IMPACT OF THE USERS' DISTRIBUTION ON THE IEEE 802.11A MAC PROTOCOL FAIRNESS AND PERFORMANCE

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Abstract - The IEEE 802.11a technology is rapidly being deployed offering many advantages to users. However, the MAC protocol suffers problems such as hidden nodes and capture effects, leading to degraded performance. This article investigates the impact of the users' distribution (uniform and micro-cluster) on the protocol fairness and performance.

Keywords - 802.11a, cell topology, fairness, goodput.

I. Introduction

In this paper, we exhibit by means of simulations that the 802.11a [1],[2] Medium Access Control (MAC) protocol is highly sensitive to the cell topology, leading to a spatially unfair system in terms of channel access, reservation and transmission success. As a consequence, cell users experience very different performance from each other.

A. Related Work

In the Wireless Local Access Network (WLAN) literature no analytical model of a single 802.11a cell with several users can be found and incorporating the effects of: cell topology, cell load and distribution, users' transmit modes, users' data payload size, MAC protocol, radio parameters. However, many simplified models have been developed. Bianchi [3], assuming that all users always see the channel in the same state, found that the system throughput expression was almost independent from the cell load when using the Request To Send (RTS) / Clear To Send (CTS) mechanism. In [4], a link adaptation algorithm is detailed for a single user, using an expression of the effective goodput. In [5], Chhaya and Gupta have studied the protocol behavior under realistic radio conditions such as hidden nodes, capture effects, collisions, etc... They derived a simplified throughput model resulting in a spatially unfair protocol in favor of users close to the Access Point (AP). Many other articles [6],[7] have pointed out the 802.11 MAC protocol unfairness and tried to measure it with some metrics, sometimes resulting in an enhanced MAC protocol. It is to be noted that our article deals with the infrastructure mode, where there is always an AP in the cell.

In this article, we highlight with several types of users' distributions that the repartition of the resource over the users is not spatially fair, due to the MAC protocol itself.

B. Organization

The rest of this paper is organized as follows. After introducing the context in section I, section II will briefly present the 802.11a system. Section III contains the study context. Then, section IV presents the simulation assumptions and obtained results. Finally, we conclude and present the future work.

II. 802.11a MAC protocol under Decentralized Coordination Function (DCF)

Using the 802.11 MAC protocol, a data transmission encompasses three main phases:

- *Channel Access*: After a null Backoff Counter (BC),
- *Medium Reservation*: RTS and CTS frames exchanges,
- *Data Transmission*: DATA and ACKnowledgement (ACK) frames exchanges.

A spatially fair MAC protocol should be fair in all these phases regardless of the users' geographical locations.

All our simulations make use of the infrastructure mode (always an AP) and the compulsory DCF mode. Thus, there is no central point of coordination in the cell, instead the coordination is distributed over all the STAtions (STAs) causing collisions. A collision is said to occur when either two nodes that are not hidden transmit simultaneously or when two hidden nodes transmit overlapping frames in time, resulting in none or only one packet being correctly decoded. The Carrier Sensing Multiple Access / Collision Avoidance (CSMA/CA) technique used by contending users is a random access method. Thus, there is no pre-established transmission schedule. Each STA delays its transmission start time by some random BC value (generated according to a uniform distribution) within a variable Contention Window (CW). A failure to transmit exponentially increases the CW size in order to reduce the probability that two users or more draw the same BC value, and simultaneously transmit. This minimizes collisions between multiple STAs by temporally spreading their transmission start times. The duration of these waiting periods is random, and depends on the number of contending users and the medium state around each STA.

Each STA must regularly listen to the medium to determine its state (idle, busy). Due to each STA having limited transmission range, the medium state perception is location-dependent leading to two important types of configurations with specific nodes:

- *Hidden Node*: A hidden node is within the range of the intended destination but out of range of the sender (increase in the number of collisions, significant performance degradation, unfairness in accessing the medium),
- *Capture Effect*: A receiver can receive clearly one transmission out of two simultaneous transmissions, both within its receiving range (unfair sharing of bandwidth).

To reduce the performance degradation due to hidden terminals, a medium reservation technique based on a reserve (RTS frame) and confirm (CTS frame) mechanism between the source and the destination is proposed in DCF mode. Once the medium is successfully reserved for a STA, the data frame can be transmitted with a higher chance of success. Also, when a collision occurs between several RTS frames, far less bandwidth is wasted when compared with a larger data frame collision. Thus, using the RTS/CTS mechanism is recommended when many users are contending for the medium to transmit large data frames.

III. Presentation of the Study

A. General Presentation

We refer to "cell topology" as the combination of AP and users' relative geographical locations. We modeled a fully deterministic channel (no shadowing effect), so the Received Signal Strength (RSS) is fully determined by the distance and the transmission power. Thus, the only random parameters are: users' distribution and random BC values. As shown in section II, the MAC protocol suffers collisions in accessing the shared medium due to: (1) distributed MAC scheduling (causing users to transmit simultaneously), and (2) hidden nodes.

Using the MAC protocol in DCF mode, several contending users cannot avoid collisions even whitout any hidden nodes or capture effects. A cell can only achieve maximum performance with a single user. However, the system is still fair if all the contending users equally suffer from the collisions. We simulated a scenario where the users are all grouped in a micro-cluster, to avoid hidden nodes between them.

Then, we investigated the effect of hidden nodes, capture effects and radio propagation on the medium state perception and thus on the spatial fairness of the MAC protocol. The constraints for two Mobile Terminals (MTs) to be in the same protocol state are:

1) Reach the AP with almost the same received signal level,
2) Receive almost the same average signal level from all the other users (excluding the AP).

As there is no power control in 802.11a, all the STAs use the same transmit power. Constraint 1 means that all users must be at the almost same distance from the AP, and constraint 2 means that all users must have almost the same average inter-distance with each other. We tested two different users' distributions: uniform distribution with various number of users, and micro-cluster distribution with a fixed number of users but a moving micro-cluster creating hidden nodes and capture effects in the cell. The simulation results are presented in section IV.

B. Metrics

Goodput and fairness are widely used metrics to compare MAC protocols.

1) Fairness: A MAC protocol is fair if it does not demonstrate preference for a particular user when multiple users are contending for the channel. In a spatially fair MAC protocol, all users, irrespective of their locations, should have (1) the same opportunity to access the medium (number of transmitted RTS frames), (2) the same level of success in channel reservation (same value of received CTS frames given the number of transmitted RTS frames) and (3) data transmission (same number of received ACK frames given the number of transmitted DATA frames). The fairness should be independent from: the number of STAs in the cell and their geographical locations, the user transmit mode, data size and distance to AP. To estimate the fairness of a topology we computed Jain's fairness index F_T, the standard traditional measure of network fairness. We used a single window size (the entire simulation time) to allow every user enough time to converge to a constant regime. We calculated γ_i the ratio of successfully transmitted packets from STA i over the entire simulation time, for N contending users in the cell. We obtained the expression:

$$F_T = \frac{(\sum_{i=1}^{N} \gamma_i)^2}{N \cdot \sum_{i=1}^{N} \gamma_i{}^2} \quad (1)$$

We also studied the extreme dispersion of values by using the $\frac{Max}{Min}$ index, ratio of the user having the maximum value by the user having the minimum value.

2) Goodput: The goodput is defined as the ratio of the delivered data payload to the total time necessary for transmission including all the protocol overheads (MAC/PHY overheads, backoff delay, inter-frame intervals, control frames, potential frame retransmission times and other users sharing the same channel). It is the effective performance offered on the top of the MAC layer. All users arrive at the beginning of the simulation and try to transmit data until the end of the simulation. Thus, they all spend the same time in the system. Also, all users transmit the same constant data payload of $L = 1500$ octets. Accordingly, the goodput for STA i is:

$$Goodput_i[Mbps] = \frac{8L_i}{T_{Simulation}} \quad (2)$$

where L_i is the number of successful data octets sent by STA i. Let us define by G_T the total aggregated goodput expressed in Mbps as the sum of all the successful data sent by all users during the entire simulation time.

In this article, we show that the 802.11 MAC protocol is very sensitive to the cell topology leading to spatially unfair situations in terms of channel access (expressed by the number of transmitted RTS frames for each STA), channel reservation and data transmission success (expressed by S):

$$S = \frac{\text{Number of expected Rx ACK frames}}{\text{Number of Tx RTS frames}} \tag{3}$$

This unfairness combined with various transmit modes result in different performance over all users.

IV. Simulation model and results

A. Simulation model

Our simulations use a model close to the 802.11a [1],[2] standard, with a single AP in DCF mode. Users always use the RTS/CTS mechanism. During a simulation, the number of users is constant and the simulation time is long enough to give every STA a chance to transmit a sufficient amount of data and to reach a fixed transmit mode.

All STAs are distributed within a 37.5m x 37.5m square building. The AP is located at the building centre and the users (always static) are distributed in the building. The maximum AP-MT distance is 26.5m (mode 4). Only the uplink is considered (from an MT to the AP), thus the AP will not try to access the medium, it only acknowledges the MTs operations. We use a saturated traffic model where all MTs constantly try to transmit fixed 1500 octets packets size.

The propagation model used is based on a power law [8], for class A scenarios referring to corporate indoor environments. No shadowing effect is included in order to capture the MAC protocol influence under various topologies. Due to the cell size, the air propagation time ($\ll 1\mu$s) is neglected.

With the Link Adaptation (LA) algorithm implemented, a STA always transmits using the highest achievable mode of operation determined by its distance to the AP. Thus, a cell is decomposed in "areas" of maximum modes around the AP. All control frames are transmitted in mode 1.

Table 1 presents the main numerical values used in our simulations.

Table 1
Simulation Parameters

Parameter Name	Numerical value
MT data payload	1500 octets
Cell radio channel	5180 MHz
AP and MT Tx power	23 dBm
AP and MT antenna gain	0 dBi
Short Retry Counter (SRC)	7
Long Retry Counter (LRC)	4

All other MAC protocol values are found in [1] and [2].

B. Micro-cluster distribution

We simulated a total real time of 100s. Several scenarios were investigated with a constant number of 6 users, to show the impact of hidden nodes, capture effects and collisions on the MAC protocol fairness. In a micro-cluster, several users are closely grouped in a 2m radius circle, all using the same transmit mode. For each series of 4 scenarios (1 to 4), the micro-cluster centre is respectively located at 0m, 7.5m, 17.5m and 22.5m from the AP.

- *Scenarios G1 to G4*: All 6 users are in the micro-cluster,
- *Scenarios IC1 to IC4*: There is always 1 user at 5m from the AP, and a micro-cluster of 5 users, diametrically opposed,
- *Scenarios IF1 to IF4*: There is always 1 user at 25m from the AP, and a micro-cluster of 5 users, diametrically opposed.

Table 2
Micro-cluster distribution fairness and performance metrics

Scenarios	User Nb Tx RTS		User S		User DATA success		G_T [Mbps]
	$\frac{Max}{Min}$	F_T	$\frac{Max}{Min}$	F_T	$\frac{Max}{Min}$	F_T	
G1	1.15	1.0	1.08	1.0	1.18	1.0	21.82
G2	1.15	1.0	1.04	1.0	1.18	1.0	21.82
G3	1.11	1.0	1.02	1.0	1.12	1.0	17.98
G4	1.13	1.0	1.03	1.0	1.16	1.0	14.26
IC1	1.15	1.0	1.08	1.0	1.18	1.0	22.40
IC2	1.23	1.0	1.04	1.0	1.27	0.99	21.57
IC3	2.33	0.87	1.49	0.97	3.46	0.71	20.82
IC4	2.30	0.87	1.49	0.97	3.4	0.72	17.67
IF1	1.45	0.98	1.06	1.0	1.38	0.98	19.37
IF2	1.46	0.98	1.07	1.0	1.38	0.99	19.33
IF3	1.20	1.0	1.80	0.97	1.68	0.98	15.99
IF4	1.21	1.0	1.72	0.97	1.55	0.98	13.19

Scenarios G1 to G4 show fair situations, no matter the distance between the micro-cluster and the AP, because all users are always in the same state, and there is no hidden node/capture effect. In scenarios IC1 and IC2, there is no hidden node/capture effect, giving also a fair situation. However, in scenarios IC3 and IC4 we have a capture effect but no hidden node: any RTS attempt from a user in the micro-cluster is always dominated by a simultaneous RTS attempt from the user close to the AP (5m) because of its much stronger RSS at the AP. Thus, he achieves almost 100% of reservation success leading to an unfair situation (RTS packets fairness index = 0.87). Once the channel is reserved, data is nearly transmitted with total fairness (0.97). In scenarios IF1 and IF2, the capture effect is dominated by the micro-cluster's users leading to an RTS packet fairness index of 0.98. Then the capture effect becomes a hidden node problem in scenarios IF3 and IF4 because the micro-cluster's centre and the isolated user are too far apart (42.5m and 47.5m respectively). The result is an unfair situation as shown in Table 2.

As a conclusion, the MAC protocol is fair when all users are always "synchronized" on the same channel and protocol state and face the same number of collisions. This is achieved when there is no hidden node nor capture effect. Such situations are found for distributions of users locally concentrated, such as users in the same small meeting room. But, as soon as hidden nodes or capture effects appear, the MAC protocol turns out to be unfair and in favor of the very close users to the AP (whether isolated or grouped in micro-cluster).

C. Uniform distribution

We simulated a total real time of 200s. We varied the cell load from 5 up to 40 users. The users are uniformly distributed in the building. Thus, when the number of users increases, the proportions of users in each mode remain almost constant. Table 3 shows the metrics used.

Table 3
Uniform distribution fairness and performance metrics

Nb of users	**User Nb Tx RTS**		**User S**		**User DATA success**		G_T **[Mbps]**
	$\frac{Max}{Min}$	F_T	$\frac{Max}{Min}$	F_T	$\frac{Max}{Min}$	F_T	
5	1.36	0.99	1.11	1.0	1.37	0.99	18.02
10	2.24	0.96	1.49	0.99	3.34	0.92	18.51
15	2.14	0.97	1.88	0.98	4.04	0.90	18.48
20	2.71	0.92	2.00	0.97	4.66	0.77	18.56
25	2.38	0.95	1.91	0.97	3.74	0.84	18.38
30	2.82	0.93	2.03	0.97	4.79	0.80	17.67
35	3.23	0.92	2.10	0.97	5.92	0.77	17.44
40	3.21	0.91	2.19	0.97	6.01	0.77	17.49

1) Distribution of BC values: Prior to data transmission, each STA draws a BC value to determine its transmission start time. The protocol retry philosophy is "the more a STA fails, the more it waits, whatever its mode and data packet size". Figure 1 shows the distribution of BC values versus the distance to the AP. These values where obtained for a cell load of 40 users.

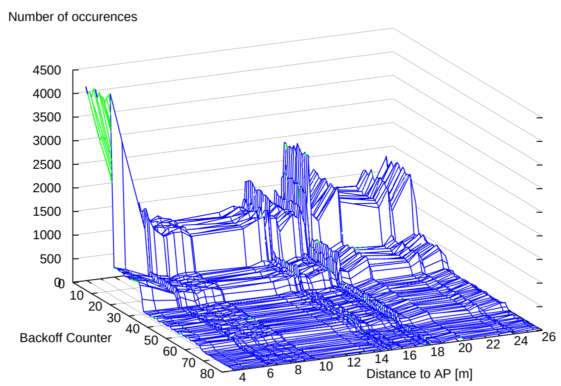

Fig. 1
Number of times each BC value was drawn versus distance to AP

In Figure 1, various "steps" are found along the BC value axis, corresponding to the different values of CW. First, the number of occurences of BC values rapidly decrease for increasing BC values. The most significant "steps" being actually contained in the first two CWs. In other words, a success usually follows a collision. Second, the function giving the successful transmit opportunities versus the distance to the AP is not a simple one. Even though the closest users from the AP are the most favored ones, the farthest are not necessarily the least favored as seen in Figure 1. This is the impact of the cell topology. If all users were equal regarding success and failure, they whould have drawn the same number of times each BC value regardless of their location in the cell. However, this is not verified by Figure 1, thus showing the spatial unfairness of the MAC protocol, even with a fairly large cell load.

2) Opportunity of channel access, and success in channel reservation and data transmission: The profile of the number of RTS frames per user versus the distance to the AP follows the BC distribution (Figure 1). MTs having few channel access opportunities are suffering a high percentage of collisions and a high waiting time between two transmissions, leading to poor performance. In Table 3, when the number of contending users increases, the number of RTS $\frac{Max}{Min}$ values, over all users, also increases and reaches up to 3.2 and a fairness index of 0.92, for 40 contending users. This indicates the spatial unfairness of the MAC protocol in the channel access.

Figure 2 shows S versus cell load and the distance to the AP.

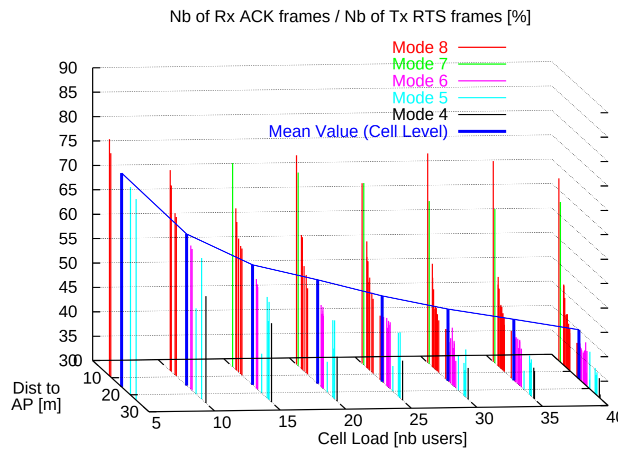

Fig. 2
Channel reservation and data transmission success (%) versus cell load and distance to AP

The spatial unfairness of the protocol is obvious. The assumption that all users have the same channel reservation and data transmission success conditions regardless of their location is not verified. The importance of using the RTS/CTS mechanism in presence of many users to minimize the effect of the hidden nodes is highlighted. Indeed, the average S value decreases for an increasing number of contending users, due to an increasing number of hidden nodes and thus of collisions. In Figure 2, the users having the best S values are the ones located close to the AP. As no power control is used in 802.11a, users close to the AP exchange stronger radio signals with the AP than the ones far from it. Thus, users at the cell border are disadvantaged regarding the channel reservation efficiency compared to the users at the centre. As cell load grows, some users become more and more disadvantaged compared to others (up to 2 times), leading to an increasingly unfair protocol. In a larger building (more hidden nodes), the users far from the AP (mode 1) would have been even more disadvantaged.

3) Goodput: Figure 3 corresponds to a combination of users operating in various transmit modes. First, the average

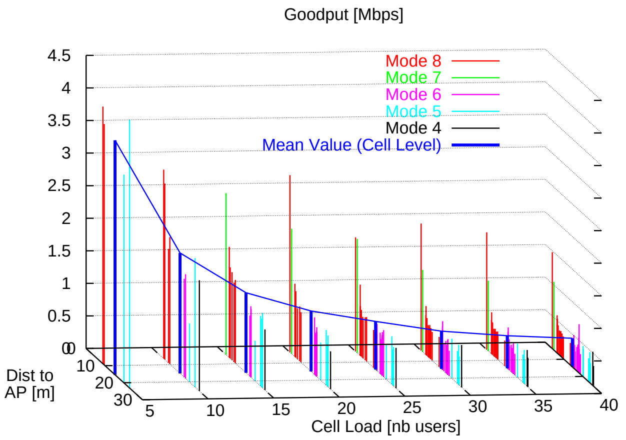

Fig. 3
Goodput versus cell load and distance to AP

goodput per user decreases for an increasing cell load, in favour of the MTs close to the AP. Indeed, they already have a better opportunity of channel access, medium reservation success and data transmission success, and they also have a better mode. Thus, for 40 contending users, the most favored users send 6 times more successful data frames than the least favored ones. Second, even under heavy load conditions, the average cell goodput (considering an average mode for all users) is almost inversely proportional to the cell load. Table 3 shows that the aggregated goodput is almost constant whatever the number of users. Thus, the user average time to transmit a given data payload almost linearly increases with the number of contending users, creating a greater delay, due to the shared radio channel.

V. Conclusions and Future Work

Our simulation results exhibit a spatially unfair 802.11 MAC protocol and the effects of hidden nodes and capture effects. Even users transmitting the same amount of data payload faced different opportunities to contend for the channel, different level of success in channel reservation and data transmission, depending on the cell topology. Cell topology is thus a key parameter to consider, for example, when triggering inter-cell handovers.

Other traffic profiles and user distributions should be investigated as a complement to this study. In addition, a more realistic channel model could be implemented, including for example the shadowing effect.

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