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Saturation Throughput Maximization in Full Duplex WLANs Using Game Theory

Anastasios C. Politis and Constantinos S. Hilas

Department of Computer, Informatics and Telecommunications Engineering
International Hellenic University - Serres Campus
62124, Serres, Greece

Abstract

This paper demonstrates how Game Theory (GT) concepts can be exploited to maximize the saturation throughput achieved in Wireless Local Area Networks (WLANs) that operate in Full Duplex (FD) communication mode under the standard Distributed Coordination Function (DCF) regime. Towards this goal, suitable analytical expressions, that lead to saturation throughput maximization, are provided. Numerical results indicate that the game-theoretic approach clearly outperforms the saturation throughput achieved by the standard FD communication mode under existing DCF rules.

Keywords: Game Theory, Saturation Throughput, Full Duplex, Distributed Coordination Function, WLANs

1 Introduction

FD WLANs have the ability to simultaneously transmit and receive data, allowing for two-way communication. FD communication mode can significantly enhance network throughput, reduce latency, and improve overall network efficiency, making it a promising technology for next-generation wireless communication systems. Several papers have demonstrated that FD communications are possible in WLANs by employing sophisticated signal processing algorithms to cancel out self-interference or interference from other devices, allowing simultaneous transmission and reception [1].

However, multiple studies have demonstrated that the existing MAC-layer mechanism (i.e., the DCF protocol) is unable to efficiently support FD communication mode [2], [3]. Indeed, these studies show that no gain is to be expected in FD WLANs operating under the DCF regime in terms of saturation throughput (i.e., the maximum achievable data rate when the system operates in saturation conditions) when compared to its half duplex counterpart. Hence, several DCF improvements have been proposed in the literature to alleviate its suboptimal behaviour in FD-capable WLANs [4], [5]. Nevertheless, these proposals require substantial modifications to the current MAC-layer specification.

In this paper, it is demonstrated how GT can be exploited to obtain the maximum saturation throughput in a DCF-based ad-hoc WLAN system operating in FD mode. Towards this goal, an analytical approach is followed and numerical results are presented that prove that FD WLANs with DCF as their MAC-layer mechanism can provide substantial performance gains in terms of saturation throughput. DCF's functional details are a well documented topic and the interested reader can refer to [6] for a detailed analysis. Hence, a lengthy (and trivial) description of DCF operation is omitted.

The rest of the paper is structured as follows. Section 2 provides a very brief description on how GT can be used to model DCF operation in WLANs. In Section 3 the game-theoretic approach for saturation throughput maximization is presented. More specifically, an expression for the best response (i.e., transmission probability) of a wireless node is analytically derived and then it is used to obtain the saturation throughput of the system. Numerical results are presented and interpreted in Section 4, and in Section 5 the implementation issues of the proposed scheme are explained. Lastly, the paper is concluded with final remarks in Section 6.

2 Game Theory in WLANs

The nodes in a WLAN system can be considered as *players* in game-theoretic terms. The players can choose among two *strategies*: transmit or stay idle (i.e., wait) at the start of a system time slot. These strategies are selected with a certain probability distribution, owing to the probabilistic nature of DCF operation. Hence, a *mixed* strategy is selected by each node. Since the game is performed at the start of each time slot, the game is referred to as a *static* game. At the end of the game, each node is awarded a *payoff* (or *utility*) which, typically, the nodes seek to maximize. Thus, the nodes are behaving *rationally* (i.e., they are *non-cooperative*).

From the above short description, the functionality of DCF in a WLAN system can be modeled as a non-cooperative static game with mixed strategies which is repeated at the start of each time slot. The payoffs are denoted as

u_s, u_f and u_i for a successful, a failed and no transmission, respectively. It is logical to assume that $u_f < u_i < u_s$ [7].

Solving the game involves determining the *Nash equilibrium* in which each player selects a strategy that is considered its *best response* to the strategies selected by all other players. In a DCF-based WLAN system this translates in determining the transmission probability, τ, of each node. This transmission probability represents the best response of a node against the strategies selected by all other participants in the system.

A detailed description on how GT concepts can be applied to WLAN systems can be found in [7] and [8].

3 Saturation Throughput Maximization

The system model considered in this work consists of an ad-hoc WLAN with n full-duplex wireless stations. Perfect self-interference cancellation at every node is also assumed with no errors induced by the wireless medium. Moreover, every node is operating in saturation conditions (the node has always a packet ready for transmission) and the system does not include any hidden terminals (i.e., the optional RTS/CTS mechanism is not used).

Based on the above configuration, an expression for the transmission probability of a wireless node based on game-theoretic concepts is obtained initially. That expression represents the best response of a node which is, then, used to compute the maximum saturation throughput.

3.1 Transmission Probability-Best Response

Given that each node follows the rationality assumption, the utility function, U_i, of a randomly chosen node i, can be expressed as [7]:

$$U_i = \tau_i \left[(1 - p_i)u_s + p_i u_f\right] + (1 - \tau_i)u_w \tag{1}$$

where p_i is the conditional collision probability of node i, given that it attempts transmission. To obtain an expression for p_i, the following cases of successful transmission of node i can be formulated:

- node i will end up with a successful transmission if no other node attempts to transmit at the start of the same time slot with node i. Note that this is the only case that leads to a successful transmission in the standard half duplex operation in WLANs.
- node i will also end up with a successful transmission if the node it is aiming will also transmit at the same time slot regardless of its destination, owing to the assumption of perfect self-interference cancellation

in every node. Assuming that node i selects its destination node with a uniform distribution, the probability of aiming at a specific node is simply $\frac{1}{n-1}$. This additional case of successful transmission results from the FD-capability of the system.

Hence, probability p_i is given by:

$$p_i = 1 - \left[\prod_{\substack{j=1 \\ j \neq i}}^{n} (1 - \tau_j) + \sum_{\substack{j=1 \\ j \neq i}}^{n} \left[\frac{1}{n-1} \tau_j \prod_{\substack{k=1 \\ k \neq j,i}}^{n} (1 - \tau_k) \right] \right]. \tag{2}$$

A rational node seeks to maximise its payoff, hence, combining the necessary condition for maximization and equations (1) and (2):

$$\frac{\partial U_i}{\partial \tau_i} = 0 \Rightarrow \prod_{\substack{j=1 \\ j \neq i}}^{n} (1 - \tau_j) + \sum_{\substack{j=1 \\ j \neq i}}^{n} \left[\frac{1}{n-1} \tau_j \prod_{\substack{k=1 \\ k \neq j,i}}^{n} (1 - \tau_k) \right] = \lambda. \tag{3}$$

The parameter λ in the above equation is given by:

$$\lambda = \frac{u_i - u_f}{u_s - u_f}. \tag{4}$$

Adopting the symmetric strategy assumption also presented in [9], which indicates that $\tau_1 = \tau_2 = ... = \tau_n = \tau$, equation (3) can be rewritten as:

$$(1 - \tau)^{n-1} + \tau (1 - \tau)^{n-2} = \lambda \tag{5}$$

which has the following unique solution:

$$\tau = 1 - \lambda^{\frac{1}{n-2}}. \tag{6}$$

The value of τ obtained by equation (6) represents the best response of node i.

Since $u_f < u_i < u_s$, it follows that $0 < \lambda < 1$. Hence, probability τ is a decreasing function of n, for a given λ, since:

$$\frac{\partial \tau}{\partial n} = \frac{\lambda^{\frac{1}{n-2}} \ln(\lambda)}{(n-2)^2} < 0. \tag{7}$$

Indeed, Fig. 1 graphically shows the decreasing behaviour of probability τ as n increases, for different values of λ.

Now, the value of τ can be used to obtain the saturation throughput.

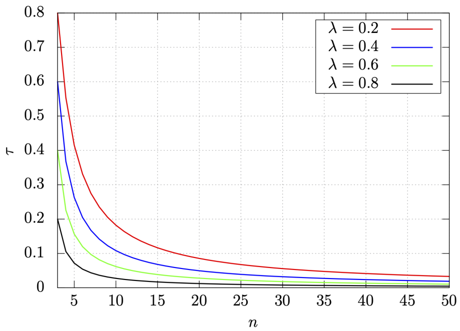

Figure 1: Transmission probability, τ, for increasing number of nodes, n.

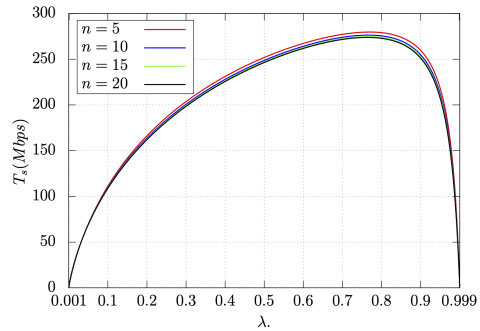

Figure 2: Saturation throughput, T_s, for varying values of the parameter λ.

3.2 Saturation Throughput

Saturation throughput, T_s, refers to the maximum achievable data transfer rate and represents the point at which the network's capacity is fully utilized. It can be defined as the fraction of time during which data bits are successfully transmitted through the wireless channel [6]. Hence, T_s is given by:

$$\begin{aligned} T_s &= \frac{P_{tr} P_s L}{(1 - P_{tr}) D_\sigma + P_{tr} P_s D_s + P_{tr}(1 - P_s) D_c} \\ &= \frac{P_{tr} P_s L}{D_\sigma + P_{tr}(D_c - D_\sigma) + P_{tr} P_s (D_s - D_c)} \end{aligned} \tag{8}$$

where D_σ, D_s and D_c are the empty time slot (i.e., a time slot with no transmission), transmission and collision durations, respectively. D_σ, D_s and D_c depend on the physical technology. D_s and D_c can be obtained as below:

$$\begin{cases} D_s = DIFS + D_{DATA} + D_{ACK} + SIFS \\ D_c = DIFS + D_{DATA}. \end{cases} \tag{9}$$

$DIFS$ and $SIFS$ are the Distributed and Short Inter-Frame Spaces, respectively, and are PHY-specific. D_{DATA} and D_{ACK} are the durations of the data and acknowledgment frames, respectively.

Probability P_{tr} represents the probability of the event that there is at least a single transmission at the start of a time slot:

$$P_{tr} = 1 - \prod_{i=1}^{n} (1 - \tau_i). \tag{10}$$

Probability P_s represents the probability of the event that a transmission during a time slot is successful, given that there is at least one transmission attempt in that time slot:

$$P_s = \sum_{i=1}^{n} \tau_i \left[\prod_{\substack{j=1\\ j\neq i}}^{n} (1-\tau_j) + \sum_{\substack{j=1\\ j\neq i}}^{n} \Big[\frac{1}{n-1} \tau_j \prod_{\substack{k=1\\ k\neq j,i}}^{n} (1-\tau_k) \Big] \right] \tag{11}$$

For $\tau_1 = \tau_2 = \tau_3 = ... = \tau_n = \tau$ (i.e., symmetric strategy), equations (10) and (11) reduce to:

$$\begin{cases} P_{tr} = 1 - (1-\tau)^{n-1} \\ P_s = n\tau \Big[(1-\tau)^{n-1} + \tau(1-\tau)^{n-2} \Big]. \end{cases} \tag{12}$$

Substituting $\tau = 1 - \lambda^{\frac{1}{n-2}}$ to the above equations:

$$\begin{cases} P_{tr} = 1 - \lambda^{\frac{n-1}{n-2}} \\ P_s = n\lambda^{\frac{n-1}{n-2}}(1-\lambda^{\frac{1}{n-2}}) + n\lambda(1-\lambda^{\frac{1}{n-2}})^2. \end{cases} \tag{13}$$

Hence, saturation throughput is a function of the parameter λ for a given number of participating nodes in the WLAN system, i.e., $T_s = f(\lambda)$:

$$T_s = \frac{nL\Big[\lambda^{\frac{n-1}{n-2}}(1-\lambda^{\frac{1}{n-2}}) + \lambda(1-\lambda^{\frac{1}{n-2}})^2\Big]}{D_\sigma + (1-\lambda^{\frac{n-1}{n-2}})(D_s - D_\sigma) + n\Big[\lambda^{\frac{n-1}{n-2}}(1-\lambda^{\frac{1}{n-2}}) + \lambda(1-\lambda^{\frac{1}{n-2}})\Big](D_s - D_c)}. \tag{14}$$

T_s can be plotted against increasing values of λ (Fig. 2) by using the PHY and MAC parameters shown in Table 1.

It can be observed that T_s is a concave function of λ and hence the optimal value of λ (λ_{opt}) can be determined, which maximizes the saturation throughput by solving the equation $\frac{\partial T_s}{\partial \lambda} = 0$.

4 Numerical Results

In this Section, numerical results are presented for the optimal value of saturation throughput (i.e., its maximum achievable value). For comparison reasons, the numerical results for the FD operation without our game-theoretic approach are also provided. The performance of the half duplex case is intentionally not included, since studies have shown that it exhibits similar performance to the FD case under the standard DCF operation (see [1]). For the latter, the transmission probability, τ, is given by [6]:

Table 1: PHY and MAC Parameters

Parameter	**Value**
Technology	IEEE 802.11ac
MCS index	8
Spatial streams	1
Data rate	780 $Mbps$
Control rate	6 $Mbps$
PHY header duration	44 μs
MAC header length	36 $bytes$
FCS length	4 $bytes$
ACK length	14 $bytes$
RTS length	20 $bytes$
CTS length	14 $bytes$
MPDU length	11454 $bytes$
Slot duration (σ)	9 μs
Propagation delay	1 μs
DIFS	34 μs
SIFS	16 μs
Minimum contention window	32
Maximum contention window	1024
Maximum backoff stage	5

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1) + pW[1-(2p)^m]} \tag{15}$$

where W is the minimum contention window and m the maximum backoff stage.

The conditional collision probability in the FD case is:

$$p = 1 - (1-\tau)^{n-1} - \tau(1-\tau)^{n-2} \tag{16}$$

The above system of equations can be solved to obtain the value of τ and then used to calculate the saturation throughput by solving equation (8).

To obtain the numerical results, the PHY and MAC parameters summarized in Table 1 are used. All equations in our approach are modelled using Python scientific programming.

First, the λ_{opt} value against the number of nodes is plotted and is depicted in Fig. 3. The saturation throughput obtained by the DCF-based FD communication mode and the game-theoretic approach are also plotted in Fig. 4. The values of λ_{opt} were obtained by solving $\frac{\partial T_s}{\partial \lambda} = 0$ for λ.

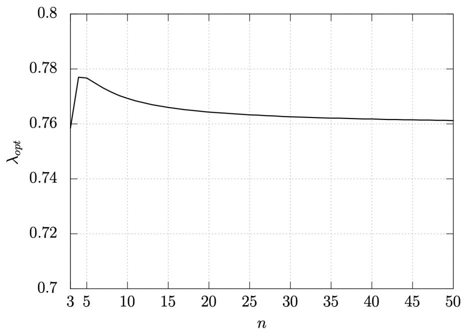

Figure 3: Optimal value of λ (λ_{opt}) for increasing number of nodes.

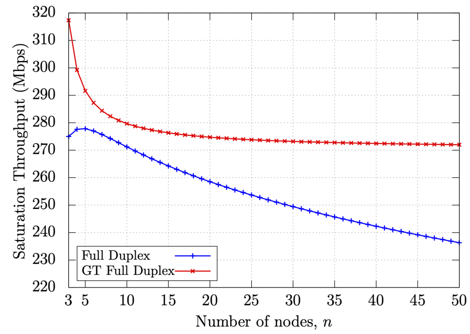

Figure 4: Saturation throughput, T_s, for increasing number of nodes.

It is clear that the game-theoretic scheme outperforms the standard FD mode (i.e., the FD communication mode under DCF functionality), especially as the number of nodes increases. While FD performance exhibits a rapidly decreasing saturation throughput performance, the GT-based FD operation tends to decrease with a slower rate, and thus, outperforming the FD case as the system becomes crowded.

As nodes enter the system there is an increased probability for three or more nodes to transmit at the same time slot. There is also an increased probability when only two nodes transmit simultaneously, that they will not satisfy the second case of successful transmission as described in Section 3.1. Hence, standard FD mode will lead to a rapid decrease in saturation throughput, which is show-casted in Fig. 4. On the other hand, the GT approach will determine the best response for every node based on the different utilities associated with its strategy profile (i.e., the optimal value of λ) which will lead to the optimal (i.e., the maximum) value of saturation throughput.

5 Implementation Details

In terms of implementing the GT approach in real ad-hoc WLANs, the main difficulty rests in the knowledge of the total number of nodes in the system that must be discovered by each node. Since the system operates in FD mode, the number of nodes can be found by rearranging equation (16):

$$n = 2 + \frac{\log(1-p)}{\log(1-\tau)} \tag{17}$$

Hence, a node must estimate at the start of each system time slot the values of τ and p. To this direction a node is required to monitor three parameters [10]: the number of time slots, N_σ, the number of data frames transmitted successfully, N_s and the number of data frame retransmissions, N_r. All these parameters must be updated, up to the point of a new estimation (the start of a new time slot). Then, the values of τ and p can be calculated as follows [10]:

$$\begin{cases} p = \dfrac{N_r}{N_s + N_r} \\ \tau = \dfrac{N_s + N_r}{N_\sigma}. \end{cases} \tag{18}$$

Now, a node can have an estimation of the total number of nodes participating in the WLAN system by solving equation (17), and use the GT approach to determine its transmission probability (i.e., its best response). To achieve its best response, a node must adjust its minimum contention window, W, which can be implemented by solving equation (15) for W:

$$W = \frac{2(1-2p) - \tau + 2p\tau}{\tau - 2p\tau + p\tau[1-(2p)^m]}. \tag{19}$$

6 Conclusions

Although FD communications in WLANs is a feasible and, theoretically, a promising technology, its performance under the current DCF specification is proven to be insignificant, in terms of saturation throughput, when compared to the standard half duplex case. This paper, demonstrates how game theory can be used to achieve the maximum saturation throughput value under the standard DCF operation. It is also shown that the game-theoretic approach presented does allow the FD advantages to manifest, without any modifications to the current DCF specification.

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