, especially in WLANs subject to high loads.

The second paper addresses the AoI both in terms of average and variance, for sensor nodes embedded in a dense WLAN that send pieces of information to a remote server via a WAN connection. We study both those metrics for a link with high variance and low variance delay. We construct and test, via means of simulations, an AoI-aware MAC, called LUPMAC — Latest Update Medium Access Scheme, aimed at reducing both the average AoI and the AoI variance at the remote server side, and is also resilient to variations on the wired remote connection.

In the appendix we present an analytical continuation of the second paper; we calculate the analytical probability of removal due to staleness of the packet in a new cooperative MAC scheme for Wireless Sensor Networks (WSNs) called COOPLUP — COOperative LUPMAC. This protocol is aimed at decreasing the number of transmissions in a WSN with sensors broadcasting updates about a measured phenomenon, while minimizing the average AoI at the receiver.

In these two papers and appendix we present three schemes suitable for the unlicensed spectrum environment, addressing both scheduling and queuing policies. These schemes are only slight modifications to the already widely deployed IEEE 802.11 MAC, but they significantly improve the metrics they focus on. They rely only lightly on a centralized unit, as most random access schemes do, but instead let the devices cooperate to a certain extent in order not to pollute the channel with undesired retransmissions.

Preface

This licentiate thesis is composed of two parts. The first part gives an overview of the research field in which I have been working during my Ph.D. studies and a brief summary of my contribution to it. The second part is composed of two included papers and one appendix that constitute my main scientific work:

[1] Antonio Franco, Saeed Bastani, Emma Fitzgerald, Bjorn Landfeldt, "OMAC: An Opportunistic Medium Access Control Protocol for IEEE 802.11 Wireless Networks" in *2015 Prooceedings of IEEE Globecom 2015*, IEEE–Institute of Electrical and Electronics Engineers Inc., Vol. 2015 IEEE Globecom Workshops (GC Wkshps).

[2] Antonio Franco, Emma Fitzgerald, Bjorn Landfeldt, Nikos Pappas, Vangelis Angelakis "LUPMAC: A cross-layer MAC technique to improve the age of information over dense WLANs" in *2016 23rd International Conference on Telecommunications (ICT) (ICT 2016)*, Thessaloniki, pp. 724-729, 2016-05-15.

[3] Antonio Franco "COOPLUP - Analytycal Probability of Removal Due to Staleness".

Acknowledgements

First and foremost, I would like to thank my supervisor, Prof. Björn Landfeldt, and my co-supervisors, Dr. Emma Fitzgerald and Dr. Saeed Bastani, for their support and guidance during my doctoral studies. Special thanks go also to Prof. Emeritus Ulf Körner for his valuable feedback and insightful discussions.

My sincere gratitude goes to the people that provided me financial support, the EU tax payers, which through the EC FP7 Marie Curie IAPP Project 324515, "MeshWise" have financed my research.

My sincere thanks go to colleagues and administrative staff at work: Dr. Mehmet Karaca, Prof. Christian Nyberg, Prof. Michal Pioro, Anne Andersson, Marianne Svensson, Pia Bruhn, Dorthe Jensen, Elisabeth Nordström, Bertil Lindvall, Erik Jonsson and Josef Wajnblom.

A special thanks to my family for supporting me during this perilous and dark journey of my PhD studies.

Finally I would like to thank all my friends and acquaintances in Lund and around the world for all the support and care they gave me.

Antonio
Franco

Antonio Franco

List of Acronyms and Abbreviations

AC Access Class for EDCA

ACK Acknowledgement

AIFS Arbitration InterFrame Space

AP Access Point

AoI Age of Information

BEB Binary Exponential Backoff

BS Base Station

CSMA Carrier Sense Multiple Access

CSMA/CA Carrier Sense Multiple Access with Collision Avoidance

CSMA/CD Carrier Sense Multiple Access with Collision Detection

CTS Clear To Send

CW Contention Window

D/M/1 Single server queuing system with constant interarrival times and exponentially distributed service times

DCF Distributed Coordination Function

DIFS DCF InterFrame Space

EDCA Enhanced Distributed Channel Access

EM ElectroMagnetic

FCFS First Come First Served

Fifo First In First Out (Synonim of FCFS)

HCF Hybrid Coordination Function

ISP Internet Service Provider

LAN Local Area Network

LCFS Last Come First Served

LHS Left Hand Side

M/D/1 Single server queuing system with exponentially distributed interarrival times and constant service time

M/G/1 Single server queuing system with exponentially distributed interarrival times and generally distributed service times

M/G/1/1 Single server queuing system with exponentially distributed interarrival times, generally distributed service times and only one place in the buffer

M/M/1 Single server queuing system with exponentially distributed interarrival times and exponentially distributed service times

M/M/1/1 Single server queuing system with exponentially distributed interarrival times, exponentially distributed service times and only one place in the buffer

MAC Medium Access Control

OSI Open Systems Interconnection model

PCF Point Coordination Function

PHY PHYsical Layer

PIFS PCF InterFrame Space

QoS Quality of Service

RHS Right Hand Side

RSSI Relative Received Signal Strength

RTS	Right To Send
SIFS	Short InterFrame Space
SINR	Signal to Interference Noise Ratio
STA	STAtion (as opposed to AP)
VANET	VehiculAr NETwork
VoIP	Voice over IP
WAN	Wide Area Network
WLAN	Wireless Local Area Network
pAoI	Peak Age of Information

Contents

Part I

Overview

Chapter 1

Introduction and Motivation

New trends in the wireless world (e.g. the Internet of Things paradigm, the Smart City paradigm etc.) present operators with the challenge of interconnecting thousands of devices wirelessly. The problem of designing efficient ways to share the electromagnetic spectrum becomes central.

In this context, the unlicensed spectrum (i.e. the portions of the electromagnetic spectrum that are free to use without purchasing a license from the local government) could be a solution. Already in this portion of the spectrum there are semi-distributed protocols (i.e. scheduling and management control do not fall entirely on a centralized entity) acting, specifically random access protocols. In this set of protocols the most widespread are the IEEE 802.11 MAC family protocols, commonly referred to as Wi-fi. The 802.11 MAC protocol, despite all the efforts put in the various versions of the standard, still suffers from a number of problems that prevent it from scaling gracefully as the number of users grows, leading to a poor user experience for very large WLANs. At the same time the physical layer continues to approach the optimal spectrum efficiency. Clearly the MAC protocol is a main bottleneck for improving the overall user experience.

In this first part of the thesis we will present the IEEE 802.11 MAC scheme and the challenges it faces, along with solutions already present in literature. We will also show a new metric recently defined in the literature called the Age of Information (AoI). This new metric is a measure of how fresh the piece of information stored in a remote receiver is. Age of Information attracted interest in the literature, but little is known about how it behaves in a IEEE

802.11 WLAN.

1.1 Motivation

The electromagnetic spectrum is a scarce and expensive resource. Operators are entities (often private companies, e.g. Telia in Sweden) that manage some portions of the spectrum, often bought from governments authorities at a very high price. On top of that, in [1] it is forecast that the global amount of data exchanged via mobile devices will increase from the current 7 ExaBytes per month to 49 ExaBytes per month in 2021. This in turn requires packing more capacity per Hz.

Operators are usually responsible for the infrastructure that end users will eventually employ with their devices[1]. This infrastructure usually consists of main wireless units, called Base Stations (BSs), that are responsible for sending and receiving informations from the users' devices. BSs are usually big, need high positions on roofs and need to be fed a considerable amount of energy — in [2] it is claimed that, in urban areas, with a typical user density of $300\,\text{users}/km^2$, LTE requires $18\,W/\text{user}$, or, to put it in perspective $4.5\,kW/km^2$ — from the grid (or worse, use diesel fueled power stations). Other parts of the infrastructure are microwave/optical links and optical fiber in order to send/receive information from the Wide Area Network (WAN), control servers, content management systems etc. In order to achieve the magnitude of capacity forecast for the future, with traditional cellular protocols, operators will have to increase the carrier frequency employed by their BSs. Since a higher frequency means reduced coverage, they will have to deploy more and more Base Stations. This presents logistical, environmental and budgetary problems.

On the other hand, small portions of the electromagnetic spectrum are free to use for anyone; the most commonly employed are the portions centered at 2.4 GHz and 5.8 GHz. This portion of the spectrum, unlike the licensed part, is open to unregulated access, so anyone could potentially interfere with ongoing communications.

This might be compared to to a group of people trying to talk to each other in a noisy environment, e.g. a club. If Alice wants to tell something to Bob, the more the noise in the club, the more difficult it is for Alice to convey the message. There is a threshold in the noise above which Bob cannot understand what Alice is saying. If we assume that two other people Charlie and Diana are talking, and both Alice and Charlie speak at the same time, their voices must

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[1] unless they are virtual operators, in which case they rent the infrastructure from a real operator.

be powerful enough to overcome the noise in the club *and* the voice of the other person speaking. The quantity that measures how the useful signal is over the disturbances is called the Signal to Interference and Noise Ratio (SINR) at the receiver, and it differs between Bob and Diana (Alice is maybe sitting on the opposite side of the table from Bob, while Diana is sitting just beside Charlie). If the "power" of the voice of Alice or Charlie is not sufficient to overcome an SINR threshold at Bob/Diana (maybe Bob has a hearing impairment that makes him less sensitive to sounds than the others, thus has a lower SINR threshold), the message will not be conveyed at all. If we imagine thousands of Alices and Charlies talking to thousands of Bobs and Dianas. This is the scenario forecast for future WLANs.

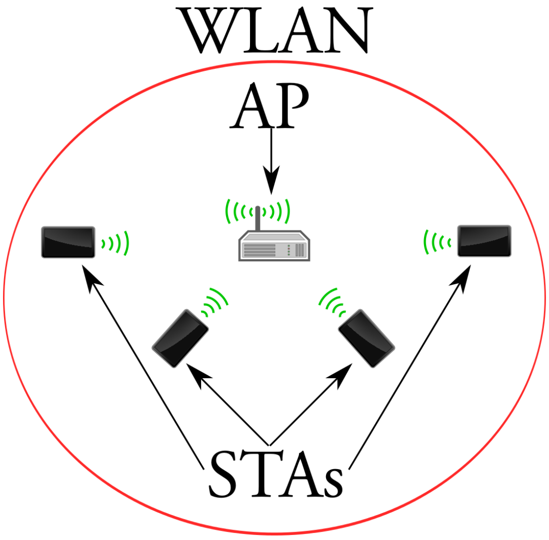

Figure 1.1: Simple WLAN. This diagram also utilizes the following third party image: [3].

In a WLAN, the main entities are the Access Points (APs) and the stations (STAs) (see Figure 1.1). STAs are devices subscribed to a particular WLAN (e.g. smartphones, laptops etc.). APs are devices capable of connecting the WLAN to the wired network (usually the WAN), and most of the traffic goes through them. In most of the residential areas Access Points operating on unlicensed bands significantly outnumber traditional BSs [4]. Since the offered bandwidth might not be fully used during most of the day, operators are looking for solutions for using this spare bandwidth in a commercial way. The fundamental problem they are facing is the lack of a coordination plane (or, at least, a cooperative protocol) between APs (and, ideally, the STAs themselves) for load balancing, resource scheduling coordination, advanced soft/hard handover etc. similar to, e.g. the X2 interface in LTE [5].

The setting could be compared to that of thousands of people in a debate hall, with a dozen different debates going on at the same time. In each debate, at any given moment, only a percentage of the people attending the meeting wish to speak. If everyone having something to say tried to speak at the same time, the noise would reach unbearable levels. Thus a moderator might allocate a time to speak by calling on one person at a time (polling). If only a percentage of the people wished to talk, there would be a lot of time (i.e. bandwidth) wasted in calling even those who had nothing to say. By removing the moderator, and having all the people in each debate agree to speak in turns, a Time Division Multiple Access (TDMA) could be achieved; it could be completely distributed, but would suffer the same problem as before. Imagine that a person who wishes to speak first listens to check if anyone is already speaking, then waits a period of time; if no one speaks, she starts her speech. Otherwise, she will defer to when the person speaking finishes. This is an example of a random access scheme and is the kind of scheme this thesis will discuss. Obviously, if the hall were not big enough, different debates would interfere with each other. An entity representing each debate that agrees on a control scheme with the other debates is what is here referred to as a “control plane”.

The future trend for wireless networks, is the so-called Internet of Things (IoT), and in particular the Smart City paradigm [6]. With the IoT, possibly thousands of devices would need to communicate with each other and with remote servers in the Wide Area Network (WAN). Central coordination of those devices would be impractical if not impossible, especially if low-delay communications are required. Random access protocols like the IEEE 802.11 MAC show promise (the IEEE 802.11ah [7] standard is devised for IoT systems), but they need to be improved in order to increase cooperation. A trade-off between unsupervised random access and a smart resource sharing scheme must be found. Coming back to our example involving Alice, Bob, Charlie and Diana, there is no way for Alice and Charlie to agree on when someone should speak. Maybe if Alice and Charlie could agree to speak in turns, or listen to whether the other person is already speaking in order will speak over him, and ideally when the track playing on the loud speakers in the club ends i.e. there is low noise in the environment, they could all convey their messages without problems. For thousands of Alices and Bobs more clever schemes must be devised, in order to exchange drink advice as smoothly as possible.

The trend in IEEE 802.11 has been constantly improving raw data rate in the physical layer (up to 10 Gbps in the upcoming ax (High Efficiency Wifi

— HEW) standard [8]), but there has been little improvement in the resource sharing mechanisms at the MAC level. This means that devices can send frames (the elementary unit of transmission in a WLAN) faster. However merely this fact does not guarantee they will not talk over each other, thus losing the transmission completely. Devising new, adaptive, scheduling mechanisms for devices is vital for future infrastructures and the upcoming 5G standard [9]. Ensuring low delay, high throughput, Quality of Service (QoS), traffic prioritization, and reliability is a challenging task.

In this scenario, our work fits in the cooperative MAC protocols area, mainly focusing on two metrics: throughput and Age of Information (see Section 2.3.1). As we have seen, one main problem in modern WLANs is the lack of cooperation when scheduling (in the Alice and Bob example: when should Alice and Charlie speak in order for both to convey their messages to Bob and Diana?). Especially for the latter — AoI — little study was done on the effect of modern random access protocols such as the IEEE 802.11 MAC in terms of AoI performance. AoI is a very important metric that captures the freshness of information flowing to an end receiver. Especially for sensor nodes or alarm devices it could be extremely important to deliver the most up-to-date information to a remote controlling server, with the best reliability and the lowest delay possible. Paper II specifically address this problem in the context of dense WLANs.

In the next section we introduce our main contributions to the field.

1.2 Contributions in Brief

In the papers included in Part III, we present our results and discuss the research questions introduced in Sections 2.1.2 and 2.3.3. Below is a brief summary of our contributions to the area of random access MAC protocols, specifically aimed to improve throughput and average Age of Information in WLANs.

1. As we introduced in the previous section, the IEEE 802.11 MAC lacks coordination in scheduling. This in turn affects effective throughput, since as the number of devices increases , collisions also increase. In Paper I we design a new MAC protocol, called OMAC — Opportunistic Medium Access Scheme — based on the IEEE 802.11 DCF. Our new protocol let STAs in a WLAN cooperate without information exchange, by using the RSSI as an identifier. STAs in turn use this information in order to cooperate amongst themselves by using different queues with different priority and access parameters. Simulations show that this scheme outperforms

the normal DCF mode of operation (described in Section 2.1) in terms of throughput and collision reduction.

2. Age of Information is a relatively new metric. It is very important, especially for sensors measuring varying phenomena that need to be monitored in the most up-to-date state possible. In this context, little work has been done on 802.11 WLAN about AoI. In Paper II we study both the average AoI (see Section 2.3.1) and its variance in a network composed of one or more sensor devices embedded in a dense WLAN, trying to send pieces of information to a remote server via a wired link. We study both those metrics for a link with high and low delay variance. Variance is especially important, since a low variance means stable monitoring of the phenomenon, ensuring minimal outage of information.

3. Also in Paper II, we construct an AoI-aware MAC, called LUPMAC — Latest Update Medium Access Scheme — aimed at reducing both the average AoI and the AoI variance at the remote server side. LUPMAC is also resilient to variations in the wired remote connection. In this protocol we make the MAC aware of the generation times of the pieces of information in order to reach our set goals. We find, through simulations, that this scheme significantly outperforms the normal DCF mode of operation both in terms of the average AoI and the AoI variance at the remote server, only requiring minimal modifications to the standard IEEE 802.11 MAC.

4. In the appendix, we start to investigate and calculate the analytical probability of removal due to staleness of the packet in a new cooperative MAC scheme for Wireless Sensor Networks (WSNs) called COOPLUP — CO-Operative LUPMAC. This protocol is aimed at decreasing the number of transmissions in a WSN with sensors broadcasting updates about a measured phenomenon, while minimizing the average AoI at the receiver.

Chapter 2

Background

2.1 The IEEE 802.11 MAC

In this section we will to introduce the IEEE 802.11 family of MAC protocols. In order to understand the contributions of this thesis it is essential that the reader understands how this protocol works and what are the problems it will face in the foreseeable future. In the following (Section 2.1.1) we will give details on how the IEEE 802.11 MAC layer works, then, in Section 2.1.2 we are going to introduce the open problems in the IEEE 802.11 family of MACs. First, though, it is important to highlight the framework in which this protocol fits in, and why we should be interested in improving it.

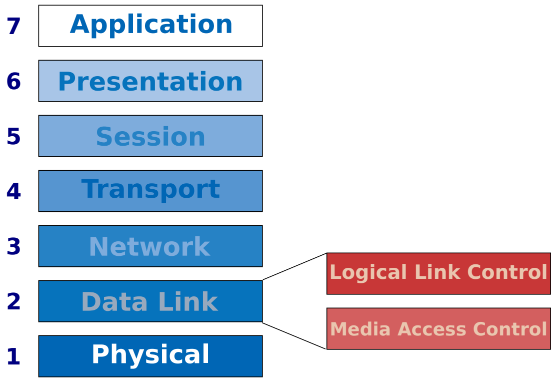

Figure 2.1: The OSI model. This diagram also utilizes the following third party image: [10].

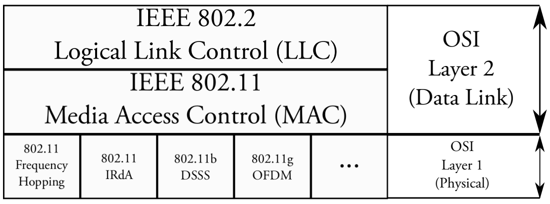

Figure 2.2: The IEEE 802.11 standard and the OSI stack.

A telecommunication capable device can be abstracted as a model device subdivided into a stack of layers with different functionalities. The best known protocol stack is the Open Systems Interconnection model [11] (OSI model — Figure 2.1). In this model each layer is only responsible for communication with the layers immediately above and immediately below it. The lowest layer (Physical) is the only one physically communicating with other devices. A message could travel through all the layers from one application layer (the layer closer to the user) to another placed in another device, but only traversing all the layers between them, not being allowed to escape the layers hierarchy. In this work we deal primarily with the Data Link layer, a layer responsible for point to point communication between devices. Specifically we will concentrate on the Medium Access Control (MAC) sublayer, responsible for accessing the channel, and scheduling accordingly.

In 1997 [12] the first standard of the IEEE 802.11 family was introduced. It included the lowest two layers of the OSI reference model (Data link and Physical — Figures 2.1 and 2.2) and was designed to operate in unlicensed spectrum. It includes a Logical Link Control Layer, which is responsible, among other things, for interfacing the MAC layer to the network layer, encapsulation of network packets and decapsulation of MAC frames. In the IEEE 802.11 standard flow control and error management is part of the MAC protocol, and not part of the LLC layer, as in other standards e.g. the ISO HDLC — High-Level Data Link Control. The MAC layer is responsible for the device to device link, communication with the Physical Layer and collision handling. Finally, there is the Physical layer (PHY), that performs the basic radio functions. Several PHY layers were introduced in various editions of the IEEE 802.11 standard family, but describing them in detail is beyond the scope of this thesis. In this section we concentrate to give a more technical introduction to the IEEE 802.11 MAC.

The 802.11 MAC is the most widespread MAC protocol used in the unlicensed spectrum. It began as a way to carry Ethernet on the air, mostly for transferring files between computers in a single office space [13]. It then continued to evolve into the standard we know today. As said earlier, the number of APs using this protocol is one order of magnitude more than traditional cellular BSs; it is now ubiquitous. A quick look at the statistics shows us that there are not only many more APs than than traditional BSs, but this number is also growing fast [14]. Exploiting the success of this protocol by improving it is now, in the author's view, a key issue. Users are more likely to use an improvement of a technology they already rely on than changing their equipment altogether [15] [16]. By using an existing infrastructure that grew in an uncoordinated manner, we can now improve the user experience, without an investment in a big one-purpose infrastructure that, in all likelihood, will have to be replaced in the next 10 years.

The next section will deal with the technical details of the IEEE 802.11 MAC mode of operation.

2.1.1 The IEEE 802.11 MAC Mode of Operation

In this section we describe in detail the mode of operation of the IEEE 802.11 MAC layer.

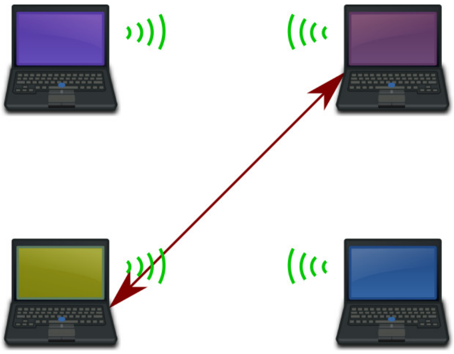

Figure 2.3: Ad-hoc mode in the IEEE 802.11. This diagram also utilizes the following third party image: [3].

The IEEE 802.11 MAC layer can work in two main modes. The simpler of the two is the Ad-hoc mode (Figure 2.3). In this mode, a direct link between two devices is established. All communication happens between those two devices (as far as the MAC layer is concerned). It is useful for example in case of bridging two connections or when a data transfer is needed only between two 802.11-compliant devices.

The more complex mode is the infrastructure mode (Figure 2.4). In this mode an Access Point (AP) is the recipient of the traffic from all the connected

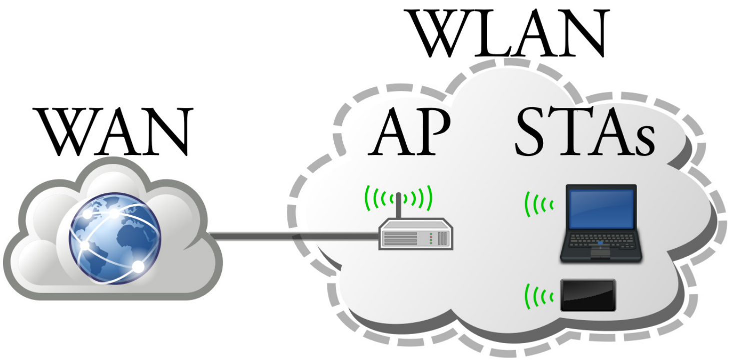

Figure 2.4: Infrastructure mode in the IEEE 802.11. This diagram also utilizes the following third party images: [3, 17].

devices (STAs). It usually communicates with other layers in order to route the traffic to the Wide Area Network (WAN) or other LANs. It comprises association mechanisms as well as security and handover.

The basic access mechanism in the IEEE 802.11 MAC was introduced in the IEEE 802.11b version and it is called the Distributed Coordination Function (DCF). The flowchart of the DCF operation mode is shown in Figure 2.5. It is a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. Time is slotted and the slot time depends on the version of the standard (typically 9 or 20 μs). The MAC layer has a buffer, which in Figure 2.5 is referred to as q. If the buffer is not empty, the DCF procedure begins.

The protocol uses a backoff parameter called Contention Window (CW), measured in slots. It is the main mechanism used to "wait before sending", in order to avoid collisions between competing devices. It uses a so called Binary Exponential Backoff (BEB) scheme. Devices are supposed to listen before sending a frame. The waiting time before sending is given by a "backoff time" that is drawn from a discrete uniform distribution between 0 and CW.

Each time delivery fails for a frame, the process is repeated with a CW two times bigger than the previous, until a certain retry limit m' is reached. Then the CW remains fixed, until another limit m (typically 7) is exceeded, after which the frame is dropped.

After the backoff counter B (in slots) is generated, the device is supposed to listen to the channel for a Distributed InterFrame Space (DIFS — defined as SIFS $+ 2 \times$ slot time). It is the main mechanism used to "listen before sending". If the channel becomes busy during DIFS (i.e. there is another transmission ongoing), the backoff counter is frozen, until it remains idle for a DIFS. If, on

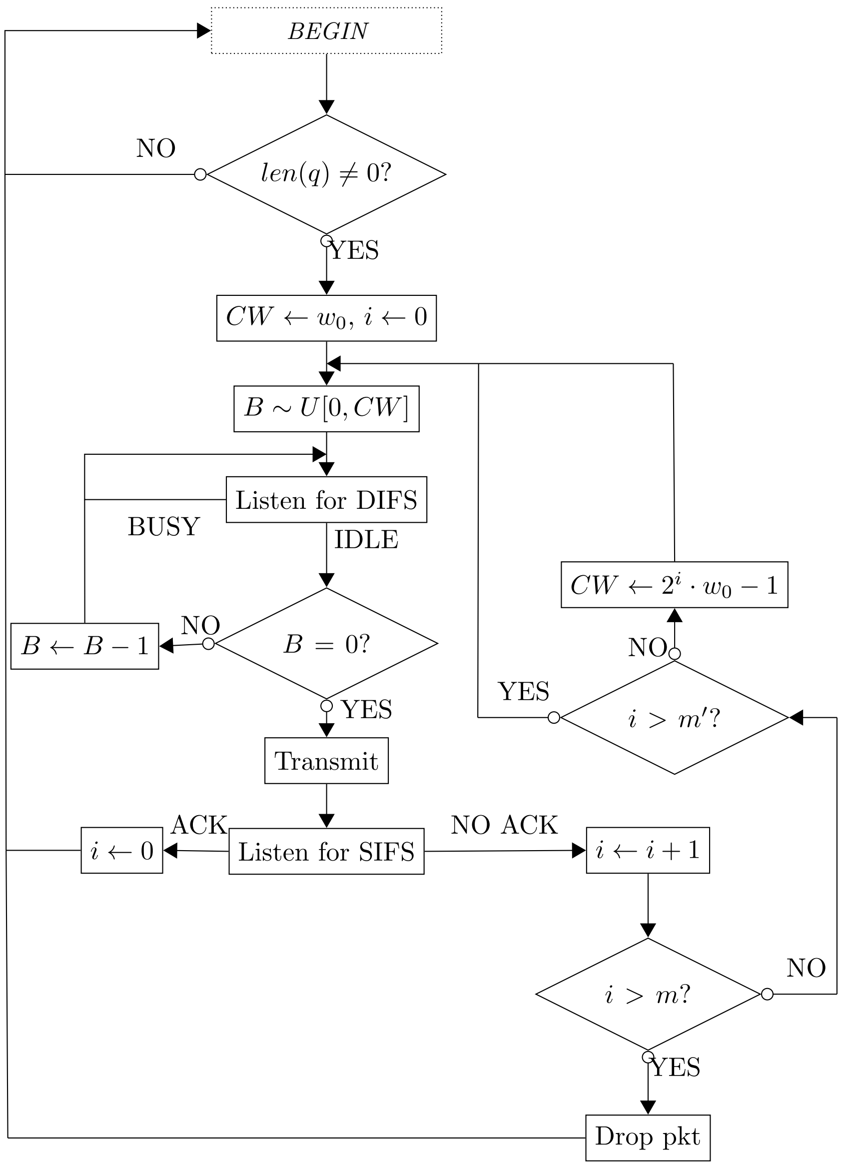

Figure 2.5: DCF mode of operation. len(q) is the buffer length. $U[a, b]$ is the discrete uniform distribution between a and b.

the other hand, the channel remains idle, if $B \neq 0$, B is decremented and the process is repeated.

When $B = 0$ the frame is transmitted. After transmission, the device listens to the channel for a Short InterFrame Space (SIFS — typically 10 or 16 μs). If an acknowledgement packet (ACK) is received within SIFS, the transmission is considered successful and the whole process repeats[1].

In case no ACK is received, the device assumes a collision has occurred. The retransmission variable i is incremented. If $i > m$ the frame is dropped, and the responsibility for retransmissions falls on the upper layers. In case still $i < m$, if $i > m'$ the entire process is repeated with the same CW. In case In case still $i < m$ and $i < m'$, the whole process is repeated with a doubled CW. Figure 2.6 shows an example of the DCF mode with two competing transmitters.

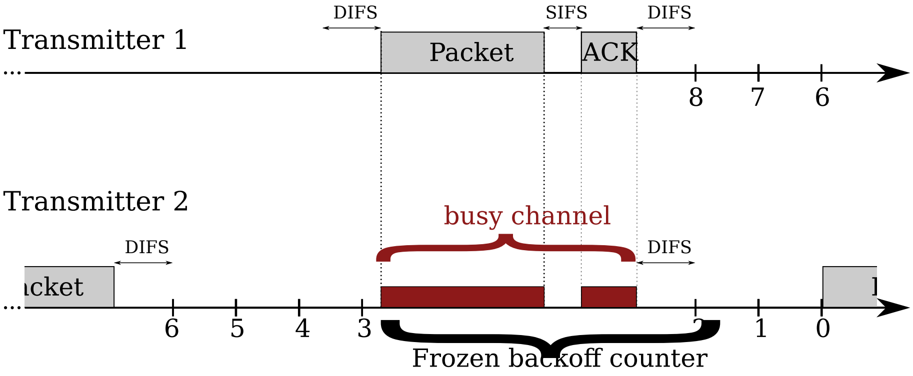

Figure 2.6: DCF with two transmitters example.

One of the first problems encountered by the designers of the standard, was the so-called hidden node problem. Given the nature of the radio channel, within a WLAN, each device has a limited range. In free space power decreases with the square of the distance and each device has a minimum SINR threshold to decode the message, thus putting a limit to the maximum transmit/receive range. It is the best case scenario, and in real life it decreases further due to obstacles, scattering and atmospheric interference, as well as external EM interference (e.g. microwave oven in the 2.4 GHz range).

In Figure 2.7 we look at a minimal example. We see that A is in range of B (and vice versa), B is in range of C (and vice versa), but A is not in range of C. Let's suppose A wants to send a frame to B. B listens to the channel for

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[1] A post-backoff DIFS is also inserted in the standard as a way to avoid one device continuously capturing the channel.

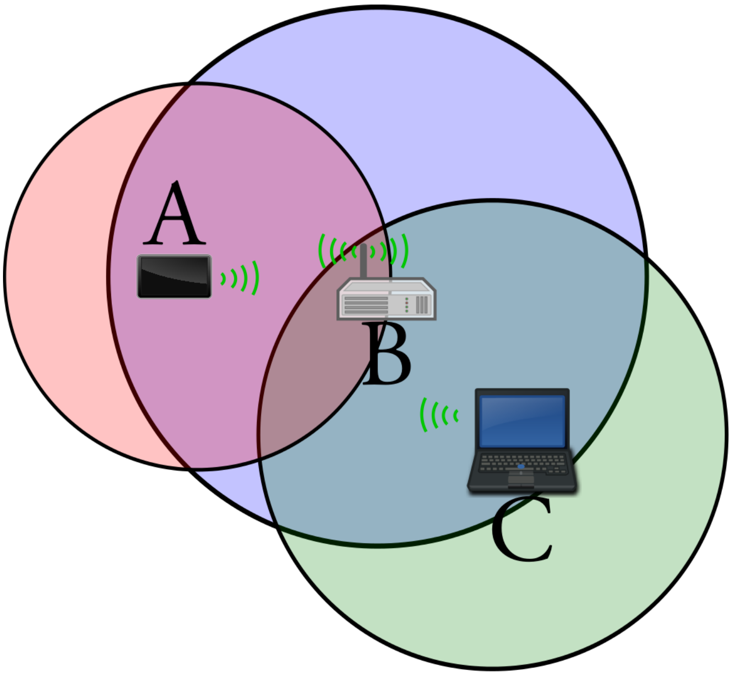

Figure 2.7: The hidden node problem. This diagram also utilizes the following third party image: [3].

DIFS and concludes it is free. Let's also suppose that C wants to send a frame to B at the same time. Also C senses the channel idle. They then both send a frame to B. Although neither device sensed the channel as busy, there is a collision. A is called "hidden" for C and the effect is called the hidden node problem.

A similar problem is called the exposed node problem. In Figure 2.8 we can look at a minimal example. Let's suppose B wants to send a frame to A, but C wants to send a frame to D at the same time. Notice that C is in range of B, but D is not. C listens to the channel and finds it busy, so has to defer to transmit to D, even though the two transmissions could have been performed at the same time. C is called "exposed" to B.

In order to overcome the hidden and exposed node problems, in the IEEE 802.11b version of the standard, instead of the two way handshake ACK scheme, a four way handshake scheme was introduced, called the RTS (Request To Send)/ CTS (Clear To Send) scheme (Figure 2.9).

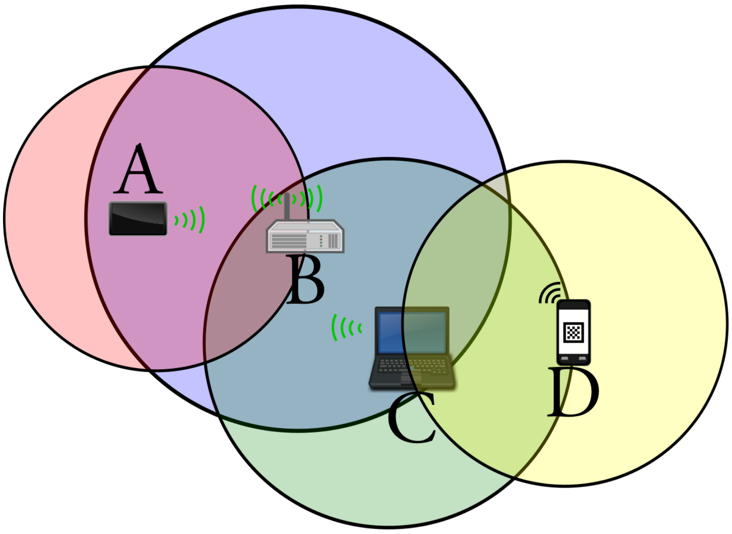

Figure 2.8: The exposed node problem. This diagram also utilizes the following third party images: [3, 18].

This scheme involves the transmitter sending a request frame called RTS to the receiver, containing the duration of the data frame to be sent. All the devices overhearing this request update a vector of the channel occupation called the Network Allocation Vector (NAV), thus deferring their own transmissions. If within a SIFS a CTS frame is received, the device waits an additional SIFS and then the transmission starts. This triggers the update of another NAV for the CTSs. This is done in order for STAs not in the transmission range of the transmitter to know there will be a transmission after a SIFS, and so not to interfere. Then the usual ACK mechanism is used. Other STAs may continue with their normal mode of operation after a DIFS. Usually the RTS/CTS mechanism is employed when a frame is bigger than a certain threshold, typically on the order of 1 KB.

In order to accommodate Quality Of Service (QoS), the Enhanced Distributed Channel Access (EDCA) was introduced in the IEEE 802.11e standard [19]. EDCA uses different DIFSs (called AIFSs — Arbitration InterFrame Spaces) and CWs for different quality classes, called Access Classes (ACs). In particular, the minimum CW $CW_{\min}$ (w_0 in Figure 2.5) and maximum CW $CW_{\max}$ ($2^{m'} \cdot w_0 - 1$) are calculated according to Table 2.1, where aCWmin and aCWmax are parameters dependent on the PHY layer used. Notice that a shorter $CW_{\min}$ grants a faster access to the channel, but a higher chance

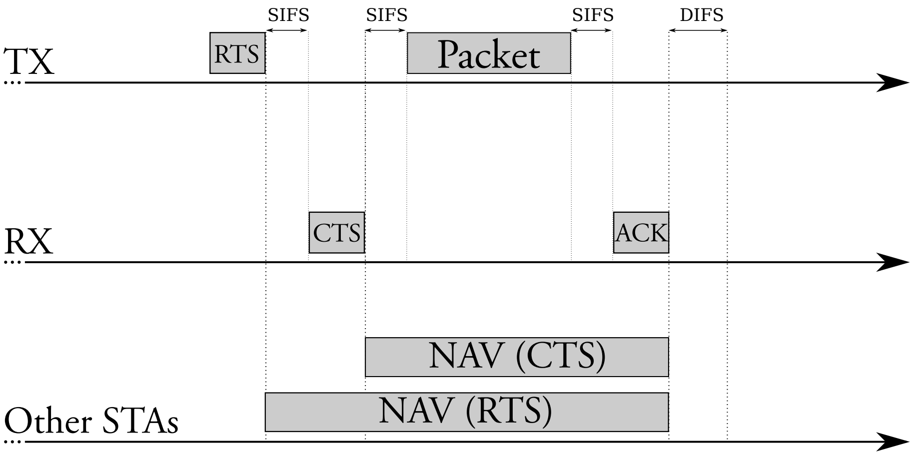

Figure 2.9: The RTS/CTS mechanism.

of contentions if all the other STAs use the same AC. The class to which the frame belongs is given by the upper layers. AIFSs are given for 802.11a OFDM PHY, in slots. Notice how a shorter AIFS grants acquiring the channel quicker. Each AC has its own queue, and priority is based on an internal virtual channel contention scheme (Figure 2.10).

Table 2.1: CW_{min} and CW_{max} for different ACs. Also the AIFS is presented. Note that the smaller CW_{min} and AIFS, the higher priority.

AC	CW_{min}	CW_{max}	**AIFS**
Background	aCWmin	aCWmax	7
Best Effort	aCWmin	aCWmax	3
Video	(aCWmin+1)/2 - 1	aCWmin	2
Voice	(aCWmin+1)/4 - 1	(aCWmin+1)/2 - 1	2

↓ priority

In the same standard the Point Coordination Function (PCF) was introduced. It only works in infrastructure mode. It is a polling technique, in which the Access Point (AP) grants contention free periods to STAs. The AP maintains a list of pollable STAs, and every CFPRate slots, it broadcasts a beacon initiating a contention free period (Figure 2.11). In this period, lasting CFPMaxDuration slots, the polled STA enjoys a contention free channel. To ensure the contention free period, a PCF InterFrame Space (PIFS) smaller than DIFS

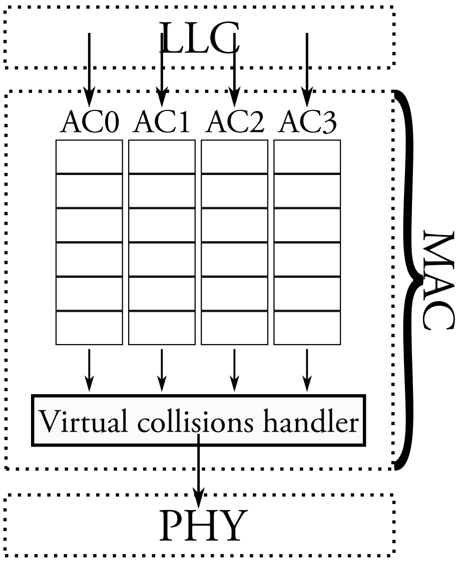

Figure 2.10: The EDCA virtual channel contention scheme.

and larger than SIFS is used. After that period normal operation begins again until the next beacon from the AP. Notice that a STA can also not have data to send during the contention free period, thus wasting bandwidth (we will investigate this further in Section 2.1.2).

The Hybrid Coordination Function (HCF), introduced in the same version of the standard, combines the PCF and the EDCA in infrastructure mode. It introduces different contention free periods for different ACs, called Transmission Opportunities (TxOps). In this version, polling frames by the AP and the STAs are additionally filled with QoS details. This overhead informs the AP on how long the next TxOp will be, according to the AC the frames in the polled STA buffer belong to. A STA that was granted a TxOp during the CFP can send a burst, similarly to the PCF, with a maximum duration given by the AC requested (an example in Table 2.2). It depends heavily on the PHY layer used, as different data rates give different transmission times per frame.

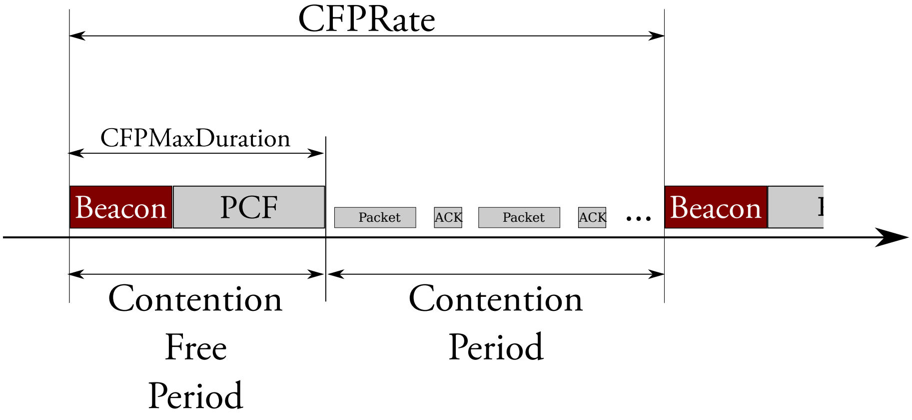

Figure 2.11: The PCF mechanism.

Table 2.2: Example of max TxOp for different ACs. Note that it depends heavily on the PHY layer used, as different data rates give different transmission times per frame.

AC	max TxOp
Background	0
Best Effort	0
Video	3.008 ms
Voice	1.504 ms

↓ priority

In the next section we will to introduce the open problems in the 802.11 MAC, central to understanding our contributions to the field.

2.1.2 Open Problems in the 802.11 MAC

In this section we will introduce the open problems in the current IEEE 802.11 MAC. An understanding of them is a key to understand where our contributions fit. Specifically we will discuss the ratio between the packet transmission time and the actual propagation time, the hidden/exposed node problem, coordination, QoS and the use of frame aggregation.

One problem known for a long time, but only recently became relevant for 802.11, as data rates have risen, is the ratio between the packet transmission time and the actual propagation time. Given the raw data rates involved in the newer versions of the IEEE 802.11 standard, the ratio between the packet transmission time and the actual propagation time has become an issue. As the data rates increase, this ratio shrinks. Also, the trend for applications is to use more small frames than the traditional big frames of desktop applications [20]. As highlighted in [21] this leads to a substantial performance degradation of CSMA as this ratio decreases, to the point when ALOHA[2] outperforms CSMA. This will only get worse as device to device communications will increase, especially in the context of the new paradigm of the Internet of Things (IoT), or the Smart City paradigm [6]. A limiting factor for the extension of a WLAN, other than the SINR at the receiver, is the length of the SIFS. If the propagation time from the extreme boundary of the coverage radius is bigger than SIFS, then all the ACKs received by either end would be discarded, as they will take more than SIFS to arrive at the transmitter. Also, when the ratio between the transmission time and the 802.11 interframe spaces decreases, they cease to be negligible. A DIFS time of 28 μs spent to send a frame which transmission time is 30 μs becomes a considerable overhead.

As mentioned earlier, one of the first problems encountered by the IEEE 802.11 MAC layer designers was the hidden/exposed node problem. The 802.11 standard introduced the RTS/CTS mechanism precisely in order to avoid the hidden node problem. In the case of Figure 2.7, B would have broadcast a CTS, which would have been received by C, thus avoiding a collision. In the case of Figure 2.8 C would have received the RTS from B, but then could not have overheard the CTS from A, so it will not defer its transmission. Although beneficial in those limited cases, the RTS/CTS introduces a moderately high overhead. In a WLAN of thousands of devices, the RTS + SIFS + CTS propagation time can become a significant bandwidth waste. To overcome this problem RTS/CTS is used only if the frame exceeds a certain threshold in bytes. In dense WLANs also, RTS/CTSs frames could be lost due to collisions [23]. Since RTS and CTS frames are quite small in size, in modern WLAN environments with increasing PHY data rates, they have a high propagation delay to frame transmission time ratio, which, especially in dense environments, can lead to significant performance degradation [21]. It was also noted that RTS/CTS can perform worse than simple CSMA even in non-saturated scenarios [24].

As mentioned previously, the IEEE 802.11 MAC lacks a well-defined coordination plane. In residential areas there is often a number of APs overlapping and giving access to the WAN provided by the same ISP. A simple coordination scheme would be to make APs agree on traffic priority. For example, we

---

[2] ALOHA is a very simple random access protocol in which devices transmit as soon as a packet to send has arrived at the MAC layer (or in the following slot, for slotted ALOHA), without listening for the channel. In case of collision the device retries the transmission at a later instant in time. For more details see [22].

may consider two overlapping APs referring to two different WLANs. AP A is performing a long file transfer, while AP B is performing a VoIP call. B would be interested in a steady stream of small frames with a jitter as low as possible, while A could bear delays of some milliseconds, since its traffic is not delay-constrained. Without coordination both A and B would suffer continuous collisions and retransmissions. On the other hand, if A leaves some space to B, both will provide a better user experience. With the data rates now offered by modern PHY layers (up to 10 Gbps in the upcoming ax standard [8]) A has to leave very little space to B in order for both to enjoy a reasonable QoS. Of course the problem as described here with only two APs could be solved by simply having two different channels in which to operate, but, as highlighted before, the density of APs is becoming high in residential areas, thus a solution with different allocated channels is no longer feasible.

QoS is also a very big issue to be addressed by the standard. While EDCA and PCF try to ensure some form of statistical QoS, they mostly fail to do so. The Point Coordination Function (PCF), developed within the 802.11 standard, was aimed at enhancing quality of service support, however it also introduces excessive overhead due to null frames sent by a central coordinator to devices without any packets to transmit [25]. On the other hand, EDCA relies on the upper layers to classify traffic. While this could be easy in a single device uploading traffic, there are privacy issues concerning an AP downstreaming traffic to a device, especially in big public WLANs.

Additionally, to counteract the effects of small frames on the overall performance of modern WLANs, one solution could be frame aggregation. It was originally proposed in the 802.11n standard. It uses two main mechanisms, MAC Service Data Unit (MSDU) aggregation and MAC Protocol Data Unit (MPDU) aggregation. In the former the entire aggregated frame is acknowledged once. In the latter each aggregated frame is acknowledged individually. Different studies investigated the performance of those mechanisms ([26–28]) and concluded that new, more efficient and traffic-aware mechanisms are needed in order to achieve the maximum gain from frame aggregation.

We introduced the most relevant open problems in the IEEE 802.11 MAC family. Schemes developed to address some of those problems will be discussed in Section 2.2.1, with a particular focus on cooperative protocols.

2.2 Cooperative MACs

The very nature of the unlicensed spectrum, available to any device wishing to transmit in those bands, discourages the use of strictly centralized protocols. Devices should, to the maximum extent possible, be able to coordinate by themselves. The lack of a reliable control channel renders the use of central controllers impractical. The desired behavior is one in which devices can communicate amongst themselves and coordinate, relying as little as possible on a central coordinator, while trying to maintain a certain level of reliability. In this context, many possible cooperative MAC protocols have been proposed to deal with the uncertainty of the unlicensed spectrum.

Additionally, overlapping WLANs often have different operators (e.g. in a residential building, each apartment operates their own network). So the issue of having a centralized controller is not just a practical/technical one, but it would also mean one operator controlling another operator's network, and the second operator may not want to cede that control.

In the next section we will present the current state of cooperative MAC protocols in the literature.

2.2.1 Related Work

In this section we will present cooperative MAC protocols present in literature. We will address the problems highlighted in Section 2.1.2. Specifically, we will present cooperative solutions for distributed scheduling, cooperative relaying and frame aggregation.

Distributed scheduling is one of the approaches investigated in order to overcome service degradation due to collisions. In [29] the authors introduce a distributed CSMA algorithm aimed at maximizing the throughput or other custom utility functions in wireless networks. They assume a simplified CSMA model where transmissions take no time to propagate and assume no hidden nodes. Under those strict assumptions they develop and test their scheme, proving that it reaches, for all practical purposes, the desired effect. They also provide hints on how to implement it in a real 802.11 WLAN. The shortcoming of this work is that it treats the WLAN as a graph, relying on distributed link scheduling, while, as discussed in Section 2.1.2, propagation time and hidden nodes play a major role in degrading performance in real world WLANs. Similarly, in [30], the authors study Ad-hoc wireless networks and related scheduling policies as a graph, so using compatible sets rather than per-frame policies. It suffers from the same shortcomings as [29]. Similar studies follow in [31–33] treating the network as a graph, and deriving appropriate optimal policies.

Regarding frame level scheduling, there are a number of works that use overhead frames to create binding scheduling [34–37]. A series of special-purpose frames and acknowledgements are used in order to negotiate a synchronous scheduling at the frame level. The main drawbacks are that STAs are then bound to a particular schedule, that must be carried out synchronously, and the large overhead due to negotiations. Obviously STAs using the standard 802.11 DCF are excluded from these kind of negotiations.

It is possible to achieve collision free distributed scheduling by learning algorithms [38, 39]. The main drawback is the convergence time since convergence is not possible when the WLAN conditions change faster than the convergence time. Those conditions may include the number of nodes, the traffic pattern etc. Also they still suffer from the hidden node problem. In [40] the authors propose a scheduling mechanism based on backoff randomization. This leads to an increase in collisions as the number of STAs in the WLAN increases, although having a beneficial effect on relatively small WLANs.

Another approach in cooperative MACs is cooperative relaying. In this approach STAs take responsibility for a limited routing inside the WLAN. One scenario could be a node on the edge of the WLAN, so other nodes could help it to deliver frames [41]. On the other hand, nodes could actively listen for repeated collisions happening to a node, so they can buffer some frames from it and relay them to the destination. Relaying in the MAC layer almost always refers to decode-and-forward schemes. The physical layer of the relay is actively decoding the received signal and passing it to the MAC layer, that in turn re-encapsulates the packet with appropriate new headers. The main drawback is that the decapsulation and re-encapsulation process takes time.

Another relaying mechanism is amplify-and-forward. It uses appropriate synchronous retransmission techniques in order to amplify the SINR at the receiver, thus improving the chance that the frame is decoded correctly at the destination. The main drawback is that it requires a high level of synchronization between the sender and the relay.

Most cooperative relaying protocols require each STA to maintain a CoopTable [42] maintaining a database of possible relays/STAs to help. For example, in [43] the authors provide a distributed scheduler that piggybacks on RTS/CTS frames, and reduces collisions in subsequent hops the frame traverses within the WLAN.

One strategy for cooperative relaying is to let the sender choose the relay (or decide to send directly by itself). In [44, 45] the authors choose to use link availability information in order to pick a relay. This scheme has failsafe mechanisms in case no ACK is received. The authors use various techniques in order to estimate the link reliability and in general make heavy use of RTS/CTS frames to protect ongoing transmissions. In [46] the authors instead have a relay helping complement retransmissions for an already burdened STA. The authors specifically let the relay and the STA independently estimate the RSSI at the receiver. On the other hand, in [47] the relay proactively proposes itself as a helper. As an example of an Amplify and Forward MAC scheme, R-MAC is used in [48] on par with other physical layer techniques in order to amplify the received signal at the destination.

Despite the fact that frame aggregation is one of the components of the upcoming High Efficiency Wifi — HEW — standard, cooperative schemes for frame aggregation are not common in the literature. The majority of the work (e.g. [49–51]) focuses on selfish behavior, and, as a side effect, benefits the entire WLAN. Instead in [52], the authors use a competitive clusterization for Virtual Frame Aggregation (VFA) in vehicular networks. The STAs are subdivided into clusters and the winning cluster sends all the allowed frames as a continuous train without interruption. Although not a true frame aggregation, the scheme still shows benefits, especially in cramped WLANs.

In [53] the authors instead *adapt* the number of frames to aggregate to the link status and particular QoS requirements of the application layer. Although not properly cooperative, it still gives an overall benefit to the network as a whole. In [54] the authors use both contention window control and frame aggregation to achieve better fairness among the nodes of a WLAN. This is an instance of a true cooperative MAC protocol that uses frame aggregation as a means of improving the overall quality of the WLAN. STAs estimate the frame aggregation size and the contention window based on the lowest transmission rate among the STAs. In [55] the authors instead use frame aggregation in a fairly creative manner, by letting a cooperative relay aggregate its own frame as well as the relayed STA frame for retransmission.

We reviewed some of the cooperative techniques used in literature to overcome the problems described in Section 2.1.2. We gave a framework in which our work and contributions fit in. We introduced three main branches: cooperative scheduling, cooperative relaying and frame aggregation. Every approach has its own advantages and drawbacks. In the next section we will explain in detail one of the metrics I tried to optimize in my work: the Age of Information.

2.3 Age of Information

Age of Information (usually abbreviated as AoI), is a relatively recent metric introduced in [56] to answer the question *"how fresh is the piece of information I am looking at?"*. It shifts the focus from the actual packets sent over a network, to the state of the information updates at the receiver itself. In contrast to the classical measure of the delay, it frames the problem in terms of information updates instead of packets, or packet flows. In broad terms, it measures the time elapsed from the last received update on a particular piece of information, instead of focusing on the packet delay. A more formal definition will be given in Section 2.3.1.

Status updates will be increasingly important as the number of devices capable of communicating automatically increases, especially in the context of the IoT. Examples of information where the latest update is the most important metric are alarms, heartbeats (i.e. status reports which carry the functionality status of a device) and vehicular information, such as the last known position or other environmental sensor measurements. A recent application is tracking global channel state information (CSI) in fully-connected wireless networks with time-varying reciprocal channels [57]. Another recent application is in Backlog-adaptive compression for continuous data streams over the network [58]. It is often especially tricky in very dense environments to ensure a low delay between the generation of a piece of information and the reception of it at the other end, while ensuring that this piece of information is received correctly.

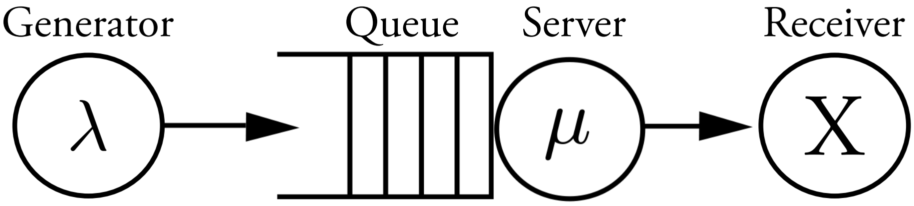

Figure 2.12: An M/M/1 system, with a generator, a queue, a server, and a receiver.

In order to get a sense of the fundamental difference between the Age of Information and packet delay, we will simulate a simple M/M/1 FIFO (First In First Out, or, alternatively, FCFS — First Come First Served) system with an average service time $\bar{S} = \mu^{-1} = 1\,s$ and a varying interarrival rate λ packets per second (Figure 2.12). Both the packet delay and the AoI are measured at the destination. The results of this simulation are shown in Figure 2.13.

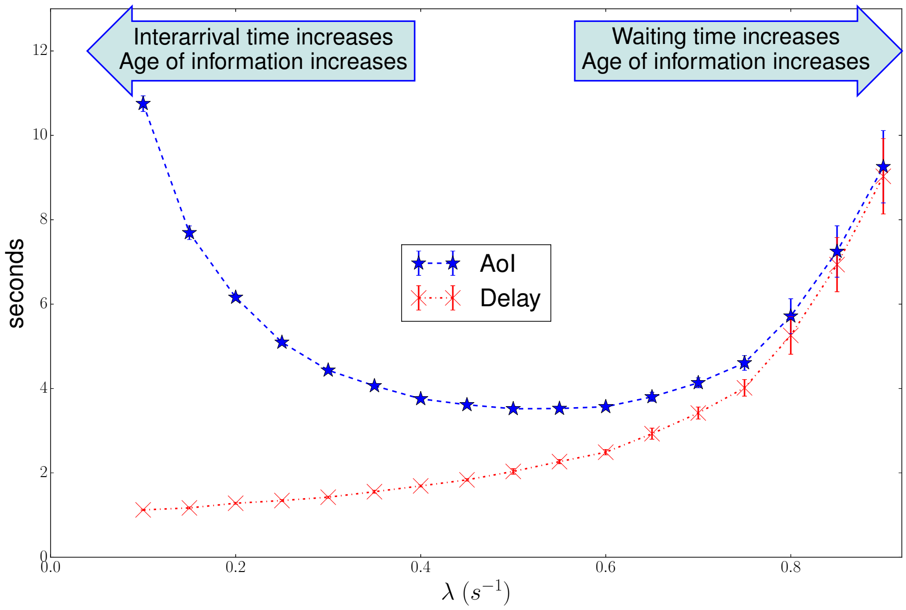

Figure 2.13: Average packet delay and Age of Information measured at the destination for an M/M/1 FIFO system with a service time $\bar{S} = \mu^{-1} = 1\,s$ and a varying interarrival rate λ packets per second.

As we can see, unlike the average packet delay, the average AoI shows a convex behavior, with a minimum[3] at $\lambda = 0.53\,s^{-1}$. Before that point, updates are too infrequent to give a sufficient update rate at the destination. On the other hand, when the packet generation rate is too fast for the server to process in a reasonable time, the waiting time for the packets becomes too high to give a sufficiently current information update at the destination.

One approach to overcome the effects of the queuing delay was introduced in [60]. Since we are only interested in the freshest piece of information available from the source, instead of using a normal FIFO system, we could use a system in which stale packets in the queue are substituted as soon as a fresher packet arrives from the source. Results from this approach are compared for the same M/M/1 system as above, both with substitution and normal FIFO, and are presented in Figure 2.14. As we can see, at high arrival rates, the substitution

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[3] In [59] the exact expression for the average AoI for an M/M/1 FIFO system at steady state is derived as a function of the interarrival rate λ and the service rate μ.

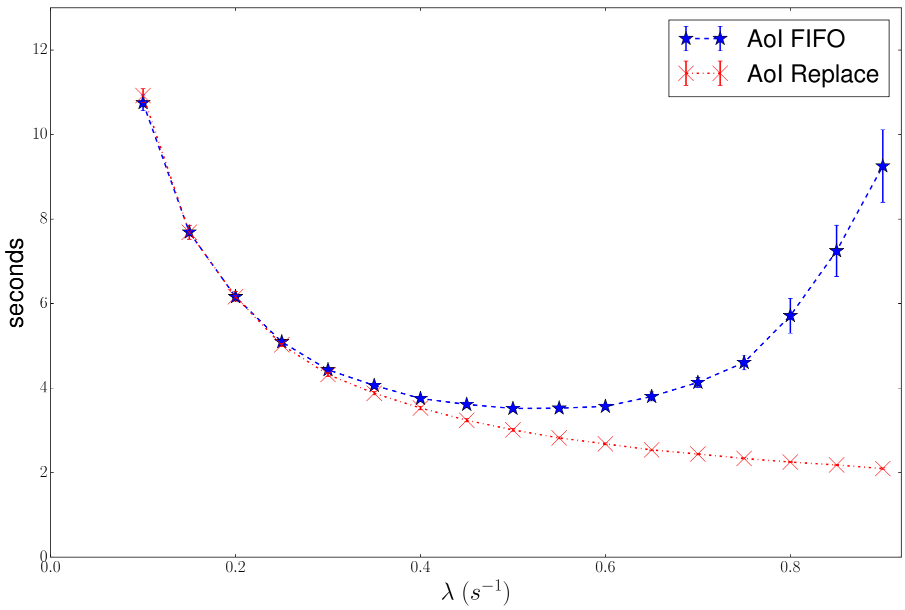

Figure 2.14: Average Age of Information measured at the destination for an M/M/1 system with a service time $\bar{S} = \mu^{-1} = 1\,s$ with both a FIFO and a substitution policy.

policy outperforms significantly the FIFO one.

This approach was extended in Paper II in order to fit in the environment of dense WLANs. The exact contributions to the field will be detailed in Section 3.

Dense environments, e.g. WLANs with thousands of devices, such as sensors, create harsh conditions for minimizing the average AoI. As the number of devices grows, the number of collisions grows exponentially [61]. With more collisions, there are more retransmissions, that in turn improve the access delay, thus penalizing the average AoI at the receiver end. It is important to shed light on the effects of those factors on the AoI, and devise mechanisms to minimize them, ideally with cooperative protocols in the MAC layer.

The rest of this section is subdivided as follows. In Section 2.3.1 a formal definition of the AoI will be given. A stable method for calculating both the average and the standard deviation of the AoI during simulations will be described. In Section 2.3.3 a literature review on AoI in telecommunication systems is presented.

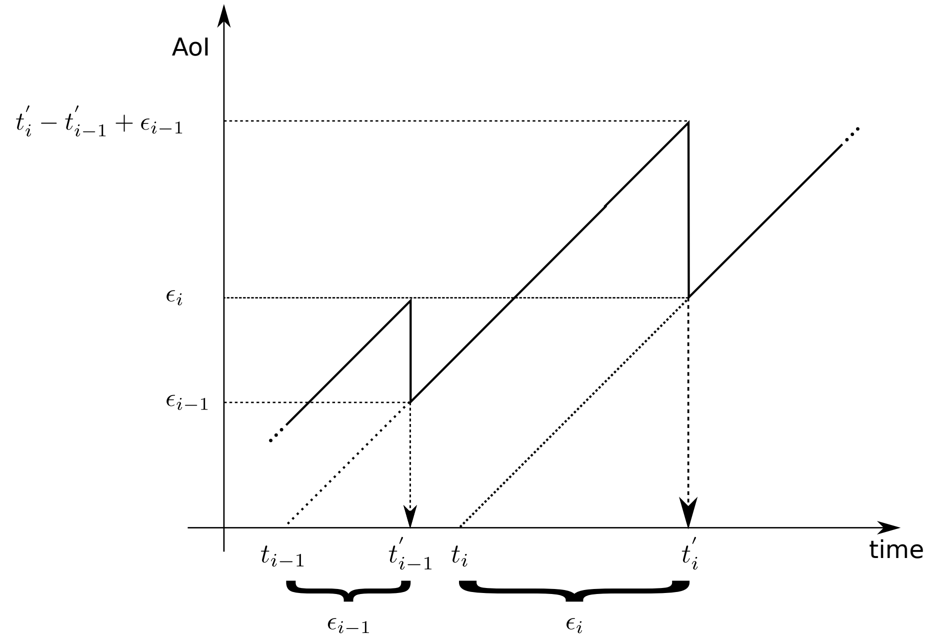

Figure 2.15: Example of the Age of Information over time at the end of a receiver.

2.3.1 Definition

We will now give a formal definition of the concept of Age of Information. Consider a transmitter sensing and sending updates of the information I over a channel to a receiver. The receiver is interested only in the freshest update of information I. An example curve of the age of information I over time is depicted in Fig. 2.15.

Assume a packet with the desired information I is generated at time t_{i-1} s by a source node. A receiver receives the information at time $t_{i-1}^{'}$ s. The packet will then have an age of $\epsilon_{i-1} = t_{i-1}^{'} - t_{i-1}$ s, so the age of information I at that time will be ϵ_{i-1} s. Then, if no information is received, the AoI will increase over time with slope 1. The next packet carrying updated information I is generated from the transmitter at time t_i s, and is received at time $t_i^{'}$ s. The age of this packet would then be $\epsilon_i = t_i^{'} - t_i$ s. If this packet is fresher than the current AoI (i.e. $\epsilon_i < t_i^{'} - t_{i-1}^{'} + \epsilon_{i-1}$) then the AoI will jump down to ϵ_i seconds, otherwise it will continue increasing. The AoI will continue to have this characteristic sawtooth behavior, and it is possible to reconstruct its curve by interpolating between the various samples when packets are received. Then it is possible to reconstruct various metrics; for example, it is possible to reconstruct the average AoI by calculating the integral over time of the curve as a sum of trapezoids and dividing over the elapsed time [62]. A way to accurately measure this without incurring numerical calculation errors is given in the next section.

In [59] the authors give a general expression for the average AoI in First Come First Serve (FCFS) systems. If X is the random variable that corresponds to the interarrival times from the source, and T is the random variable that corresponds to the service time, then the average AoI at the receiver $\bar{\Psi}$ is:

$$\bar{\Psi} = E\left[\texttt{AoI}(t)\right]_{t\in[0,\infty)} = \lambda \cdot \left(E\left[XT\right] + \frac{E\left[X^2\right]}{2} \right)$$

. Note that this depends on the expected value of the product of X and T, whose quantities are, in most cases, not independent random variables.

Another derived measure is the peak Age of Information (pAoI), first introduced in [62]. It is defined as the maximum value of age achieved immediately prior the reception of an update. The Average pAoI is calculated as:

$$E\left[\texttt{pAoI}(t)\right]_{t\in[0,T]} = \langle b(i) \rangle \ , \ i = 1, \ldots, n$$

, where $b(n)$ is the major base of the trapezoid whose base ends precisely at T, i.e. $t_n^{'} = T$.

2.3.2 Numerically Stable Measure of the Average AoI

In order to avoid the so-called catastrophic cancellation in the computation of the variance of the AoI, instead of computing the square sum of the trapezoids forming the AoI curve, it is possible to compute the average AoI as a running weighted mean, and the AoI variance as a running weighted variance [63].

Let's consider the i-th trapezoid in the AoI function over time as in Figure 2.16 (highlighted in red). Let's call its height $h(i) = t_i^{'} - t_{i-1}^{'}$, and its two bases $a(i) = \epsilon_{i-1}$ and $b(i) = t_i^{'} - t_{i-1}^{'} + \epsilon_{i-1}$. The area under the trapezoid will then be:

$$A(i) = \frac{h(i)}{2} \cdot (a(i) + b(i))$$

, with $\epsilon_0 = 0\,s$ and $t_0^{'} = 0\,s$.

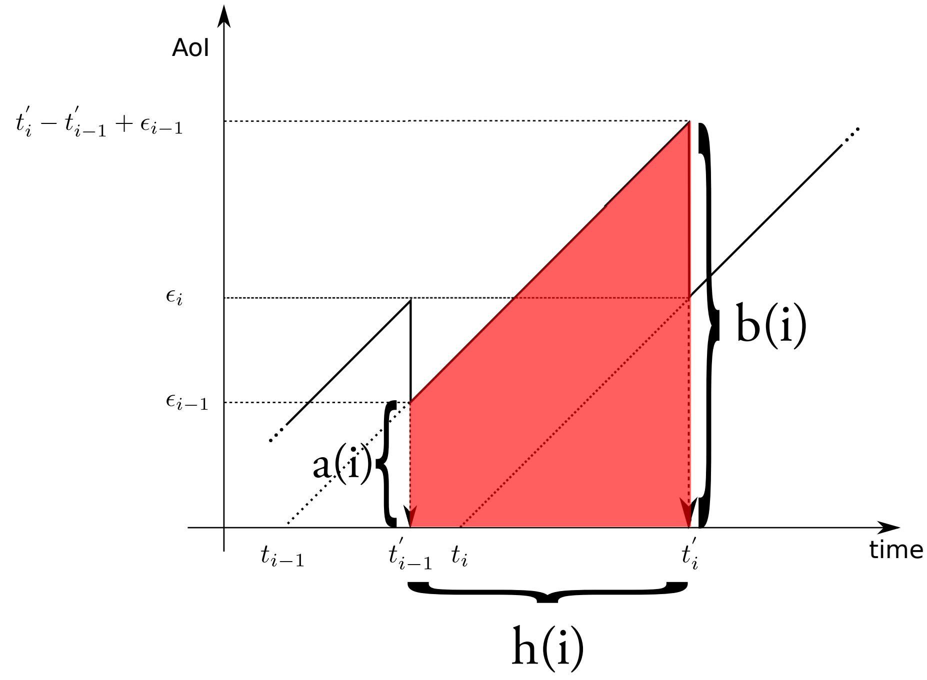

Figure 2.16: Area under the i-th trapezoid in the AoI function over time.

The overall area under the curve until a point T in time will then be[4]:

$$\int_0^T \texttt{AoI}(t)dt = \sum_{i=0}^{n} A(i)$$

, with $t_n^{'} = T$ i.e. the n-th trapezoid has the base ending precisely at T. The average AoI will then be:

$$E\left[\texttt{AoI}(t)\right]_{t\in[0,T]} = \frac{1}{T}\int_0^T \texttt{AoI}(t)dt = \frac{1}{T}\sum_{i=0}^{n} A(i) \tag{2.1}$$

. We then proceed to modify (2.1) as a recursive relation. We can write T as a sum of time differences i.e. $T = \sum_{i=0}^{n} \Delta t_i$, where $\Delta t_i = t_i^{'} - t_{i-1}^{'}$, $i = 1, \ldots, n$.

---

[4] We suppose, without loss of generality, that T lies precisely at the end of the last trapezoid. It is always possible to cut a trapezoid artificially at one arbitrary point in time considering a fictitious updated packet coming at T.

We then rewrite (2.1) as:

$$
\begin{aligned}
E\left[\mathtt{AoI}(t)\right]_{t\in[0,T]} &= \frac{1}{\sum_{i=0}^{n}\Delta t_i}\sum_{i=0}^{n} A(i)\\
&= \frac{1}{\sum_{i=0}^{n}\Delta t_i}\sum_{i=0}^{n}\Delta t_i\cdot\frac{A(i)}{\Delta t_i} = \frac{1}{\sum_{i=0}^{n}\Delta t_i}\sum_{i=0}^{n}\Delta t_i\cdot B(i)
\end{aligned}
$$

where $B(i) = A(i)\cdot\Delta t_i^{-1}$. We essentially transform the time average into a weighted average with weights $W_i = \Delta t_i$ and samples $x_i = B(i)$. We can then use the formulas derived in [63] to write:

$$
E\left[\mathtt{AoI}(t)\right]_{t\in[0,T]} = \mu_n = \mu_{n-1} + \frac{\Delta t_n}{T_n}\cdot\left(B(n) - \mu_{n-1}\right)
$$

, with $\Delta t_0 = 0\,s$, $T_k = \sum_{i=0}^{k}\Delta t_i$, $t_n = T$ and $\mu_0 = 0\,s$. Using the same formulas, we can write the variance as:

$$
\mathtt{Var}\left[\mathtt{AoI}(t)\right]_{t\in[0,T]} = \frac{S_n}{T_n}
$$

where

$$
S_n = S_{n-1} + \Delta t_n\cdot\left(B(n) - \mu_{n-1}\right)\cdot\left(B(n) - \mu_n\right)
$$

, with $S_0 = 0\,s^2$. Note that, since S_k is an increasing sum, in case of long simulations, approaches to chunk it out may be required in order to avoid numerical overflows[5].

2.3.3 Related Work

There is a lack of work on the AoI in IEEE 802.11 networks, and, in random access networks more generally. The Age of Information in IEEE 802.11 systems was first addressed in [56]. The authors study the age of information in a vehicular network (VANET) via simulation and with a VANET testbed. In their scenario, each vehicle acts as a node. Each node beacons a particular piece of information to nearby vehicles, and it is interested in the other vehicles having the most up to date piece of that information. Each node broadcasts its information, so no acknowledgements are involved. The authors introduce a cross

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[5] One approach used by the author is to create a particular structure that sums until a certain threshold (say, half the maximum of the data type used to count the simulation time), then after exceeding this, stores a new piece of the sum in an array, and so on. Then it sums all the pieces individually divided by T_n (i.e. the final simulation time, unknown at the beginning of the simulation in most cases) at the end of the simulation.

layer MAC technique called “Latest state Out” (LO), in which the application sensing information fills the packet at the front of the MAC buffer with the latest available piece of information whenever the opportunity of transmitting a frame arises. They show how this technique efficiently minimizes the average AoI in all the nodes in the VANET. They also show that using the optimal Contention Window (CW) from the Bianchi model [64] the average AoI is further minimized. They then show how neither maximizing the throughput nor minimizing the delay automatically minimizes the average AoI. Finally they introduce a cross-layer rate control mechanism that works with a normal FIFO queue and no CW adaptation in order to minimize the average AoI at the nodes.

Their work differs from our work, carried out in Paper II, since it studies a vehicular network, while we studied a dense IEEE 802.11 WLAN of static nodes; we are interested in minimizing the AoI in a remote server instead of distributing the information to a set of nodes in the same network. Also the authors do not address the problem of other contenders (i.e. other devices trying to access the same wireless channel) in the network. Additionally, STAs are broadcasting the information, thus using only the first CW, not retrying to send the frame in case of a missing acknowledgment. Finally, in our work the MAC layer should only be aware of the application that generated the packet and the packet’s age, while in LO the MAC layer should signal the application whenever a transmission opportunity arises. In our work also, if the packets are sent by the application in order, the MAC layer will automatically infer that the new packet is the freshest, thus not even needing an additional field with the packet’s age.

The proposed LO technique is impractical. The time needed for the MAC layer to signal the application when it is ready to transmit, and then wait for the application layer to fill the MAC buffer is bigger than one IEEE 802.11 slot time ($\sim 10\,\mu s$), which is the time granularity in an IEEE 802.11 MAC. In addition, with this approach, the application must be allowed to write to the MAC buffer. This is in most cases impractical. In short, this approach requires very close coupling between the MAC and the application, which is both difficult and undesirable in practice. Finally, we did not use the optimal CW from the Bianchi’s model, since it is not possible in current hardware to change it at run time [64].

Different works then dealt with the calculation of the average AoI and the development of various techniques to improve it in several queuing systems. In [59] the authors give the first formal definition of the AoI, then they proceed to give expressions for the average AoI at the receiver end in M/M/1, M/D/1 and D/M/1 FIFO systems. They then derive a lower bound for the AoI when the arrival rate is controlled by the source for these types of systems, given that the source has information about the server status. In [65] the authors address the problem of information updates traversing a network that could potentially scramble the order of arrival at the receiver end. They assume the traversing times to be i.i.d. according to an exponential distribution. They then proceed to derive an expression for the average AoI at the destination. Then they also find upper and lower bounds for the AoI. In [62] (and further expanded in [66]) the authors study the AoI for the case of an M/M/1/1 queue and introduce a policy for packet management in a system that they call M/M/1/2*, in which stale packets in the queue are discarded upon the arrival of a newer packet from the source. They also introduce a new metric called the *peak age of information* (pAoI), as introduced already in Section 2.3.1. They provide analytical results for the systems involved.

In [60] the authors design a new queuing policy similar to the one introduced in [65], but optimized for multiple sources generating information updates that end up in the same queue. The server then generates service times to be i.i.d. according to an exponential distribution. The authors perform simulations on the system and conclude it to be beneficial. In [67] the authors consider M/G/1 and M/G/1/1 systems, whose sources generate packets belonging to different classes of information. The authors then find an analytical expression for the average pAoI. They then formulate an optimization problem for the newly found pAoI w.r.t. the information generation rates. In [68] the authors study the AoI in an emulated LAN with 2 nodes and compare their results with the theoretical results for various simple queuing systems. Their main result is the study of the buffer size on the AoI and pAoI. In [69] the authors consider an M/M/1 system in a case where there is a constant probability of dropping a packet after it has been serviced. They consider the pAoI and consider both Last-Come-First-Served (LCFS) scheduling and persistent retransmission. They derive expressions for the average pAoI for both scenarios.

In [70] the authors study a system with exponentially distributed arrival times and gamma distributed service times. They present both the average AoI and average pAoI analytical formulas for both preemptive and non preemptive LCFS in such systems. In [71] the authors study both M/M/1/1 and M/M/1/2 systems in which packets are constrained by a deadline, i.e. they are dropped if the waiting time is above a certain threshold. They then study the performance both analytically and numerically for these systems in terms of the average AoI in relation to the deadline. They then extend their work to M/M/1/k systems in [72] accounting also for the buffer size. In [73] the authors derive an invariant relation among the distributions of the AoI, the peak AoI, and the system delay. For the stationary, ergodic FCFS GI/GI/1 queue, they show that the stationary distributions of the AoI and the peak AoI are given in terms of the system delay distribution. Finally, they derive explicit formulas for the

Laplace-Stieltjes transforms (LSTs) of the stationary distributions of the AoI and the peak AoI, as well as the first two moments of AoI, in the stationary FCFS M/GI/1 and GI/M/1 queues.

In [74] the authors introduce two new metrics to capture the effect of AoI on correlated samples: Cost of Update Delay (CoUD) and the Value of Information of Update (VoIU) to capture the degree of importance of the information received at the destination. Small CoUD corresponds to timely information while VoIU represents the impact of the received information in reducing the CoUD. They then proceed to analytically address the expressions of those new metrics in a simple M/M/1 FCFS system. The problem of characterizing the AoI in network of queues is addressed in [75]. In this paper the authors prove that a preemptive Last Generated First Served (LGFS) policy results in smaller age processes at all nodes of the network (in a stochastic ordering sense) than any other causal policy, if the packet transmission times over the network links are exponentially distributed. In addition, for arbitrary distributions of packet transmission times, the non-preemptive LGFS policy is shown to minimize the age processes at all nodes among all non-preemptive work-conserving policies (again in a stochastic ordering sense).

In [76] the authors find the optimal policy for when the sender should generate status updates, if the number of updates per time it is allowed to send is constrained by an arbitrary time-varying upper bound. This models a sensor trying to optimize the AoI at the receiver end when it has energy-replenishment constraints. They formulate the optimization problem relative to the problem described, and also introduce a heuristic for the on-line solution of the problem. Similarly, in [77] the authors design optimal online status update policies to minimize the long-term average Aol, subject to the energy causality constraint at the sensor. They assume the service time is negligible with respect to the information generation process average time, and analytically characterize the long-term average AoI under different battery policies. Finally in [78] the authors obtain a lower bound on the average age for a general battery size.

While the previously described papers are important analytical works in the field, as far as the author is aware the more practical problem of studying the AoI in scenarios with a shared channel was only addressed in the following other works. In [79] and [80] the authors formulate an optimization problem for finding an optimal schedule for a number of transmitters sending information updates over a common slotted time-shared channel. The interference model is an SINR threshold model. They formulate the problem and prove it to be NP-hard. While this is an important work, that gives a benchmark for all subsequent schemes aimed at optimizing the average AoI in networks with devices sharing a radio channel, it is still an abstract model for a real world scenario. In [81] the authors study optimal non-anticipative policies with respect to the average AoI, for a Base Station (BS) to send updates to a number of clients (i.e. policies that do not use future knowledge in selecting clients). They consider fixed error probabilities per slot, but different for every client. They find the optimal policy both for symmetric networks (i.e. all the channels to each client have the same probability of failure per slot) and for the general case. Still an important work which gives us a benchmark in performances for networks with a sufficiently stable transmission error rate (which is practically achieved in saturated WLANs [64]), it does not address networks where the frame error rate is dependent on the devices, as in unsaturated WLANs. The in unsaturated scenario is not an unlikely one, since status updates could be sent with a low rate, but still suffer congestion.

In [82] the authors study a scenario with a BS serving N users. The BS sends pieces of information to the users with a particular focus on the average AoI. The channel is considered noiseless (i.e. without errors, although they address noise in [83]) and time slotted. Information is disseminated in a TDMA fashion, i.e. only one user can be served at a time. Each user is interested in a different source of information. By formulating a Markov decision process (MDP) they show that an optimal scheduling algorithm is stationary and deterministic; in particular, it is a simple switch-type algorithm, i.e., given the ages of other users, an optimal decision for a user is based on a threshold and the BS optimally updates the user if the age of the user is larger than the threshold. The authors propose a sequence of finite-state approximations and rigorously show its convergence. Finally, they proposed an optimal off-line scheduling algorithm based on the finite-state approximate MDPs as well as an on-line approximation.

In [84] the authors study a Cognitive WSN (CWSN), where N sensors opportunistically use the channel when a primary unit is not using it. They propose a joint framing and scheduling policy that optimizes energy efficiency of communication system under strict constraints on the expected age of information. Then, they quantify the impact of this policy on the age of information and communication energy efficiency by characterizing the utilized queuing dynamics, packet discard rate and retransmission probability. The derived closed-form expressions for the age of information and energy efficiency are used to regularize packet lengths based on the current sampling rate, channel quality and channel utilization rate by primary users. They study the CWSN under two different access schemes: polling and slotted ALOHA. The main drawback is that they consider the channel to be free of collisions between sensors when polling is used (although they use ARQ when sensors collide with frames sent by the primary unit), and it is well known that ALOHA has a constant collision probability (thus the arrival process at the MAC layer is decoupled from the service time) given non-bursty traffic models.

None of the works, beside [56], addresses an IEEE 802.11 scenario. In Paper II we will address some of the problems faced in dense WLANs by devices whose purpose is to minimize the average AoI at the receiver end.

Chapter 3

Summary and Contributions

3.1 Research Contributions

This thesis is based on two papers which summarize the result of our research. The contents of our research and contributions of each paper are described below.

OMAC: An Opportunistic Medium Access Control Protocol for IEEE 802.11 Wireless Networks

Antonio Franco, Saeed Bastani, Emma Fitzgerald, Bjorn Landfeldt, in *2015 Proceedings of IEEE Globecom 2015*, IEEE–Institute of Electrical and Electronics Engineers Inc., Vol. 2015 IEEE Globecom Workshops (GC Wkshps).

The ambitious goal of the upcoming IEEE 802.11ax (HEW) standard for wireless LANs (WLANs) is to enhance throughput by four times (and beyond), compared with IEEE 802.11ac,. This demands a radical improvement of present medium access control (MAC) functionality. To this end, a promising paradigm would be a graceful migration towards new MAC protocols which incorporate higher certainty in their decisions. However, this requires adequate information to be available to the devices, which in turn incurs excessive costs due to information exchange between devices. Also, scalability becomes an issue for emerging dense networks.

In this paper, we took a step forward by proposing an opportunistic MAC (OMAC), which restrains these costs, while increasing throughput of the new generation HEW. OMAC eliminates overhead costs by solely relying on the local capability of devices in measuring signal activities on the channel. A particular OMAC node continually collects and records the received signal strengths (RSS) overheard from the channel, and regards each individual RSS level as being transmitted by a unique node without the need to know the actual identity of the node. The OMAC node uses this knowledge to select a recorded RSS as its reference, and triggers a desired transmission policy whenever a transmission with an RSS sufficiently close to this reference RSS is detected.

Our results, obtained using simulations, indicate that OMAC improves the throughput performance significantly, and that the performance gain increases with an increase in network density. In particular, we tested OMAC versus randomly assigning frames to low and high priority queues in the MAC layer, using only a low priority queue, and using an high priority queue. OMAC outperforms those schemes both in terms of throughput and in terms of collision reduction. Furthermore, we also suggested a way of using OMAC with EDCA, for traffic differentiation.

I am the main contributor to this paper, and I was involved in all parts of the scientific work and writing of the paper.

LUPMAC: A cross-layer MAC technique to improve the age of information over dense WLANs

Antonio Franco, Emma Fitzgerald, Bjorn Landfeldt, Nikos Pappas, Vangelis Angelakis in *2016 23rd International Conference on Telecommunications (ICT) (ICT 2016)*, Thessaloniki, pp. 724-729, 2016-05-15.

Age of Information (AoI) is a relatively new metric introduced to capture the freshness of a particular piece of information. While throughput and delay measurements are widely studied in the context of dense IEEE 802.11 Wireless LANs (WLANs), little is known in the literature about the AoI in this context.

In this work we studied the effects on the average AoI and its variance when a sensor node is immersed in a dense IEEE 802.11 WLAN. We have also introduced a new cross layer MAC technique, called Latest UPdate MAC (LUPMAC), aimed at modifying the existing IEEE 802.11 in order to minimize the average AoI at the receiver end. This technique lets the MAC layer keep only the most up to date packets of a particular piece of information in the buffer. LUPMAC can be integrated into the existing IEEE 802.11ah standard with minimal modifications to the existing standard, and fits in the wider scope of IoT and 5G.

We show, through simulation, that this technique achieves significant advantages in the case of a congested dense IEEE 802.11 WLAN, and it is resilient to changes in the variance of the total network delay. It shows substantial benefits in terms of both the average AoI and its variance compared to the normal, unmodified IEEE 802.11 when the WLAN becomes saturated with traffic. This technique is also resilient to changes in the variance on the experienced delay.

I am the main contributor to this paper, and I was involved in all parts of the scientific work and writing of the paper.

COOPLUP - Analytical Probability of Removal Due to Staleness

Antonio Franco.

In the appendix, we start to investigate and calculate the analytical probability of removal due to staleness of the packet in a new cooperative MAC scheme for Wireless Sensor Networks (WSNs) called COOPLUP — COOperative LUPMAC. This protocol is aimed at decreasing the number of transmissions in a WSN with sensors broadcasting updates about a measured phenomenon, while minimizing the average AoI at the receiver.

I am the main contributor of this work, and I was involved in all parts of the scientific work and writing of the appendix.

3.2 General Conclusions and Future Work

3.2.1 Conclusions

The work performed in this thesis is aimed at designing new MAC protocols in order to tackle some of the problems in the modern IEEE 802.11 MAC DCF mode of operation in terms of scheduling, according to different metrics.

We first devised a MAC scheduling mechanism relying on the existing DCF mode of operation (OMAC), that uses different priority queues and priority access mechanisms in order to increase the throughput of WLANs. This method significantly outperforms existing IEEE 802.11 MAC schemes, as we have shown by means of simulations. OMAC eliminates the need for explicit exchange of information by relying only on the signal measurement capability of the devices, thus cutting the overhead due to cooperation frames exchanged between nodes. By only using the received RSSI of a device, OMAC does not require decoding of the signal, thus it is robust to varying channel conditions. It preserves privacy because it does not require the actual identities (e.g. MAC addresses) of the signal sources. Additionally, it is adaptive to changes in channel conditions and network topology since the RSS measurement and reference selection is a continuous process.

Then we tackled the problem of a new metric recently introduced: the Age of Information. We studied the effect on the AoI at a remote server of the DCF and transmission delay variance from an STA to the server. We also devised a new MAC protocol, LUPMAC, that significantly improves the average AoI and variance at the remote receiver end and is as transparent as possible to the MAC layer, requiring only minor modifications to the existing IEEE 802.11 MAC layer. The advantages of LUPMAC become even greater the more the network is congested (i.e. the pieces of information update are more frequently sent by the devices), particularly in terms of resilience to the variance of the transmission delay.

Finally, we started to expand and specialize the work on LUPMAC for WSNs, by introducing a new protocol called COOPLUP. We started by tackling the problem analytically.

3.2.2 Future work

Future work will involve expanding both OMAC and LUPMAC. First, our future work will address the theoretical bounds of OMAC performance. Several extensions for OMAC could be carried out, including the design of more sophisticated reference selection mechanisms to ensure an eligible node is guaranteed to have a unique reference node, where eligibility is determined by fairness, traffic priority, and the contribution of the node to the overall network performance and energy efficiency. Another equally important extension is to adapt OMAC for frame aggregation as an important feature of the upcoming HEW standard.

Secondly, it is important to expand the design of new MAC layer schemes that take into account information updates, and in particular AoI. For example, assigning different traffic priorities to different information sources (i.e. different ACs, as defined in the IEEE 802.11e EDCA), or making the devices cooperate in order to not contend for the channel with stale information updates. Our approach will be to give an analytical foundation to the AoI in DCF systems, in order to devise more sophisticated and energy-aware schemes, especially considering the upcoming IoT and Smart City scenarios, where thousands of devices will compete for the channel, thus stretching the limit of the existing MAC schemes.

In this framework, we started to expand and specialize the work on LUP-MAC for WSNs. We will expand this work by investigating the behavior of the analytical model for different parameters for the sampling rate, contention window, and data rate.

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Part II

Included Papers

Paper I

OMAC: An Opportunistic Medium Access Control Protocol for IEEE 802.11 Wireless Networks

The ambitious goal of the upcoming IEEE 802.11ax (HEW) standard for wireless LANs (WLANs) to enhance throughput by four times (and beyond), compared with IEEE 802.11ac, demands a radical improvement of present medium access control (MAC) functionality. To this end, a promising paradigm would be a graceful migration towards new MAC protocols which incorporate higher certainty in their decisions. However, this requires adequate information to be available to the devices, which in turn incurs excessive costs due to information exchange between devices. Also, scalability becomes an issue for emerging dense networks. In this paper, we take a step forward by proposing an opportunistic MAC (OMAC), which restrains these costs, while increasing throughput of the new generation HEW. OMAC eliminates overhead costs by solely relying on the local capability of devices in measuring signal activities in the channel. A particular OMAC node continually collects and records the received signal strengths (RSS) overheard from the channel, and regards each individual RSS level as being transmitted by a unique node without the need to know the actual identity of the node. The OMAC node uses this knowledge to select a recorded RSS as its reference, and triggers a desired transmission policy whenever a transmission with an RSS sufficiently close to this reference RSS is detected. Our results, obtained using simulations, indicate that OMAC improves the throughput performance significantly, and that the performance gain increases with an increase in network density.

A. Franco, S. Bastani, E. Fitzgerald, B. Landfeldt
"OMAC: An Opportunistic Medium Access Control Protocol for IEEE 802.11 Wireless Networks"
in *Prooceedings of IEEE Globecom 2015, IEEE GC 2015 Workshop on Enabling Technologies in Future Wireless Local Area Network (ETFWLALN))*, San Diego, USA, Vol. 2015 IEEE Globecom Workshops (GC Wkshps), 2015-12-06.

1 Introduction

There is an increasing demand for high throughput wireless access, driven by the proliferation of mobile devices, the increasing demand for bandwidth-hungry services, and the growing trend of dense network scenarios. This has led to an unprecedented growth of the market for wireless local area networks (WLANs), as evidenced by their ubiquitous penetration in homes and enterprises, as well as public hot spots. Moreover, wireless operators are embracing WLANs as an enabling technology for offloading cellular traffic and to expand network capacity and coverage by means of device to device (D2D) communications and small-cell deployments within future generation 5G technology [1]. The result is that the demand for WLANs will continue to grow and, according to recent forecasts [2], a significant proportion of traffic will originate from devices capable of using this access technology.

This trend has spurred a new wave of standardization activities, leading to the recently-developed, multi-gigabit IEEE 802.11ac (WiGig) standard, and moving towards a new standard, called High Efficiency Wireless (HEW), with an ambitious target of achieving at least a four times increase of medium access control (MAC) throughput per station compared to WiGig [3]. While the previous standardization efforts were highly focused on increasing link throughput through physical layer developments such as high-density modulation and multi-user MIMO technology, the new efforts are mobilized towards enhancing MAC performance in terms of spectrum utilization and the achieved user experience (e.g. latency) in the face of applications with stringent quality of service requirements. However, the inefficiency of the conventional CSMA/CA-based random access mechanism of 802.11 potentially compromises the mentioned targets. It yields a satisfactory performance when the network is in light traffic conditions, while imposing decreased channel utilization in dense networks and bursty traffic situations due to the increase of idle backoff slots and collisions [4, 5]. The performance of the random access mechanism deteriorates further when the population of small frames is substantially high [6]. The Point Coordination Function (PCF), developed within the 802.11 standard, was aimed at enhancing quality of service support, however it also introduces excessive overhead due to null frames sent by a central coordinator to devices without any packet to transmit [7]. At the other extreme, there are deterministic control access mechanisms (e.g. TDMA) which perform well under saturated traffic conditions, at the cost of excessive overhead that is imposed when traffic is non-saturated. Moreover, TDMA-based methods do not scale well with network size, and the implementation of these mechanisms requires tight synchronization and the presence of a central entity responsible for resource allocation. An alternative scheme would be the use of hybrid CSMA/CA and TDMA techniques, as in IEEE 802.15.4. However, these inherit the weaknesses of the two schemes, plus the challenges arising from the need for adaptive duty-cycle configuration and balancing between the contention-free (CFP) and contention access periods (CAP) of the underlying duty cycles [8].

In this paper, we propose a novel, opportunistic medium access control mechanism for IEEE 802.11 networks, called OMAC. OMAC takes advantage of the physical-layer capabilities of 802.11 devices and the fact that such capabilities are increasingly enhanced with the recent advancement of signal processing techniques, leading to the proliferation of high sensitivity wireless devices. Our main idea is to augment CSMA/CA with a higher level of certainty in transmission control policy without requiring explicit information exchange and coordination between participating nodes. To this end, each node relies on its physical carrier-sensing capability in order to overhear the channel, and collects information about received signal strength (RSS) levels from (active) peer nodes. Knowing that each RSS level uniquely maps to an active node, an OMAC node can use this fact to choose a reference RSS, and trigger an appropriate policy when a transmission from a node with RSS close to its reference RSS is detected. Such a policy can take on many different forms and in this work it is limited to a simple reconfiguration of backoff parameters. The RSS collection and reference selection process is continual; therefore, the proposed mechanism adapts to changes in network topology by selecting new reference nodes. OMAC can be thought of as a point on a spectrum with its extreme points corresponding to the conventional random and deterministic channel access control mechanisms. However, OMAC is different from the existing hybrid CSMA/CA and TDMA protocols as it does not involve collocated CAP and CFP periods, synchronization, and explicit exchange of control information between nodes and a central coordinator (e.g. an access point).

The remainder of this paper is organized as follows. Section 2 presents an overview of related work. In Section 3, we detail the proposed medium access control mechanism. Section 4 describes our simulation results, followed by Section 5 which concludes the paper and puts forward the future extensions of the present work.

2 Related Work

Our work in this paper has properties in common with (semi-) deterministic medium access control mechanisms. In the following, we present the features of this approach and contrast with our approach.

Hybrid medium access control has been the focus of a significant body of previous work. Examples of such studies are [9,10], where the authors proposed hybrid mechanisms by combining random access and TDMA. These slotted-based mechanisms — either hybrid or pure TDMA — require synchronization between nodes, which is usually performed by explicit beaconing. By contrast, OMAC is fully asynchronous, without the need for centralized coordination.

The idea of a hybrid deterministic and random access mechanism was later introduced in IEEE 802.11-based networks to support the quality of service requirements of high priority, real-time applications. The Point Coordination Function (PCF) in the basic 802.11 and HCF Controlled Channel Access (HCCA) designed for 802.11e are examples of this kind. Both schemes rely on a polling service performed by a centralized coordinator. The centralized architecture and the waste of bandwidth due to null polling packets are found as the main drawbacks of the basic PCF and HCCA schemes [11]. Distributed polling [11] and multi-polling [12] were proposed to combat the weaknesses of the basic polling services. These methods led to substantial improvements compared to the primary polling methods, however relying on a point coordinator was not fully eliminated. Also, the enhancements with regard to standard 802.11 were solely targeted to the contention-free period in favour of high priority traffic. Thus, the case of the contention-based operation mode and its significant performance degradation in congestion scenarios were not addressed. By contrast, OMAC does not rely on a single coordinator (as in polling mechanisms); it is not limited to a single operation mode; and it treats sparse and dense traffic regimes in a unified manner. Moreover, OMAC is generally neutral to traffic priority, but can be tailored with a high granularity to various traffic prioritization schemes and the resultant traffic classes.

More recent works on hybrid CSMA/TDMA can be found in [8,13]. In [8], a Markov decision process (MDP) was proposed to use the local information in a node to dynamically determine the length of CAP and CFP in 802.15.4 wireless networks. While this work achieves a substantial improvement in throughput, it suffers from excessive computation complexity. Furthermore, similar to other hybrid schemes, it relies on the coordination and the broadcast of superframes by a central node, thus, it is not applicable to WLANs as the main target of OMAC. In [13], a protocol termed Z-MAC [13] was introduced to leverage the strengths of CSMA and TDMA methods in different situations. Z-MAC uses CSMA as the baseline operation and TDMA as a supporting mechanism to enhance contention resolution. The overall goal of Z-MAC is to achieve collision-free operation by assigning an owner(s) to each slot, but other nodes can also contend for an owned slot, albeit with longer window size. Z-MAC is a slot-based method, thus its operation requires synchronization. Additionally, it requires explicit exchange of owned slots between neighbouring nodes, whereas OMAC only relies on information measured locally by each node. OMAC also does not require synchronization and does not mandate any slotted scheme.

Distributed scheduling is regarded as an alternative approach to migrating from random to deterministic medium access control. Distributed scheduling schemes are classified as link-level [14–16] and packet-level [17] methods. In the former approach, the on/off states of links are scheduled with regard to some objectives of interest such as interference mitigation, while in the latter method scheduling is performed on a per-packet basis. Most distributed scheduling techniques suffer from multiple drawbacks including the need for explicit information exchange, tight synchronization, incompatibility with the legacy 802.11 standard, and, above all, scalability. Our proposed protocol is not a scheduling method, but it resembles the packet-level scheme in that it enforces a (batch) packet-level strategy when a certain triggering event occurs, that is, when a transmission from a reference node is detected. Furthermore. OMAC does not involve signaling and resource reservation.

In another direction, the migration from random to (semi) deterministic MAC has been the focus of a body of research works with a primary objective of reducing collisions by means of applying a higher level of determinism to the backoff procedure and/or contention window adjustment. Reservation-based backoff methods are the prevalent schemes of this kind. In these methods, the participating nodes inform (implicitly or explicitly) each other of their future backoff strategies (e.g. the backoff slot). When a node is informed of the backoff strategy of its peers, it adjusts its strategy accordingly and informs others. EBA [18] and BCR-CS [19] are examples of backoff reservation methods using explicit announcement of future backoff strategies. These reservation-based methods impose excessive overhead due to the exchange of backoff strategies. Tuysuz et. al. [20] proposed UCFA, a zero-overhead deterministic backoff. It keeps track of empty slots and the last backoff slot resulting in successful transmission to determine the next backoff slot. Misra et. al. [21] proposed a semi-deterministic backoff procedure by enforcing a receiver-side backoff stage when the sender encounters a collision. In [22], the authors present a mechanism to achieve a perfect collision-free operation by changing reserved slots upon detecting transmission failures. Unlike the above methods, OMAC does not rely on backoff reservation, rather it activates a predetermined backoff policy when it detects its awaited opportunity, i.e. when a transmission from a reference node is detected.

3 Opportunistic Medium Access Control

The main objective of OMAC is to improve throughput performance by reining in the negative impacts of random medium access. To this end, a higher level of determinism is incorporated in the medium access policy. OMAC achieves this by measuring and collecting information about physical activity on the channel and using this information to create opportunities for switching to a desired medium access policy.

The operation of OMAC is depicted in Figure 1 (a). In this figure, the vertices correspond to the nodes and the directional edges correspond to the pair-wise relation of the nodes. The relation describes a node (u_2) selected as a reference by a node (u_1) The details of the reference selection process will be described later. Once u_1 has selected its reference node (u_2), it continues to overhear the channel in order to detect when a transmission from u_2 occurs. Then u_1 uses this opportunity to enable a desired policy. The desired strategy for OMAC nodes is defined as a channel access policy superior to the default strategy. More concretely, an OMAC node becomes more aggressive upon detecting its opportunity.

The performance of OMAC is significantly governed by the unique selection of reference nodes. In an undesirable situation, as depicted in Figure 1 (b), two nodes u_1 and u_2 have selected a common reference node (u_3). The consequence is that u_1 and u_2 simultaneously enable their desired (i.e. more aggressive) policies once they detect a transmission from u_3. A solution to avoid situations of this kind is to allow the nodes to explicitly coordinate and agree on their selected reference nodes, or otherwise delegate the task to a central coordinator (e.g. an access point). However, OMAC pursues a substantially different mechanism which does not rely on explicit coordination between the nodes or enforcement by an external entity. Each OMAC node considers each unique RSS Indicator (RSSI) detected on the channel as a unique identifier of a device, and tries to select an RSSI as its reference which is less likely to be selected by peer nodes. This approach is corroborated by the fact that, in a normal environment where WiFi is used, devices are usually stationary. Therefore, fast fading should be more limited than, for example, a cellular scenario. Also, a typical 802.11 WLAN usually covers a limited area, so the detected RSSIs should present substantial differences. Our conjecture is also supported by our results presented in Section 4.

The reference selection process in OMAC is dynamic. Whenever a new frame is received from the physical layer, OMAC classifies and records the received RSSI in a set of unique RSSI elements. Denote this set, recorded until time t, by $\mathcal{P}(t)$. Also denote by $\overline{p_t}$ the mean RSSI of the members of $\mathcal{P}(t)$. Each OMAC node selects as its reference the element of $\mathcal{P}(t)$ that is closest to $\overline{p_t}$, i.e.

$$p_T(t) = \{p_T \in \mathcal{P}(t) : |p_T - \overline{p_t}| \leq |p' - \overline{p_t}| \; \forall \; p' \in \mathcal{P}(t)\} \tag{1}$$

When a transmission with RSSI p_i is detected by the node, it triggers an event $< Trigger >$ if $|p_T(t) - p_i| < \epsilon$, where ϵ is the maximum sensitivity of the

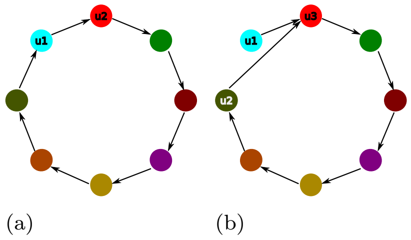


Figure 1: Reference node selection in OMAC.

device. This event, in turn, activates the desired strategy in the node.

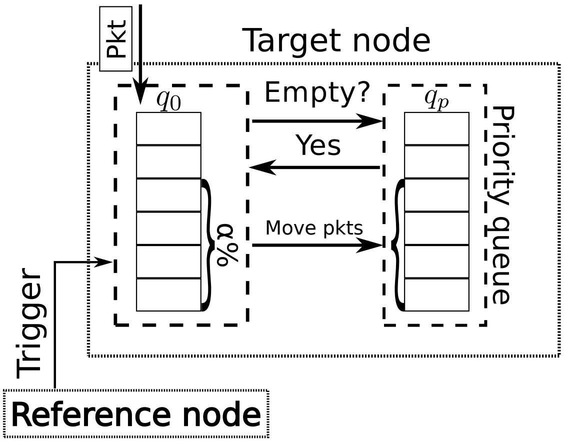


Figure 2: OMAC operation with a single class of traffic.

OMAC implements a priority queue q_p to enact its policy. If a packet is enqueued in q_p, it will be assigned the highest priority amongst packets in all queues. This property is achieved by tuning the Arbitration Inter-frame Spaces (AIFSs) and minimum Contention Window (CW) parameters in the 802.11 MAC. In the most basic form, we assume there is only a single traffic class and a predefined queue q_0. As shown in Figure 2, packets arriving from the upper layer are enqueued in q_0. When an event $< Trigger >$ occurs, OMAC checks whether the priority queue q_p is empty. If so, an $\alpha\%$ of the packets from the front of q_0 are transferred to the priority queue, where α is a tunable parameter of OMAC, otherwise the node waits for q_p to discharge and waits for the next opportunity (see Algorithm 1). Note that OMAC does not affect the maximum queue length (q_{max}) dedicated by the MAC layer, and the total number of packets in queues q_0 and q_p does not exceed q_{max}.

OMAC behaves differently in cases where there is a single class of traffic, versus multiple classes of traffic priorities (e.g. EDCA). The former case is depicted in Figure 2.

Algorithm 1 OMAC operation with a single class of traffic.

```
on event $< Trigger >$ do
    if $q_p$ is empty then
        ToMove $\leftarrow \alpha\%$ of sizeof $q_0$
        move ToMove packets in the front of $q_0$ to $q_p$
```

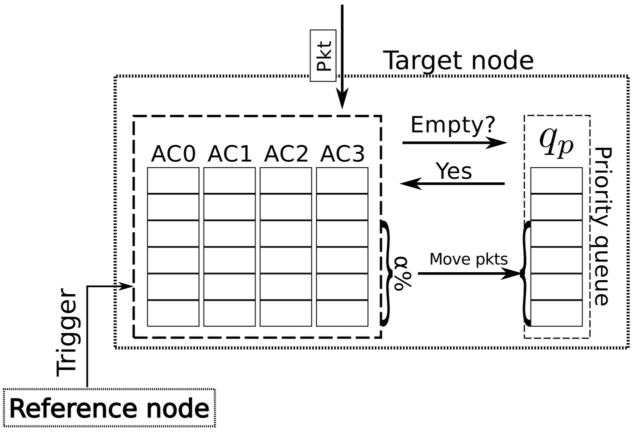


Figure 3: OMAC extension to multiple classes of traffic priorities.

OMAC differs from the standard 802.11e EDCA in the way packets are distributed between queues. It opportunistically moves packets from the pre-existing queues to the priority queue q_p, while in 802.11e the decision is made in the upper layer with respect to a predefined packet classification scheme. However, like the EDCA scheme, it uses different Arbitration Inter-frame Spaces (AIFSs) and minimum Contention Windows (CW) parameters to differentiate between q_p and the other queues.

The extension of OMAC to support multiple-queue scenarios like 802.11e is straightforward. In such scenarios, OMAC must preserve the existing traffic priorities while enforcing its opportunistic policy. The new, modified procedure is depicted in Figure 3 and described by Algorithm 2. When an event $<$

$Trigger >$ occurs and q_p is empty, an $\alpha\%$ of the packets in all predefined queues are transferred to q_p, starting from the front of AC_3, where AC_s denotes the traffic class queues in decreasing order (similar to $AC_s, s \in \{3, 2, 1, 0\}$ in 802.11e). This new mechanism also takes into account the arrival of new packets from the upper layer. When a packet *pk* with traffic class n (with $n > 0$) arrives from the upper layer, if q_p is not empty and there is at least one packet pk' in q_p with traffic class $n' < n$, then pk' is returned to $AC_{n'}$, and *pk* is enqueued in q_p in its place. This mechanism prevents any deviation from the traffic classification mandated by the application layer.

Algorithm 2 OMAC extension to multiple classes of traffic priorities.

```
on event $< Trigger >$ do
    if $q_p$ is empty then
        ToMove ← $\alpha\%$ of $\sum_{n \in ACs}$ sizeof $AC_n$
        for $n \in ACs$ do
            if ToMove > 0 then
                move min{ sizeof $AC_n$, ToMove } in the front of $AC_n$ to $q_p$
                Decrease ToMove by the number of moved packets
            else
                exit loop
```

4 Simulation Results

We have conducted simulation studies using OMNeT++ and the INET package to verify the performance of OMAC. The simulation studies were performed using the base use-case depicted in Figure 2. The upper layer traffic is directly enqueued in a predefined queue q_0. This traffic is opportunistically moved to a priority queue q_p, according to the procedure described in Section 3. We have compared the proposed protocol, termed OMAC-RSSI for distinction, with four other medium access mechanisms described as follows:

- OMAC-Perfect: unlike OMAC-RSSI, the selection of reference nodes is performed using MAC addresses. Also, unlike OMAC-RSSI, a centralized entity (e.g. an access point) is responsible for generating a non-conflicting sequence (like in Figure 1 (a)) of active MAC addresses in the network, and informing each node about the MAC address assigned as its reference node. This process is performed only once, at the beginning of the simulation. The rest of the operation is similar to the OMAC-RSSI.

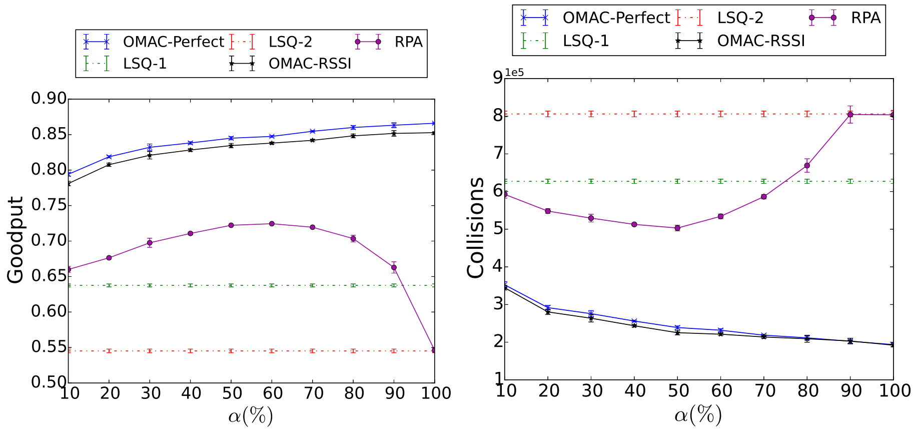
- Random Packet Assignment (RPA): a packet arriving at the MAC layer is enqueued in q_p and q_0 with probabilities α and $1 - \alpha$, respectively. OMAC is disabled.
- Legacy Single Queue (LSQ)-1: this scenario corresponds to the legacy 802.11 DCF. All arriving packets are enqueued in the predefined queue q_0. OMAC is disabled in this scenario.
- Legacy Single Queue (LSQ)-2: this scenario also corresponds to the legacy 802.11 DCF with single queue. The difference of this scenario with LSQ-1 is that all arriving packets are directly buffered in the priority queue q_p. OMAC is disabled in this scenario.

Simulation parameters and configuration values are summarized in Table 1. Packets are generated in the application layer with a Poisson distribution. Packet lengths are uniformly distributed between 14 bytes (the ACK size) and 2000 bytes. The AIFS and contention window size (CW) of q_0 and q_p are respectively similar to the default configuration of AC_0 and AC_3 in 802.11e. Experiments using the AC_1 configuration for q_0 are comparable to our results. For each configuration scenario, 100 simulation runs are conducted, with a duration of 100 seconds per run. In the simulated scenarios, only uplink traffic is considered, i.e., the nodes send data to a sink (i.e. an access point).

In the following, we present a number of results corresponding to saturation scenarios since, in non-saturation scenarios, the performance of the described medium access control mechanisms is almost perfect and the gain achieved by the OMAC scheme is not significant. Nonetheless, the gain is always positive. Our selected scenarios include network densities of 10, 30 and 60 nodes. The saturation traffic is different for the considered network densities. For the 10 node scenario, this occurs at 200 packet/second and beyond, whereas for 30 and 60 nodes the saturation occurs at 100 packets/sec.

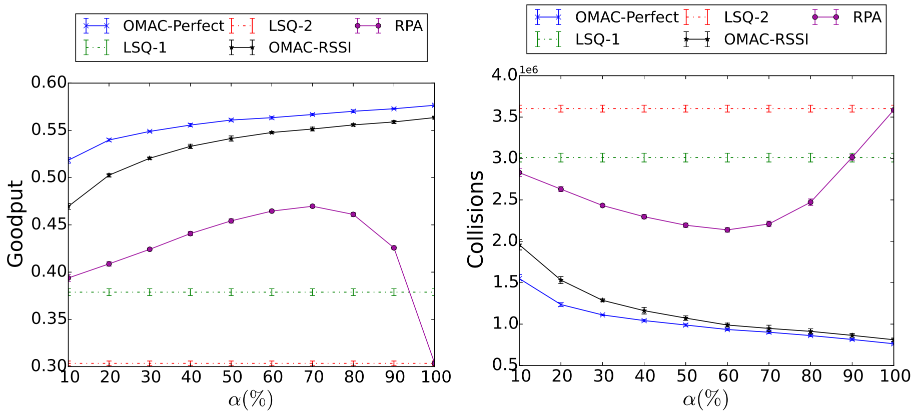
The Figures 4, 5 and 6 show the performance of OMAC-RSSI compared with other schemes for 10, 30 and 60 node densities and in saturation conditions. In these figures, the goodput is normalized. It is defined as the ratio of successfully received bits (by the sink) to sent bits (by all nodes), and measured in the application layer. The results are presented with 95% confidence interval. The delay performance is omitted due to the lack of space, however, our simulations indicate that the packet delay is always lower in OMAC compared to the other schemes.

From the figures it can be observed that the OMAC scheme (OMAC-RSSI and OMAC-Perfect) outperforms the other schemes in terms of reduced number of collisions and goodput. However, the performance gain varies between node densities and with respect to parameter α (the proportion of packets moved



(a) (b)

Figure 4: 10 nodes, $\lambda_r = 200$ packets/sec.



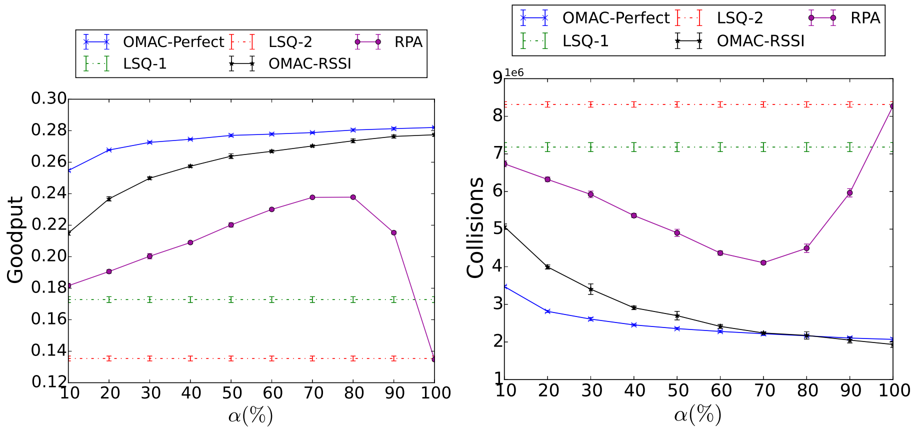
(a) (b)

Figure 5: 30 nodes, $\lambda_r = 100$ packets/sec.

Table 1: Parameters and configuration values.

	Parameter	Value
Physical	Frequency	2.4 GHz
	Noise Power	-110 dBm
	SINR Threshold	4 dB
	Transmission Power	20 mW
	Reception Threshold	-85 dBm
	Data Rate	54 Mbps
	Slot Time (σ)	9 μs
Scenario	Scenario dimensions	600 x 400 m
	Channel model	Free space
	Free space exponent	2
	Number of nodes	10, 30, 60
Application	λ_r	10 to 200 packets/sec
	Packet generation rate	$\sim Poisson(\lambda_r)$ packets/sec
	Packet length	$\sim Uniform(14, 2000)$ bytes
MAC	CW_0^{min}	31
	CW_p^{min}	7
	AIFS (q_0)	7σ + SIFS
	AIFS (q_p)	2σ + SIFS
	q_{max} (packets)	100
	$\alpha(\%)$	10, 20, … 100

to q_p). The general trend shows that, with an increase in node density, the performance gain increases, indicating the suitability of OMAC for the emerging dense scenarios targeted by HEW standard. The goodput improvement in OMAC-RSSI compared to the basic LSQ-1 scheme and averaged over the entire range of α is approximately 30%, 41% and 50% for 10, 30 and 60 node densities, respectively. It achieves around 60% less collisions in each of the three node densities. The achieved gain compared to LSQ-2 is substantially higher, indicating the fact that the blind increase of the MAC aggressiveness



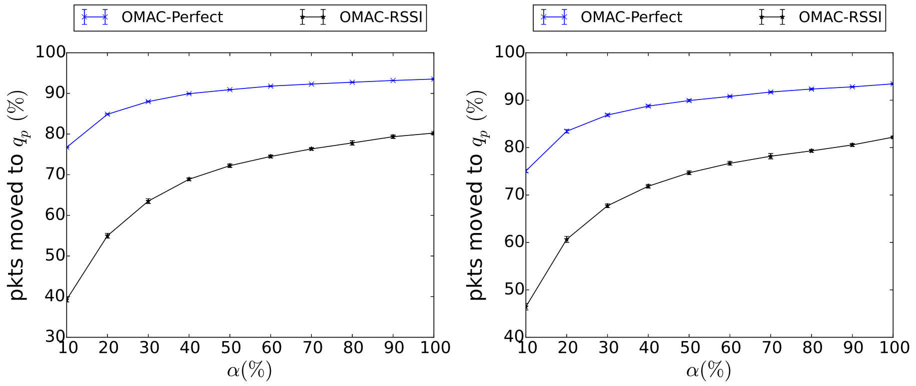
(a)

(b)

Figure 6: 60 nodes, $\lambda_r = 100$ packets/sec.

leads to performance deterioration. Surprisingly, the RPA scheme outperforms both LSQ-1 and LSQ-2 for the most part of the α range. However, as shown in the figures, it looses its gain when α grows, which eventually converges to the worst performing scheme (i.e. LSQ-2). The OMAC schemes, on the other hand, show a growing performance gain with the increase of α. With the OMAC-RSSI, when $\alpha = 100\%$, the goodput gain compared to LSQ-1 is approximately 34%, 49% and 61% for 10, 30 and 60 nodes, respectively. The trend also shows that the performance of the OMAC schemes improve with an increase in node density. This observation suggests a straightforward tuning of the parameter α in the OMAC schemes. That is, by setting α to 100%, the maximum gain is achieved. This implies that a node will be better-off if it moves all packets from its default queue q_0 to the priority queue q_p, when its opportunity comes and the queue q_p is already discharged.

Another observation is the difference between the behaviour of the OMAC-RSSI and OMAC-Perfect schemes. As shown in the figures, OMAC-Perfect almost always outperforms OMAC-RSSI. This is not surprising, recalling the fact that in the OMAC-Perfect scheme the assignment of reference node is perfect and no pair of nodes share a single reference node. This perfect reference selection implies that the contention between opportunistic OMAC nodes decreases compared to the non-perfect RSSI based OMAC. This leads to a reduced number of collisions and an increased chance of moving more packets from q_0 to q_p. This is verified by observing Figure 7 which shows the popu-



(a) (b)

Figure 7: Proportion of packets moved to q_p. $\lambda_r = 100$ packets/sec. (a) 60 nodes, (b) 30 nodes.

lation of packets moved from q_0 to q_p. For both node density scenarios, the percentage of packets moved to q_p is substantially higher in OMAC-Perfect compared to OMAC-RSSI. This observation implies for the enhancement of the node selection mechanism in the OMAC-RSSI, which will be addressed as part of our future work.

5 Conclusion and Future Work

In this paper, we proposed OMAC, a novel opportunistic medium access control mechanism. OMAC eliminates the need for explicit exchange of information by relying only on the signal measurement capability of the devices. An OMAC node continuously measures the different RSS levels by overhearing the ongoing signal activities on the channel. The OMAC node uses this information to select a reference RSS which, subsequently, is regarded as an opportunity for the node to switch to a desired strategy whenever a channel activity with a similar RSS level is detected.

OMAC does not require decoding of the signal, thus it is robust to varying channel conditions. It preserves privacy because it does not require the actual identities (e.g. MAC addresses) of the signal sources. Additionally, it is adaptive to changes in channel conditions and network topology since the RSS measurement and reference selection is a continuing process. OMAC is also a lightweight protocol and easy to implement in devices.

Our simulations show that OMAC achieves a significant throughput gain compared to the legacy 802.11 MAC. Our future work will address the theoretical bounds of OMAC performance. We also plan several extensions for OMAC, including the design of more sophisticated reference selection mechanisms to ensure an eligible node is guaranteed to have a unique reference node, where eligibility is determined by fairness, traffic priority, and the contribution of the node to the overall network performance and energy efficiency. Another equally important extension is to adapt OMAC for frame aggregation as an important feature of the upcoming HEW standard.

Acknowledgment

This work is funded by the EC FP7 Marie Curie IAPP Project 324515, "Mesh-Wise".

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Paper II

LUPMAC: A Cross-Layer MAC Technique to Improve the Age of Information Over Dense WLANs

Age of Information (AoI) is a relatively new metric introduced to capture the freshness of a particular piece of information. While throughput and delay measurements are widely studied in the context of dense IEEE 802.11 Wireless LANs (WLANs), little is known in the literature about the AoI in this context. In this work we study the effects on the average AoI and its variance when a sensor node is immersed in a dense IEEE 802.11 WLAN. We also introduce a new cross layer MAC technique, called Latest UPdate MAC (LUPMAC), aimed at modifying the existing IEEE 802.11 in order to minimize the average AoI at the receiver end. This technique lets the MAC layer keep only the most up to date packets of a particular piece of information in the buffer. We show, through simulation, that this technique achieves significant advantages in the case of a congested dense IEEE 802.11 WLAN, and it is resilient to changes in the variance of the total network delay.

Antonio Franco, Emma Fitzgerald, Björn Landfeldt, Nikolaos Pappas, Vangelis Angelakis
"LUPMAC: A Cross-Layer MAC Technique to Improve the Age of Information Over Dense WLANs"
in *23rd International Conference on Telecommunications (ICT) (ICT 2016)*, Thessaloniki, Greece, pp. 724-729, 2016-05-15.

1 Introduction

The concept of the Age of Information (AoI) was first introduced in [1], and then formalized in [2]. This new metric answers the question: how fresh is that particular information stored at the receiver? It is different from the delay, since it includes the time from when a destination has received the last update about a particular piece of information (e.g. the temperature, the water flow/level etc.) from a source. It also has a broader scope than the delay, since it measures a quality of a particular piece of information not a quality of the individual packets themselves.

In some sensor applications, only the most updated measurement of a particular piece of information is relevant, e.g. the current water level in a sewer pipe in order to ensure it does not exceed a given threshold. In this sense, the AoI metric is of crucial importance. Especially in the context of the new paradigm of the Internet of Things (IoT), or the Smart City paradigm [3], a typical application scenario might be sensor nodes continuously measuring and sending data, using a dense IEEE 802.11 Wireless Local Area Network (WLAN) shared amongst numerous other devices. For example, the sensor node might be interested in uploading the measured information to a remote unit, for storing or further processing. If the remote server is only interested in the freshest possible piece of the information sent by the sensor node, it is interested in the sensor node trying to minimize the AoI at the receiver.

In this work we will study a scenario where a sensor node is immersed in a dense IEEE 802.11 WLAN, where a number of devices are subscribed. It tries to send information to a remote destination. Dense WLANs are a specifical scenario that will be covered in the forthcoming IEEE 802.11ax HEW (High Efficiency WiFi) standard [4]. The IEEE 802.11ah standard is also specifically designed for the IoT [5]. In this standard, an Access Point (AP) can cover up to 1 km in range, and is possible to foresee that overlapping networks with hundreds of devices would not be uncommon. Devices will have to compete for the channel with possibly hundreds of other devices, with a very hetereogeneous population of traffic patterns. For example, there could be devices trying to offload traffic from the existing cellular infrastructure, futher congesting existing IEEE 802.11 WLANs, as in the 5G HETereogeneous NETwork (HETNET) paradigm [6]. Competing with numerous devices degrades both throughput and delay performance, due to the increasing number of collisions, and in case of traffic burstiness, increases the idle time [7]. In case also of a high number of small frames, it deteriorates further [8]. The effects on the AoI are, however, not entirely clear.

In this paper, we extend the work in [1, 9] with a more practical implementation by introducing a new cross layer approach between the application layer and the MAC layer, called Latest UPdate MAC (LUPMAC), aimed at modifying the existing IEEE 802.11 in order to minimize the average AoI at the receiver end. We let the MAC know about the "freshness" of a packet received from the application layer, along with the particular application that generated it, in order to develop a strategy to minimize the AoI at the receiver. Briefly, it will always try to send the packets carrying the freshest update of that particular information, without trying to transmit (or re-transmit) older packets.

The remainder of this paper is organized as follows. In Section 2 we will present an overview of the related work. In Section 3 we describe the concept of Age of Information. In Section 4 we describe LUPMAC. In Section 5 we describe the scenario under test. In Section 6 we present our simulation results and in Section 7 we conclude the paper.

2 Related Work

The Age of Information in IEEE 802.11 systems was first addressed in [1]. The authors study the age of information in a vehicular network (VANET) via simulation and with a VANET testbed. In their scenario, each vehicle acts as a node. Each node beacons a particular piece of information to nearby vehicles, and it is interested in the other vehicles having the most up to date piece of that information. Each node broadcasts its information, so no acknowledgements are involved. The authors introduce a cross layer MAC technique called "Latest state Out" (LO), in which the application sensing informations fills the packet at the front of the MAC buffer with the latest available piece of information whenever the opportunity of transmitting a frame arises. They show how this technique efficiently minimizes the average AoI in all the nodes in the VANET. They also show that using the optimal Contention Window (CW) from the Bianchi model [10] the average AoI is further minimized. They then show how neither maximizing the throughput nor minimizing the delay automatically minimizes the average AoI. Finally they introduce a cross-layer rate control mechanism that works with a normal FIFO queue and no CW adaptation in order to minimize the average AoI at the nodes.

Their work differs from the work carried out in this paper, since it studies a vehicular network, while we study a dense IEEE 802.11 WLAN of static nodes; we are interested in minimizing the AoI in a remote server instead of distributing the information to a set of nodes in the same network. Also they do not address the problem of other contenders (i.e. other devices trying to access the same wireless channel) in the network. Additionally, they are broadcasting the information, thus using only the first CW, not retrying to send the frame in case of a missing acknowledgment. Finally, in our work the MAC layer should be aware only of the application that generated the packet and the packet's age, while in LO the MAC layer should signal the application whenever a transmission opportunity arises. In our work also, if the packets are sent by the application in order, the MAC layer will automatically infer the new packet is the freshest, thus not even needing an additional field with the packet's age. The proposed LO technique is impractical. The time needed for the MAC layer to signal the application when it is ready to transmit, and then wait for the application layer to fill the MAC buffer is bigger than one IEEE 802.11 slot time ($\sim 10\mu s$), that is the time granularity in an IEEE 802.11 MAC. In addition, with this approach, the application must be allowed to write in the MAC buffer. This is in most of the cases, impractical. In short, this approach requires very close coupling between the MAC and the application that is both difficult and undesirable in practice. Finally, we will not use the optimal CW from the Bianchi's model, since it is not possible in current hardware to change it at run time [10].

In [2,9,11–13] the authors study the AoI in different simple queuing systems with multiple classes of service, modeling the channel as a single server. For example, in [2] the authors derive a lower bound for the AoI given any service distribution in a simple queuing system with only one server. In [12] the authors study the minimization of the AoI under energy constraints, particularly a sensor that harvests energy from the environment via numerical simulation. While important properties of the AoI are derived, the effects on the AoI in a real life scenario such as a dense IEEE 802.11 WLAN are not investigated.

The only other study that uses a real network scenario in order to study the AoI, as far as the authors are aware, is [14]; there the authors study the AoI in an emulated WLAN with 2 nodes and compare their results with the theoretical results for various simple queuing systems. The study focuses on a small WLAN, and an IEEE 802.11 stack is not used, whereas we consider a dense WLAN with many more nodes and conduct simulations using a full 802.11 implementation.

As a final note, our cross-layer MAC technique is also a continuation of the work in [9], where the authors study the AoI in a system with N sources, a single queue and a delay channel. They introduce a new queuing discipline based on the age of information. It only holds the freshest packets of each class of information in the queue. On the other hand, the authors study the AoI in an abstract queueing system with N sources, where we make use of a full 802.11 implementation.

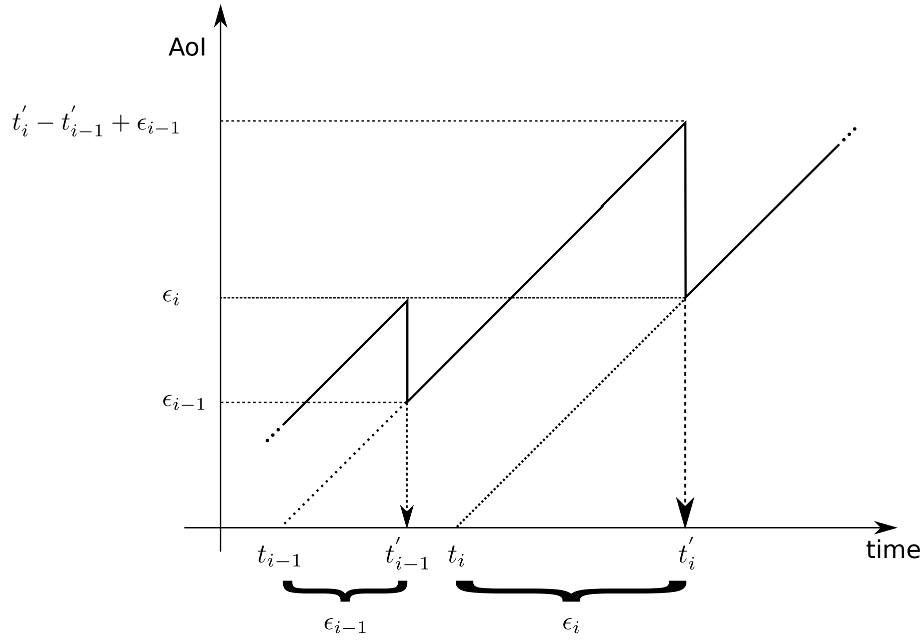


Figure 1: Example of the Age of Information over time at the end of a receiver.

3 Age of Information

We will now give an overview of the concept of Age of Information. Consider a transmitter sensing and sending updates of the information I over a channel to a receiver. The receiver is interested only in the freshest update of information I. An example curve of the age of information I over time is depicted in Fig. 1.

Assume a packet with the desired information I is generated at time t_{i-1} s from a a source sensing that information. The receiver receives it at time t_{i-1}' s. The packet will then have an age of $\epsilon_{i-1} = t_{i-1}' - t_{i-1}$ s, so the age of the information I will be at that time ϵ_{i-1} s. Then, if it is not receiving new packets, the AoI will increase over time with slope 1. The next packet carrying the updated information I is generated from the transmitter at time t_i s. It is received at time t_i' s. The age of that packet would then be $\epsilon_i = t_i' - t_i$ s. If this packet is fresher than the current AoI (i.e. $\epsilon_i < t_i' - t_{i-1}' + \epsilon_{i-1}$) then the AoI will jump down to ϵ_i seconds, otherwise it will continue increasing. The AoI will continue to have this characteristic sawtooth behaviour, and it is possible to reconstruct its curve by interpolating between the various samples when packets are received. Then it is possible to reconstruct various metrics; for example, it is possible to reconstruct the average AoI by calculating the integral over time of the curve as a sum of trapezoids and dividing over the elapsed time [11].

In our work, in order to avoid the so-called catastrophic cancellation in the computation of the variance of the AoI, instead of computing the square sum of the trapezoids forming the AoI curve, we compute the average AoI as a running weighted mean, and the AoI variance as a running weighted variance [15].

4 Latest UPdate MAC

We extend the work in [1] and [9] with a more practical implementation of their algorithm, in order to apply a more advanced cross layer approach in an IEEE 802.11 MAC. The procedure is summarized in Algorithm 3.

Algorithm 3 The LUPMAC algorithm.

```
on event $p'$ comes from the network layer do
    $n \leftarrow 0$
    for all $p \in \mathcal{P}$ do
        if $p.id == p'.id \bigwedge p'.age < p.age \bigwedge n < 2$ then
            Substitute $p$ with a copy of $p'$
            $n \leftarrow n + 1$
    if n == 0 then
        Append $p'$ at the end of $\mathcal{P}$
    else if n==1 $\bigwedge$ $p'$ is at the front of $\mathcal{P}$ then
        Append $p'$ at the end of $\mathcal{P}$
on event ACK received upon transmission of $p'$ do
    for all $p \in \mathcal{P}$ do
        if $p.id == p'.id$ then
            remove $p$ from $\mathcal{P}$
```

The MAC layer is aware of the time a packet is generated in the upper layer. If we assume the sources sending the respective pieces of information do not scramble the order of the generated packets, LUPMAC can simply assume the newest packets from the source are also the freshest. The applications running in a sensor all map one-to-one to an information source, and have an ID. The ID thus identifies one information stream. This ID is stamped into the packet at generation time, for example in a field in the header of the network packet. When a new packet p' arrives from the upper layer, the MAC inspects the packets in the transmission buffer $\mathcal{P}$, including the packet in backoff (i.e. the one at the front of the buffer queue), to check if there is one that has the same ID as the newly arrived packet. We call this subset $\mathcal{P}_i$, where i is the source ID. Then, the MAC checks each packet $p \in \mathcal{P}_i$; if p is older than p', it is substituted with a copy of p'.

In the IEEE 802.11 standards the access mechanism is the so-called Distributed Coordination Function (DCF). A frame (that encapsulates a packet) waits a random time before being transmitted. A frame in this state is said to be in “backoff”. If a collision occurs after a backoff period, the frame goes again into the backoff state, with a longer period to wait (on average). After a number of retransmissions, 7 in the current basic access mechanism, the frame is dropped. In case of an heavily loaded network, there is always a chance that the packet in front of $\mathcal{P}$ has already been into several retransmissions. So the chance for this particular packet to be dropped is higher, with negative effects on the AoI at the receiver end. In order not to have a newer packet at the last stage of the backoff be thus penalized, if the only substituted packet is the one currently in backoff, a copy is appended at the end of $\mathcal{P}$. Also, in order to not have too many packets of a particular source in $\mathcal{P}$, only two copies of a packet from a particular source are allowed in the buffer. If there are no packets substituted, p' is appended at the end of $\mathcal{P}$.

In order not to transmit multiple copies of the same piece of information, upon the reception of an ACK for p' (i.e. p' is succesfully transmitted), LUPMAC will delete every packet in $\mathcal{P}$ having the same ID as p'.

It is important to point out that LUPMAC is not doing deep packet inspection in order to substitute or remove packets in the MAC buffer. The application ID could be inserted in the packet header in the application layer, and then propagated all the way to the MAC layer in a field in the header. It is also unreasonable for applications in the sensor node to scramble the order of the generated packets, so LUPMAC will just infer the freshness of the piece of information contained in the packet by the time it is received from the upper layer, i.e. the latest received packet is the freshest.

5 Scenario Description

The scenario considered in our work is depicted in Fig. 2. It models a sensor node immersed in a dense IEEE 802.11 WLAN with no hidden nodes, in order to better inspect the effects of LUPMAC on the average AoI. Such scenarios occur, for example, in a city, where a public hotspot serves a large number of users, and sensor nodes, such as smartgrid sensors or water flow sensors, use the existing infrastructure to send information remotely. Another example that

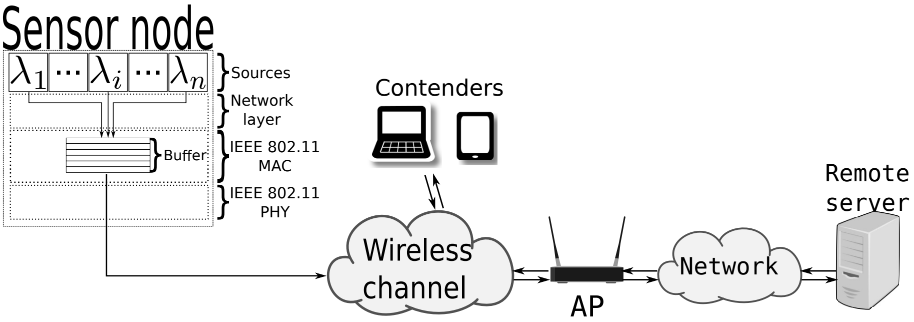


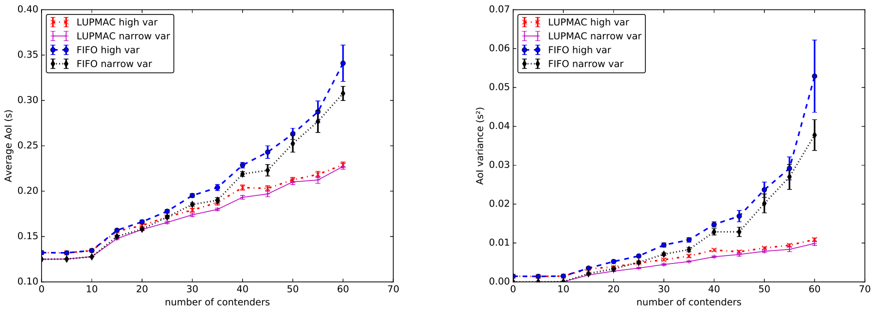
Figure 2: Scenario for our simulation studies. This diagram also utilises the following third party images: [16–19].

could be modeled by this scenario is an industrial one, where sensor nodes have to send status updates about machinery to a central server while competing for the channel with other devices. These sensor nodes send information fairly frequently, and the last reading of this information is what counts, i.e. we are interested in minimizing the average AoI.

In our studied scenario, a sensor node is sending various information streams to a remote server. A packet from the sensor has to be sent first via the wireless channel, then it is routed via a normal fixed-link connection, labelled as "Network" in the diagram, to a remote server. A sensor node is formed by an application layer stack, where there are a number of applications, labeled in the figure as sources, each one of those measures a particular piece of information, and sends updates about their own information to a remote server. In case LUPMAC is used, the applications running in the application layer insert their unique ID in a field in the packet header, that is propagated all the way to the MAC layer, in order to let LUPMAC know which application generated that particular packet. Then, there is a network layer, and then an IEEE 802.11 MAC, that holds the packets generated by the various sources in its buffer. Next there is an IEEE 802.11 PHY to access the channel.

A sensor node is competing for the channel with a number of contenders, each one requesting content from the remote server. The contenders send requests to the remote server, then the server fullfills those requests by sending back content to them. They send relatively small packets for the request, and receive packets of various sizes back. This models a variety of users that stream content, offload traffic using the IEEE 802.11 WLAN or simply browse the web.

The remote link introduces a delay according to a random distribution. Since the metro (or backbone) part of the network is usually reliable, at least in



(a) (b)

Figure 3: Average Age of Information (a) and variance (b) measured at the destination with narrow variance on the wire delay and high variance with LUPMAC or FIFO.

big cities, we will assume the remote link to be reliable, so no packet is dropped there. This models, for example, a routed path to a remote destination via the internet. On the other end, we tested the reliability of LUPMAC by measuring the average AoI both with high and low variance in the network part of the simulation.

6 Results

We have conducted our simulation studies using OMNeT++ and the INET package [20]. The parameters used in the simulations are summarized in Table 1.

All the plots are presented with 95% confidence, allowing for a sufficient warm-up period before taking measurements. The scenario simulated is the one described in Section 5. There is a sensor node uploading data to a remote server. It has an application (source) running, taking measurements. The sensor node is using an IEEE 802.11g WLAN with a number of contenders varying from 0 to 60. It is uploading small packets deterministically at a fairly slow rate (10 pk/s). The contenders are issuing requests to a remote server with exponentially distributed interarrival times, with an average rate of 100 pk/s, in order to increase the traffic load on the WLAN and congest it. The request packets are small (10 bytes on average, exponentially distributed), while the reply packets are uniformly distributed from small packets (14 bytes, a control frame) to big packets (1000 bytes). The delay on the wire connecting the

Table 1: Parameters and configuration values.

	Parameter	Value
Physical	Frequency	2.4 GHz
	Noise Power	-110 dBm
	SINR Threshold	4 dB
	Transmission Power	20 mW
	Reception Threshold	-85 dBm
	Data Rate	54 Mbps
	Slot Time (σ)	9 μs
Scenario	Scenario dimensions	600 x 400 m
	Channel model	Free space
	Free space exponent	2
App	number of sensor nodes	1
	number of contenders	variable
	information generation (sensors only)	every 0.1 s
	request generation (contenders only)	$\sim$ exp{0.01} s
	Packet length (sensors)	10 bytes
	Packet length (contenders)	$\sim$ exp{10} bytes
	Requested packet length (contenders)	$\sim U(14, 1000)$ bytes[1]
MAC	type	802.11g (AC1)
	buffer length (packets)	100

access point to the remote server is considered to be a reliable metro/backbone connection. The average roundtrip time is however considered to be challenging with respect to VoIP traffic (150ms).

The average AoI and its variance are measured with an increasing number of contenders in the case that the delay has narrow variance, i.e. the one-way delay is uniformly distributed between 74ms and 76ms (so as to have an average roundtrip time of 150ms) with LUPMAC or the standard IEEE 802.11 FIFO approach. Then it is tested in the case it has a large variance, i.e. the

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[1] $U(a, b)$ is the uniform distribution between a and b.

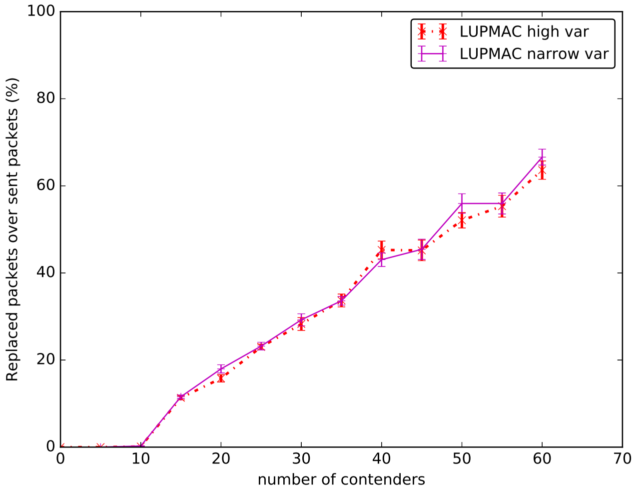
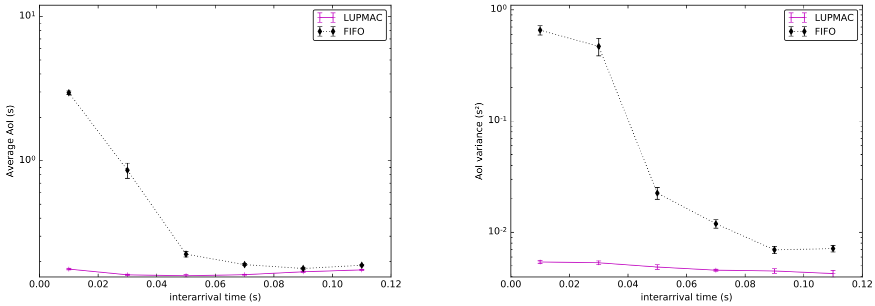


Figure 4: Percentage of the replaced packets according to Algorithm 3 over the totality of packets sent by the application layer in the sensor.

one-way delay is uniformly distributed between 0s and 150ms (still an average round trip time of 150ms) with LUPMAC or the standard IEEE 802.11 FIFO approach. In Fig. 3 the AoI for all the cases is presented.

As we can see from Fig. 3, the difference between high and narrow variance in the standard case (i.e. IEEE 802.11 FIFO) is quite small, only a fraction of the average AoI even with a totally saturated network with 60 contenders. In both cases the average AoI grows almost two tenths of a second from 10 to 60 contenders. This is quite a high increase, considering that the source on the sensor node is generating one packet every tenth of a second.

Then, we tested LUPMAC (introduced in Section 4). As we can see, LUPMAC significantly improves the AoI in case of a highly saturated scenario (when the number of contenders grows over 30), with an improvement of almost a tenth of a second with 60 contenders on the average AoI. Also, the AoI appears more stable, as the variance grows much more slowly when LUPMAC is on. The improvement over the average AoI is extremely good, considering that the source on the sensor node generates one packet each tenth of a second. The improvement can be explained by the number of replaced packets in the MAC buffer when LUPMAC is used. In Fig. 4 the percentage of the replaced packets according to Algorithm 3 over the totality of packets sent by the ap-



(a)

(b)

Figure 5: Average Age of Information (a) and variance (b) measured at the destination both with and without LUPMAC with the sensor generating up 100 pk/s, 30 contenders and narrow variance on the one-way network delay. Notice that the y-axis is in log-scale.

plication layer in the sensor is presented. As we can see, LUPMAC starts to replace packets in the MAC buffer as soon as we have a sufficiently high number of contenders in the WLAN (in this case ≥ 15), exactly when the average AoI starts to diverge from the one measured in the standard case (i.e. IEEE 802.11 FIFO).

If we allow for a faster update generation, the benefits are overwhelming. In Fig. 5, the source on the sensor node is allowed to generate up to 100 pk/s, i.e. one packet every hundreth of a second with 30 contenders and narrow variance on the one-way network delay. Notice that the y-axis is in log-scale.

When LUPMAC is enabled, the average AoI is improved by up to an order of magnitude compared with when the sensor is simply relying on an unmodified IEEE 802.11 MAC. In addition, when LUPMAC is used, the average AoI is fairly stable, and its variance limited.

7 Conclusions and Future Work

In this paper we investigated the effects of contenders on the age of information of a sensor node immersed in a dense IEEE 802.11 WLAN via simulation. We then investigated the effects of variance of the transmisson delay on the age of information. We also introduced a new MAC technique called LUPMAC designed to improve the performance of the IEEE 802.11 MAC for sensor nodes in terms of the average AoI.

An extension to this work will be to dynamically assign different traffic priorities to different information sources (i.e. different ACs, as defined in the IEEE 802.11e EDCA) according to priority and traffic load, following the findings from [1]. Another approach would be to use the technique described in [21], in order to use a probabilistic technique on top of LUPMAC, thus approximating the throughput optimal CW in order ot minimize further the average AoI at the receiver end. Since sensors are usually low power devices, we will investigate the effects of the contenders in terms of energy usage of the sensors, while trying to minimize the average AoI at the receiver end taking inspiration from the findings in [12] and extending them in a realistic environment. Further steps are also a real implementation of LUPMAC in a sensor node and a mathematical evaluation of its performances in terms of the average AoI at the receiver end.

LUPMAC can be integrated into the existing IEEE 802.11ah standard, and fits in the wider scope of the IoT and 5G. It shows substantial benefits in terms of both the average AoI and its variance compared to the normal, unmodified IEEE 802.11 when the WLAN becomes saturated with traffic. This technique is also resilient to changes in the variance on the experienced delay.

Acknowledgment

This work was supported by the Excellence Center at Linköping-Lund in Information Technology. It has also received funding from the EU's 7th Framework Programme (FP7/2007-2013) under grant agreements 324515 (MESH-WISE), 612316 (SOrBet), and 609094 (RERUM).

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Part III

Appendix

COOPLUP - Analytycal Probability of Removal Due to Staleness

In this Appendix, we will show an approach to continue the work done in *LUPMAC: A cross-layer MAC technique to improve the age of information over dense WLAN*. We are interested in calculating the analytycal probability of removal due to staleness of the packet in a new cooperative MAC scheme for Wireless Sensor Networks (WSNs) called COOPLUP — COOperative LUPMAC. This protocol is aimed at decreasing the number of transmissions in a WSN with sensors broadcasting updates about a measured phenomenon, while minimizing the average AoI at the receiver.

Antonio Franco

1 Model

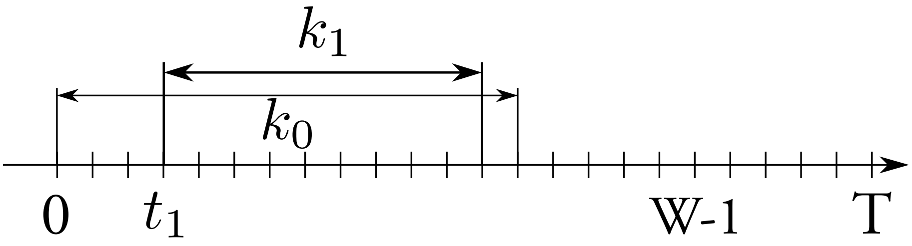

Figure 1: Our model.

Consider two STAs, STA0 and STA1. Time is assumed slotted. They deterministically sense information at an interval of T slots. In case a previous information (encapsulated in a frame) is still in the queue when new information is generated, it gets replaced as head of the queue, and the previous information is discarded. The STAs use the broadcasting mechanism of the IEEE 802.11 DCF. When the information is at the head of the queue, a random backoff between 0 and $W-1$ is generated according to a discrete uniform distribution. W is the first Contention Window (CW), typically 32 slots. They count down until the backoff counter is exhausted and then they attempt to transmit. We assume very small frames sent, with a transmission time of one slot. This rules out the backoff freezing mechanism. No retransmission mechanism is in force.

Both STAs broadcast their information to an access point (AP), which, in turn, broadcasts the time stamp of when the last information received was sensed. If the information in the queue of an STA was sensed before (or at the same instant) the current timestamp of the information at the AP, the frame is discarded. It is possible to piggyback on the ACK mechanism, in which case we have to add a SIFS (typically less than one slot) and an ACK transmission time and use it as an AP broadcast.

Assuming $T > W$, the model is presented in Figure 1. We take the point of view of STA0. Since STA0 does not know when STA1 is going to sense again, we assume the sensing time of STA1, t_1, to be uniformly distributed between 0 and T, so to have $T+1$ slots in total. We seek the probability P_0^{succ} of the information from STA0 to be successfully transmitted without collisions and replacement due to the AP broadcasting. Since $T > W$ — and backoff freezing does not apply — no replacement will take place due to later samples by the STA itself. The probability of success is the complement of the probability of being discarded, i.e.:

$$P_0^{\text{succ}} = 1 - P_0^{\text{fail}}\,.$$

The probability of discarding the frame is the probability that the frame from STA1 is sent before the frame from STA0 and to the sensing time for STA1 t_1 being in the interval $[0, W-2]$[1], i.e.:

$$P_0^{\text{fail}} = \Pr\{t_1 + k_1 < k_0 \wedge t_1 \in [0, W-2]\}\,. \tag{1}$$

The probability of t_1 being in the interval $[0, W-2]$ is simply:

$$\Pr\{t_1 \in [0, W-2]\} = \frac{W-1}{T+1}\,,\; W < T\,.$$

For (1) we can write:

$$\begin{aligned}
&\Pr\{t_1 + k_1 < k_0 \wedge t_1 \in [0, W-2]\}\\
&= \sum_{t=0}^{W-2} \Pr\{t + k_1 < k_0\} \times \Pr\{t_1 = t\}\\
&= \sum_{t=0}^{W-2} \sum_{k=0}^{W-1} \Pr\{t + k < k_0\} \times \Pr\{k_1 = k\} \times \Pr\{t_1 = t\}\\
&= \sum_{t=0}^{W-2} \sum_{k=0}^{W-1} [1 - \Pr\{k_0 \le t + k\}] \times \Pr\{k_1 = k\} \times \Pr\{t_1 = t\}\,.
\end{aligned} \tag{2}$$

We know that

$$\Pr\{k_1 = k\} = \frac{1}{W}\,,\; k \in [0, W-1]$$

and

$$\Pr\{t_1 = t\} = \frac{1}{T+1}\,,\; t \in [j, j+T]\,,\; j \in \mathbb{Z}_+\,.$$

Also $\Pr\{k_0 \le t + k\}$ is the CDF of the uniform discrete distribution $f_{K_0}(k_0) = \frac{1}{W}\,\mathrm{rect}_W\left(k_0 - \lfloor \frac{W}{2} \rfloor\right)$ calculated at $t + k$:

$$\Pr\{k_0 \le t + k\} = \begin{cases} \frac{t+k+1}{W} & , 0 < t+k+1 \le W \\ 1 & , t+k+1 > W \\ 0 & , t+k+1 \le 0 \end{cases}\,.$$

---

[1] If $t_1 = W - 1$ then either the STA has not enough time to be transmitted before k_0, or a collision would occur.

It follows that

$$\begin{aligned}
&\Pr\{t+k<k_0\} \\
&\qquad = 1 - \begin{cases} \frac{t+k+1}{W} & , 0 < t+k+1 \leq W \\ 1 & , t+k+1 > W \\ 0 & , t+k+1 \leq 0 \end{cases} \\
&\qquad = \frac{1}{W} \begin{cases} W-t-k-1 & , 0 < t+k+1 \leq W \\ 0 & , t+k+1 > W \\ W & , t+k+1 \leq 0 \end{cases} .
\end{aligned}$$

By applying this to (2):

$$\begin{aligned}
&\Pr\{t_1+k_1<k_0 \wedge t_1 \in [0, W-2]\} \\
&= \frac{1}{W^2(T+1)} \sum_{t=0}^{W-2} \sum_{k=0}^{W-1} \begin{cases} W-t-k-1 & , t+k+1 \leq W \\ 0 & , t+k+1 > W \end{cases} .
\end{aligned} \tag{3}$$

As we can see in Figure 2, we can modify the extrema of the innermost sum in order to consider only the region where the sum is not 0. We then rewrite (3) as:

$$\begin{aligned}
&\Pr\{t_1+k_1<k_0 \wedge t_1 \in [0, W-2]\} \\
&= \frac{1}{W^2(T+1)} \sum_{t=0}^{W-2} \sum_{k=0}^{W-t-1} W-t-k-1 \\
&= \frac{W^2-1}{6\,W\,(T+1)} , T > W .
\end{aligned} \tag{4}$$

(4) is the final form of (1). So finally:

$$P_0^{\text{fail}} = \frac{W^2-1}{6\,W\,(T+1)} , T > W . \tag{5}$$

2 n Transmitters Case

In case there are n transmitters competing, the frame from STA0 is discarded if and only if there is at least one sampling between 0 and the backoff from STA0, namely the random variable k_0 and at least one sample generated from one of the other stations in-between 0 and does not collide and gets transmitted

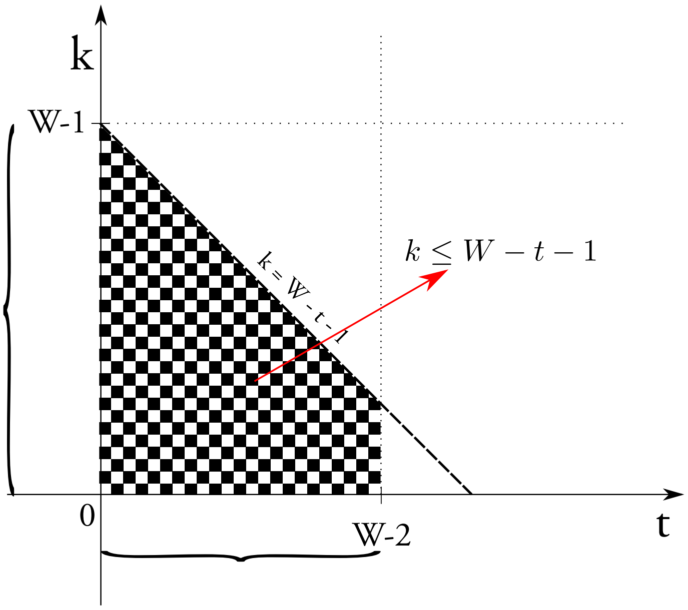

Figure 2: Area where the sum is not zero (i.e. $t + k + 1 \leq W$).

before k_0. This obviously would include any sample generated before time 0 (given the time axes as in Figure 1). We will for the moment discard the effect of the latter and investigate instead the effect of the samples generated after time 0.

First we are going to look simply at the expected number of samples generated in the interval $[0, W-1]$, $W-1$ being the maximum value that k_0 can take. The probability that exactly q samples are generated between 0 and $W-1$ is:

$$\Pr\left\{\bigcap_{i=1}^{q} t_i \in [0, W-1]\right\} = \binom{n-1}{q}\left(\frac{W}{T+1}\right)^{q}\left(1-\frac{W}{T+1}\right)^{q-1-k}, T > W$$

where $\frac{W}{T+1}$ is the CDF of a discrete uniform distribution between 0 and T calculated at the point $W-1$. Then, since we have a binomial distribution, the expected value is:

$$E\left[\Pr\left\{\bigcap_{i=1}^{q} t_i \in [0, W-1]\right\}\right] = (n-1)\frac{W}{T+1}, T > W\,. \tag{6}$$

As we can see, as $T \gg W$, the expected value will go to 0 (as expected). In Figure 3 we can see how the expected value drops to 0 as T/W grows.

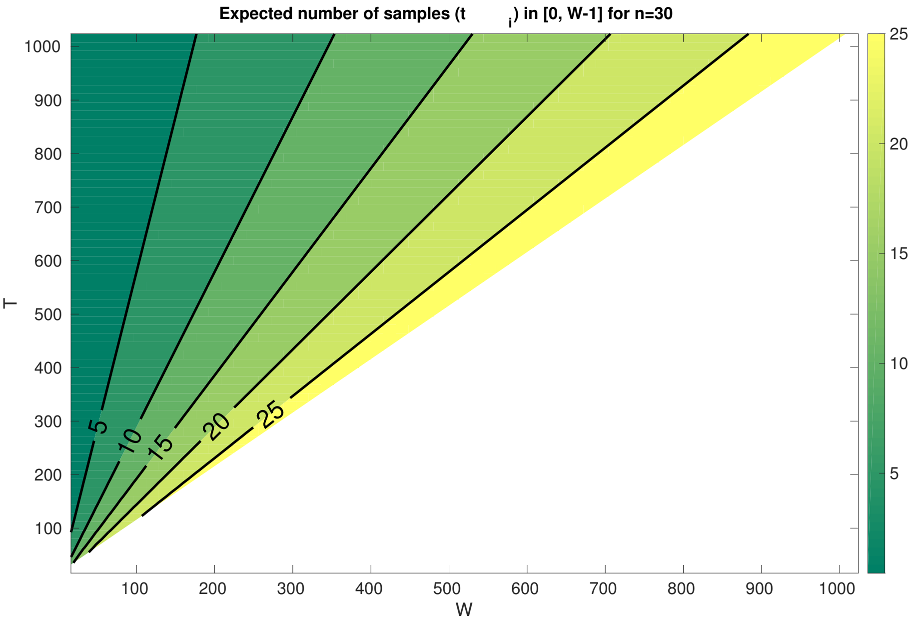

Figure 3: Expected number of samples (t_i) generated in one interval $[0, W-1]$.

Now, if we consider the backoff as well, from (4), we can calculate the expected value of frames sent before k_0 (excluding collisions between the other $n-1$ STAs), and generated after 0 just as we did in (6):

$$
\begin{aligned}
&E\left[\Pr\left\{\bigcap_{i=1}^{q} t_i + k_i < k_0 \wedge t_i \in [0, W-2]\,,\, i \neq 0\right\}\right] \\
&= (n-1)P_0^{\text{fail}} = (n-1) * \frac{W^2-1}{6\,W\,(T+1)}\,,\, T > W\,. \qquad (7)
\end{aligned}
$$

As we can see from Figure 4, as $T \gg W$, this expected value will go towards 0 (as expected).

This result indicates that we can use just one other STA as an approximation for n competing stations when T is large enough with respect to W. Of

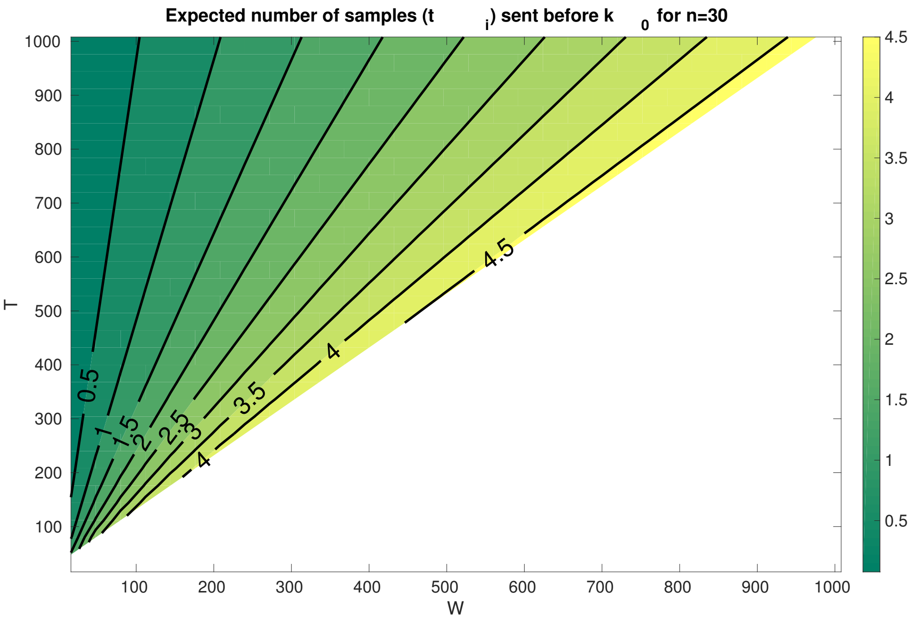

Figure 4: Expected number of samples sent before k_0 for n=30.

course the probability of collisions between the different STAs must be taken into account, which grows with the number of stations involved.

We are now going to charachterize collisions between two or more of the remaining $n-1$ stations inside the interval $[0, W-1]$. The The main idea behind this is to calculate the expected number of collisions inside that interval as T becomes larger than W. We chose the interval $[0, W-1]$ since it is larger than the interval $[0, k_0]$, so it is an upper bound to the latter. We suppose, without loss of generality:

$$t_i \in \left[-\left\lfloor \frac{T}{2} \right\rfloor , \left\lceil \frac{T}{2} \right\rceil \right] , i \in \{1 \dots n-1\} .$$

We define the event of exactly two STAs collding in this interval as:

$$E^{\text{coll},2} = t_i + k_i \in [0, W-1] \wedge t_j + k_j \in [0, W-1] \wedge t_i + k_i = t_j + k_j : i \neq j \, , \, i, j \neq 0 \, .$$

The probability of two STAs colliding in this interval is:

$$
\begin{aligned}
&\Pr\{E^{\text{coll},2}\} \\
&= \sum_{t'_i=-\lfloor \frac{T}{2} \rfloor}^{\lceil \frac{T}{2} \rceil} \sum_{t'_j=-\lfloor \frac{T}{2} \rfloor}^{\lceil \frac{T}{2} \rceil} \sum_{k'_i=0}^{\max\{W-1-t'_i,0\}} \Pr\{k_j = t'_i + k'_i - t'_j\} \\
&\times \Pr\{t_i = t'_i\} \Pr\{t_j = t'_j\} \Pr\{k_i = k'_i\} \\
&= \frac{1}{W(T+1)^2} \sum_{t'_i=-\lfloor \frac{T}{2} \rfloor}^{\lceil \frac{T}{2} \rceil} \sum_{t'_j=-\lfloor \frac{T}{2} \rfloor}^{\lceil \frac{T}{2} \rceil} \sum_{k'_i=0}^{\max\{W-1-t'_i,0\}} \Pr\{k_j = t'_i + k'_i - t'_j\}\,.
\end{aligned}
$$

The innermost sum stems from the fact that $t_i + k_i \in [0, W-1]$, by solving for k_i, and recalling that $k_i \in [0, W-1]$. Figure 5 shows the convex hull of the domain of k_i with respect to t_i (red area). The convex hull of the entire domain of k_i, t_i and t_j is depicted in Figure 6. The innermost probability is:

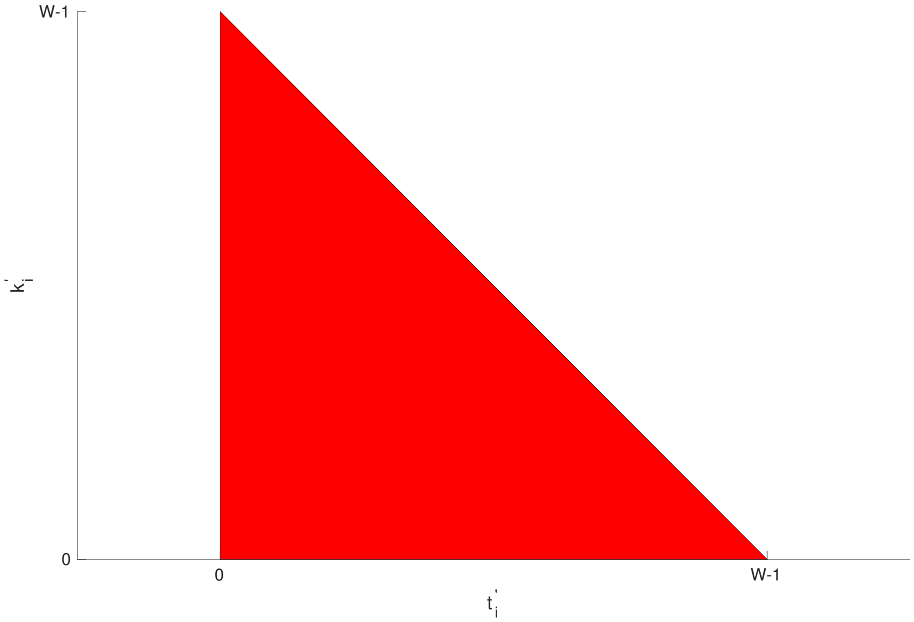

Figure 5: Domain of k_i w.r.t. t_i.

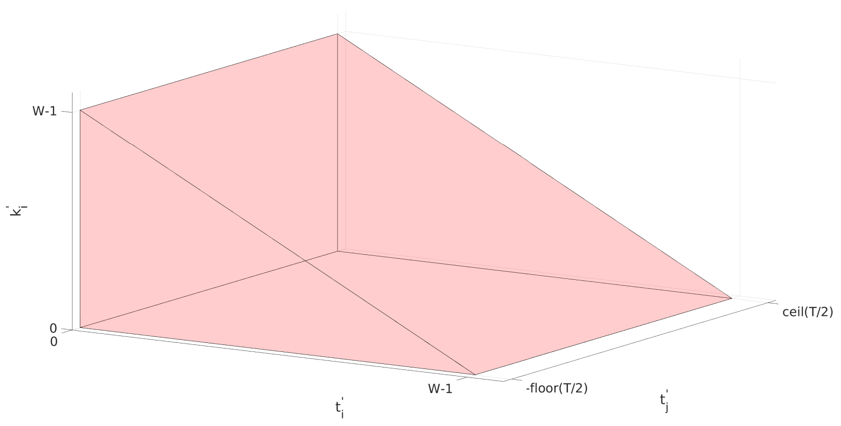

Figure 6: Domain of k_i w.r.t. t_i and t_j.

$$\Pr\{k_j = t_i' + k_i' - t_j'\} = \begin{cases} \frac{1}{W} & , t_i' + k_i' - t_j' \in [0, W-1] \\ 0 & , \texttt{otherwise} \end{cases} .$$

This means that, in order for the innermost sum to not be 0, the convex hull of Figure 6 will be delimited by two regions, namely, $k_i' \geq t_j' - t_i'$ and $k_i' \leq W - 1 + t_j' - t_i'$. We will suppose, for the sake of simplicity, that $\left\lfloor \frac{T}{2} \right\rfloor > W - 1$. In Figure 7 and Figure 8 we can see that the planar constraints both affect the convex hull of the domain. The convex hull of the lattice volume in which the convex hull of the domain. The convex hull of the lattice volume in which the innermost sum will not be 0, then be the one depicted in Figure 9. t_i' will go from 0 to $W - 1$. If we take the point of view of a generic slice of the plane t_j' k_i' (Figure 10) — i.e. any plane in which t_i' is constant — we can then write:

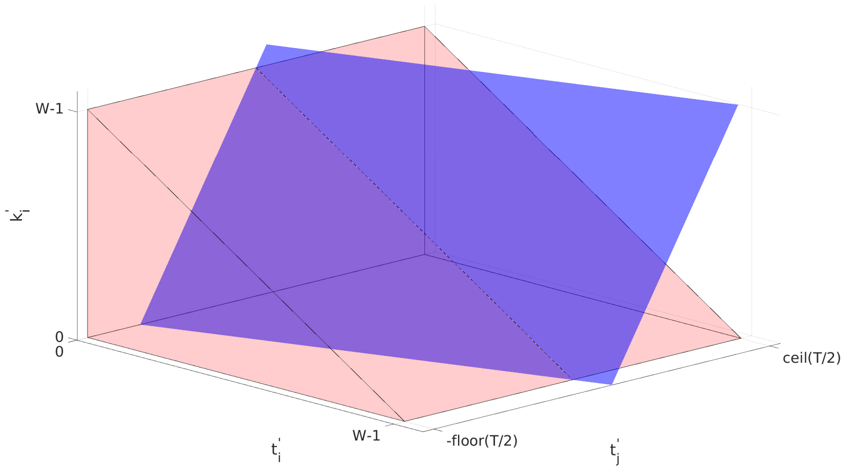

Figure 7: Domain of k_i limited by the plane $k'_i \leq W - 1 + t'_j - t'_i$ (in blue).

$$\begin{aligned}
&\Pr\{E^{\text{coll},2}\} \\
&\qquad = \frac{1}{W^2(T+1)^2} \sum_{t'_i=0}^{W-1} (R_1 + R_2 + R_3) \\
&\qquad = \frac{W+1}{2\,(T+1)^2}\,, \quad \left\lfloor \frac{T}{2} \right\rfloor > W - 1\,,
\end{aligned}$$

where

$$R_1 = \sum_{t'_j = t'_i - W + 1}^{0} \; \sum_{k'_i = 0}^{t'_j - t'_i + W - 1} 1$$

$$R_2 = \sum_{t'_j = 1}^{t'_i} \; \sum_{k'_i = 0}^{W - t'_i - 1} 1$$

$$R_3 = \sum_{t'_j = t'_i + 1}^{W-1} \; \sum_{k'_i = t'_j - t'_i}^{W - t'_i - 1} 1\,.$$

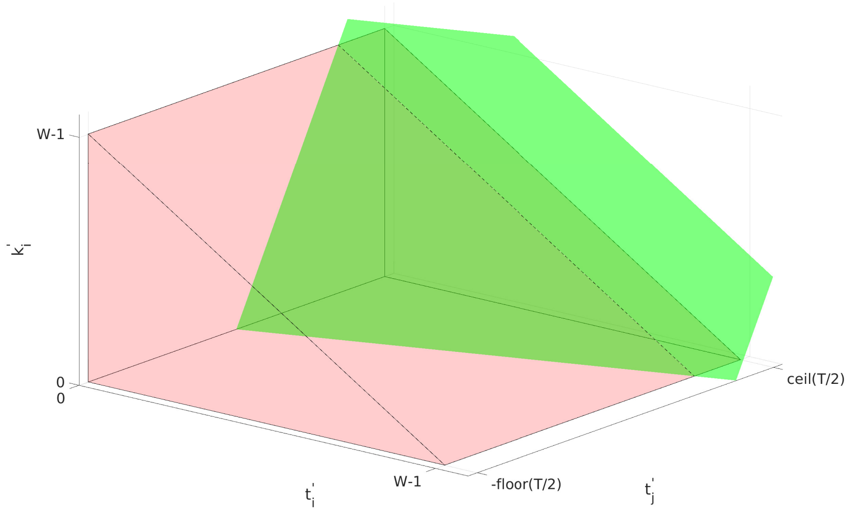

Figure 8: Domain of k_i limited by the plane $k_i' \geq t_j' - t_i'$ (in green).

The probability then that exactly $q \in \{1 \ldots n\}$ stations will collide with another station in the interval $[0, W-1]$ is:

$$P_q^{\mathtt{coll},2} = \binom{n-1}{q} \left(\frac{W+1}{2\,(T+1)^2} \right)^k \left(1 - \frac{W+1}{2\,(T+1)^2} \right)^{n-1-k} , \quad \left\lfloor \frac{T}{2} \right\rfloor > W-1 \, .$$

The expected value of stations colliding with exactly one other station in $[0, W-1]$ is thus:

$$E\left[P_q^{\mathrm{coll},2}\right] = (n-1)\frac{W+1}{2\,(T+1)^2} , \quad \left\lfloor \frac{T}{2} \right\rfloor > W-1 \, . \tag{8}$$

As we expected, in Figure 11 we can see that the expected value of stations colliding with exactly one other station in $[0, W-1]$ goes much faster to 0 as T becomes greater than W than the preceding expected values. We can infer that the probability of two or more stations colliding in one slot in that interval will be even smaller. It is therefore safe to assume that no collisions between two or more STAs other than STA0 will occur in the interval between 0 and

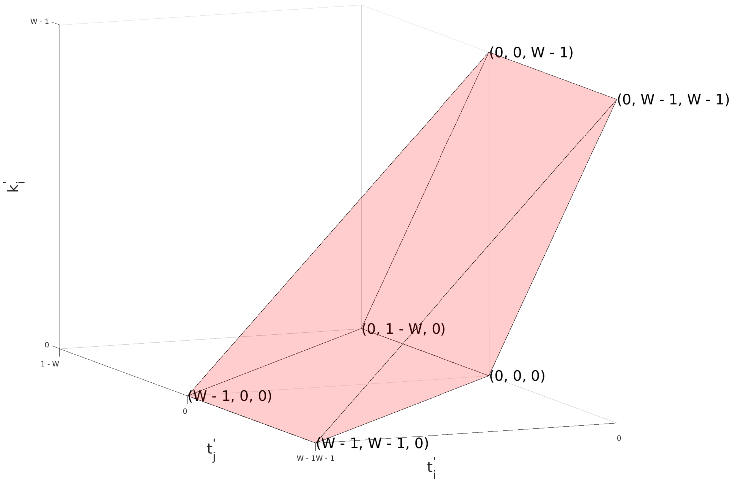

Figure 9: Domain of k_i limited by the two planes.

$W-1$. And this is therefore an upper bound on collisions occurring between 0 and $k_0 \leq W-1$.

In conclusion, we found that it is possible, when the sampling interval T is much larger than the CW W, and the update transmission time is comparable to one slot, to discard the collisions between STAs other than STA0 and STA1 and use (7) in order to calculate the probability of an update by STA0 to be discarded due to staleness at the receiver end.

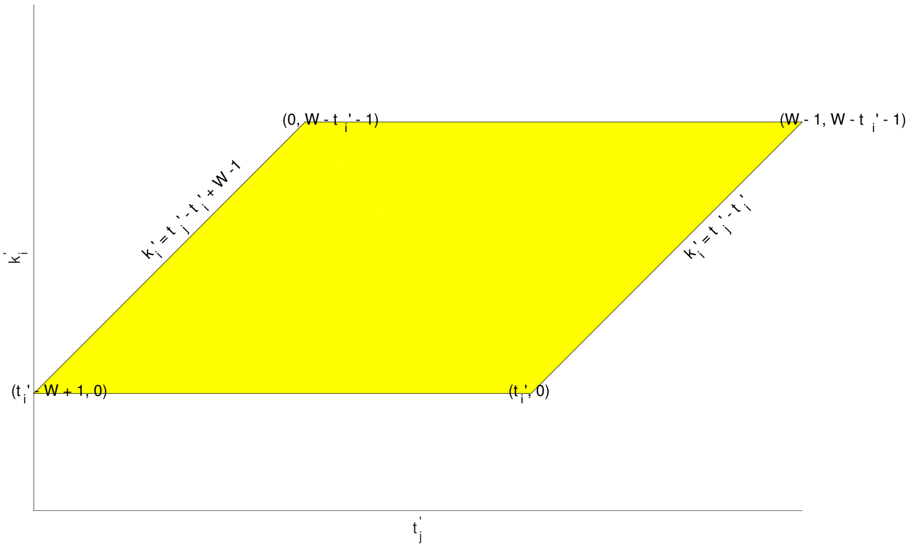

Figure 10: Domain of k_i from the point of view of the t'_j k'_i plane.

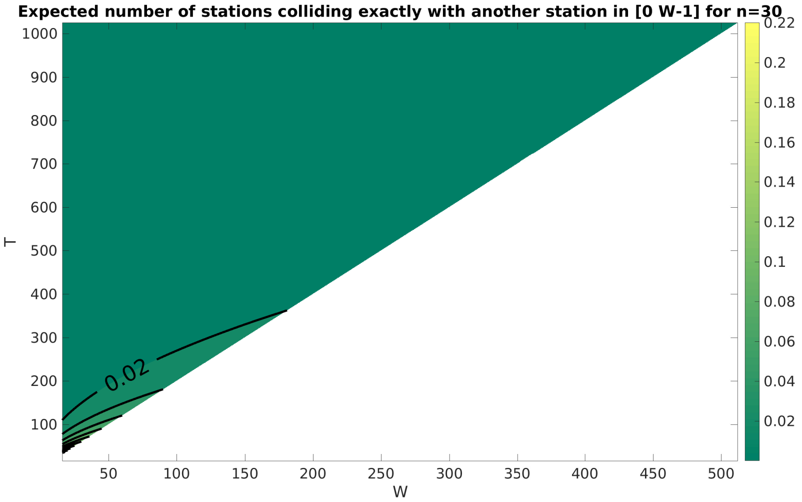

Figure 11: Expected value of stations colliding with exactly one another station in $[0, W-1]$ for n=30.