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The Piece-by-Piece Channel Access Paradigm for Wireless Networks: Discussion and Performance Evaluation

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Abstract

In this letter we discuss the Piece-by-Piece (PbP) access paradigm: a novel way of getting access to the widest channel B_w of a WLAN that supports different channel widths. Adapting the IEEE 802.11 DCF access method to PbP leads B_w to be organized into primary channel, in which contention occurs, and secondary narrow orthogonal channels. Upon winning a contention in the primary channel, nodes also get access to each secondary channel but in a sequential way rather than All-at-Once (AaO). Based on infinite horizon steady-state simulations and analytic results, we show that PbP causes the IEEE 802.11 access method to put up to twice more data bits into B_w in comparison to the conventional paradigm.

1 Introduction

The channel width plays a fundamental role to wireless network performance. The Shannon theorem [1] states that the wider the channel width, the higher the link capacity. Hence, an intuitive way to achieve higher throughputs consists in doing the best-effort to access the widest channel B_w supported in a wireless network with channel width diversity (i.e., network that supports different channel widths). However, such is a hard challenge specially in unlicensed bands that have potential to be rapidly crowded. In this context, Chandra et al. [2] report the first study about using different channel widths in WLANs. They argue that channel width should be adaptive per specified policy. Then when throughput maximization is required, nodes should be provided with B_w each time the access protocol grants them the right to get access to the medium (i.e., the Transmission OPportunity, TxOP). In accordance with this trend, different proposals have employed an adaptive method to maximize throughput and channel spectrum usage in the presence of multiple contending nodes (e.g. [3, 4]). A notable instance in this sense is the dynamic channel access method of the emerging IEEE 802.11ac standard [5], in which nodes compete to get access to B_w at once whenever possible. We refer to this as the *All-at-Once* (AaO) channel access paradigm.

In this letter we firstly discuss the recent literature's findings to identify the negative side-effects of the AaO paradigm on network throughput. Thus, rather than evolving any prior AaO proposal, we argue for an alternative paradigm that we refer to as the Piece-by-Piece (PbP) access paradigm. In that, nodes never get access to B_w at once, even if it is entirely idle by the time of the TxOP. Adapting the 802.11 DCF access method to PbP leads B_w to be organized into primary channel, in which contention occurs, and secondary narrow orthogonal channels. Upon winning a contention in the primary channel, nodes also get access to each secondary channel but in a sequential way rather than All-at-Once (AaO). By expanding the so-called Bianchi's IEEE 802.11 DCF performance model [6] to account the PbP paradigm we show that PbP causes the access method to put up to twice more data bits into B_w in comparison to the AaO paradigm.

2 AaO paradigm Shortcomings

In a WLAN access method under the AaO paradigm, one underlying axiom is that capacity is proportional to channel width. Although such statement holds from the perspective of a particular link (Shannon theorem [1]), it not necessarily does from the perspective of a whole network, where the contention overhead among several nodes impairs network capacity. Different from narrow channels that require less subcarriers idle in the medium before transmitting, to get access to B_w entirely becomes harder as chunks of it get busy by third party activities.

The employment of wide channels can also suffer from shortcomings even if one considers a single transmission aside from contention limitations. Indeed, the wider the channel, the more data bits it can carry per wireless symbol. In turn, the Signal to Noise Ratio (SNR) requirement to successfully demodulate a wireless symbol increases as it carries more data bits. Nonetheless such a requirement, wide channels are more prone to noise than narrow ones due to delay spread [2]. Additionally, they decrease the signal strength with which waves leave the card because the same transmit power is uniformly distributed across a higher number of subcarriers [4]. The IEEE 802.11ac, for instance, requires an improvement of at least 3 dB (about $10\log(B_1/B_2)$ dB) at the receiver sensitivity to keep same modulation when channel width doubles from B_2 MHz to B_1 MHz [5].

In summary, these limitations make a case for an alternative access method paradigm based on narrow channels. In this sense, recent proposals in the literature have proposed to split the widest supported channel B_w into narrow orthogonal channels to provide WLANs with multiple concurrent transmissions [7][8]. In these proposals the access method can not benefit from all narrow channels within B_w per TxOP, since such channels are governed by independent instances of the IEEE 802.11 DCF running in parallel. In the PbP paradigm we propose nodes can coordinate to get access to multiple orthogonal channels per TxOP through a single access method.

3 The PbP Access Paradigm

The main goal of the PbP paradigm is twofold, namely, to make each TxOP benefiting from the good properties of narrow channel transmissions without sacrificing the right to get access to all narrow channels within B_w. To demonstrate such paradigm in action, in this section we briefly overview the IEEE 802.11 DCF access method and describe general guidelines to adapt it to PbP.

3.1 The AaO IEEE 802.11 Access Method: Overview

The IEEE 802.11 DCF access method couples the widely known CSMA/CA method together an exponential backoff algorithm to get access the channel. In earlier versions of the standard (e.g. IEEE 802.11b), the channel width is fix in 20 MHz, which makes their corresponding access method AaO by nature. Even in versions of the standard that support multiple channel widths (e.g. 5, 10 and 20 MHz in 802.11a) the access methods are also AaO because they drive each node to get access to the widest idle channel regardless its width. In the emerging IEEE 802.11ac, for instance, most of the contention procedure is performed in a 20 MHz wide channel P_c named *primary channel*. If one or three additional 20 MHz channel adjacent to P_c (named *secondary channels*) are idle a PIFS before the transmission in P_c, then they are also reserved to achieve a 40 MHz or 80 MHz transmission, respectively.

3.2 PbP-DCF: Adapting the IEEE 802.11 DCF to PbP

Similarly to the channelization adopted in [5], adapting the IEEE 802.11 DCF to PbP (i.e., PbP-DCF), requires to organize the widest supported channel B_w into N_c narrow orthogonal channels with width $B_n < B_w$, i.e. $N_c = B_w/B_n$. Among these channels, one plays the role of P_c and all other are secondary channels. After winning a contention in P_c, a node is granted with the right to sequentially get access to the remainder $N_c - 1$ secondary channels with no extra backoff. More precisely, before transmitting through the j-th narrow channel ($0 \leq j < N_c - 1$), the winning node sets a Channel Negotiation Bit (CNB) in the data frame asking its destination to transmit another frame via the $j+1$-th channel. In turn, the destination acknowledges that by setting similar bit in its ACK.

To restrict transmissions within B_w to a specific piece j can be achieved in different ways. One example is the OFDM nulling technique, in which specific subcarriers of a transmission can be released by feeding them with zero power. A concern in this sense happens when a node unilaterally decides the portion of spectrum to transmit [3]. However, PbP-DCF naturally overcomes that by means of the CNB. Finally, the whole contention procedure is restarted in P_c if any error occurs or if the $(Nc-1)$-th transmission succeeds. The performance model we propose in the next section captures the whole dynamics intrinsic to PbP-DCF. Deeper details about operational aspects of the PbP-DCF protocol we leave to future work.

4 PbP-DCF Throughput Analysis

In [6], Bianchi proposes a bi-dimensional Markovian process to compute the throughput of a 802.11 DCF system assuming saturated traffic and ideal channel conditions. The model has been shown as very accurate and is a good foundation to assess the performance intrinsic to any access scheme based on the 802.11 DCF. In this sense, we expand such model using same notation and assumptions to also account the channel stochastic process $h(t)$ of a station at the time t, in addition to the stochastic processes for backoff stage and counter $s(t)$ and $b(t)$, respectively. Next we explain the resulting PbP-DCF model.

The backoff *stage* $i \in [0, m]$ of a station at time t refers to the increments in the contention interval W_i upon collisions i.e. $W_i = 2^i W$ where W and $2^m W$ are the sizes of the minimum and maximum contention intervals, respectively. Once a station reaches stage i, it picks a uniform random number $k \in [0, W_i - 1]$ to *count* down before accessing the primary channel. A successful transmission in the primary channel leads a station to transmit in the remainder $N_c - 1$ (secondary) channels following a PbP approach, i.e., $c \in [0, N_c - 1]$ where N_c is the number of channels. Upon these observations, the three-dimensional process $\{s(t), b(t), h(t)\}$ consists in a discrete-time Markov chain (as illustrated in Fig. 1) whose nonnull one-step transition probabilities are:

$$\begin{cases} P_{i,k,0|i,k+1,0} = 1, & k \in [0, W_i - 2]; i \in [0, m] \\ P_{i,0,1|i,0,0} = 1 - p, & i \in [0, m] \\ P_{i,0,c|i,0,1} = 1, & i \in [0, m]; c \in [2, N_c - 1] \\ P_{0,k,0|i,0,N_c-1} = 1/W_0, & i \in [0, m]; k \in [0, W_0 - 1] \\ P_{i,k,0|i-1,0,0} = p/W_i, & i \in [1, m]; k \in [0, W_i - 1] \\ P_{m,k,0|m,0,0} = p/W_m, & k \in [0, W_m - 1] \end{cases}$$

Let $b_{i,k,c} = \lim_{t\to\infty} P\{s(t) = i, b(t) = k, h(t) = c\}$ $i \in [0, m]$, $k \in [0, W_i - 1]$ and $c \in [0, N_c - 1]$ be the stationary distribution of the chain. A corresponding closed-form solution can be obtained by firstly noting that our protocol behaves just like the IEEE 802.11 DCF *while a data frame transmission does not succeed* in the primary channel. Consequently, under such condition, the Bianchi model becomes a case of ours and the following equalities hold for $c = 0$ and $k \in [1, W_i - 1]$:

$$\begin{aligned} b_{i,0,0} = b_{i-1,0,0} \cdot p \rightarrow b_{i,0,0} = p^i \cdot b_{0,0,0} \qquad 0 < i < m \\ b_{m-1,0,0} \cdot p = (1 - p) b_{m,0,0} \cdot p \rightarrow b_{m,0,0} = \frac{p^m}{1 - p} \cdot b_{0,0,0} \end{aligned} \tag{1}$$

$$b_{i,k,c} = \frac{W_i - k}{W_i} \cdot \begin{cases} (1 - p) \sum_{j=0}^{m} b_{j,0,N_c-1} & i = 0 \\ p \cdot b_{i-1,0,0} & 0 < i < m \\ p \cdot (b_{m-1,0,0} + b_{m,0,0}) & i = m \end{cases} \tag{2}$$

Upon a successful transmission in the primary channel at any stage $i \in [0, m]$, a node transmits in each secondary channel $c \in [1, N_c - 1]$ in the stage i and

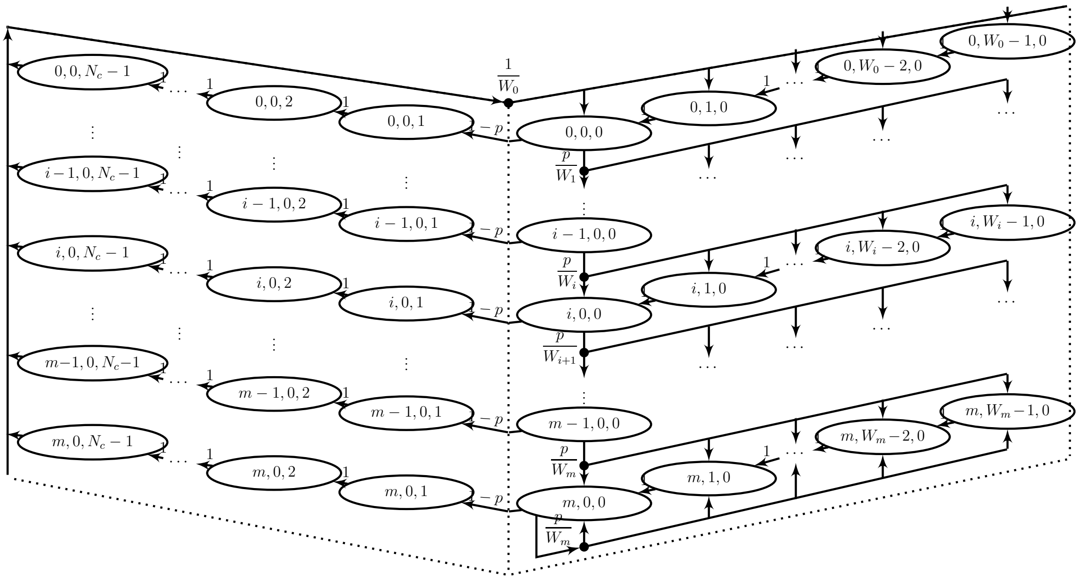

Figure 1: Markov chain model for the PbP-DCF channel access scheme.

goes back to the first stage in the primary channel. As a consequence of keeping the basic assumptions of the Bianchi model [6], a station transmits with no contention on secondary channels if it does not collide in the primary channel for each stage i. Then it is true that $b_{i,0,N_c-1} = \cdots = b_{i,0,2} = b_{i,0,1} = (1-p)b_{i,0,0}$ and:

$$b_{0,0,0} = \sum_{i=0}^{m} b_{i,0,N_c-1} \rightarrow \sum_{i=0}^{m} b_{i,0,0} = \frac{b_{0,0,0}}{(1-p)} \tag{3}$$

Based on relations (1) and (3), and considering the chain regularities for each $c \in [0, N_c-1]$, $i \in [0,m]$ and $k \in [0, W_i-1]$, (2) becomes:

$$b_{i,k,c} = \begin{cases} \dfrac{W_i-k}{W_i} b_{i,0,0} & c=0 \\ (1-p)b_{i,0,0} & 0<c<N_c \end{cases} \tag{4}$$

By means of (1) and (4) it is possible to express all occurrences of $b_{i,k,c}$ in terms of the collision probability p and $b_{0,0,0}$. This latter can be determined by imposing the normalization condition, as follows:

$$
\begin{aligned}
1 &= \sum_{c=0}^{N_c-1} \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} b_{i,k,c} = \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} \sum_{c=0}^{N_c-1} b_{i,k,c} \\
&= \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} \left(\frac{W_i - k}{W_i} b_{i,0,0} + \sum_{c=1}^{N_c-1} (1-p) b_{i,0,0} \right) \\
&= \left(\sum_{i=0}^{m} b_{i,0,0} \frac{2^i W + 1}{2} \right) + (1-p) \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} \sum_{c=1}^{N_c-1} b_{i,0,0} \\
&= \frac{b_{0,0,0}}{2} \cdot \left[W \left(\frac{1-(2p)^m}{1-2p} + \frac{(2p)^m}{1-p} \right) + \frac{1}{1-p} \right] + \\
&\quad (1-p) b_{0,0,0} (N_c - 1) W \left[\frac{1-(2p)^m}{1-2p} + \frac{(2p)^m}{1-p} \right] \qquad (5)
\end{aligned}
$$

from which

$$
b_{0,0,0} = \frac{2(1-p)(1-2p)}{[W - pW(1+(2p)^m)][1+2(1-p)(N_c-1)]+1-2p} \qquad (6)
$$

Now, the probability that a station transmits in a randomly chosen time slot can be determined from the probabilities τ_1 and τ_2, that represent the probabilities of transmission in the primary and the secondary channels, respectively. Based on the fact that $\tau_1 = \sum_{i=0}^{m} b_{i,0,0} = b_{0,0,0}/(1-p)$, on (4) and (6), τ_2 can be determined as follows:

$$
\tau_2 = \sum_{i=0}^{m} \sum_{c=1}^{N_c-1} b_{i,0,c} = (1-p)(N_c-1)\tau_1 \qquad (7)
$$

Strictly speaking, the transmission probability of a station depends on both the probability of a node to transmit in the primary channel τ_1 and the number of secondary channels $N_c - 1$. Since collisions can happen in the primary channel, τ_1 is a function of the collision probability p. In turn, p can be determined considering that collisions arises whenever the time intervals of different transmissions overlap. Particularly, given n stations, p is given by $1-(1-\tau_1)^{n-1}$ [6].

p and τ_1 (then τ_2) can be computed by numerical techniques. From these values, it is possible to determine $P_{tr}(\tau)$ (8) and $P_s(\tau, \kappa)$ (9). The former is the probability that in a slot time there exists at least one transmission through the piece of spectrum whose access probability is τ. The latter is the probability that, in a single slot time of the system, κ simultaneous transmissions are successful in a portion of spectrum whose access probability is τ. In the proposed PbP scheme, these probabilities are $P_{tr}(\tau_1)$ and $P_s(\tau_1, 1)$ (shorter P_{tr1} and P_{s1}), for the primary channel, and $P_{tr}(\tau_2)$ and $P_s(\tau_2, N_c - 1)$ (shorter P_{tr2} and P_{s2}) for the overall spectrum of the secondaries channels.

$$P_{tr}(\tau) = 1 - (1 - \tau)^n \tag{8}$$

$$P_s(\tau, \kappa) = \frac{n\tau(1 - \tau)^{n-\kappa}}{1 - (1 - \tau)^n} \tag{9}$$

In turn, the normalized system throughput S is defined as the fraction of time used to successfully transmit payload bits in the overall available spectrum of the network, it is:

$$S = S_1 + S_2 \tag{10}$$

In the proposed PbP-DCF, S is given by (11) plus (12), that are the throughputs simultaneously achieved in the primary and secondaries channels, respectively. They are

$$S_1 = \frac{P_{s1}P_{tr1}E[P]}{P_{s1}P_{tr1}T_s + P_{tr1}T_c(1 - P_{s1}) + (1 - P_{tr1})\sigma} \tag{11}$$

$$S_2 = \frac{P_{s2}P_{tr2}E[P]}{P_{s2}P_{tr2}T_s + P_{tr1}T_c(1 - P_{s2}) + (1 - P_{tr2})\sigma} \tag{12}$$

where $E[P]$ is the average packet length, T_s and T_c are the average time a channel is sensed busy due to a successful transmission and a collision, respectively. Particularly for the basic access mode of IEEE 802.11, they are defined as follows:

$$T_s = H + E[P]_t + SIFS + \delta + ACK + DIFS + \delta \tag{13}$$

$$T_c = H + E[P]_t + DIFS + \delta \tag{14}$$

in which $E[P]_t$ is the time to transmit the data payload, H is the time spent to transmit the MAC and PHY overheads (header + frame check sequence and preamble + header, respectively) and δ is the propagation delay.

5 Model Validation and Conclusion

To validate the model and evaluate the PbP-DCF scheme, we performed infinite-horizon simulations [9] on the Network Simulator 3 [10]. We compare our scheme under $N_c = 2 \times 10$ MHz against AaO 802.11a DCF (20 MHz) for the basic access mode. The common parameters are reported in table 2 while the channel-width related ones are as specified in [11]. Particularly, the

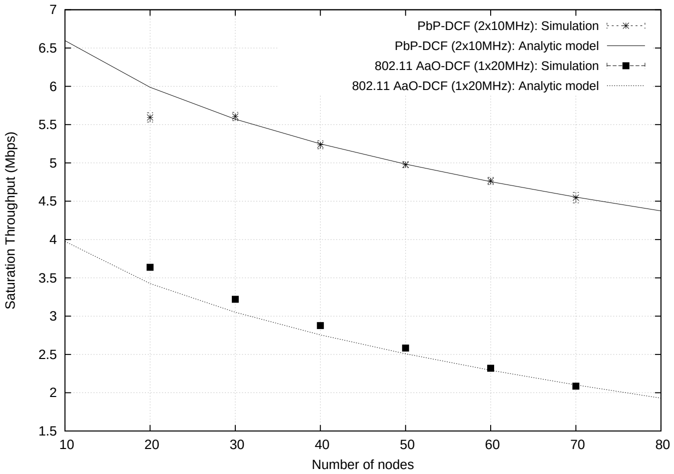

Figure 2: PbP-DCF × AaO-DCF: Saturation throughput for the IEEE 802.11a basic access mode with $m = 3$ e $W = 16$

data modulation scheme set for AaO-DCF is BPSK 1/2 ("6 Mbps"), which requires a receiver sensitivity of -82 dBm [11]. The standard also mandates that same sensitivity as enough to employ QPSK 1/2 in 10 MHz channel ("6 Mbps") but we use BPSK 3/4 ("4.5 Mbps") to be conservative. Finally, the saturation throughput steady-state mean $\overline{X}$, half width of confidence interval H (with 95% of confidence and relative error below 0.05), number of simulated samples s and number of discarded transient samples d^* are reported on table 1 for n nodes.

Fig. 2 shows the model is accurate to capture performance of schemes. Regarding performance, PbP-DCF clearly outperforms throughput of AaO-DCF. The key reason behind that is twofold: lower contention and high throughput per transmission opportunity. In other words, the PbP approach can keep multiple nodes simultaneously transmitting in different pieces of the spectrum without sacrificing their rights to fully use it upon winning a contention in the primary channel. In fact, when a node's transmission finishes in the 10 MHz primary channel, it is allowed to transmit via the 10 MHz secondary channel, resulting in an effective use of 20 MHz. Moreover, compared to wide channels, narrow channel transmissions improve SNR [2][4] and require lower sensitivity [11]. Then, each transmission can employ better modulation schemes. Taken together, they almost double the throughput achieve by a wide channel alone, as shown in the figure.

n	Scheme(N_c×MHz)	$\overline{X}$(Mbps)	H	s	d^*
20	PbP-DCF (2×10)	5.59	0.0603551	1482	247
	AaO-DCF (1×20)	3.63	0.00449008	1506	251
30	PbP-DCF (2×10)	5.60	0.0543127	1530	255
	AaO-DCF (1×20)	3.21	0.00526956	1548	258
40	PbP-DCF (2×10)	5.23	0.0520148	1500	250
	AaO-DCF (1×20)	2.87	0.00624076	1500	250
50	PbP-DCF (2×10)	4.97	0.0384245	1494	249
	AaO-DCF (1×20)	2.58	0.00464795	1566	261
60	PbP-DCF (2×10)	4.76	0.0466859	1632	272
	AaO-DCF (1×20)	2.31	0.00483892	1446	241
70	PbP-DCF (2×10)	4.54	0.0684082	1530	255
	AaO-DCF (1×20)	2.08	0.00459679	1452	242

Table 1: PbP-DCF×AaO-DCF: steady-state simulation throughputs.

Table 2: Common simulation parameters.

Packet payload	1436 bytes
MAC overhead	224 bits
ACK length	112 bits
Control modulation scheme	BPSK 1/2
Propagation delay	1 μs

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