CSMA/CA analysis and enhancement for IEEE 802.11ax WLANs operating in STR mode

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An analytical model is described to estimate the performance of the carrier sense multiple access with collision avoidance (CSMA/CA) protocol during the simultaneous transmit/receive (STR) operation of the upcoming IEEE 802.11ax amendment for WLANs. Furthermore, based on that model, an enhancement to the operation of CSMA/CA to increase its performance during the STR mode is proposed.

Introduction: The IEEE 802.11ax amendment [1] is considered as the sixth generation of WLANs and aims at providing high efficiency operation in dense wireless station (STA) deployments. To accomplish that goal, several new features are under consideration by the IEEE standardisation task group. One of these features is the simultaneous transmit/receive (STR) mode of operation which provides full duplex communication among the STAs and the access point (AP) in the wireless environment. However, to efficiently support the STR operation mode, the medium access control (MAC) layer functionality must be adjusted accordingly [2–4].

This Letter has a dual purpose. First, we examine the performance of the current MAC-layer functionality [i.e. carrier sense multiple access with collision avoidance (CSMA/CA)] during STR mode in IEEE 802.11ax WLANs. To accomplish that goal, an analytical model based on Markov chains is provided. Next, we describe an enhancement modification to the functionality of the CSMA/CA protocol in order to facilitate the STR operation mode.

Background: The IEEE 802.11ax amendment specifies orthogonal frequency division multiple access to allow spectrum sharing among the STAs and the AP. Slices of the available spectrum, known as resource units, are assigned to STAs by the AP. By exploiting smart antenna and beamforming techniques at the AP, simultaneous downlink and uplink frame transmissions are feasible through the wireless medium. This means that frame collisions are completely avoided during the STR operation in IEEE 802.11ax WLANs.

IEEE 802.11ax retains the quality of service features defined by its predecessors. Each STA and the AP implement four priority queues, known as access categories (ACs), to accommodate four traffic classes. These ACs are abbreviated as $AC[VO]$, $AC[VI]$, $AC[BE]$ and $AC[BK]$ and they serve voice, video, best effort and background traffic, respectively.

Once a multimedia AC acquires channel ownership, it may retain it to perform multiple sequential frame transmissions for a pre-specified period. This feature is known as transmission opportunity (TXOP) and is available only to multimedia ACs. On the contrary, non-multimedia ACs are allowed to perform one frame transmission per channel access.

Analytical model: In this section, we propose a Markov chain model in order to determine the transmission probability, $\tau[q]$, of a specific $AC[q]$ (with $q \in (VO, VI, BE, BK)$) during STR operation. Based on that probability, we can provide an estimate of the achieved throughput for each $AC[q]$.

For our analysis we assume that all n wireless nodes (including the AP) have a single AC active (being the same AC on all nodes) which operates at saturation conditions. Furthermore, we assume an error-free wireless channel. The model presented is based on previous works described in [5, 6].

Let $s_{[q]}(t)$ be the stochastic process representing the backoff stage $(0, \ldots, m)$ of the $AC[q]$ at time t. Since there is zero probability of frame collisions during the STR mode there is a single backoff stage for each node. Thus, $s_{[q]}(t) = 0$. Furthermore, let $b(t)$ be the stochastic process representing either the backoff time counter k (with $k \in (0, 1, \ldots, W_0[q]-1)$), or the kth transmitted frame (with $k \in (1, 2, \ldots, \nu[q])$) of the $AC[q]$ at time t. $W_0[q]$ is the minimum contention window for $AC[q]$. $\nu[q]$ is the number of frames included in the TXOP of $AC[q]$ and is given by

$$\nu[q] = \left\lfloor \frac{\mathrm{TXOP_{lim}}[q]}{T_{\mathrm{MPDU}} + T_{\mathrm{BA}} + T_{\mathrm{SIFS}}} \right\rfloor \tag{1}$$

where $\mathrm{TXOP_{lim}}[q]$ is the contention-free period available for $AC[q]$. T_{MPDU} and T_{BA} are the transmission times of the data frame (MAC-layer protocol data unit) and the block acknowledgement (BA) frame, respectively. There is no need for a BA request frame preceding the BA transmission, since BA request can be indicated in the data frame. Finally, T_{SIFS} is the short inter-frame space time. Note that $\nu[q] = 1$ for $AC[BE]$ and $AC[BK]$.

In the absence of frame collisions, the only blocking factor of the backoff procedure of a node is the reception of a transmission during the backoff countdown. In this scenario, the node (i.e. STA or AP) will freeze its backoff when it senses another node transmitting in the wireless medium.

To model the current MAC-layer functionality during the STR mode, we propose the one-dimensional Markov chain model depicted in Fig. 1.

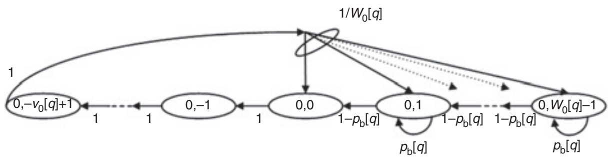

Fig. 1 *One-dimensional Markov chain of an IEEE 802.11ax node during STR mode*

From Fig. 1, the following transition probabilities are straightforward:

$$\begin{cases} P\{0, k|0, k+1\} = 1 - p_b[q], & k \in (0, W_0[q]-2) \\ P\{0, k|0, k\} = p_b[q], & k \in (1, W_0[q]-1) \\ P\{0, k-1|0, k\} = 1, & k \in (0, -\nu[q]+2) \\ P\{0, k|0, 0\} = 1/W_0[q], & k \in (0, W_0[q]-1). \end{cases} \tag{2}$$

The third equation in (2) describes the fact that once the $AC[q]$ reaches its transmission state, multiple frames from that AC may be transmitted sequentially for a period of $\mathrm{TXOP_{lim}}[q]$. Lastly, the fourth equation in (2) models the fact that the backoff is uniformly chosen in the range $(0, W_0[q]-1)$.

Let $b_{0,k} = \lim_{t\to\infty} P\{s_{[q]}(t) = 0, b_{[q]}(t) = k\}$ with $k \in (-\nu[q]+1, -\nu[q]+2, \ldots, W_0[q]-2, W_0[q]-1)$ be the stationary distribution of the proposed Markov chain, and consider that

$$\begin{cases} b_{0,-k} = b_{0,0}, & k \in (1, \nu[q]-1) \\ b_{0,k} = \dfrac{b_{0,0}}{W_0[q](1-p_b[q])} + b_{0,k+1}, & k \in (1, W_0[q]-2) \\ b_{0,k} = \dfrac{b_{0,0}}{W_0[q](1-p_b[q])}, & k = W_0[q]-1. \end{cases} \tag{3}$$

We can now provide a closed-form solution for the Markov chain as below:

$$b_{0,k} = \frac{W_0[q]-k}{W_0[q](1-p_b[q])} \cdot b_{0,0}, \quad k \in (1, W_0[q]-1). \tag{4}$$

As seen in (4), $b_{0,k}$ is a function of $b_{0,0}$ and $p_b[q]$. By imposing the normalisation condition

$$\begin{aligned} 1 &= \sum_{k=0}^{W_0[q]-1} b_{0,k} + \sum_{k=1}^{\nu[q]-1} b_{0,-k} \\ &= b_{0,0} + \frac{b_{0,0}}{1-p_b[q]} \cdot \sum_{k=1}^{W_0[q]-1} \frac{W_0[q]-k}{W_0[q]} + (\nu[q]-1) b_{0,0}. \end{aligned} \tag{5}$$

Substituting the term $\sum_{k=1}^{W_0[q]-1} (W_0[q]-k)/W_0[q]$ with $(W_0[q]-1)/2$ we can obtain $b_{0,0}$

$$b_{0,0} = \frac{2(1-p_b[q])}{W_0[q]-1+2\nu[q](1-p_b[q])}. \tag{6}$$

Now, the transmission probability can be expressed as

$$\tau[q] = b_{0,0} + \sum_{k=1}^{\nu[q]-1} b_{0,-k} = \nu[q] \cdot \frac{2(1-p_b[q])}{W_0[q]-1+2\nu[q](1-p_b[q])} \tag{7}$$

The backoff countdown is blocked when at least one of the other stations transmits

$$p_b[q] = 1 - (1 - \tau[q])^{n-1} \tag{8}$$

Equations (7) and (8) form a set of non-linear equations, which can be solved using numerical methods.

Given the $\tau[q]$ obtained by solving the set of non-linear equations, we can establish an achievable throughput estimation for a particular $AC[q]$ operating at saturation conditions.

First, the successful transmission time of an MPDU burst by $AC[q]$ during TXOP is given by

$$T_s[q] = T_{\mathrm{AIFS}}[q] + \nu[q](T_{\mathrm{MPDU}} + 2 \cdot T_{\mathrm{SIFS}} + T_{\mathrm{BA}}) - T_{\mathrm{SIFS}} \tag{9}$$

where $T_{\mathrm{AIFS}}[q]$ is the arbitration inter-frame space and is given by $T_{\mathrm{AIFS}}[q] = \mathrm{AIFSN}[q] \cdot T_{\mathrm{SLOT}} + T_{\mathrm{SIFS}}$. T_{SLOT} is the slot duration equal to 9 μs and AIFSN$[q]$ is AC specific.

The probability that exactly i nodes begin transmitting in the wireless medium is given by

$$p_i[q] = \tau[q]^i (1 - \tau[q])^{n-i} \tag{10}$$

Now we can obtain an estimate for the achievable throughput, $S[q]$, of $AC[q]$ as below:

$$S[q] = \frac{\sum_{i=1}^{n} p_i[q] \cdot i \cdot \nu[q] \cdot l_{\mathrm{MPDU}}}{T_s[q]}. \tag{11}$$

Performance enhancement: Based on the model presented previously, the influencing factor is $p_b[q]$ which, obviously, increases as the number of actively participating nodes rises. The proposed CSMA/CA enhancement eliminates $p_b[q]$ by allowing every node to continue its backoff decrement even if it detects another transmission. This simple modification can be turned on or off depending on the co-existance of non-STR capable nodes in the network. Each IEEE 802.11ax node has the capability of identifying the STR-capable nodes due to management frames that will carry that information in existing reserved bits of their MAC-layer headers [4]. Upon detecting the presence of legacy-STAs, each STR-capable node will fall back to the legacy CSMA/CA operation.

Although one could argue that disabling the backoff procedure completely and transmit continuously would provide even higher benefits for the STR operation mode, this idea is dismissed since the $1/W_0[q]$ probability facilitates the internal inter-AC contention.

Since $p_b[q] = 0$ under the proposed enhancement, $\tau[q]$ is increased and independent of the blocking probability

$$\tau[q] = \frac{2\nu[q]}{W_0[q] - 1 + 2\nu[q]}. \tag{12}$$

Performance evaluation: To evaluate the performance of both the legacy CSMA/CA protocol and the proposed enhancement, we used the parameters depicted in Table 1.

Table 1: IEEE 802.11ax PHY and MAC parameters

PHY	MAC
$T_{\mathrm{SIFS}} = 16$ μs	AIFSN$[VO, VI, BE, BK] = 2, 2, 3, 7$
Rate(data) = 1201 Mbps	Header(data, control) = 240 bits
Rate(control) = 282 Mbps	$W_0[VO, VI, BE, BK] = 8, 16, 32, 32$
Preamble(data) = 68.8 μs	TXOP$_{\mathrm{lim}}[VO, VI] = 1504, 3008$ μs
Preamble(control) = 64.8 μs	MPDUsize = 11454 bytes

The throughput results per AC with the legacy CSMA/CA operation and the proposed modification are illustrated in Fig. 2.

A first observation is that during STR operation the throughput decreases rapidly as the number of nodes increases due to the increase in $p_b[q]$. This is a finding also implied in [2]. The proposed enhancement provides a significant throughput improvement, especially for $AC[VO]$ and $AC[VI]$ for low number of nodes. On the other hand, the non-multimedia ACs exhibit very low achievable throughput. This stems from the large values of $W_0[BE]$ and $W_0[BK]$ and that $AC[BE]$ and $AC[BK]$ are allowed a single MPDU transmission per channel access. A possible solution would be to assign lower values of minimum contention window and/or allow frame bursting to the non-multimedia ACs. However, care must be taken in order to ensure the internal inter-AC contention.

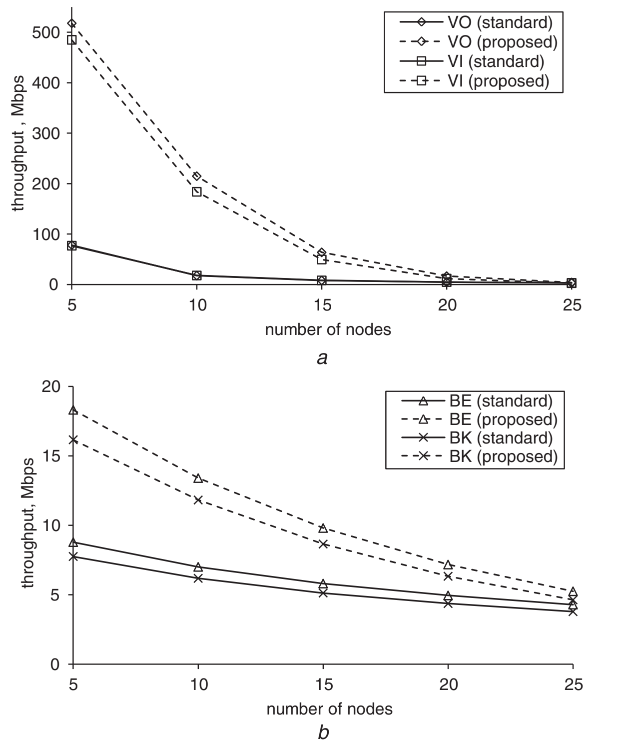

Fig. 2 *Saturation throughput with the standard and the enhanced CSMA/CA operation for*
a $AC[VO]$ and $AC[VI]$
b $AC[BE]$ and $AC[BK]$

Conclusion: This Letter provides, for the first time, an analytical model that describes the functionality of the CSMA/CA protocol during the STR operation mode in IEEE 802.11ax WLANs. Based on that model, a simple enhancement with minimal modifications is introduced to increase the protocol performance. Results indicate a significant performance increment in terms of achieved throughput.

Acknowledgment: This work has been supported by the Research Committee of the Technological Educational Institute of Central Macedonia, Greece, under grant SAT/IE/18418-86/9.

Submitted: *28 February 2018* E-first: *4 May 2018*
doi: 10.1049/el.2018.0716
One or more of the Figures in this Letter are available in colour online.

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