Laura Giarré, Giovanni Neglia, and Ilenia Tinnirello

Medium Access in WiFi Networks: Strategies of Selfish Nodes

The majority of wireless local area network (WLAN) technologies, including the wireless fidelity (WiFi) [1] standard IEEE 802.11 [2], is characterized by the use of a single shared channel. The use of a single channel is very different from most wireless cellular technologies [for example, Global System for Mobile communications (GSM)], where communications simultaneously occur in independent wireless channels deployed in different time slots and frequency bands. Indeed, the use of a shared channel necessitates the specification of some access rules to guarantee that terminals transmit in different time intervals without collision. These rules are defined in the medium access control (MAC) layer, which represents a fundamental part of every WLAN standard.

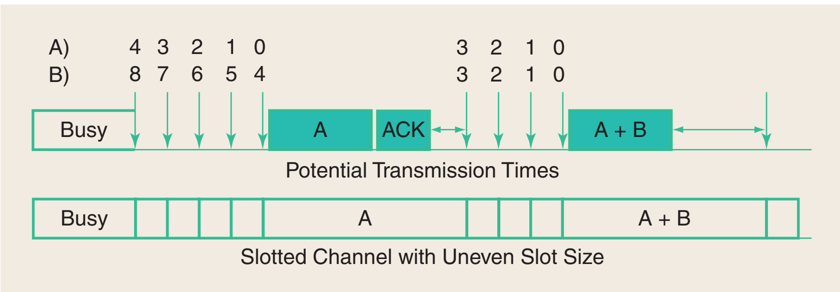
The MAC layer employed in IEEE 802.11 WLANs is based on a mechanism called distributed coordination function (DCF), which relies on the listen-before-talk paradigm, coupled with random access delays called "backoffs." Although all WiFi cards should carefully implement the MAC rules described in the standard, in actual networks it has been observed that some cards exhibit noncompliant behaviors. In many cases, such unexpected behaviors have been recognized as a consequence of selfish settings of the backoff extraction ranges [3], whose configuration is made available to end users thanks to the proliferation of open-source card drivers. Nodes using nonstandard backoff ranges can improve their performance at the expense of compliant nodes. These behaviors are difficult to prevent, since the backoff scheme is entirely under the control of end users. This consideration motivates this article, which provides a game theoretical analysis of the WiFi MAC protocol to understand the risks or the advantages offered by possible modifications of MAC functionalities implemented at the driver level.

REVIEW OF DCF

DCF uses a technique called carrier sense multiple access. Historically introduced by Bob Metcalfe in 1973 for the Ethernet wired local area network, this technique requires every station to listen to the channel for a time interval called the DCF interframe space (DIFS) before transmitting. In wireless networks, the sender is not able to determine whether a transmission is successful, so the receiver has to immediately reply with an acknowledgment message whenever it successfully receives a MAC frame. Hence, the lack of acknowledgment informs the sender that the current frame has either collided or it has been corrupted by channel noise and thus that the frame must be retransmitted.

DCF prevents collisions by trying to minimize the probability that two stations start their frame transmission simultaneously. To this purpose, a station that senses the channel as busy not only defers the transmission until the channel is idle again but further waits for an additional random delay (the backoff), which is slotted for efficiency reasons. This operation is called collision avoidance. Note that similar to many other networking protocols, the range in which the random backoff time is applied increases with the number of times that the frame is retransmitted. This procedure adapts the backoff to the level of congestion encountered in the network, roughly measured as the number of times a packet transmission fails. Standard DCF assumes that the number of backoff slots are extracted in the range $[0, CW_{min}]$ at the first transmission attempt. At each failure, the contention window (CW) is doubled up to the CW_{max} value. The values CW_{min} and CW_{max} are specified in the standard and are the same for all contending stations. Therefore, DCF protocol is long-term fair, since each station has the same probability of accessing the channel.

Figure 1 shows an example of two stations competing for the channel. After the medium has been sensed busy, stations A and B extract their backoff values (four and eight, respectively, in the example). Since station A expires its backoff first, it acquires the right to transmit on the channel. Station B freezes its backoff until the channel is sensed idle again. At this point, station



[FIG1] An example of slotted channel access and uneven slot size.

Digital Object Identifier 10.1109/MSP.2009.933378

1053-5888/09/$26.00©2009IEEE

A extracts a new backoff (3) and the next transmission (which results in a collision) is performed again after an integer number of backoff slots. We observe that the time is then divided in slots of uneven duration: potential transmission instants are separated by a single backoff slot (namely, σ) when no station accesses the channel, and by the frame transmission time (namely, T) when one or more stations transmit.

In a generic channel slot, it has been shown [4] that each station has approximately a fixed probability τ to transmit. This probability depends on CW_{min} and CW_{max} settings, and the probability to double the contention window because of collisions. It is well known that, by dynamically tuning the CW_{min} and CW_{max} parameters of all competing nodes as a function of the network load, the network aggregated throughput can be much higher than the one perceived under the standard protocol [4]. However, such a flexibility in the contention window settings also represents a risk for encouraging selfish node behaviors, which may select CW_{min} and CW_{max} to increase their channel access probability τ. This is an actual threat to WLAN operation, because in modern cards CW_{min} and CW_{max} values are no longer hard-wired and can be changed by the user.

CHANNEL ACCESS AS A NONCOOPERATIVE GAME

If selfish stations can set their channel access probability to get a higher share of the common radio spectrum, it is natural to adopt a game theoretic framework (see, e.g., [10]) to study their interaction. Consider a network of n contending nodes, and let $\boldsymbol{\tau} = (\tau_1, \tau_2, \ldots, \tau_n) \in [0, 1]^n$ be the corresponding access probability vector, i.e., the vector of strategies chosen by the stations. Performance perceived by a given station i depends not only on the probability τ_i to access the channel, but also on the probability that no other station interferes on the same slot. This happens with probability $\prod_{j \neq i}(1-\tau_j) = 1 - p_i$, where p_i is the collision probability experienced by station i because of other nodes. From the station point of view, the vector strategy $\boldsymbol{\tau}$ can be represented by the pair of values (τ_i, p_i), where p_i summarizes the interactions with all the other mobile stations.

What is crucial in analyzing the strategies of selfish nodes, is to define the utility (payoff) function that nodes want to maximize. Most papers about DCF modeling in presence of selfish settings assume that each node wants to maximize its bandwidth share [5], i.e., its throughput. The throughput S^i perceived by the ith station can be expressed as $S^i = \tau_i(1-p_i)P/(P_{idle}\sigma + (1 - P_{idle})T)$, where P is the frame payload assumed to be fixed, σ and T are the empty and the busy slot duration, respectively, and P_{idle} is the probability that a given channel slot is empty. When the node utility function J^i coincides with S^i, the Nash equilibrium (NE) (the vector of strategies such that no station has interest to unilaterally deviate) of the channel access game are all and only the vectors of strategies τ, such that $\exists\, i \in \{1, 2, \ldots, n\} \mid \tau_i = 1$ [5]. Indeed, when station i deterministically transmits in all channel slots, all the other stations receive a null throughput and do not have any gain in deviating from their strategies. Moreover, station i achieves a throughput $S^i \propto \prod_{j \neq i}(1-\tau_j)$, that can also be null if another station is transmitting with probability one. Hence, the corresponding network performance at these NEs can be very poor.

More complex utility functions combining throughput and costs related to collision rates [5] or to energy consumptions [7] lead to different equilibria. For example, in [5], the utility function is defined as $J^i = S^i - B^i$, where B^i denotes a penalty function, proportional to the transmission probability, defined as $B^i = k_i(\tau_i - c)$. The authors prove that, by opportunely defining the parameters k_i and c so that $\partial J_i/\partial \tau_i = 0$, it is possible to find Nash equilibria in which no player i adopts $\tau_i = 1$. Similarly, the authors of [7] prove that resource collapse can be avoided by assigning each station a per-slot payoff, according to the station strategy outcome (deferring transmission, successful transmission, collision). However, these other utility functions do not appear as natural as throughput, so that it is questionable if they can really capture the behavior of a selfish station.

Some studies have considered throughput as the utility metric and have studied how to introduce penalty mechanisms to achieve better performance despite the presence of selfish stations. For example, in [5] the authors suggest implementing a cooperative jamming mechanism for destroying the extra transmissions performed by selfish nodes. However, selfish behaviors may also involve the jamming operation, and legacy nodes have no guarantee to not be jammed. Conversely, in [8] a sort of tit-for-tat strategy is proposed, according to which nodes autonomously limit their channel access probability in presence of legacy nodes and react to selfish contenders by adopting selfish behaviors themselves.

CHANNEL ACCESS IN INFRASTRUCTURE MODE

Previous studies of node strategies in WiFi networks have only considered that nodes are interested in transmitting data as fast and energy efficiently as possible. In fact, we argue that nodes are usually interested in bidirectional traffic streams, especially when connected in infrastructure mode to a common access point (AP) acting as a gateway toward external networks, like the Internet. In this scenario, users are motivated to limit their channel access probability, to leave space for AP transmissions. We are going to show that a new NE with better properties arises in such a scenario, even without the adoption of penalty mechanisms.

It is reasonable to assume that the AP contends for the channel as a legacy DCF station, and equally allocates its downlink throughput to all the associated stations. The overall collision probability suffered by a generic station i is $1 - (1-p_i)(1-\tau_{AP})$, where τ_{AP} is the channel access probability employed by the AP. Since the AP is a legacy station, its transmission probability is not chosen by the AP, but it is function of the perceived collision probability p_{AP} according to the expression $\tau_{AP} = f(p_{AP})$ derived in [4] (which decreases monotonically as

p_{AP} increases). The AP collision probability is function of the whole vector strategy τ and can be expressed as $p_{\mathrm{AP}} = 1 - \prod_{j=1}^{n}(1-\tau_j) = 1-(1-p_i)(1-\tau_i)$.

The uplink throughput S_u^i and the downlink throughput S_d^i perceived by a generic station i can be readily expressed as

$$S_u^i(\tau_i, p_i) = \frac{\tau_i(1-p_i)(1-\tau_{\mathrm{AP}})P}{P_{\mathrm{idle}}\sigma + (1-P_{\mathrm{idle}})T},$$
$$S_d^i(\tau_i, p_i) = \frac{1}{n}\frac{\tau_{\mathrm{AP}}(1-p_{\mathrm{AP}})P}{P_{\mathrm{idle}}\sigma + (1-P_{\mathrm{idle}})T},$$

where P_{idle} is the probability that neither the stations, nor the AP transmit on the channel, i.e., $P_{\mathrm{idle}} = (1-p_{\mathrm{AP}})(1-\tau_{\mathrm{AP}})$.

Since the downlink throughput is equal for all the stations, we can avoid the superscript i. We define the utility function J^i for the mobile station i as $J_i = \min\{S_u^i, kS_d\}$. The rationale of such a definition is the assumption that the station applications require bandwidth on both directions. The coefficient $k \in [0, \infty)$ takes into account the desired ratio between the uplink and the downlink traffic. We assume that the application is the same for all the stations, thus using a fixed k for all the utility functions. When $k = 1$ all the stations require the same throughput in both directions. Note that $k = \infty$ corresponds to the unidirectional traffic case, in which no station is interested in downlink throughput.

Figure 2 plots the utility of a given station i, in case of 802.11b physical layer, $P = 1{,}500$ B, a data rate equal to 11 Mb/s, and an acknowledgment rate of 1 Mb/s. In such a scenario, by including physical preambles, acknowledgment transmissions, MAC headers, and interframe times T and σ durations are equal to 1,667 μs and 20 μs, respectively. Different network conditions, summarized by the p_i probability have been considered. From the figure, it is evident that, for each p_i, the utility is maximized for a given best response value (about 0.01 for $p = 0.15$), which slightly decreases as p_i grows. Figure 2(b) plots again the utility of a given station in case of homogeneous outcomes $\boldsymbol{\tau}|\tau_i = \tau, \forall i$, for differing number of competing mobile stations. In these curves $p_i = (1-\tau_i)^{n-1}$ is not fixed, because the strategy changes are not unilateral. The optimal strategy is function of the number of competing stations.

From the utility definition in case of infrastructure mode, it is evident that the strategies $\boldsymbol{\tau}$ such that $\exists!\, i\,|\tau_i = 1$ are not Nash equilibria as in [5]. Indeed, when one station employs a channel access probability equal to one, the AP collides with probability $p_{\mathrm{AP}} = 1$, thus resulting in a downlink throughput S_d equal to zero. Thus, the station is motivated to reduce its transmission probability to a value lower than one.

We are going to show that there is an NE where all the stations achieve a nonnull utility. The following remark will be useful to this purpose.

REMARK 1

Consider a generic station i and the collision probability p_i suffered because of the other station strategies. The AP channel access probability τ_{AP} depends on τ_i and p_i according to $f(1-(1-\tau_i)(1-p_i))$. Then, for a given $p_i \in (0,1)$, $S_d(\tau_i)$ is a monotonic decreasing function of τ_i, starting from $S_d^i(0) > 0$, and $S_u^i(\tau_i)$ is a monotonic increasing function of τ_i, starting from $S_u^i(0) = 0$.

From the previous remark, we can state that for $p_i \neq 1$, the best response of player i to p_i is the access probability $\tau_i^{(\mathrm{br})}$ such that $S_u^i(\tau_i^{(\mathrm{br})}, p_i) = kS_d(\tau_i^{(\mathrm{br})}, p_i)$. It follows that $\tau_i^{(\mathrm{br})}$ is the solution of the following implicit equation:

$$\tau_i^{(\mathrm{br})} = \frac{kf(1-(1-p_i)(1-\tau_i^{(\mathrm{br})}))}{n-(n-k)f(1-(1-p_i)(1-\tau_i^{(\mathrm{br})}))} \triangleq g(\tau_1, \ldots, \tau_i^{(\mathrm{br})}, \ldots, \tau_n). \qquad (1)$$

It can be shown that the previous equation has a single solution in the range $(0,1)$, which can be numerically solved in a few fixed point iterations.

Let us consider $\tilde{\tau}$ such that $\tilde{\tau} = g(\tilde{\tau}, \tilde{\tau}, \ldots, \tilde{\tau})$.

PROPOSITION 1

The outcome $\tilde{\boldsymbol{\tau}} = (\tilde{\tau}, \tilde{\tau}, \ldots, \tilde{\tau})$ is the unique NE of the game with nonnull utility for all the players.

PROOF

We can restrict our analysis to the set $[0,1)^n$ for which $p_i < 1$ for each i and then best response satisfies (1). $\tilde{\boldsymbol{\tau}}$ is an NE because it satisfies (1) considering $p_i = (1-\tilde{\tau})^{n-1}$. Indeed the equation can be read as a mutual best response. Since (1) has a single solution, there exists a unique symmetric NE.

Now we need to prove that there is no asymmetric NE in $[0,1)^n$. Being that

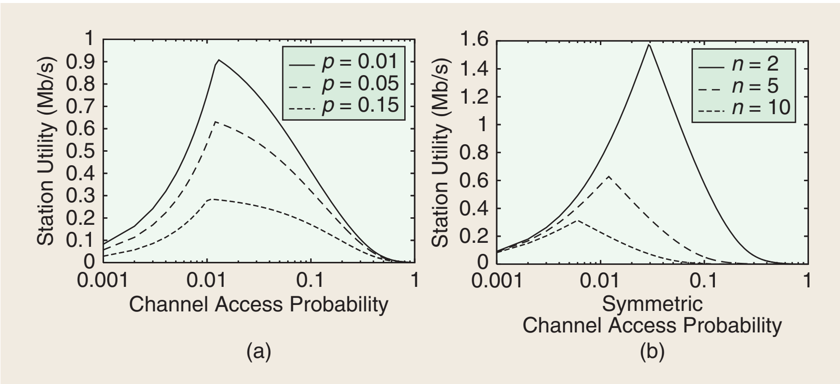
$$(1-p_i)(1-\tau_i) = \prod_{j=1}^{n}(1-\tau_j), \forall i,$$

then the right hand of the best response (1) is the same for all the stations. This excludes that a nonhomogeneous outcome can satisfy the equation and be an NE. ■

We can consider which outcomes maximize the minimum utility perceived in the network and prove the following proposition.

PROPOSITION 2

There is a unique outcome that maximizes the minimum utility perceived in the network and such outcome is



[FIG2] Station utility for (a) different access probability p_i values and (b) symmetric access probability ($k = 1$).

homogeneous, i.e., $\boldsymbol{\tau}^* = (\tau^*, \tau^*, \ldots, \tau^*)$, and Pareto optimal.

The proof is omitted in this article to conserve space and can be found in [9].

It is interesting to investigate what is the relation between τ^* and $\tilde{\tau}$. For example, Figure 2 shows how the utility changes for homogeneous outcomes and that $\tau^* = \tilde{\boldsymbol{\tau}}$ because the maximum of J^i corresponds to the value where $S_u^i = kS_d$ as it is evident from the cusp in the curve. This happens when the point of maximum of $S_u^i((\tau, \tau, \ldots, \tau))$ is for $\tau \geq \tilde{\tau}$, so that $\tilde{\tau}$ is the point of maximum of J^i. Our numerical results show that this is the case for $k = 1$ and for the realistic values we considered for the 802.11b $CW_{\min}$ and $CW_{\max}$ parameters.

An interesting remark is that the NE $\tilde{\boldsymbol{\tau}}$ only depends on the number of stations n and it is not affected either by the PHY layer parameters (such as backoff slot duration, and interframe spaces) or by the frame length.

CONCLUDING REMARKS

The medium access process in WiFi networks can be very suitably modeled in terms of noncooperative game among contending nodes. Indeed, current WiFi cards allow users to implement greedy strategies at the driver level for increasing their bandwidth share at the expenses of compliant users. Therefore, a game theoretical analysis of the user interactions is essential, to prevent unfair resource repartitions or resource collapse due to continuous collisions.

Previous studies have shown the need to introduce penalty mechanisms to have acceptable performance in presence of selfish stations that try to maximize their transmission throughput. In this article, we consider a bidirectional traffic scenario that arises naturally in infrastructure networks where applications at wireless stations exchange data with remote destinations through an AP. We show that a homogeneous (fair) NE arises, where all the stations reach the same nonnull utility. Moreover, numerical results show that this NE is Pareto optimal when the AP adopts standard-compliant contention window settings.

AUTHORS

Laura Giarré (giarre@ieee.org) is an associate professor of control at the University of Palermo, Italy. She is a member of the editorial board of *Systems and Control Letters* and the IEEE Control Systems Society on Identification and Adaptive Systems and the IEEE Control Systems Society on System Biology.

Giovanni Neglia (giovanni.neglia@inria.fr) is a researcher with the MAESTRO team at the Institut National de Recherche en Informatique et en Automatique, Sophia-Antipolis. He received a master's degree in electronic engineering and a Ph.D. degree in telecommunications from the University of Palermo, Italy, in 2001 and 2005, respectively.

Ilenia Tinnirello (ilenia.tinnirello@tti.unipa.it) is an assistant professor in the Electrical Engineering Department of the University of Palermo, Italy. Her research activity focuses on wireless networks, in particular on multiple access algorithms, cross-layer interactions, and mobility management.

REFERENCES

[1] Wi-Fi Alliance [Online]. Available: www.wi-fi.org

[2] *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, IEEE Standard 802.11–1999, Nov. 1999.

[3] G. Bianchi, A. Di Stefano, C. Giaconia, L. Scalia, G. Terrazzino, and I. Tinnirello, "Experimental assessment of the backoff behavior of commercial IEEE 802.11b network cards," in *Proc. IEEE Infocom 2007*, Anchorage, AK, May 2007, pp. 1181–1189.

[4] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Select. Areas Commun.*, vol. 18, no. 3, pp. 535–547, Mar. 2000.

[5] M. Cagalj, S. Ganeriwal, I. Aad, and J. P. Hubaux, "On selfish behavior in CSMA/CA networks," in *Proc. IEEE Infocom*, Miami, FL, Mar. 2005, vol. 4, pp. 2513–2524.

[6] L. Chen, S. H. Low, and J. Doyle, "Contention control: A game-theoretic approach," in *Proc. IEEE Conf. Decision and Control*, New Orleans, LA, Dec. 2007, pp. 3428–3434.

[7] G. Zhang and H. Zhang, "Modelling IEEE 802.11 DCF in wireless LANs as a dynamic game with incompletely information," in *Proc. Conf. Wireless, Mobile and Multimedia Networks*, Mumbai, Jan. 2008, pp. 215–218.

[8] J. Konorski, "A game-theoretic study of CSMA/CA under a backoff attack," *IEEE/ACM Trans. Networking*, vol. 14, no. 6, pp. 1117–1178, 2006.

[9] L. Giarré, G. Neglia, and I. Tinnirello, "The role of the access point in Wi-Fi networks with selfish nodes," in *Proc. GameNets*, Istanbul, 2009 (INRIA Tech. Rep. N. RR6737, 2008).

[10] T. Basar and G. J. Olsder, *Dynamic Noncooperative Game Theory*. Philadelphia, PA: SIAM, 1999.

[SP]

 continued from page 6

things, "Received the initial copy of the Content Gazette about two days ago and think that this may finally be the solution to the 'online journals' dilemma. I have switched several journals from 'paper' to 'electronic' copies and, with hindsight and some assistance from the Rev. Dr. Bayes, find that I should have saved the money and simply cancelled the subscriptions: Specifically, if I don't have a paper copy sitting there reminding me to look at it, it never gets looked at unless I happen to see a citation to one of the papers someplace later. …

With the Gazette, I can sit in my favorite armchair with a pen and some Post-It notes, mark the articles that look interesting, and get copies later. If it arrives in the middle of a busy week, it will keep along with *Science, Nature, Physics Today, Proceedings*, various IEEE transactions, etc. until I have a free evening to look at them and not just disappear off the top of the screen." [SP]