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IEEE 802.11af 網路之增強版公平性

Enhanced Fairness for IEEE 802.11af Networks

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Enhanced Fairness for IEEE 802.11af Networks

本論文係尚馬提君（學號R05942126）在國立臺灣大學電信工程學研究所完成之碩（博）士學位論文，於民國106年6月29日承下列考試委員審查通過及口試及格，特此證明

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ABSTRACT

The IEEE 802.11af, also called White-Fi, employs unused TV spectrum at frequencies between 470 MHz and 790 MHz, which provides bandwidth for sensors and monitors. The IoT technology revolution pushes IEEE 802.11af networks to handle a big number of stations and a wide transmission range. These constraints endanger one of the most important concerns of the protocol which rules these networks : providing fairness among stations. The most known causes to the fairness issue are the Capture Effect and the Hidden Terminal problem. The first one occurs when two stations of the same network, including the Access Point (AP), attempt a transmission at the same time and then instead of both failing, one of the two transmissions is successful. In the second one, two stations do not hear each other. Then a station can attempt a transmission while another one is already transmitting, inducing a collision and the failure of both transmissions. The original DCF has already been improved with the adding of RTS/CTS frames to prevent hidden nodes collisions but this mechanism just reduces the time of collision and does not completely treat the unfairness problem caused by this issue.

In this thesis, we first design a fully distributed mechanism to detect capture effect relationships in mixed uplink and downlink transmissions. When the transmission of a station is captured, our new protocol forces this station to transmit again, directly after the reception of the Acknowledgement (ACK) addressed to the station which has just captured it. Then both stations are aware of the capture effect relationship and can adjust their Contention Window (CW) in order to have the same probability of successful transmission as the other stations of the network. In addition, we deal with the hidden node problem and establish a distributed way to inform the whole

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network about the hidden node relationships. As a result, every station of the same network has the same knowledge of its network topology and optimizes its contention window to have the same Successfull Count Transmission (STC) as each other . Our detection protocol uses the fact that when two hidden stations collide, there is a probability that one succeeds according to the arrival time of the frames. Then, the station which is the second to attempt a transmission will transmit again two times directly after receiving the ACK addressed to the first one. This double transmission will inform the whole network of a hidden node relationship.

We compare through differents simulations our new mechanism with the original DCF of IEEE 802.11 af. In terms of fairness, our mechanism provides, for example to a network touched by only capture effect, a min-max fairness index of 96% and a Jains index value of 100%. In comparison, for the same network ruled by the original DCF, these indexes are respectively 35% and 86%. The STC fairness is achieved, instead of having twenty stations with a STC two times greater than twenty others, and every station has around the same STC. Moreover, for a network composed by twenty stations with six hidden nodes relationships, all these relationships are detected in less than 4 seconds by the whole network with our mechanism.

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CHAPTER 1

INTRODUCTION

1.1 Introduction to TV White Space

With the spread of wireless communications, there is a necessity in new and better approaches to share licensed spectrum. White spaces represent unused spectrum resources at specific locations and time that can be exploited through spectrum sharing. IEEE 802.11af, also referred as White-Fi and Super Wi-Fi, is a fresh wireless computer networking standard in the 802.11 family approved in February 2014. This standard allows wireless local area network (WLAN) operations in TV white space (TVWS) spectrum in the VHF and UHF bands between 480 MHz and 790 MHz. It avoids the congested unlicensed 2.4GHz/5GHz bands which are used by the other standards as WiFi, Bluetooth or Zigbee. 802.11af also presents an excellent propagation characteristic with a large coverage, because its frequency band resides under the 1 GHz frequency where material obstruction is less harmful than at higher frequencies. These features make the IEEE 802.11af standard an interesting solution for the deployment of a large scale of applications as Internet of Things.

In a near future, the world will see dozens of billions of smart devices transmitting tiny amounts of data to us, to the cloud and to each other. The Internet of Things (IoT) has the potential to touch and instrument an enormous range of connected devices, including home appliances, manufacturing tools or cities metrics. Theses applications need a spectrum where they can establish their communications. In the past year, the unlicensed 2.4GHz and 5GHz frequency bands have been stormed by domestics standards as WiFi or Bluetooth and they are now overcrowded. Instauring IoT networks in these bands would not be a benefit for their applications and would

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result in performance degradation of individual devices. Radio spectrum is the most expensive asset in wireless communication and this is the reason why the exploitation of unused licensed band becomes a smart solution to fill this gap. Furthermore, investment of companies in IoT development grows everyday and they need clear solutions in terms of spectrum availability and capability.

US FCC, UK Ofcom, and many regulators around the world have cleared the obstacle for IEEE 802.11af in terms of spectrum access. For instance, FCC has allowed the secondary operation of radio devices in the VHF/UHF bands since 2014, provided that no harmful interference is caused to the primary users (i.e., TV broadcaster and wireless microphones). In order to verify the opportunity of such secondary operation even in a very busy city in Taiwan, real measurements of the spectrum activity between 400MHz and 700MHz have been conducted in the Barry Lam (BL) building, National Taiwan University. A result of a 24-hour measurement starting from 00:00 of 2014/10/23 is shown in Fig. 1. The figure shows that at the upper 500MHz bands, five to six of 6-MHz wide bands are available, known as TV white space (TVWS), let alone an almost-unused 100MHz band in the 600MHz band (for military mostly). These unutilized bands, if used properly by IEEE 802.11af stations, could be a green field for many IoT applications.

IEEE 802.11af devices are required to operate in unoccupied spectrum, which can vary in size, location, and time. That means 802.11 networks must be able to learn from an approved geolocation database where channels are available and for what time duration and how to not interfere with primary users once a channel is available. In order to achieve this clean access, there are three main components in the IEEE 802.11 architecture, as shown in Fig. 2. The first one,which mainly differentiates this standard from other 802.11 standards, is the geolocation database (GDB). This database has the role to store , by geographic locations, the available frequencies and operating parameters for 802.11 af stations to satisfy regulatory requirements. The

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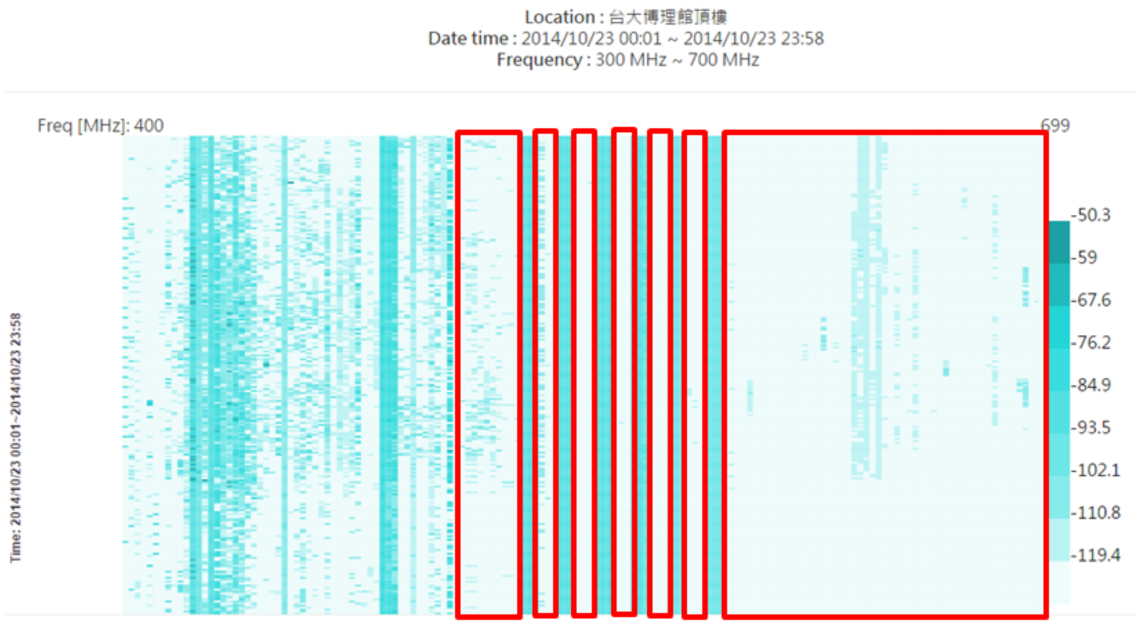

Figure 1: The measurement of spectrum activities between 400MHz and 700MHz

next component is the registered location secure server (RLSS). This element operates as a local database which assigns the geographic location and operating parameters to different access points (AP) among a small number of basic service sets (BSSs). The last one is the geolocation database dependent components (GDD). They are controlled by a GDB which ensures they satisfy regulatory requirements. There are two types of GDD, the GDD-enabling stations and the GDD-dependent stations. The first one is the equivalent of an AP. The GDD-enabling stations gets the operations frequencies and the parameters permitted in its coverage region through the White Space Map (WSM) from the GDB. Then, with this information, the GDD-enabling stations can allow and control the operation of the STAs under its service, called GDD-dependent stations. This last category of device can be identified as the stations of the BSS which can only communicate to their own GDC-enabling stations. By using this architecture, IEEE 802.11af stations can utilize the unused TVWS without causing interference to either TV broadcasters or wireless microphones.

Numbers of efforts from IEEE groups have been undertaken to make the VHF/UHF

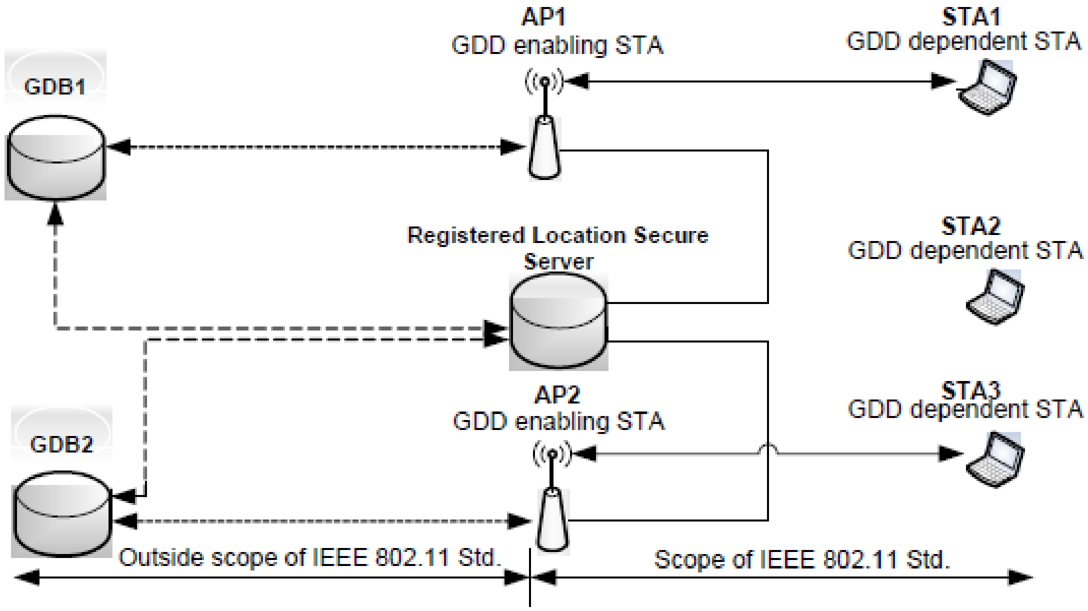

Figure 2: The architecture of geo-location access in the IEEE 802.11af standard

bands operational for new wireless networks application. The excellent propagation characteristics of the TVWS band coupled with underutilization in many locations is an attractive opportunity for the deployment of IoT networks. However, this solution presents some non-negligible drawbacks. As matter of fact, the DCF in the MAC layer of a 802.11af network uses a CSMA-based solution. A transmitter attempts to determine whether another transmission is in progress before initiating a transmission using a carrier-sense mechanism. If a carrier is sensed, the node waits for the transmission in progress to end before initiating its own transmission, if the channel is sensed idle, the station transmits its packet data in its entirety. This protocol includes different time duration specifications as the inter-frame spaces (IFS) or the back-off slot length which are important parameters for the share of the medium by different stations of a BSS. These parameters depend on the round trip propagation delay and due to the large coverage of TVWS bands, IEEE 802.11af networks present larger parameters than other 802.11 networks, as shown in Table 1. In large networks as IoT applications, the length of these parameters has an impact of the channel

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quality in terms of efficiency and fairness among stations which will be elaborate in this thesis.

	802.11af	802.11g
Operation frequency (MHz)	600	2400
Bandwidth (MHz)	6	22
Slot time (us)	24	9
SIFS (us)	120	10
DIFS (us)	168	28
EIFS (us)	669	342
PLCP length (us)	300	20

Table 1: Comparison of IEEE 802.11af and IEEE 802.11g parameters

1.2 Main issues and objectives

Our work is focus on the fairness provided by IEEE 802.11 networks. In the literature, there are two different ways to define fairness in wireless networks : the throughput fairness and the time fairness. The first one aims to provide the same throughput to the different stations of a same network while the second one manage to give the same transmission time to the whole network. In our thesis, we do not use either throughput or time index to measure the fairness level but the successful transmission count (STC) instead, defined as the number of successful transmissions of a station. Our objective in choosing this fairness index is that STC can be easily converted into throughput or time fairness. Indeed, when every station uses the same payload size for data transmission, achieving STC fairness is equal to throughput fairness. Also, when every station uses the same amount of time to transmit frames when they successfully access the channel, the STC fairness induces the time fairness.

The original DCF in the MAC layer of IEEE 802.11af devices follows the CSMA/CA mechanism explain as follows. When a station wants to transmit, it first has to randomly choose a back-off counter value in the interval [0, CW] where CW is its

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contention window. Then the station counts down by one its back-off every time the channel is sensed idle for one slot time length. Once the back-off counter of a station reaches zero, the station senses the channel for a DIFS time and if this last is idle during all the sensing time the station starts transmitting. After having transmitting its data, the station waits a SIFS time for receiving an acknowledgement (ACK) from the access point (AP). Every stations in the network can decode the ACK sent by AP and so wait a DIFS time before counting down their back-off counter again. In the original protocol, when a station station successfully access the channel,or wants to transmit for the first time ,it chooses a new back-off counter in the interval [0, CW_{min}]. But when its transmission fails for any reason , ie. no reception of ACK from the AP, the station has to increase its CW that becomes $2 * CW_{previous}$, with $CW_{previous}$ the previous value of its contention window.

This IEEE 802.11 MAC protocol has been designed to ensure STC fairness as shown in [] []. However, with the new technology revolution, 802.11 networks have to handle a bigger number of stations and a wider transmission range than in the past. This kind of network topology is subjected to space issues which degrade their efficiency and their fairness. In the literature, two main issues have been highlighted , the capture effect and the hidden node problem.

1.2.1 The capture effect

The distance of the stations from their AP belongs to the topology of the network and in large networks, the difference of range can be important. The capture effect occurs when two stations attempt a transmission at the same time and instead of both failing, one of the transmission is successful. Then it is said that the successful station has captured the one which has failed. As a matter of fact, the AP can decode one of the two transmissions because the received signal of this one is much stronger than the other one. The capture effect is a space issue, in a network in which all

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the stations have the same transmission power, this difference of signal intensity at the AP is caused by a difference of distance to the AP between two stations. Some experiments have been done in our lab to observe the capture effect consequences in a real IEEE 802.11af networks with a simple network . The topology of this network and the settings are as follows :

Data rate of station A	8Mbps
Data rate of station B	12Mbps
Distance between station A and AP	60m
Distance between station B and AP	10m

Table 2: The parameters used in capture effect

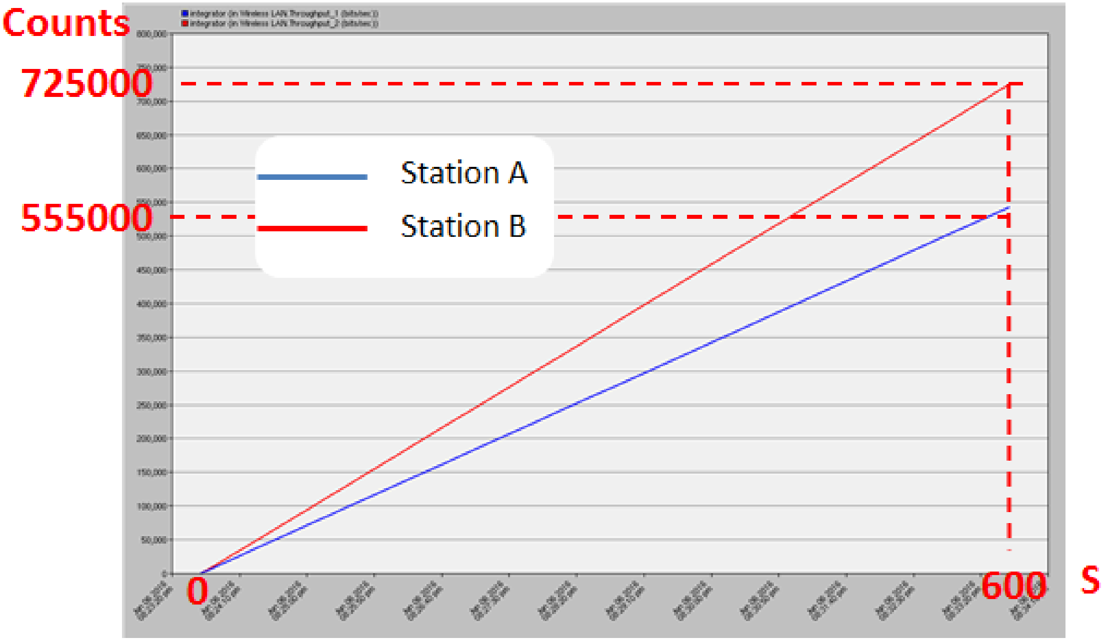

Figure 3: The STC of stations for capture effect

The behavior of the network is analysed during 10 minutes and the number of successful transmission is counted for station A and B. The results are exposed in Fig. 3. We can clearly note a gap of STC between the two stations. The STC of station B is 1208 counts/s and the STC of A is 917 counts/s. This difference is the consequence of the capture of the transmissions of station A by station B when the

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two stations attempt a transmission at the same time.

In the point of view of the DCF protocol, this capture of station B by A induces a two-level unfairness between these two stations. The first one is obviously that stations B successfully transmits while the transmission of station A fails. The second one concerns the size of the contention window after the capture : station B will reset its CW to CW_{min} and station A will multiply its CW by 2. Station B will succeed instead of colliding with station A but also most frequently have a smaller CW and according to this a bigger probability to attempt a transmission than the other stations in the network. Due to this two consequences of the capture effect, the Successful Transmission Count (STC), ie. the number of successful transmissions within a time duration, of station B will be higher than the one of station B creating an STC unfairness. This phenomena has been observed in many works as [2], in which the authors demonstrate through several experiences that the successful transmission probability of a station is dependant to its capture effect relationships.

1.2.2 The hidden node problem

In a network, every station has a Carrier Sense (CS) range and can only hear the transmissions of stations that are inside this range. The hidden node problem occurs when two stations with the same AP cannot hear each other, that means one station is not in the carrier sense range of the other one and vice versa. Then a station can attempt a transmission while another one is already transmitting, inducing a collision and the failure of both transmissions. This problem results in not only serious throughput degradation but also unfairness. The original DCF has already been improved with the adding of RTS/CTS frames to prevent hidden nodes collisions but this mechanism just reduces the time of collision and does not treat the unfairness problem caused by this issue. An experimentation has been done in our lab to observe the hidden node problem consequences in a real IEEE 802.11af network with a simple

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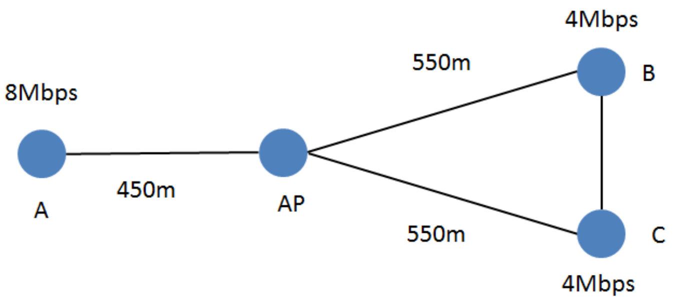

Figure 4: The topology of simple network with Hidden Nodes

topology and using RTS/CTS frames. This network is composed by three stations A, B and C, and a access point. Station A is hidden to both station B and station C. Station B and station C are not hidden to each other. The settings are illustrated in Table. 3 and Fig. 5 shows the STC of data frames from each station.

Data rate of station A	8Mbps
Data rate of station B	4Mbps
Data rate of station C	4Mbps
Distance between station A and AP	450m
Distance between station B and AP	550m
Distance between station C and AP	550m

Table 3: The parameters used in Case 2.2

In the results of experiment, the STC of station A is 150 counts/s, the STC of station B is 683 counts/s, and the STC of station C is 683 counts/s. Station A cannot hear the transmission of stations B and C and so A is able to attempt a transmission while B or C are already transmitting. Station B is hidden to A but not to C so B will not attempt a transmission if C is already transmitting. It is the same for C with station B. Then, the probability of frame collision of station A is bigger than the probabilities of collision of stations B and C, which are the same. Therefore, station A is more likely to double its CW size than station B and station C. This two differences produce the observed STC unfairness.

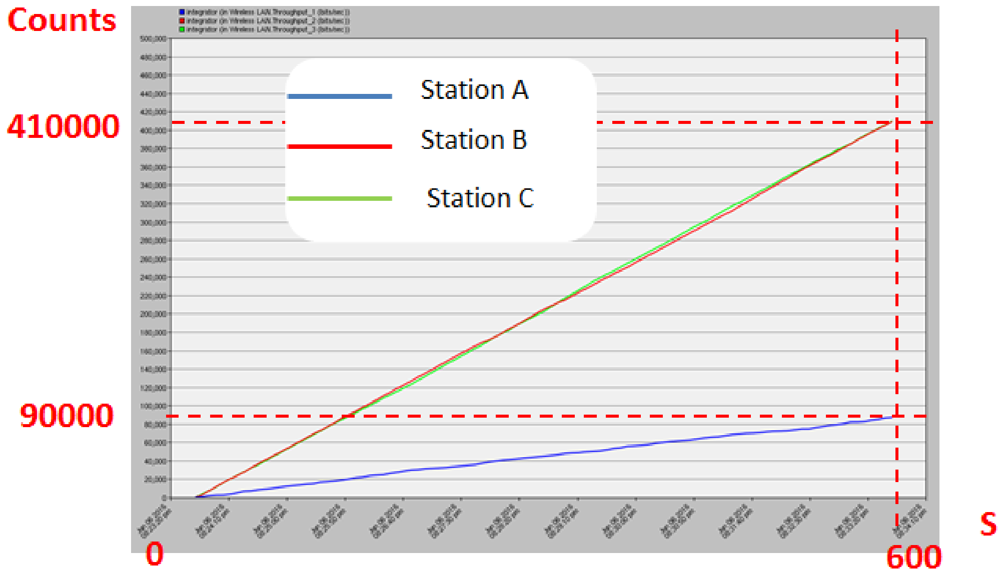

Figure 5: The STC of stations with Hidden Nodes

1.2.3 The combination of capture effect and hidden node problem.

Our work focus on large networks, with a big number of station within a large coverage. These types of networks are known to be touched by hidden nodes and capture effect and a combination of these two issues is possible. It is a serious problem and the degradation of the channel quality is worse than the two previous cases. The Fig. 6 presents the results of an experimentation on a network touched by this combination. In this case, stations A and B are hidden to each other and station A captures station B. Some articles as [6] , have demonstrated that a capture event between hidden stations does not depend on the time of the frame arrivals. That means that the AP will decode the transmission of A instead of B transmission every time there is a collision of RTS and even if A is the second one to transmit. So station will have a probability of collision smaller than Bs and a smaller contention window according to the CSMA/CA mechanism. The results of the simulation confirms these disparities. The STC is 1625 counts/s and 0 counts/s for station A and station B, respectively, as illustrated in Fig. 6. It is obvious that the channel is absolutely unfair

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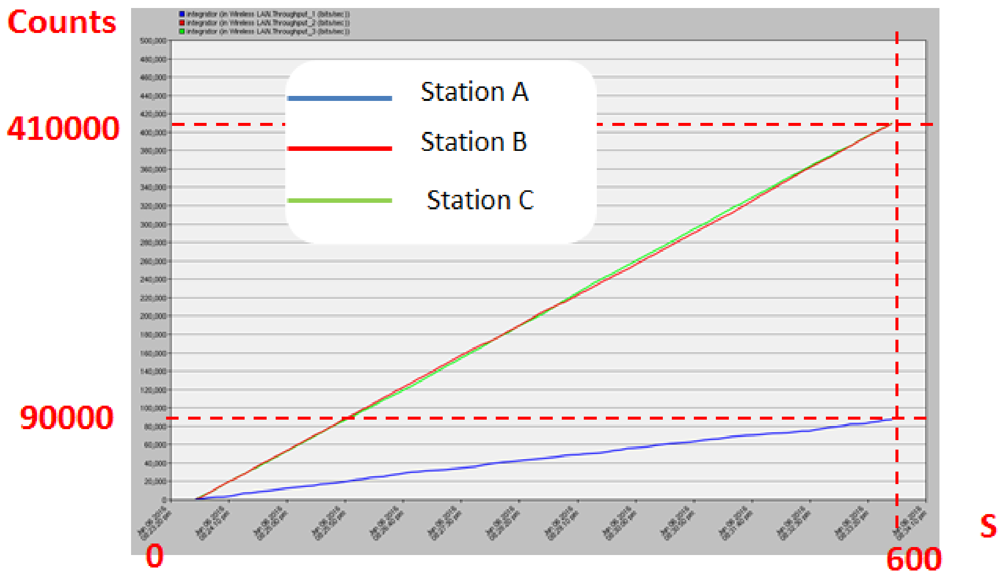

Figure 6: The STC of stations with both capture effect and hidden nodes

for station B in terms of STC.

In our thesis, we develop a fully distributed mechanism to first detect the capture effect and hidden node relationships of the entire network and to second adjust the contention window of the stations to achieve STC fairness. In our mechanism, the CW of each station is fixed, the binary exponential backoff is deactivate. For the capture effect detection, the key of our protocol is very simple to understand. For instance, when the transmission of station A is captured by station B, our protocol forces the retransmission of station A just after DIFS after receiving the ACK addressed to B. Then, the both stations are aware of this capture effect relationship and can take it in consideration to adjust their CW. In presence of hidden nodes in the network, every stations has to reserve the channel for two consecutive transmissions when it successfully access the channel to provide a safe retransmission to the captured station. For the hidden node detection, a collision of two hidden stations can lead to a successful transmission if the second transmission arrives in the SIFS waiting time of the first one. For instance, if A and B are hidden to each other, we consider

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the case A transmits its RTS successfully and B transmits its RTS between As RTS transmission and the reception of As CTS. Our mechanism will force B to transmit two times directly after the end of As transmission. Then the whole network will be aware of this hidden node relationship.

The rest of this thesis is organized as follows. In Chapter 2, we introduce the existing works of the above problems. In Chapter 3, our new mechanism to detect the capture effect relationships is presented. In Chapter 4, we extend our mechanism to networks with both hidden nodes and capture effect. In Chapter 5, we compare our mechanism with the original DCF and Shi-Huas mechanism. Chapter 6 concludes the thesis.

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CHAPTER 2

RELATED WORK

The fairness issue in IEEE 802.11 networks has been the subject of numbers of studies in the past decades. Although, unfairness in terms of air-time and throughput have been observed. The causes of unfairness are various and, in the papers about this issue, the capture effect and the hidden problem are not always considered. In a first time, we will present the different researches about the fairness definitions and improvement in IEEE 802.11 networks. In a second time, papers which brings solutions to provide fairness in networks with the capture effect or the hidden node problem will be introduced. In spite of our deep exploration of the literature, we did not find any paper which treats the unfairness caused simultaneously by the capture effect and the hidden node problem. To finish, we will present the thesis from a previous member of our laboratory. In his thesis, he has developed a new mechanism, called Non-Frozen Back-off Mechanism (NFBM) to detect the capture effect and the hidden nodes relationships of a network and to provide STC fairness. We will discuss about the limitations of his protocol.

2.1 Different fairness approaches

2.1.1 Air-Time fairness

Since the 802.11 MAC implicitly provides equal transmission opportunities, slower stations tend to occupy more airtime as compared to faster stations, provided that equal-sized packets are used by all stations. Then, when stations of a same network choose different data rates, their transmission time are different. Even if each station has the same probability of successful transmission, the air-time fairness

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occurs. In addition the performance of the stations using high rates is bounded by the performance of the stations using low rates. An obvious solution would be to give the same transmission time to every station, regardless of their data rate, and let them send as many frame as they want during this time period. The temporal fairness would be achieved but stations with higher data rate will transmit more frames than stations with a lower one, inducing a throughput unfairness.

The temporal fairness in multi-rate contention based 802.11e network is evaluated in [1]. They analyzed different transmission opportunity (TXOP) policies of channel release and fragmentation rules. The exploitation of these two parameters can lead to temporal fairness and throughput improvement . For the fragmentation rules, the MPDUs exceeding the TXOP limit are divided into equal-sized fragments and for the channel release, their simulations shows that it can be release the channel before the TXOP expiration. In [2], the author design a distributed medium access control algorithm for fairly sharing network resources among contending stations. The exponential back-off is disabled, ie. the CW of a station is not doubled after a failed transmission but stays constant. They first establish a relation between the contention window of two stations and their channel access time. With this relation, every station can select an appropriate contention window to achieve fair sharing of the channel occupancy time. Indeed, stations analyzed the frame header of the transmissions of their network and create a table with the MAC address of all the stations and their corresponding data rate. When a new station access the channel, a new case of this table is created with the MAC address of this station and its data rate. To adjust its CW, A station needs to know the data rates used by every stations of its network. Another approach is used in [3]. The binary exponential back-off is enabled and the value of a station chooses its values of CWmin and CWmax according to its data rate.

2.1.2 Throughput fairness

In a long term, the DCF basically provides an equal opportunity to access the shared wireless channel to the contending stations, that means the throughput fairness is achieved. However , the short-term fairness implies long-term fairness, but not vice versa. In particular, under certain scenarios, though the bandwidth allocation is fair in a long-term, it is very unfair as the perspective of the system from a short-term viewpoint. In [4] define an access method able to dynamically adapt to physical channel conditions and to provide a good short-term access fairness. Each station estimates the number of consecutive idle slots between two transmission attempts and uses it to compute its CW. By adjusting its CW, a station makes this own number of idle slots converge to a target value, common for all stations. This target value is determined as a function of the number of stations in the network. Then the idle sense protocol is followed by every station and the short-term fairness is achieved. This mechanism can also achieve time-fairness by providing a higher throughput to the stations with a higher data rate and then the channel time used by all hosts is equal.This idea of observing the channel idle period has also been studied in [5] and [6] (DCWA method) to achieve throughput fairness by observing, this time, the channel average idle interval. Then recently a new method called ACWB [7] has overcome the drawback of Idle Sense and DCWA methods by proposing better throughput and fairness. In [8] the authors proposed two schemes, the first computes the CW and the second deals with the transmission length, to achieve throughput short-term fairness. Their both mechanisms have a centralized and a distributed version which are comparing in term of delay performance.

2.1.3 Min-max fairness and proportional fairness

The notions of proportional fairness and min-max fairness frequently appear in works around fairness in 802.11 networks. The first one is achieved when

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the throughput of a station is proportional to its weight factor. In [3] and [4] the authors demonstrate that if a network is saturated , and all the stations have the same priority, then the proportional fairness leads to the time fairness. The second one allocates the throughput among stations such that the stations with the lower throughput cannot gain any more by reducing the throughput of some other stations. In a saturated network, max-min fairness leads to throughput fairness.

To conclude, in a saturated network where all the stations have the same data rate, the same payload size and the same priority, the STC fairness leads to the throughput fairness, the time fairness, the proportional fairness and the min-max fairness.

2.2 The Capture Effect and the Hidden Node problem

In the previous section, the papers presented did not consider the influence of the capture effect and hidden node problem on the fairness and throughput degradation of the IEEE 802.11 networks, as shown in the introduction. In the following section we will present some papers that has studied these two channel behaviour.

2.2.1 The capture effect

The known capture effect issue in IEEE 802.11 network has also been studied in many works. Some papers as [9], [10] and [11] focus on experimental studies on the capture effect. For instance, in [9] the authors realize an experimental test-bed to demonstrate that the throughput of stations is determined by their relative locations and severe throughput unfairness can occur even if the stations use the same transmission bit rate. However they do not provide any solutions to fix the unfairness issue. [11] demonstrates that a capture event does not depend on the timing of frame arrivals from the different stations . In the other hand, some papers try to analytically analyse the influence of capture effect by taking it into consideration in their

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mathematical model as [12] and [13] but none of these papers explain how to detect the capture effect relationships.

However, the authors in [14] propose a new MAC layer transmission opportunity (TXOP) adaptation algorithm for achieving temporal fairness in 802.11 WLANs, with the consideration of capture effect. The key of their algorithm is to adjust the TXOP of a station in function of its successful transmission probability (STP). For example, in a network where a station is the only one to capture other stations, its STP is higher than others and so its TXOP will be compute to be longer than the other stations of the network. To avoid fragmentation at the end of a TXOP, a STA only transmits an integral number of frames within its TXOP that has been carefully sized. They proposed a centralized and a distributed algorithm. In the centralized algorithm, the AP measures each STAs STP by counting received frame burst during a measurement window (MW) , calculates the appropriate TXOP for each stations and broadcasts the TXOP assignments in its beacon frames. This centralized approach is limited by its scalability, a large number of stations leads to a lot of overhead. In the distributed approach, a station has to measure the total channel occupation time by all stations and its own during every MWs.

Although the temporal fairness is achieved by this algorithm, it needs a lot of resources from the stations and does not take in consideration the hidden node problem. As a matter of fact, with the presence of hidden nodes, the stations and the AP will not estimate the correct channel occupation time.

2.2.2 The hidden terminal problem

The hidden node problem is considered as the most famous network issue and also the easiest to understand. Since the beginning of wireless networks, solutions have emerged to minimize the throughput degradation caused by this problem. The MACA medium access protocol first proposed by Karn [15] and later defined

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by Biba [16], uses an RTS-CTS-DATA packet exchange and uses binary exponential backoff. In [17], the authors improve this frame exchange mechanism by introducing the MACAW access method which uses RTS-CTS-DS-DATA-ACK exchange and includes a significantly different backoff algorithm. The throughput is improved by this mechanism but for complex network temporal or throughput fairness are not achieved.

In [18], the authors propose to design a game theoretic model which can optimize both throughput and channel access delay in each node in the presence of hidden terminals and thus optimize good short-time fairness. Their protocol computes a fixed CW size independently for each stations, regarding the consecutive number of idle slots between transmission. They employ the same idle sense method as in [4]. Their algorithm is strongly dependent on the estimation of the consecutive idle slot times and a wrong choice of initial parameters can lead to a collapse of the game. In addition, for larger and larger networks, the observation window gets larger and larger and the convergence time bigger and bigger. There is a limitation is the scalability of this method.

In [19] a clustering algorithm is presented for resolving the hidden node problem in infrastructure mode in IEEE 802.11 networks. The stations are partitioned into clusters and all the stations from a same cluster can hear each others. Then a Contention-Period (CP) is divided into Sub-Periods (SPs), each of which is non-overlapping assigned to a cluster. Taking into consideration the fairness among the clusters, they also propose a fairness algorithm for dividing a CP into SPs and so achieve the total network fairness. This is a centralised mechanism which needs modifications of the polling frames format of the PCF mode of 802.11 networks. However the clustering algorithm presents some limitations in the computation of the length of the SPs when cluster have different numbers of stations. Therefore, the fairness in networks with complex hidden node relationships is hardly achievable.

In conclusion to this first part, we observe a lack of protocols treating both capture effect and hidden node problems and also the non-scalability of existing detection mechanisms of these both issues for large networks.

2.3 Paper [20]

In our laboratory, the fairness issue caused by the capture effect and hidden nodes in IEEE 802.11af networks has already been studied. In [20], the author proposes its own mechanism to first detect the capture effect and hidden node relationships among stations and to second provide STC fairness in the whole network. We are going to briefly introduce the main features of his protocol and expose our motivations which lead us to this new research on the same subject.

2.3.1 Main features

The first step of [20]s protocol is the detection of the capture effect and hidden node relationships. In order to detect the capture effect relationships among stations, [20] brings the following modifications to the original DCF:

- every stations has to send two consecutive frames for its access to the channel.
- a station does not freeze its back-off timer if it identifies that the channel is busy caused by an RTS frame but count it down until receiving a CTS/data/ACK frame.
- when a station continue to count down its back-off timer after having frozen its back-off, the back-off value will be decremented by 1
- if a station count down the back-off timer to zero when the channel is busy, stations will send neither the first RTS frame nor the second RTS frame, and will choose a new delayed back-off value.

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Therefore, the relation of the capture effect between two stations can be detected when the first data frame of one station collides with the second data frame of another station. For instance, we take a simple network where A and B are hidden to each other and A captures B. Due to the capture effect as illustrated in Figure 36, the second frame of station A is successfully decoded by the AP. After successfully sending two consecutive transmissions, station A keeps monitoring the channel during an HP. If station A receives a CTS frame sent to station B, it can identify that it captures B. Similar to the case without hidden terminals, station A has to wait for one more HP to prevent the false alarm. If station A receives the second ACK frame sent to B, it will not identify that it captures station B.

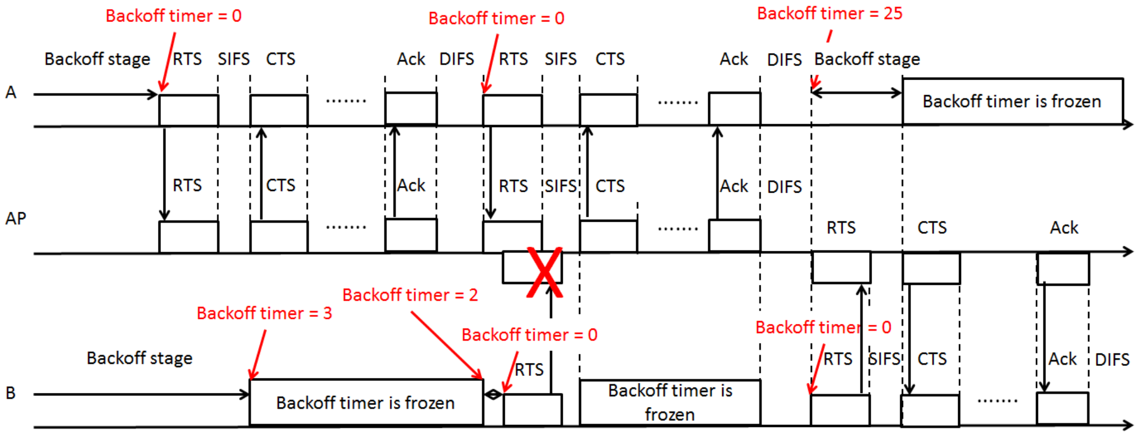

Figure 7: [20]'s mechanism : Detection of the hidden node relationships

For the detection of the hidden node relationships, a station analyses which type of frame it can decode from another station. If a station never decodes a RTS or data frame from another station but hears the CTS and ACK addressed to this station, it concludes this station is hidden to itself. But, if a station can hear the data frame sent from station j then it detects that station j is not hidden to itself. In a simple network composed by two stations A and B and an AP, if A and B are hidden to each other, then station B detects that it is hidden to A.

In a second step, every station broadcasts the number of its hidden stations and the number of stations which are captured by itself and are hidden to itself at the same time, using AMPDU frames. Doing that, the whole network should be informed of the capture effect and hidden node relationships of a station.

In a third step, every station calculates the CW size based on the information received from other stations in the BSS.

2.3.2 Limitations

Shi-Hua leads simulations with his mechanism and the results show a large improvement of the fairness of a network. Meanwhile, its protocol has some limitations.

Firstly, the capture effect in mixed downlink/uplink transmissions is not considered. As we will see in this paper, during a downlink transmission the AP may be able to capture the uplink transmissions of the stations in its BSS. This capture effect induces a STC fairness that has to be considered in the computation of the contention window sizes.

Secondly, two stations in the same BSS may not have the same understanding of the capture effect and hidden node relationships of the whole network. Indeed, when stations receive the effects relationships from the other stations, they record the information into two arrays. The number hidden array (NHA), records the numbers of hidden stations send from other stations and the number hidden capture array (NHCA) records the numbers of simultaneously hidden and captured stations sent from other stations. Then, the target of stations is to obtain the matrices HM and CM defined as follows:

- Hidden matrix (HM) stores the hidden information of the stations. The size of HM is N × N, where N is the number of total stations in the BSS. The element (i,j) of HM represents the hidden relation of station i and station j:

  HM(i,j)=1, if station i and station j are hidden to each other

HM(i,j)=0, if station i and station j are not hidden to each other

Therefore, HM must be a symmetric matrix

- Capture matrix (CM) stores the capture information of the stations. The size of CM is N × N, same as HM. The element (i,j) of CM represents the capture relation of station i and station j:

CM(i,j)=1, if station i captures station j

CM(i,j)=0, if station i do not capture station j

We denote the matrix, which are guessed by stations, as guessed hidden matrix (GHM) and guessed capture matrix (GCM), respectively. A station computes these matrices following an algorithm which only uses the value of NHA and NHCA.

For example, if the inputs are:

$$NHA = [2 \quad 2 \quad 1 \quad 1] \quad and$$
$$NHCA = [2 \quad 0 \quad 0 \quad 0]$$

then the outputs are

$$GHM = \begin{pmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \quad or \quad GHM = \begin{pmatrix} 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \quad or$$

$$GHM = \begin{pmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \quad or \quad GHM = \begin{pmatrix} 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \quad and$$

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$$GCM = \begin{pmatrix} 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad or \quad GCM = \begin{pmatrix} 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

As shown in the example, these matrices are not unique and a station will get one pair of the GHM and GCM by the algorithm, which may be different from the actual HM and CM. In addition, two stations of the same network, which receive the same NHA and NHCA, may not compute the same HM and CM. To conclude, due to this centralized approach, the stations from the same network may not have the same understanding of the capture effect and hidden node relations among stations. Therefore, their computation of the optimum CW may be wrong and the desired STC fairness or throughput may not be reached.

In this paper, we will present a complete new mechanism which avoids the drawbacks of [20]s. Our fully distributed mechanism first aims to provide the same and complete understanding of the capture effect and hidden node relationships to all the stations from the same network in uplink and downlink transmissions. Once the detection part is complete, each station will adjust its CW according to these relationships with the intention of maximizing the total throughput of the network .

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CHAPTER 3

GSR WITH CAPTURE EFFECT ONLY

In this paper, we consider a IEEE 802.11af networks in infrastructure mode. Stations are randomly located in the transmission range of the AP and have always something to transmit. Mixed downlink and uplink transmissions are considered in which all stations transmit the same payload length at the same data rate. For downlink transmissions, we assume that a transmission of the AP is addressed to the different stations of the network with the same probability. In this chapter, we consider network without hidden node problem. ie. every station can hear each other.

3.1 Different level of capture effect

The capture effect between stations and between stations and AP is different. For uplink transmissions, if a device A captures another device B, then device A will always capture device B. However, for a collision between an AP in downlink transmission and a station in uplink transmission, the capture effected is more complex, as shown in Fig. 1. In Fig. 1 b) the AP and station B attempt a transmission at the same time. At the recipient of APs transmission, here station A, the signal from the AP is stronger than Bs signal so station A can decode its signal and answer with an ACK to the AP. In this case, the AP captures the transmission of station B. But, in Fig. 1 c), the AP and station B still attempts a transmission at the same time, at the difference that the transmission of the AP is addressed to a different station called station C. At the recipient of APs transmission, here station C, the signal from the AP is not enough stronger than Bs signal so station A cannot decode its signal and do not answer with an ACK to the AP. At the same moment, the AP, which is in

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transmitter mode, does not hear the transmission of B. There is no emission of any ACK inducing no capture effect and the both transmissions failed. In conclusion of this last category, there is no way a station can capture the AP, so we do not have to consider this case, but when the AP captures a station we have to know which station is the receiver of its transmission.

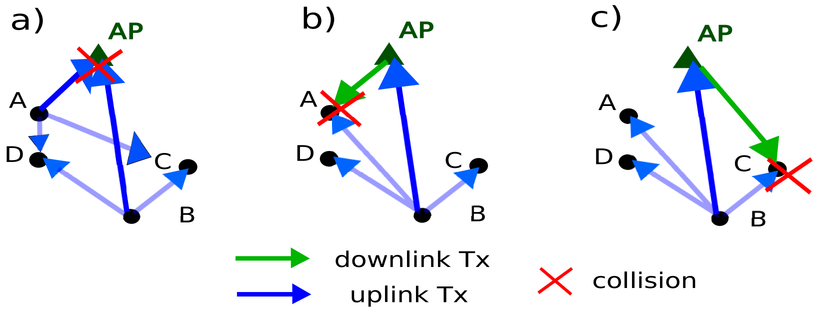

Figure 8: Topology of mixed downlink/uplink transmissions for the two different cases of capture effect.

3.2 *Our capture effect detection mechanism*

In order to detect the capture effect relationships of the whole network, our mechanism proposes the following modifications of the original DCF:

- every station has a non-zero fixed contention window [1, CW].
- if a station attempts a transmission and receives an ACK addressed to another station instead of receiving a ACK addressed to itself, this station will transmit again its data at the end of the ACK as if its back-off counter is still equal to 0.

In the case of a transmissions collision in uplink transmissions only, the capture effect is illustrated in Fig. 9. Station A receives the right acknowledgement meaning that its transmission is successful but A does not know it has collide with B yet. From B's perspective, it transmits but receives an ACK addressed to A and understands its has been captured by A. Based on our protocol, station B transmits again directly after the ACK addressed to A and its transmission is successful because

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A has to choose a non-zero back-off value. Station A will in turn hear the retransmission of B and understand it has captured station B during its last transmission.

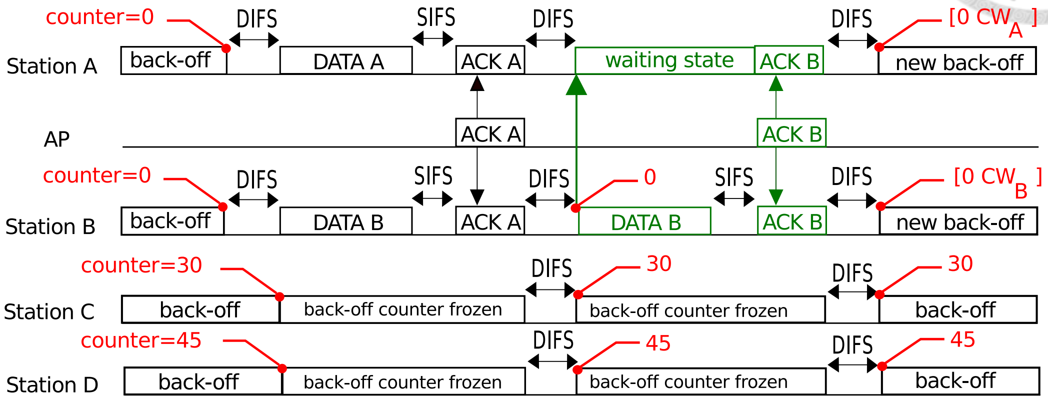

Figure 9: Capture event detection with the new mechanism in uplink transmissions.

The capture effect detection protocol is exactly the same when it occurs in a mixed uplink/downlink transmissions collision. In addition, if two stations collides without capture effect, there is no ACK or if there is just a successful transmission one back-off slot has to elapse to announce that no collision happened.

Based on this detection mechanism, devices will know the number of devices they captured N_C and the number of devices they are captured by N_{BC} . According to these two parameters, each station will select an optimum CW as their STC will be equal and the total throughput will be optimized. In the next section we will derive the optimum CW for every station with the Markov Chain.

3.3 Computation of the contention window .

3.3.1 Markov Model

Once the devices know the capture effect among each others, they have to choose a contention window based on their capture effect relationships. In order to simplify the protocol, devices do not increment their CW size as in original DCF. We establish a Markov chain in Fig. 20 of our protocol inspiring by [1]. and that reflects

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the main modification announced in part III. to calculate the CW for each devices.

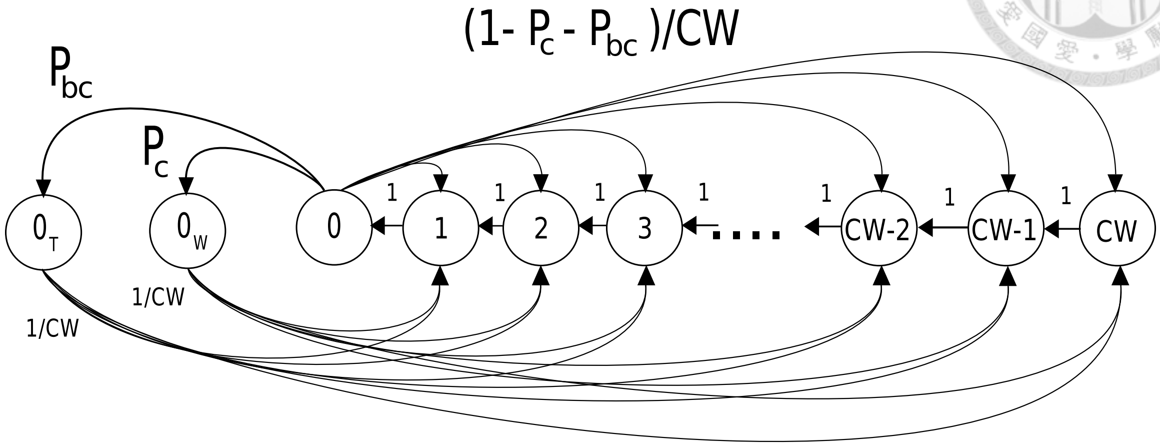

Figure 10: Markov chain of the new protocol

The different states of our Markov chain are described below:

- O : The device attempts a transmission.
- O_T : The device keeps its back-off counter to 0 and transmits for the second time in this transmission attempt, directly after waiting DIFS after the last ACK received.
- O_W : The device waits a transmission time before counting down its back-off.

The Markov Process of Fig. 20 for a station i is governed by the following transition probabilities:

$$\begin{cases} P(k/k+1) = 1\ , \quad k \in [0, CW-1] \\ P(0_T/0) = P^i_{bc}\ , \\ P(0_W/0) = P^i_c\ , \\ P(k/0_T) = P(k/0_W) = 1/CW, \quad k \in [1, CW] \\ P(k/0) = (1 - P^i_c + P^i_{bc}))/CW,\ k \in [1, CW] \end{cases} \tag{3.1}$$

Let $b^i_s = lim_{t\to\infty} P(station\ i\ is\ in\ state\ s)$ denotes the stationary distribution of the chain. The probability b^i_0 represents the probability that the back-off counter of station i reaches the value 0 in a random chosen time slot.
In the rest of our study, we will consider that for large networks:

$$CW_i \gg 1\ \forall i \in \{N\} \Rightarrow b^i_0 = b^j_0\ \forall i, j \in \{N\} \tag{3.2}$$

The different probabilities that appear in the Markov chain can now be defined and simplified considering (2) :

- P^i_c is the probability that *station i* captures 1 station knowing that *station i* collides with 1 station.

$$P^i_c = b^i_0 * \sum_{j=1}^{N^i_C} b^j_0 \prod_{h=1}^{N-2} (1 - b^h_0) \tag{3.3}$$

$$P^{AP}_c = b^i_0 * \sum_{j=1}^{N^i_C} b^j_0 * \frac{N^j_{AP}}{N-2} \prod_{h=1}^{N-2} (1 - b^h_0) \tag{3.4}$$

  where N^i_C is the total number of stations that *station i* captures,N^i_{AP} is the number of stations for which AP capture *station i* when it transmits to.

- P^i_{bc} is the probability that *station i* is captured by 1 station knowing that *station i* collides with 1 station:

$$P^i_{bc} = b^i_0 * (\sum_{j=1}^{N^i_{BC}} b^j_0 + \frac{N^j_{AP}}{N-2}) \prod_{h=1}^{N-2} (1 - b^h_0) \tag{3.5}$$

  where N^i_{BC} is the total number of stations that capture *station i.*

We now want to obtain a closed-form solution for our new protocol Markov chain. The first step is to express all the steady state probabilities as a function of b^i_0:

$$b^i_{0_T} = P^i_{bc} * b^i_0 \tag{3.6}$$

$$b^i_{0_W} = P^i_c * b^i_0 \tag{3.7}$$

The other stationary probabilities for any $k \in [0, CW-1]$ follow by resorting to the state transition diagram:

$$b_k^i = \frac{CW_i - k}{CW_i} \begin{cases} (1-(P_c^i + P_{bc}^i))/CW_i * b_0^i \\ +P_{bc}^i/CW_i * b_0^i \\ +P_c^i/CW_i * b_0^i \end{cases} \tag{3.8}$$

The normalization condition imposes:

$$1 = b_{0_T}^i + b_{0_W}^i + b_0^i + \sum_{k=1}^{CW} b_k^i \quad \forall i \in \{N\} \tag{3.9}$$

So by using (2),(3) and (4) we have:

$$b_0^i = \frac{1}{\frac{CW_i+3}{2} + (P_{c,1}^i + P_{bc,1}^i)} \tag{3.10}$$

Knowing that we are working with large networks which involve big contention windows, the right hand term at the denominator can be neglected and the equation becomes:

$$b_0^i \simeq \frac{2}{CW_i + 3} \tag{3.11}$$

The last step is to extract from the Markov chain closed-form the probability of transmission attempt in random given time slot P_0^i of a station i. In our mechanism, every time a station is captured, this station is going to directly attempt a new transmission as shown in Fig. 9. Therefore, according equations (3),(5) and (10), the probability of transmission attempt is equal to:

$$P_0^i = \frac{2}{CW_i + 3} * (1 + (N_{BC}^i + \frac{N_{AP}^i}{N-2}) * {b_0^i}^2 * (1 - b_0^i)^{N-2}) \tag{3.12}$$

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3.3.2 STC Fairness

The STC fairness in a network $\{N\}$ is defined by:

$$P_S^i = P_S^j \quad \forall i, j \in \{N\} \tag{3.13}$$

where P_S^i is the probability of successful transmission of station i when station i attempt a transmission. For each station following our new protocol, this probability is equal to :

$$P_S^i = b_0^i * (\prod_{j=1, j\neq i}^{N-1} (1 - b_0^j) + \sum_{h=1}^{N_C^i + N_{BC}^i} b_0^h \prod_{j=1, j\neq(i,h)}^{N-2} (1 - b_0^j)) \tag{3.14}$$

and for the AP :

$$P_S^{AP} = b_0^{AP} * (\prod_{j=1, j\neq i}^{N-1} (1 - b_0^j) + \sum_{h=1}^{N-1} \frac{N_{AP}^h}{N-2} b_0^h \prod_{j=1, j\neq(i,h)}^{N-2} (1 - b_0^j)) \tag{3.15}$$

We consider now a station *neutral* called n that has no capture effect relationships, ie. this station does not capture any stations ($N_C^n = 0$) and is not captured by any other stations ($N_{BC}^n = 0$). We assume this station has a fixed contention window called CW_n that we will be able to modify later to achieve other enhancements as power efficiency or total STC maximization. To achieve the STC fairness we need :

$$P_S^i = P_S^n \quad \forall i \in \{N\} \tag{3.16}$$

By using the equations (12), (13) and (14) we obtain for every station :

$$\frac{1 - b_0^i}{b_0^i} = \frac{1 - b_0^n}{b_0^n} (1 + \frac{\sum_{h=1}^{N_C^i + N_{BC}^i} b_0^h \prod_{j=1, j\neq(h)}^{N_C^i + N_{BC}^i - 1} (1 - b_0^j)}{\prod_{h=1}^{N_C^i + N_{BC}} (1 - b_0^h)}) \tag{3.17}$$

and for the AP:

$$\frac{1 - b_0^{AP}}{b_0^{AP}} = \frac{1 - b_0^n}{b_0^n} (1 + \frac{\sum_{h=1}^{N-1} \frac{N_{AP}^h}{N-2} b_0^h \prod_{j=1, j\neq(i,h)}^{N_C^{AP} - 1} (1 - b_0^j))}{\prod_{h=1}^{N_C^{AP}} (1 - b_0^h)}) \tag{3.18}$$

Considering the large networks assumption made in (2), we finally find that, to achieve STC fairness, the value of the contention window of the AP and a station i from the same network is :

$$CW_i = CW_n + 2 * (N_C^i + N_{BC}^i) + \lfloor 2 * \frac{N_{AP}^i}{N-2} \rfloor \tag{3.19}$$

$$CW_{AP} = CW_n + \lfloor 2 * \sum_{h=1}^{N_C^{AP}} \frac{N_{AP}^h}{N-2} \rfloor \tag{3.20}$$

3.3.3 Throughput optimization

We want to maximize the total throughput of the whole network by choosing a optimum value of CW_n. In [1], Bianchi formulates the quantity that has to be maximized for a IEEE 802.11 network using the original DCF and without considering the capture effect. According to the different analytical results from part III and IV, we can modify his equation to make it correspond to our mechanism :

$$S = \frac{\sum_{i=1}^{N} P_S^i}{1 - \prod_{i=1}^{N}(1 - P_0^i)} * \frac{1}{\frac{(1-\prod_{i=1}^{N}(1-P_0^i))}{\prod_{i=1}^{N}(1-P_0^i))} + T_C\sigma} \tag{3.21}$$

where $T_C\sigma$ is the duration of a collision measured in slot time units σ. Based on our mechanism, each stations knows the capture effect relationships of the whole network and can find the optimum CW_n which maximizes the quantity S and then the total throughput of the network.

CHAPTER 4

GSR WITH BOTH CAPTURE EFFECT AND HIDDEN NODES

In this chapter, we will consider 802.11af networks with capture effect and hidden nodes. We enable for all stations the RST/CTS frame exchange to reduce the cost of collisions. Our main goals are the distributed detection of the capture effect relationships and the hidden node relationships by the whole network. We want all the stations to have the same understanding of the capture effect and hidden nodes relationships among stations.

4.1 Detection mechanism of the capture effect relationships in IEEE 802.11af networks with hidden nodes.

In chapter 3, we introduced a distributed detection mechanism of the capture effect relationships in IEEE 802.11af networks without hidden nodes and without the RTS/CTS frame exchange. Now, we take in consideration the hidden nodes and the previous approach cannot be considered. Indeed, when a station is captured its retransmission is not safe any more in an environment with hidden nodes. For instance, as illustrated in Fig. 11, if station B is captured by station A and station B is hidden to station C, then there is a probability that station C also transmits its RTS during Bs retransmission.

This is a reason why we need a safe space to be sure of a successful retransmission and we bring these new modifications of the DCF :

- every time a station access the channel, it reserves the channel for two consecutive transmissions by setting the duration of its RTS to D1= 2*dataLength+CTS+RTS+5*SIFS+DIFS+1
- if the first transmission of a station is successful, its does not start to transmit its

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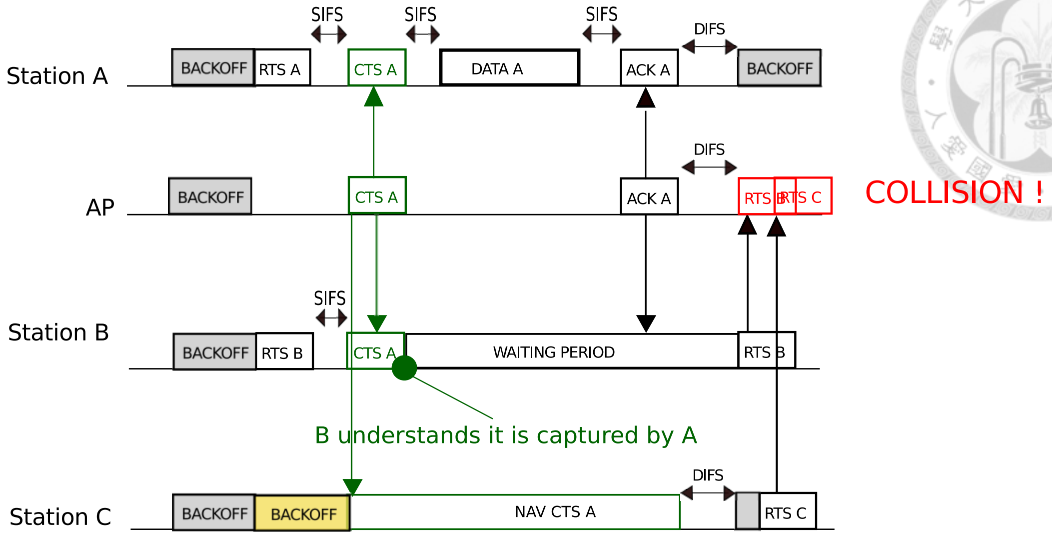

Figure 11: Previous mechanism applied to networks with hidden nodes

RTS for the second transmission but instead it waits for a timeout time T1 equal to RTS+SIFS+1 = 23 slots. After this timeout, the station directly transmits its data (no RTS/CTS exchange).

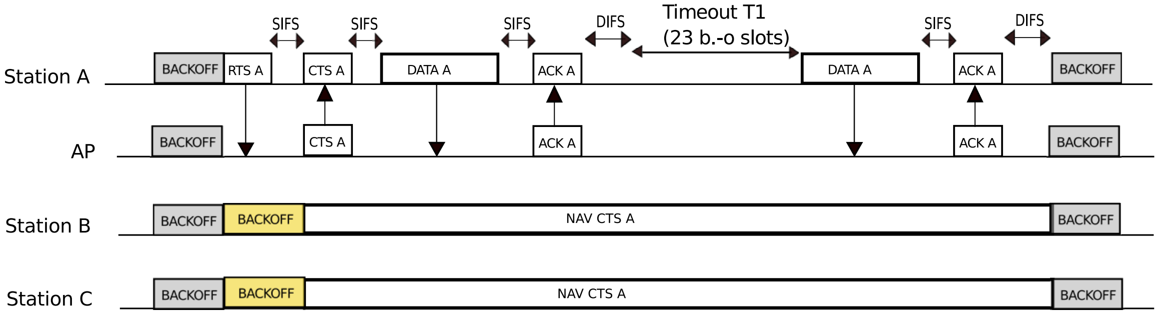

Figure 12: Creation of a safe space for retransmissions

Our idea is simple, every time a station attempts a transmission it will reserve the channel for two transmissions. Then, if the first transmission of a station is successful, the other stations will not try to transmit during its second transmission and that transmission is assured to be successful. The timeout T1, gives an available space for a station that has just been captured to transmit its RTS and receive the CTS from the AP.

We take a simple example, as illustrated in Fig. 13, where station A captures station B and station C is hidden to B. Station A and B send their RTS at the same time and AP answers with a CTS addressed to A because A captures B:

- from As perspective : its RTS transmission is successful and so it can start transmitting
- from Bs perspective : it receives a CTS addressed to A so it understands it has been captured by A
- from Cs perspective : it receives a CTS with a duration time set to D1, so it sets its NAV to this duration time

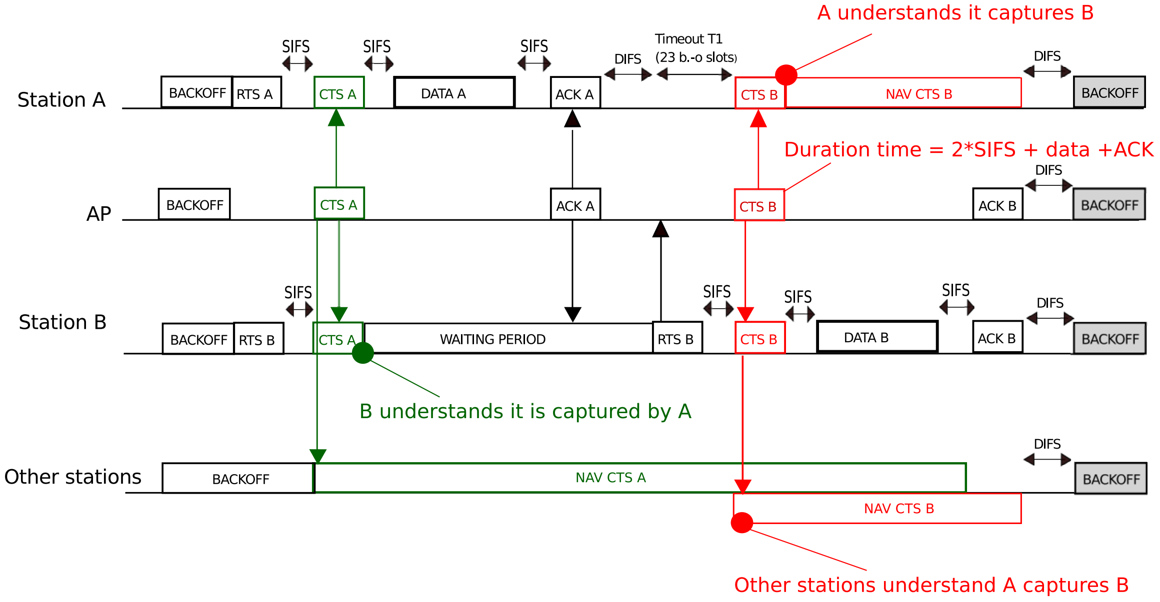

Figure 13: Capture effect detection mechanism

At this time point, station B is the only one to know it is captured by A and we want it to pass the information to the other stations. To do that, we force station B to transmit again one time after the reception of the ACK to A. This protocol is similar to the previous mechanism but this time B transmits a RTS with the duration time set to one transmission. The AP is going to decode this RTS and answer with a CTS. This CTS which has duration time set to D2=2*SIFS+dataLength will inform the whole network as follows:

- from As perspective : it decodes a CTS with a duration time set to D2 during its timeout T1. Then station A understands it has captured station B and sets its NAV to D2.

- from Bs perspective : its RTS transmission is successful and so it can start transmitting.
- from Cs perspective : it receives a CTS addressed to station B with a duration time set to D2 while its NAV has already been set to a duration time D1. The value of D2 is bigger than the remaining time of D1, so station C sets a new NAV with a new duration time D2. This changement of NAV from CTS A/D1 to CTS B/D2 makes station C understand that station A captures station B.

With this new mechanism, adapted to networks with hidden nodes, every station has the same understanding of the captured effect relationships of the network. We now want the same result with the detection of the hidden nodes.

4.2 Detection mechanism of the hidden node relationships in IEEE 802.11af networks.

4.2.1 Detection of hidden nodes of a station by itself

A station can easily understand if it is hidden to another station or not by analyzing the header frames it receives on the channel. As illustrated in Fig. 14, if station B can decode the RTS and the header of data frames from station A, then station B concludes it is not hidden to A. On the contrary, as illustrated in Fig. 15, if station B cannot decode the RTS and the header of data frames from station A, but just decodes the CTS and ACK frame addressed to station A, then station B concludes it is hidden to A and vice-versa.

4.2.2 Detection of hidden nodes of a station by the whole network

As far, no works have been done to achieve that kind of distributed detection for the hidden node problem. By this kind of detection, we mean that the whole network understands by itself an hidden node relation. For instance, in Shi-huas thesis, a station detect only its own hidden nodes, but not the ones of other stations. To achieve this detection, we use the timing properties of IEEE 802.11af networks. We define two periods as illustrated in Fig. 16, where station B is hidden to station A while station C is not hidden to station A.

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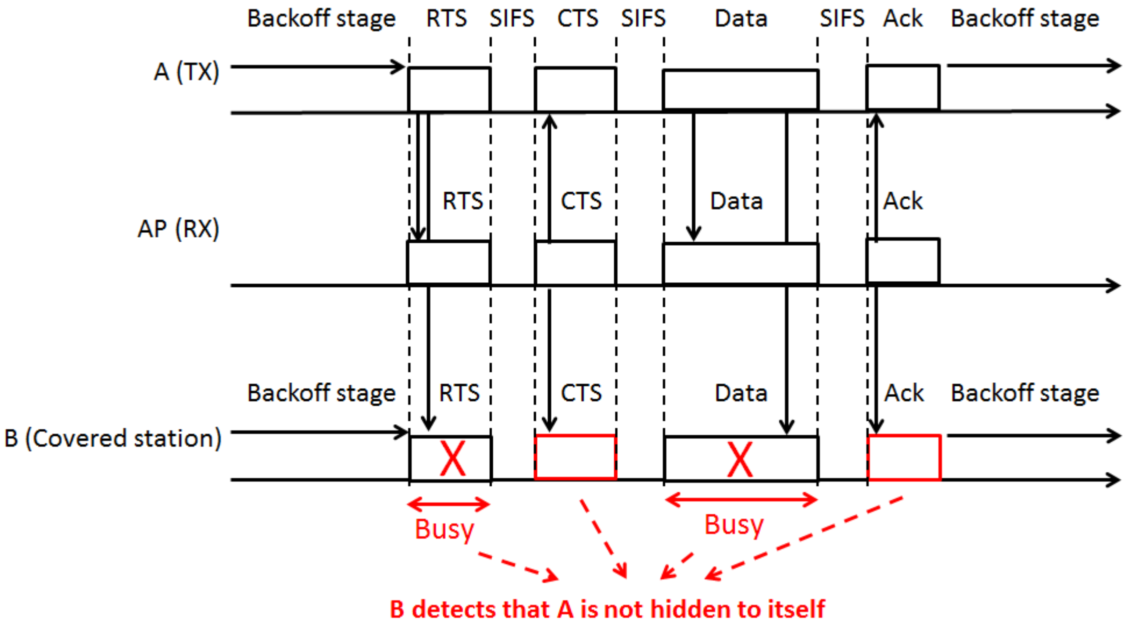

Figure 14: B no hidden

The first period is called hidden period (HP). When a station attempts a transmission, it first sends a RTS frame and then waits a SIFS time for the CTS response. If a *station i*attempt a transmission and is hidden to *station j* therefore *station j* will sense the channel idle until the reception of the CTS frame for station i. The HP represent this whole period, equal to RTS+SIFS, the channel is idle for *station j* instead of being busy because of the hidden node relationship between i and j. In Fig. 16, In the IEEE 802.11af standard, a RTS transmission time with the lowest data rate is 408us and a SIFS time is 120us. As a consequence, an HP is 408us+120us=528us=22 backoff slots, where the backoff slot length is 24 us. The second period is called collision period (CP). If a station attempts a RTS frame transmission while one of its hidden station is already transmitting a RTS frame, a collision of RTS frame happens. If there is no capture effect, then the AP cannot decode any frames and the both RTS transmissions failed. We define CP as the possible collision period between two hidden stations, as illustrated in figure. Therefore, a CP is equal to and RTS transmission time and in the IEEE 802.11 standard, CP is 408us=17 backoff slots.

Between the end of these two periods, there is an interesting gap of 5 backoff slots. Indeed, if station A first transmits its RTS and station B starts transmitting its RTS in the

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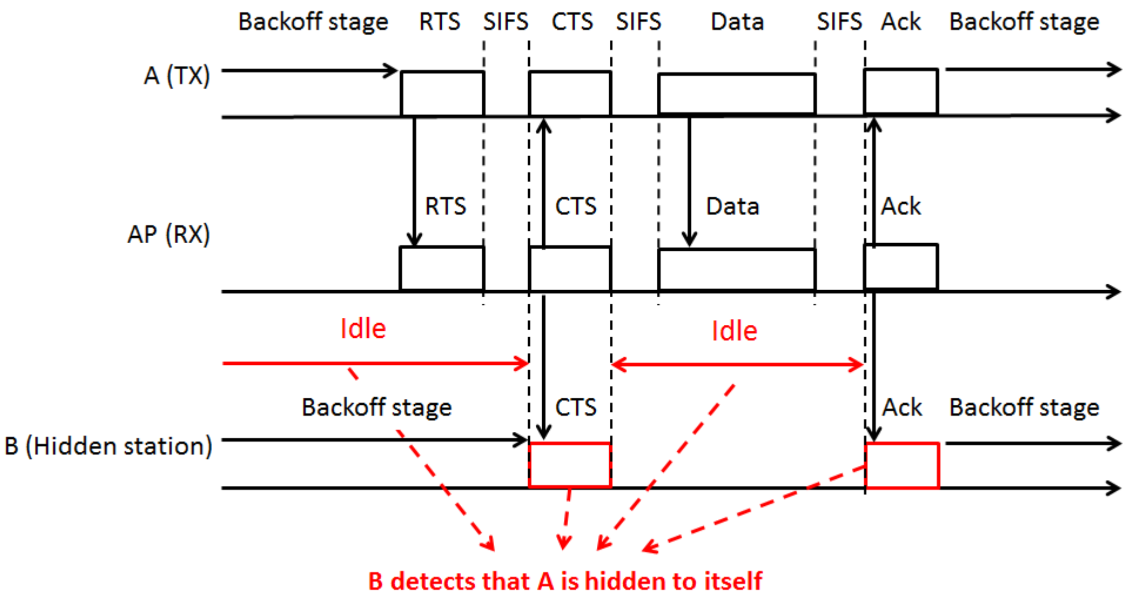

Figure 15: B hidden

NCP of A , the transmission of A is still successful. The transmission of B does not have any effect on As. A receives a CTS and transmits its data and waits for an ACK from the AP. The AP sends an ACK to A and if B can hear this ACK, then B can understand that is it hidden to A. We are going to use this event as the key idea of our hidden node detection.

We take a simple network, where A and B are just hidden to each other but C is not hidden to A and B. A is the first station to transmit. During the transmission of its RTS, there is no collision so the AP can perfectly decode it and starts switching to the receiver mode during the first slot after the RTS reception. But station B, which is hidden to A, starts sending its RTS during the SIFS waiting time of station A. Then the AP has already switched from receiver mode to transmitter mode and cannot hear this RTS from B. Station B ends transmitting its RTS and start waiting for a SIFS time. At the same time, the AP has sent a CTS to station A, announcing that A can send its data. Station B cannot decode this CTS because it did not have the time to pass in receiver mode and so will not receive an CTS. Then,we introduce a new timeout T1, equal to 2*SIFS+dataLength , to allow station B to wait for the ACK addressed to station A and then understand it has transmitted in the NCP period of this station.

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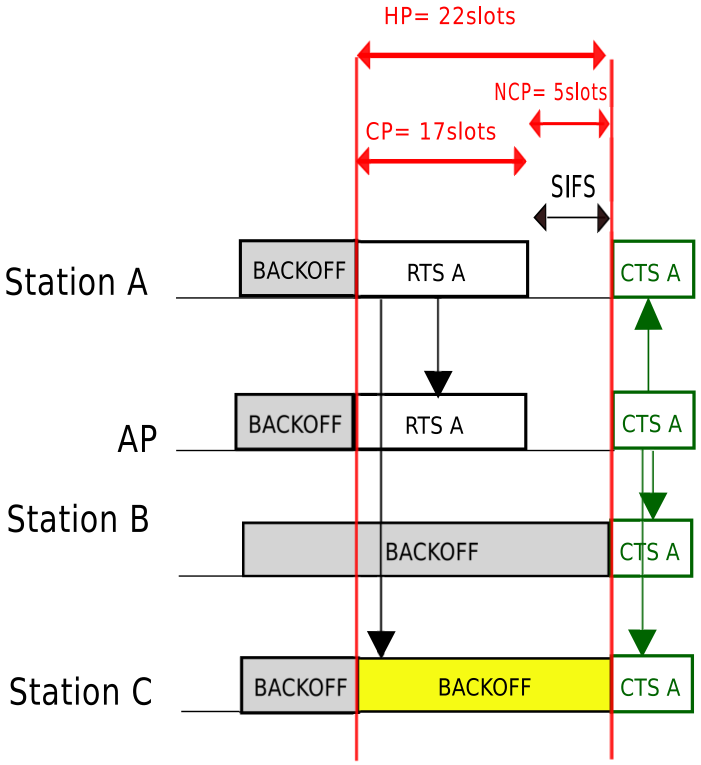

Figure 16: Hidden periods

As a matter of fact, if station B sends a RTS but does not receive its CTS frame after SIFS + 1 time slot, then station B starts counting down a timeout. If during this timeout the station decodes an ACK frame addressed to a station A, then station B understands it is hidden to station A and has transmitted its RTS the NCP period of station A.

Now, station B is the only one to know this information and we want it to inform the whole network. If station B transmits again one time, the other stations will understand a capture effect relationship as we design for the capture effect detection mechanism. To make a difference, we force station B to transmit again two times : the first time with the RTS/CTS mechanism and the second time by sending its data directly. Then the duration time in its RTS will be unique and equal to D3=2*dataLength+ACK+DIFS+3*SIFS. By doing this, station B will inform the whole network of its hidden node relationship with A as follows:

- from As perspective : the first transmission of station A is successful and station A starts counting down the timeout T2. Then, it decodes a CTS addressed to station

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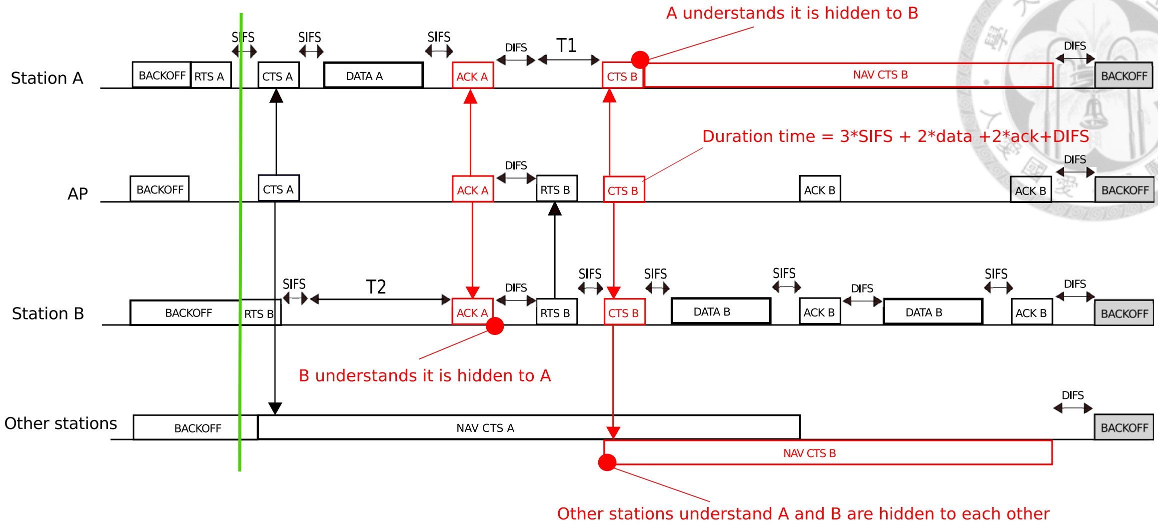

Figure 17: Both issue: detection of the hidden node relationship

B with the duration time set to D3 . So, station A concludes it is hidden to B and sets its NAV.

- from other stations perspective : they decode the CTS addressed to station A and sets their NAV to the CTS As duration time. But, during this NAV, they decode a new CTS addressed to station B with a unique duration time set to D3 . So, they understand station B is hidden to station A due to this specific duration time and they set their NAV to the CTS Bs duration time.

4.2.3 Special scenario : station A and B are hidden and station A captures station B

In this scenario, we separate the capture effect and the hidden node informations as if they were independent. The whole network will be informed of these two relations in separated ways and at different moments, depending on the circumstances of the collision between A and B.

4.2.3.1 detection of the hidden node relationship

The collision between station A and B leads to the detection of their hidden node relationship if station A is the first station to transmit and station B transmits in the HP of station A, at least one slot after As transmission starts. As a matter of fact, in these circumstances, B is too late to decode the CTS addressed to A. As shown in Fig. 18 , station B starts the timeout T2, receives the ACK addressed to A and then transmits two times. This double transmission informs the whole network that A and B are hidden to each other.

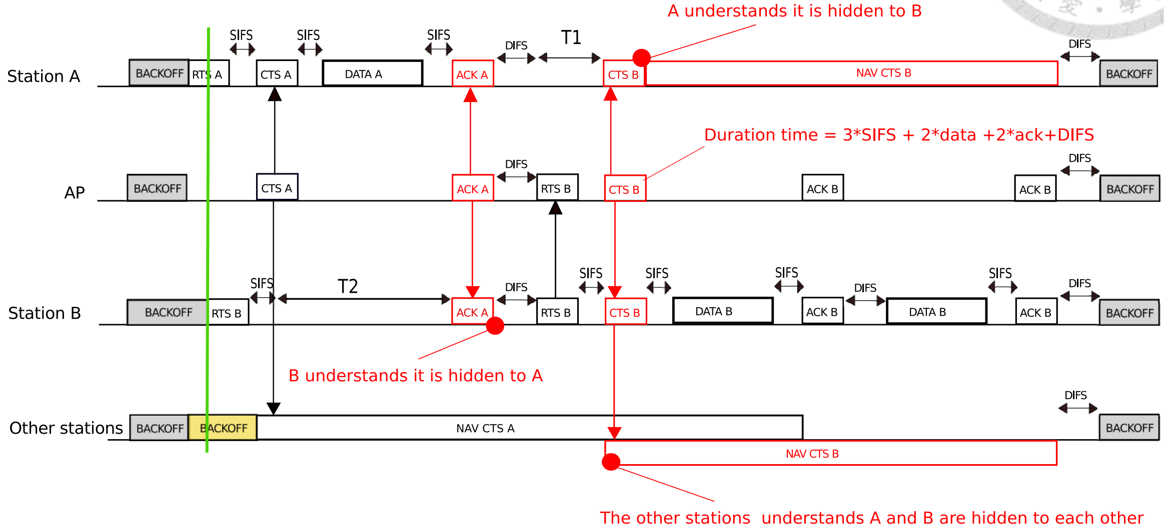

Figure 18: Both issue: detection of the hidden node relationship

4.2.3.2 detection of the capture effect relationship

The collision between station A and B leads to the detection of their capture effect relationship if station B is the first station to transmit and station A transmit in the HP of station B, at least one slot after Bs transmission start, or if A and B transmit at the same time. As a matter of fact, in these circumstances, B can decode the CTS addressed to A. As shown in Fig. 19 , station B starts the timeout T1 and receives the CTS addressed to A during the 17 first slots of this timeout. Then station B understands it has been captured by A and transmits one time to inform the whole network of this relation.

4.2.4 Record of the capture effect and hidden nodes infromations

To conclude, during the detection part, a station records the relationships of every stations of its network into three matrix :

- Hidden matrix (HM) stores the hidden information of the stations. The size of HM is N × N, where N is the number of total stations in the BSS. The element (i,j) of HM represents the hidden relation of station i and station j:

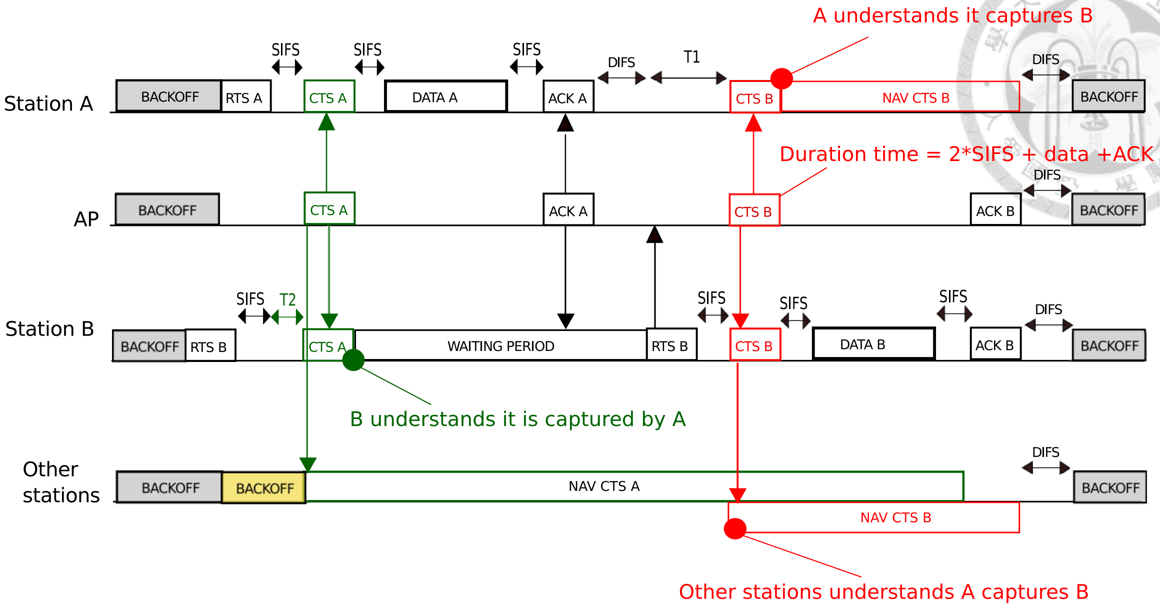

Figure 19: Both issue: detection of the capture effect relationship

HM(i,j)=1, if station i and station j are hidden to each other

HM(i,j)=0, if station i and station j are not hidden to each other

Therefore, HM must be a symmetric matrix

- Capture matrix (CM) stores the capture information of the stations. The size of CM is N × N, same as HM. The element (i,j) of CM represents the capture relation of station i and station j:

CM(i,j)=1, if station i captures station j

CM(i,j)=0, if station i do not capture station j

With these two matrix, every station can now compute its CW by taking in consideration the capture effect and hidden node relationships of the whole network.

4.3 Computation of the contention window

4.3.1 Markov Model

Once the devices know the capture effect and hidden node relationships among each others, they have to choose a contention window based on this. In order to simplify the

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protocol, devices do not increment their CW size as in original DCF and have a fixed CW. We establish a Markov chain in Fig. 20 of our protocol inspiring by [1]. and that reflects the main modification announced in part IV. to calculate the CW for each devices.

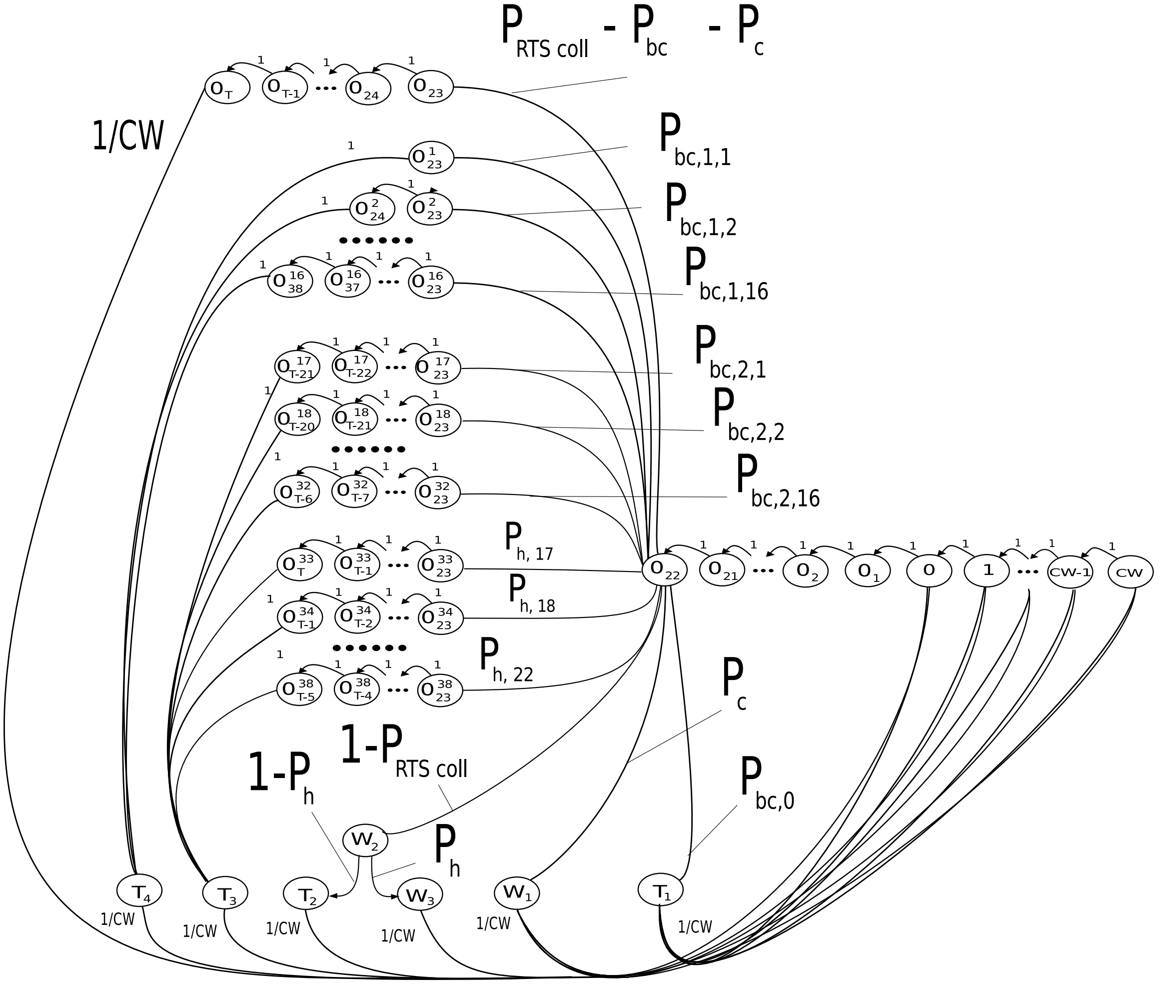

Figure 20: Markov chain of the new protocol

The different states of our Markov chain are described below:

- O : The device attempts a transmission bys ending an RTS.
- W_1 : the station captures another station during its first transmission. After itreceived a CTS during its T1 with the time duration set to D2 .Then this station has to wait a D2 time before counting down its backoff again. (capture effect detection).

- W_2 : the station transmit its RTS without collision. Then it waits a T1 timeout.
- W_3 :This stations received a CTS during its T1 with the time duration set to D3 .Then this station has to wait a D3 time before counting down its backoff again (hidden node detection)
- T_1 : this station has been captured by another station while they transmitted their RTS at the same time. Now this station is going to retransmit one time (capture effect detection).
- T_2 : the station does not receive any CTS during T1. Then, the station directly transmits its data.
- T_3 : the station receives an ACK addressed to another station during the timemout T2 and now transmits two times (hidden node detection)
- T_4 : the station receives a CTS addressed to another station during the first 17 slots of the timemout T2 and now transmits one time (capture effectdetection)

The Markov Process of Fig. 20 for a station i is governed by the following transition probabilities:

$$\begin{cases} P(k/k+1) = 1\ , \quad k \in [0, CW-1] \\ P(0_i/0_{i+1}) = 1\ , \quad i \in [0, 22] \\ P(W_1/0) = P_{c,(0,16)}\ , \\ P(W_2/0) = P_{RTScoll}\ , \\ P(W_3/W_2) = P_{hidd}\ , \\ P(W_3/W_2) = P_{hidd}\ , \\ P(T_1/0) = P_{bc,0}\ , \\ P(T_2/W_2) = 1 - P_{hidd}\ , \\ P(0_{23}^{k}/0_{22}) = P_{bc,1,k}\ , \quad k \in [1, 16] \\ P(0_{23}^{k+16}/0_{22}) = P_{bc,2,k}\ , \quad k \in [1, 16] \\ P(0_{23}^{k+32}/0_{22}) = P_{hidd,k+16}\ , \quad k \in [1, 16] \\ P(0_23/0_22) = P_{RTScoll} - P_{bc} - P_c\ , \end{cases} \tag{4.1}$$

The different probabilities that appear in the Markov chain can now be defined and simplified considering (2) :

- $P^i_{becapt,0}$ is the probability that *station i* attempts a transmission at the same slot that another station and is captured by this station

  $$P^i_{bc} = b^i_0 * (\sum_{j=1}^{N^i_{BC}} b^j_0) \prod_{h=1}^{N-2} (1 - b^h_0) \tag{4.2}$$

  where $N_B C^i$ is the total number of stations that *station i* is captured by captures.

- P^i_{bc} is the probability that *station i* collides with another station during its CP period and captures this stations:

  $$P^i_c = b^i_0 * (\sum_{j=1}^{N^i_C} b^j_0) \prod_{h=1}^{N-2} (1 - b^h_0) + b^i_0 * (\sum_{j=1}^{N^i_{CH}} 15 * b^j_0) \prod_{h=1}^{N-2} (1 - b^h_0) \tag{4.3}$$

  where N^i_C is the total number of stations that *station i* captures and N^i_{CH} the total number of stations that *station i* captures and *station i* is hidden to at the same time.

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- $P^i_{RTScoll}$ is the probability that *station i* collides with another station during its CP period :

$$P^i_{RTScoll} = b^i_0 * (\sum_{j=1}^{N-1} b^j_0) \prod_{h=1}^{N-2} (1 - b^h_0) + b^i_0 * (\sum_{j=1}^{N^i_H} \sum_{k=1}^{16} b^j_k) \prod_{h=1}^{N-2} (1 - b^h_0) \quad (4.4)$$

where N^i_H is the total number of stations which are hidden to *station i*.

- P^i_{hidd} is the probability that *station i* transmits its RTS and a hidden station transmits within its NCP period:

$$P^i_{hidd} = b^i_0 * (\sum_{j=1}^{N^i_H} \sum_{k=17}^{22} b^j_k) \prod_{h=1}^{N-2} (1 - b^h_0) \quad (4.5)$$

- $P^i_{bc,1,k}$ is the probability that *station i* transmits first its RTS and a hidden station starts transmitting within O_k state and captures it:

$$P^i_{bc,1,k} = b^i_0 * (\sum_{j=1}^{N^i_{BCH}} b^j_k) \prod_{h=1}^{N-2} (1 - b^h_0) \quad (4.6)$$

- $P^i_{bc,2,k}$ is the probability that *station i* transmits its RTS in second position during the state O_k of a hidden sation and is captured by this station :

$$P^i_{bc,2,k} = b^i_0 * (\sum_{j=1}^{N^i_{BCH}} b^j_k) \prod_{h=1}^{N-2} (1 - b^h_0) \quad (4.7)$$

- $P^i_{hidd,k}$ is the probability that *station i* transmits its RTS in the NCP perdiod of a hidden node and within the stateO_k of this hidden node:

$$P^i_{hidd,k} = b^i_0 * (\sum_{j=1}^{N^i_{BCH}} b^j_k) \prod_{h=1}^{N-2} (1 - b^h_0) \quad (4.8)$$

- P^i_{bc} is the probability that *station i* is captured during its transmission:

$$P^i_{bc} = P^i_{bc,0} + \sum_{k=1}^{16} (P^i_{bc,1,1} + P^i_{bc,2,1}) \quad (4.9)$$

We now want to obtain a closed-form solution for our new protocol Markov chain. The first step is to express all the steady state probabilities as a function of b_0:

$$
\begin{cases}
b_{0_i} = b_0 \ , \quad i \in [0, 22] \\
b_{0_i} = (P_{RTScoll} - P_{bc} - Pc) * b_0 \ , \quad i \in [23, T2] \\
b_{0_i^j} = (P_{bc,1,j}) * b_0 \ , \quad i \in [23, 22+j] \quad j \in [1, 16] \\
b_{0_i^{j+16}} = (P_{bc,2,j}) * b_0 \ , \quad i \in [23, T-22+j] \quad j \in [1, 16] \\
b_{0_i^{j+16}} = (P_{h,j}) * b_0 \ , \quad i \in [23, T-17+j] \quad j \in [17, 22] \\
b_{T_1} = P_{bc,0} * b_0 \ , \\
b_{W_1} = P_c * b_0 \ , \\
b_{W_2} = (1 - P_{RTScoll}) * b_0 \ , \\
b_{W_3} = P_h * (1 - P_{RTScoll}) * b_0 \ , \\
b_{T_2} = (1 - P_h) * (1 - P_{RTScoll}) * b_0 \ , \\
b_{T_3} = \sum_{i=17}^{22} P_{h,i} * b_0 + \sum_{i=1}^{16} P_{bc,2,i} * b_0 \ , \\
b_{T_4} = \sum_{i=1}^{16} P_{bc,1,i} * b_0 \ ,
\end{cases}
\tag{4.10}
$$

The other stationary probabilities for any $k \in [0, CW]$ follow by resorting to the state transition diagram:

$$
b_k^i = \frac{CW_i - k}{CW_i}
\begin{cases}
(1 - P_{RTScoll})/CW * b_0^i \\
+P_c^i/CW * b_0 \\
+(P_{bc,0} + \sum_{i=1}^{16} P_{bc,1,i} + \sum_{i=1}^{16} P_{bc,2,i})/CW * b_0 \\
+P_{RTScoll} - P_{bc} + P_c/CW * b_0
\end{cases}
\tag{4.11}
$$

The normalization condition imposes:

$$
\begin{aligned}
1 = \sum_{i=1}^{22} b_{0_i} + \sum_{i=23}^{T} b_{0_i} + \sum_{j=17}^{22} \sum_{i=23}^{T-17+j} b_{0_i^{j+16}} + \sum_{j=1}^{16} \sum_{i=23}^{T-22+j} b_{0_i^{j+16}} \\
\sum_{j=1}^{16} \sum_{i=23}^{22+j} b_{0_i^j} + b_{0_{T_1}} + b_{0_{W_1}} + b_{0_{W_3}} + b_{0_{W_2}} + b_{0_{T_2}} + b_{0_{T_3}} + b_{0_{T_4}} + \sum_{k=1}^{CW} b_k^i
\end{aligned}
\tag{4.12}
$$

By using this equation above, we can expressed the probability b_0 for every *station* i of the network:

$$
b_0^i \simeq \frac{2}{CW_i + 43 + 2 * (P_{RTScoll} - P_{bc}^i - Pc^i)} \forall i \in N
\tag{4.13}
$$

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Now that we have the expression of b_0 for each stations, we can compute que CWs to achieve STC fairness.

4.3.2 STC fairness

The STC is defined as the count of successful transmission of a station for a limited period of time. If we define P_S^i, as the probability of successful transmission of a *station i* then achieving STC fairness leads to the same P_S for all the station of the network. This probability depends on the capture effect and hidden nodes relationships of a station:

- if a *station i* does not have any capture effect or hidden nodes reationships, ie. $\forall j \in N,\ HM(i,j) = CM(i,j) = BCM(i,j) = 0$ then

$$P_S^i = 2 * b_0^i * \prod_{j=1, j\neq i}^{N-1} (1 - b_0^j) \tag{4.14}$$

- if a *station i* does not have any capture effect relationships but have hidden nodes , ie. $\forall j \in N,\ CM(i,j) = BCM(i,j) = 0$ then

$$\begin{aligned} P_S^i &= 2 * b_0^i * \textstyle\prod_{j=1,j\neq i}^{N-1}(1-b_0^j) * \prod_{h=1}^{N_H^i}\prod_{k=1}^{22}(1-b_k^h) \\ &+ b_0^i * \textstyle\sum_{h=1}^{N_H}\sum_{k=17}^{22} b_k^h \prod_{j=1,j\neq h}^{N-2}(1-b_0^j) \\ &+ 2 * b_0^i \textstyle\sum_{h=1}^{N_H^i} 6 * b_0^h * \prod_{j=1,j\neq h}^{N-2}(1-b_0^j) \end{aligned} \tag{4.15}$$

- if a *station i* does not have any hidden nodes but have capture effect relationships , ie. $\forall j \in N,\ HM(i,j) = 0$ then

$$\begin{aligned} P_S^i &= 2 * b_0^i * \textstyle\prod_{j=1,j\neq i}^{N-1}(1-b_0^j) \\ &+ b_0^i * \textstyle\sum_{h=1}^{N_C+N_{BC}} b_0^h \prod_{j=1,j\neq i}^{N-2}(1-b_0^j) \\ &+ b_0^i * \textstyle\sum_{h=1}^{N_{HC}^i+N_{BCH}^i}\sum_{k=1}^{16} b_0^h \prod_{j=1,j\neq h}^{N-2}(1-b_0^j) \\ &+ 2 * b_0^i * \textstyle\sum_{h=1}^{N_{BCH}^i} 16 * b_0^h \prod_{j=1,j\neq h}^{N-2}(1-b_0^j) \end{aligned} \tag{4.16}$$

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- if a *station* i has both capture effect and hidden node relationships, then

$$\begin{aligned}
&P_S^i = 2 * b_0^i * \textstyle\prod_{j=1,j\neq i}^{N-1}(1-b_0^j)\prod_{h=1}^{N_H^i}\prod_{k=1}^{22}(1-b_k^h)\\
&+b_0^i * \textstyle\sum_{h=1}^{N_H^i}\sum_{k=17}^{22} b_k^h \prod_{j=1,j\neq h}^{N-2}(1-b_0^j)\\
&+2 * b_0^i \textstyle\sum_{h=1}^{N_H^i} 6 * b_0^h * \prod_{j=1,j\neq h}^{N-2}(1-b_0^j)\\
&+b_0^i * \textstyle\sum_{h=1}^{N_C^i+N_{BC}^i} b_0^h \prod_{j=1,j\neq h}^{N-2}(1-b_0^j)\\
&+b_0^i * \textstyle\sum_{h=1}^{N_{HC}^i+N_{BCH}^i}\sum_{k=1}^{16} b_0^h \prod_{j=1,j\neq h}^{N-2}(1-b_0^j)\\
&+2 * b_0^i * \textstyle\sum_{h=1}^{N_{BCH}^i} 16 * b_0^h \prod_{j=1,j\neq h}^{N-2}(1-b_0^j)
\end{aligned} \tag{4.17}$$

With the matrixes $HM(i,j), CM(i,j) and BCM(i,j)$ and the equations above, every station has the expression of its probability of successful transmission and the one of the other stations of the network. Therefore, every station has a system of equation composed by N probability of successful transmissions.

The STC fairness in a network $\{N\}$ is defined by:

$$P_S^i = P_S^j \quad \forall i,j \in \{N\} \tag{4.18}$$

We consider now a station *neutral* called n that has no capture effect and hidden nodes relationships, ie. this station does not capture any stations ($\forall j \in N,\ CM(i,j) = 0$), is not captured by any other stations ($\forall j \in N,\ BCM(i,j) = 0$ and does not have any hidden nodes ($\forall j \in [1N],\ HM(i,j) = 0$). We assume this station has a fixed contention window called CW_n that we will be able to modify later to achieve other enhancements as power efficiency or total STC maximization. To achieve the STC fairness we need :

$$P_S^i = P_S^n \quad \forall i \in \{N\} \tag{4.19}$$

We want to express the probability $P_S^i \forall i \in N$ depending on the value of CW_n and the relationship matrixes.

- if a *station* i does not have any capture effect or hidden nodes relationships, i.e.

$\forall j \in N,\ HM(i,j) = CM(i,j) = BCM(i,j) = 0$ then

$$\begin{aligned}
&P_S^n = P_S^i \\
&2 * b_0^n * \textstyle\prod_{j=1,j\neq n}^{N-1}(1-b_0^j) = 2 * b_0^i * \prod_{j=1,j\neq i}^{N-1}(1-b_0^j) \\
&\Leftrightarrow \\
&\tfrac{(1-b_0^i)}{(b_0^i} = \tfrac{1-b_0^n}{b_0^n} B_0^i = B_0^n
\end{aligned} \tag{4.20}$$

- if a *station i* does not have any capture effect relationships but have hidden nodes , i.e. $\forall j \in N,\ CM(i,j) = BCM(i,j) = 0$ then

$$\begin{aligned}
&P_S^n = P_S^i \\
&2 * b_0^n * \textstyle\prod_{j=1,j\neq n}^{N-1}(1-b_0^j) = 2 * b_0^i * \prod_{j=1,j\neq i}^{N-1}(1-b_0^j) * \prod_{h=1}^{N_H^i}\prod_{k=1}^{22}(1-b_k^h) \\
&+b_0^i * \textstyle\sum_{h=1}^{N_H}\sum_{k=17}^{22} b_k^h \prod_{j=1,j\neq h}^{N-2}(1-b_0^j) \\
&+2 * b_0^i \textstyle\sum_{h=1}^{N_H^i} 6 * b_0^h * \prod_{j=1,j\neq h}^{N-2}(1-b_0^j) \\
&\tfrac{(1-b_0^i)}{(b_0^i} = \tfrac{1-b_0^n}{2*b_0^n}(2\textstyle\prod_{h=1}^{N_H^i}\prod_{k=1}^{22}(1-b_k^h) + \sum_{h=1}^{N_H}\sum_{k=17}^{22} b_k^h + 2` * \sum_{h=1}^{N_H^i} 6 * \tfrac{b_0^h}{1-b_0^h}
\end{aligned} \tag{4.21}$$

- if a *station i* does not have any hidden nodes but have capture effect relationships , i.e. $\forall j \in N,\ HM(i,j) = 0$ then

$$\begin{aligned}
&P_S^n = P_S^i \\
&\Leftrightarrow \\
&2 * b_0^n * \textstyle\prod_{j=1,j\neq n}^{N-1}(1-b_0^j) = 2 * b_0^i \prod_{j=1,j\neq i}^{N-1}(1-b_0^j) \\
&+b_0^i * \textstyle\sum_{h=1}^{N_C+N_{BC}} b_0^h \prod_{j=1,j\neq i}^{N-2}(1-b_0^j) \\
&+b_0^i * \textstyle\sum_{h=1}^{N_{HC}^i+N_{BCH}^i}\sum_{k=1}^{16} b_0^h \prod_{j=1,j\neq h}^{N-2}(1-b_0^j) \\
&+2 * b_0^i * \textstyle\sum_{h=1}^{N_{BCH}^i} 16 * b_0^h \prod_{j=1,j\neq h}^{N-2}(1-b_0^j) \\
&\Leftrightarrow \\
&\tfrac{(1-b_0^i)}{(b_0^i} = \tfrac{(1-b_0^n)}{2*b_0^n}(2 + \textstyle\sum_{h=1}^{N_C+N_{BC}} \tfrac{b_0^h}{1-b_0^h})
\end{aligned} \tag{4.22}$$

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- if a *station i* has both capture effect and hidden node relationships, then

$$\begin{aligned}
&P_S^n = P_S^i \\
&\Leftrightarrow \\
&P_S^i = 2 * b_0^i * \textstyle\prod_{j=1,j\neq i}^{N-1}(1-b_0^j)\prod_{h=1}^{N_H^i}\prod_{k=1}^{22}(1-b_k^h) \\
&+b_0^i * \textstyle\sum_{h=1}^{N_H^i}\sum_{k=17}^{22} b_k^h \prod_{j=1,j\neq h}^{N-2}(1-b_0^j) \\
&+2 * b_0^i \textstyle\sum_{h=1}^{N_H^i} 6 * b_0^h * \prod_{j=1,j\neq h}^{N-2}(1-b_0^j) \\
&+b_0^i * \textstyle\sum_{h=1}^{N_C^i+N_{BC}^i} b_0^h \prod_{j=1,j\neq h}^{N-2}(1-b_0^j) \\
&+b_0^i * \textstyle\sum_{h=1}^{N_{HC}^i+N_{BCH}^i}\sum_{k=1}^{16} b_0^h \prod_{j=1,j\neq h}^{N-2}(1-b_0^j) \\
&+2 * b_0^i * \textstyle\sum_{h=1}^{N_{BCH}^i} 16 * b_0^h \prod_{j=1,j\neq h}^{N-2}(1-b_0^j) \\
&\Leftrightarrow \\
&\tfrac{(1-b_0^i)}{(b_0^i} = \tfrac{1-b_0^n}{2*b_0^n}(2 * \textstyle\prod_{h=1}^{N_H^i}\prod_{k=1}^{22}(1-b_k^h) + \sum_{h=1}^{N_H}\sum_{k=17}^{22} b_k^h + 2` * \sum_{h=1}^{N_H^i} 6 * \tfrac{b_0^h}{1-b_0^h} \\
&+\tfrac{(1-b_0^n)}{2*b_0^n} * (\textstyle\sum_{h=1}^{N_C+N_{BC}} \tfrac{b_0^h}{1-b_0^h} + \sum_{h=1}^{N_{HC}^i+N_{BCH}^i}\sum_{k=1}^{16} \tfrac{b_0^h}{1-b_0^h} + 2 * \sum_{h=1}^{N_{BCH}^i} 16 * \tfrac{b_0^h}{1-b_0^h})
\end{aligned} \tag{4.23}$$

Now, every stations has a system composed by N equations representing relations between the b_0 of every station, depending on the relationships matrix.

$$\begin{cases}
P_S^1 = f((HM),(CM),,CW_j \forall j \in N) \\
P_S^2 = f((HM),(CM),,CW_j \forall j \in N) \\
P_S^3 = f((HM),(CM),CW_j \forall j \in N) \\
.... \\
P_S^i = f((HM),(CM),CW_j \forall j \in N) \\
... \\
P_S^{N-1} = f((HM),(CM),CW_j \forall j \in N) \\
P_S^N = f((HM),(CM),CW_j \forall j \in N)
\end{cases} \tag{4.24}$$

By using the first system of equations provided by the Markov chain, the relationships

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between the CW of every station can be established:

$$\begin{cases} CW_1 = f(CW_n, (HM), (CM), CW_j \forall j \in N) \\ CW_2 = f(CW_n, (HM), (CM), CW_j \forall j \in N) \\ CW_3 = f(CW_n, (HM), (CM), CW_j \forall j \in N) \\ .... \\ CW_i = f(CW_n, (HM), (CM), CW_j \forall j \in N) \\ ... \\ CW_{N-1} = f(CW_n, (HM), (CM), CW_j \forall j \in N) \\ CW_N = f(CW_n, (HM), (CM), CW_j \forall j \in N) \end{cases} \tag{4.25}$$

By resolving the system above, each station can calculate its optimum CW as a function of CW_n. As in Chapter III, the value of CW_n is optimized to maximize the total throughput of the network.

CHAPTER 5

SIMULATION RESULTS

In this chapter, we analyse the performance of SRM compared to the original DCF and [20]'s thesis [16]. The first metric we take in consideration in our comparison is the STC of every stations of a network. By using it we can measure the fairness of the network show the evolution of the total STC when the number of stations in the network increases . For the fairness, we use two indexes:

- the Jain's fairness index defined as

$$Jain(STC_1, STC_2, ..., STC_N) = \frac{(\sum_{i=1}^{N} STC_i)^2}{N * \sum_{i=1}^{N} STC_i^2} \tag{5.1}$$

  The result ranges from $\frac{1}{N}$(worst case) to 1 (best case), and it is maximum when all users receive the same STC.

- the Min-Max fairness index is defined as

$$MinMax(STC_1, STC_2, ..., STC_N) = \frac{min(STC_1, STC_2, ..., STC_N)}{max(STC_1, STC_2, ..., STC_N)} \tag{5.2}$$

  represents the gap between the minimum STC and the maximum STC of the stations of the same network. It is an ideal index for fairness in wireless networks.

The second analysis deals with the convergence time of the computation of the CW of a new station with the different mechanisms. We simulate the entry of a new station in a network and note the time it takes for this station to detect the capture effect and hidden node relationships of the whole network and then to compute its optimum CW.

5.1 Only the capture effect

In this section we consider a network with capture effect only and no hidden nodes. Our goal is to see if the fairness is still achieved when the number of stations gets bigger. To

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do that we take networks defined as follows: if the network has N stations then station 1 captures $\frac{N}{2} - 1$ stations.

5.1.1 STC

We record the STC of each stations for the parameters for three protocols: the original DCF, our new approach (SRM) and Shi-Hua's thesis (NFBM) [20]. For SRM and NFBM we use the simplified mechanisms addressed for networks with just capture effect. We can do the following observations according to the results of the simulations:

- for the original DCF, when the number of devices in the network increases, the STC decreases. We have the same phenomena for the Min/Max and the Jain indexes. The Min/Max index goes from 0.95 for 4 devices to 0.42 for 60 devices. Therefore, the STC fairness is not achieved by the original DCF when the network have a big number of devices and the capture effect is important. As observed with the Min/Max diagram, station 1, which captures the half of the network, will have a STC two times greater than the other stations of the network. This result confirm our observation in the introduction.

- for our new approach called SRM, when the number of devices in the network increases, the STC remains around the same value of $1.63 * 10^5$ successful transmissions. The STC fairness is also still achieved for big networks with a Min/Max value greater than 0.9 and a Jain's index equal to 1.

- for [20]'s mechanism, we have the same results as our approach, however the STC is a little greater due to the two consecutive transmissions needed by his mechanism.

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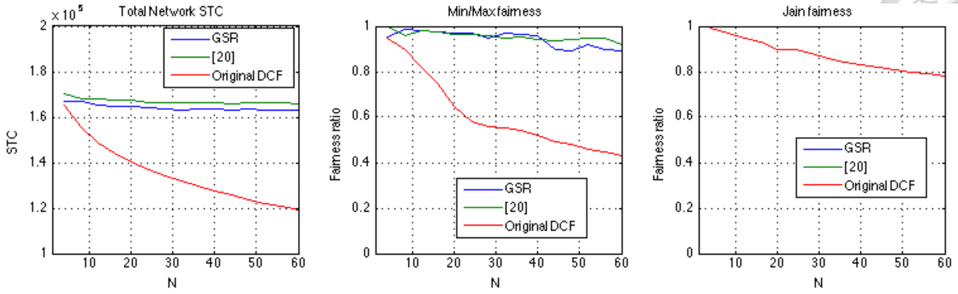

Figure 21: STC and fairness: Only the capture effect

5.1.2 Convergence

In this section we compare the detection convergence time of the SRM and NFBM mechanisms. A station enters in an established network and we measure the time it takes for this station to detect all the capture effect relationships of the network. The results are shown in Fig. 22.

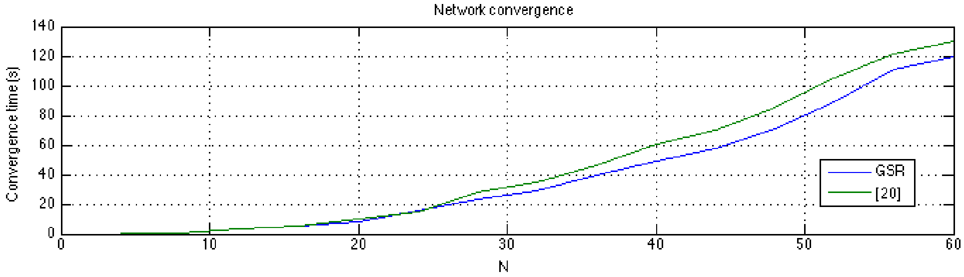

Figure 22: Convergence time: Only the capture effect

The convergence time of the both mechanisms are very closed. However, when networks are bigger than 30 stations, our approach is faster than [20]'s. This is due to the choice of the optimized CW_n. Indeed, in order to achieve a better throughput, the CW_n of NFBM is around the twice of SRM's, and so the probability of collision between stations becomes smaller than SRM. Capture effect relationships are detected when the stations involved collide, so if CW_n^{NFBM}¿CW_n^{NFBM} then the convergence time of NFBM is bigger than the one of SRM .

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5.1.3 Conclusions for capture effect only

To conlude, for networks with capture effect only, SRM and NFBM achieve around the same STC fairness when the number of stations and capture effect relationships increases. However, a compromise has to be done between the maximization of the total STC and the convergence time.

5.2 Only the hidden terminal problem

In this section we consider a network with hidden nodes only and no capture effect. Our goal is to see if the fairness is still achieved when the number of stations gets bigger. To do that we take networks defined as follows: if the network has N stations then station 1 is hidden to $\frac{N}{2} - 1$ stations.

5.2.1 STC

We record the STC of each stations for three protocols: the original DCF, our new approach (SRM), [20]'s thesis (NFBM) [20] and the original DCF with a constant CW equal to CW_n^{SRM}. In this last protocol, the exponential back-off is disabled, every station has a fixed contention window equal to the optimum CW_n of SRM. We can do the following observations according to the results of the simulations:

- for the original DCF, we can observe the degradation of the network STC and fairness when the number of hidden nodes and stations increases. In addition, the total number of collisions increases from $0.4 * 10^6$ for 4 stations to $3.5 * 10^6$ collisions.

- for the original DCF with a fixed CW, the STC keeps constant around $7.5 * 10^5$ but the fairness follows the same road as the original DCF and is really degraded. For 60 stations and 30 hidden nodes relationships, we have a Min/Max fairness index of 0.05, which is really unfair.

- for [20]'s, the STC increases when the number of stations increases and after 30 stations remains around $7.75 * 10^5$. This is confirmed by the number of failed transmissions which decreases a little. About the fairness, it goes from 1 to 0.9 according

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to the Min/Max index. So the channel remains fair for the stations touched by hidden nodes.

- for [20]'s, the STC increases when the number of stations increases and after 30 stations remains around $7.75 * 10^5$. This is confirmed by the number of failed transmissions which decreases a little. About the fairness, it goes from 1 to 0.9 according to the Min/Max index. So the channel remains fair for the stations touched by hidden nodes.

- for SRM, the STC remains constant at $8.5 * 10^5$ which is greater than the other protocols. The min/Max index goes from 1 to 0.95, so the channel is really fair even when the number of devices increases.

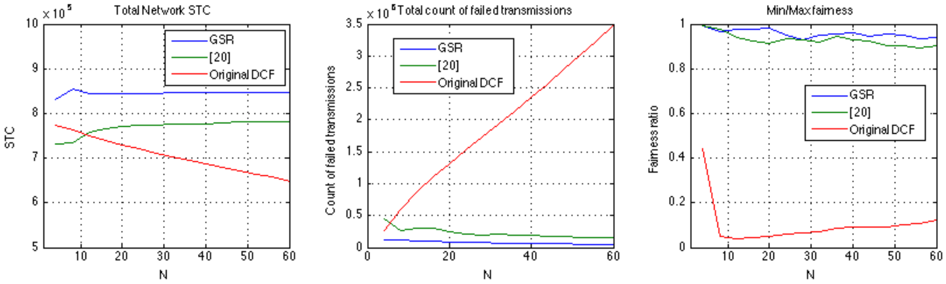

Figure 23: STC, collisions and min-max index: Only the hidden nodes problem

5.2.2 Convergence

The distributed detection of the hidden nodes is only accomplished by our mechanism, so there is no possible comparison with another protocol. The convergence detection time is presented in Fig. 24. For 60 stations and 30 hidden nodes relationships, we have a detection time of 110 s which is approximatively the same as the convergence time for the capture effect detection.

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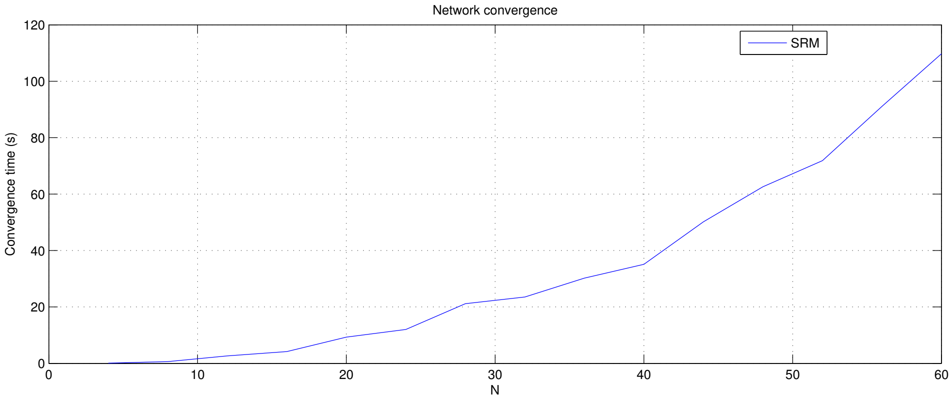

Figure 24: Convergence time: Only the hidden nodes

5.2.3 Conclusions for hidden nodes only

To conclude, our new approach achieves the best performances in terms of total STC and STC fairness for networks with only hidden nodes relationships. With SRM, the total STC remains constant and greater than the other mechanisms. Indeed, our protocol limits the collisions between stations and the number of failed transmissions. With 60 stations and 30 hidden nodes relationships, the Min/Max fairness index with SRM is around 0.95, a little bigger than [20]'s, while the original DCF is totally unfair (0.1). Regarding the convergence time, the detection of hidden nodes takes around the same time as the detection of the capture effect. In the next part we will compare the convergence time for the capture effect and hidden nodes in a network with both capture effect and hidden nodes.

5.3 Both capture effect and hidden terminal problem

In this section we consider a network with hidden nodes and capture effect. Our goal is to see if the fairness is still achieved when the number of stations and capture and hidden relations get bigger To do that we take networks defined as follows: if the network has N stations then station 1 is hidden to $\frac{N}{2} - 1$ stations and captures these stations. Then we have the same number of hidden nodes and captures effect relationships.

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5.3.1 STC

Firstly, we record the STC of the stations for networks with different number of stations and using the three following protocols : SRM, [20]'s and the original IEEE 802.11af DCF. The results are described below:

- for the orignal DCF, the network is completely unfair in terms of STC. The Min/Max and the Jain's fairness indexes are around 0.02 and 0.2 respectively. As in previous cases, the total STC drops from$8*10^5$ to $7*10^5$ when the number of devices increases but here is greater than with hidden nodes only, due to the capture effect.
- for [20]'s protocol, the total STC remains constant around $7.9*10^5$ and the fairness is approximatively achieved with a Min/Max index equal to 0.75 and a Jain's index equal to 0.98.
- our new approach (SRM) has the best performances. The STC fairness is achieved with a Min/Max index around 0.95 and the total STC, which is equal to $8.55*10^5$ is greater than the other protocols.

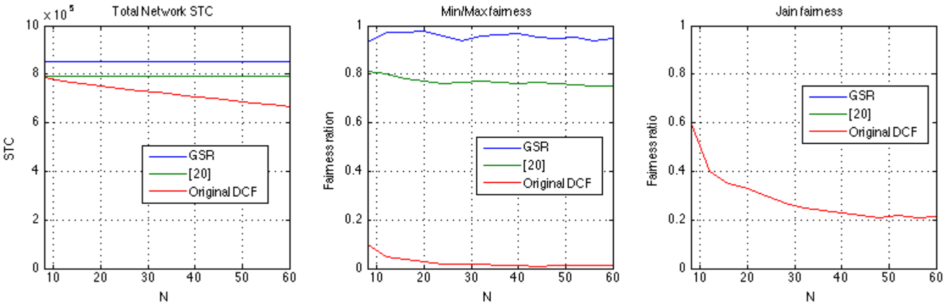

Figure 25: STC: Both capture effect and hidden nodes

5.3.2 Convergence

We now compare the detection convergence time of networks using our new approach and [20]'s. For SRM we observe the detection time for hidden nodes and the one for capture effect. As predicted, the detection for the hidden nodes takes the longest time. Indeed, the probability of transmitting in the NCP is smaller than the probability of transmitting in the CP period. For the capture effect detection, our approach and [20]'s are equivalent.

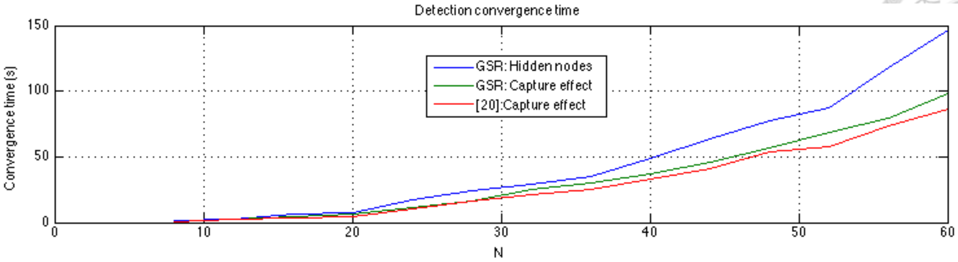

Figure 26: Convergence time: Both capture effect and hidden nodes

5.3.3 Conclusions for both capture effect and hidden nodes

In networks with both capture effect and hidden nodes, our new approach achieves STC fairness and a better total throughput than the other protocols. The convergence time for the capture effect relationships detection is mostly the same than [20]'s. However, our distributed approach of the hidden node detection takes longer.

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CHAPTER 6

CONCLUSIONS

In this thesis, we develop a fully distributed mechanism to improve fairness in IEEE 802.11af networks with both capture effect and hidden nodes.

In a first time, our new approach, called Successful Retransmission Mechanism (SRM), achieves the distributed detection of capture effect and hidden nodes relationships. The exponential back-off algorithm is disabled and every stations has a fixed contention window (CW). When a station attempts a transmission, it reserves the channel for two consecutive transmissions. During its second transmission, it lets the channel idle for a time-out T1 and, by doing this, creates a safe space for the retransmission of another device. Indeed, a station which has earlier detected a capture effect or hidden node relationship, will transmit during this time-out T1 to inform the other stations and then its transmission will be successful. This earlier detection is also ruled by another time-out T2. From the other stations perspective, a capture or hidden relationship is detected by the change of NAV to a longer one. Therefore, every station will have the same understanding of the topology of the network and record the informations in three matrices which resume all the capture effect and hidden nodes relationships. In a second time, according to these matrices, a station can compute its CW in order to achieve STC fairness. We develop a Markov model of our mechanism to elaborate the mathematical model which provides the system needed to the computation of the CW.

Our new protocol achieves more than 90% fairness in terms of STC in networks with capture effect, hidden nodes and a big number of stations. We compare SRM with the original DCF and Shi-Hua's mechanism. In all the cases, our approach provide the greatest STC to the networks, composed from 4 to 60 stations. It also achieves the same fairness as [20]'s, when the original DCF is totally unfair. We also measure the detection convergence time and it remains reasonable with an average of 150s for the hidden node detection and

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100s for the capture effect detection in network with both capture effect and hidden nodes.

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