All-at-Once or Piece-by-Piece: How to Access Wide Channels in WLANs with Channel Width Diversity?

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***Abstract*—In this letter we propose the Piece-by-Piece (PbP) medium 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 AaO paradigm.**

***Index Terms*—Multiple access protocol, VHT IEEE 802.11, dynamic channel width, performance evaluation.**

I. Introduction

Channel width plays a fundamental role to the performance of wireless networks. A common policy adopted in the design of Medium Access Control (MAC) protocols consists in doing the *best-effort* to get access to the widest channel B_w supported in a wireless network (e.g. [1][2][3]). We refer to this as the *All-at-Once* (AaO) MAC paradigm. The AaO's underlying axiom comes from the Shannon theorem [4], which states that throughput is proportional to channel width. However, although this holds for a single link, it does not necessarily do for actual WLANs, where contention overhead among several nodes impairs the network capacity. Moreover, getting access to B_w at once require it to be entirely idle, which can become harder as wider channels are supported.

AaO MAC protocols also suffer from higher Signal to Noise Ratio (SNR) requirements to keep Bit Error Rate (BER) low. The WLAN standards [5][1], for instance, require an improvement of at least 3 dB in the 'receiver minimum input sensitivity' every time a channel width doubles for a modulation scheme, even considering the abilities of OFDM to cope with narrowband interference and fading. In fact, notwithstanding OFDM organizes the channel into *narrow* orthogonal subcarriers to combat fading, it simultaneously feeds them with a single power of source. Thus, the signal strength with which each subcarrier leaves the card becomes weaker as wider channels are allowed [6][3]. This explains why OFDM can improve fading mitigation against other modulation schemes but becomes more prone to impairments as channel width increases. To face that, recent proposals split B_w into N_c narrow orthogonal channels to provide WLANs with concurrent transmissions e.g. [7]. However such arrangement cannot mitigate network's collision probability since it enables all nodes to simultaneously compete to all available sub-channels.

Manuscript received July 24, 2013. The associate editor coordinating the review of this letter and approving it for publication was E. Liu.

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Digital Object Identifier 10.1109/LCOMM.2013.091913.131699

In face of the AaO MAC paradigm limitations, in this letter we propose the Piece-by-Piece (PbP) MAC paradigm. In it, nodes never get access to B_w at once, even if it is entirely idle at the time of the transmission opportunity. Based on analytic and simulation results we show that PbP causes the IEEE 802.11 access method to put up to twice more data bits into B_w against the AaO MAC paradigm.

II. The PbP MAC Paradigm

The main goal of the PbP MAC paradigm is to provide nodes with the good SNR properties of narrow channel transmissions without preventing them to entirely get access to B_w after winning a contention. To demonstrate such paradigm in action, we briefly overview the IEEE 802.11 DCF MAC and describe general guidelines to adapt it to PbP.

A. 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 back-off algorithm for channel access control. In earlier versions of the standard (e.g. IEEE 802.11b), the channel width is fix in 20 MHz, which makes the access method AaO by nature. By its turn, the dynamic access method of the emerging IEEE 802.11ac also falls in the AaO MAC paradigm. In it, 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. Consequently, when secondary channels are always idle, a single IEEE 802.11ac WLAN behaves just like a bandwidth static network in which all nodes compete to get access to an 80 MHz wide channel at once.

B. PbP-DCF: Adapting the IEEE 802.11 DCF to PbP

Similarly to the channelization adopted in the IEEE 802.11ac [1], 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. $N_c = \lfloor B_w/B_n \rfloor$. Among these channels, one plays the role of P_c and all other are secondary channels. After winning a contention in P_c and getting access to it, a node is also granted with the right to *sequentially* get access to the each secondary channel $c \in [1, N_c - 1]$ with no extra back-off.

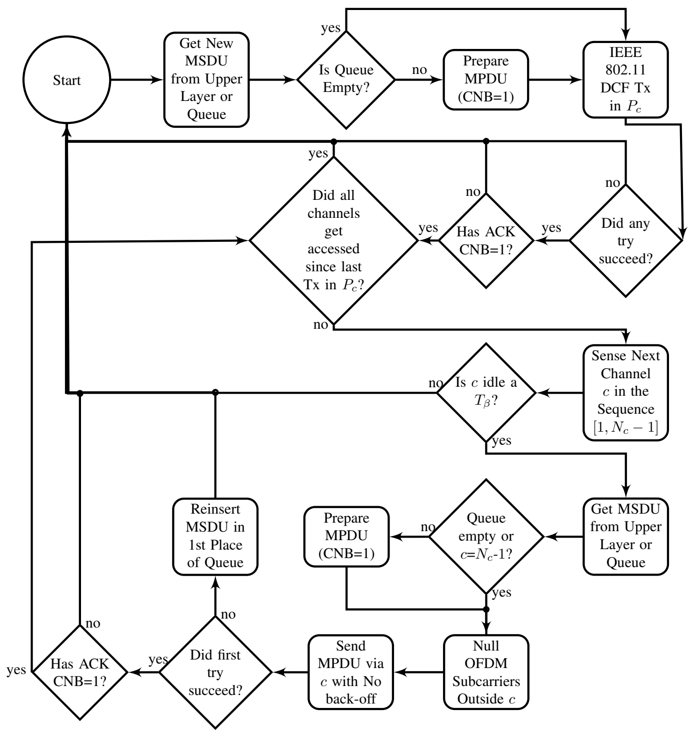

Fig. 1. General guidelines to adapt the IEEE 802.11 transmission procedure (Tx) to the PbP MAC paradigm: resultant flowchart. For simplicity, it is assumed one MSDU yields one MPDU.

The general guidelines to adapt the IEEE 802.11 Transmission procedure (Tx) is illustrated on the flowchart of Fig. 1. After getting a MSDU (MAC Service Data Unit) from the queue, the sending node prepares the corresponding MPDU (MAC Protocol Data Unit) with the *Channel Negotiation Bit* (CNB) bit equals to 1 if there is still one MSDU awaiting in the queue. CNB=1 indicates to the destination that the sending node intends to send other data frame in the next channel c of the sequence $[1, N_c - 1]$. Then, the sender follows the typical IEEE 802.11 procedure in P_c to contend and send the MPDU. If this succeeds, it will receive an ACK with CNB=1, meaning that the destination is now waiting the other MPDU in the next c during a configurable period of time T_α (Rx process not shown in the flowchart). Then, if sender did not get access to all channels in the sequence $[1, N_c-1]$ since last transmission in P_c, it senses the next c by a configurable period of time $T_\beta < T_\alpha$ (e.g. T_β=PIFS, T_α=ACK duration + DIFS (DCF Inter Frame Space time interval)). In case medium is idle during T_β, the sender nulls all OFDM subcarriers outside the current secondary channel c and *immediately* sends other MPDU. Finally, the whole procedure is restarted in P_c if all sequential transmissions succeed or if any one of the failure conditions described in Fig. 1 takes place.

III. PbP-DCF Saturation Capacity

In [8], Bianchi proposes a Markovian process to compute the throughput of an 802.11 DCF system assuming saturated traffic and ideal channel conditions. 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 back-off stage and counter $s(t)$ and $b(t)$, respectively. Next, we explain the resulting PbP-DCF analytic model.

The back-off *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., $c \in [0, N_c - 1]$. Upon these observations, the three-dimensional process $\{s(t), b(t), h(t)\}$ consists in a discrete-time Markov chain (as illustrated in Fig. 2) 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 $k \in [1, W_i - 1]$:

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

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

Upon a successful transmission in the primary channel at any stage $i \in [0, m]$, a node transmits in each secondary channel $c \in [1, N_c - 1]$ of i and goes back to the first stage in the primary channel. As a consequence of keeping the basic assumptions of the Bianchi model [8], a station transmits with no contention on secondary channels of i if it does not collide in the primary channel. Then it is true that $(1-p)b_{i,0,0} = b_{i,0,1} = b_{i,0,2} = \cdots = b_{i,0,N_c-1}$ and:

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

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:

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

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 $b_{0,0,0}$.

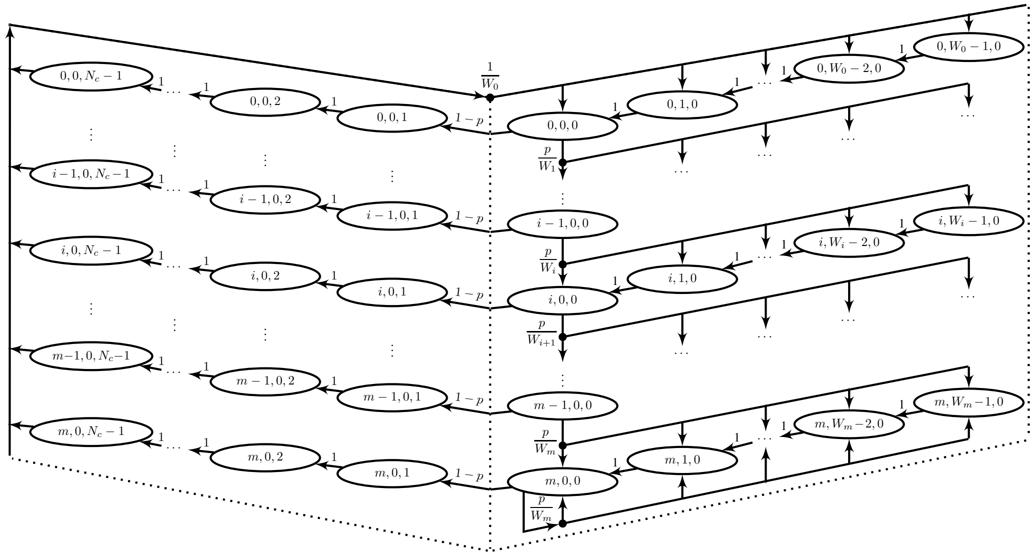

Fig. 2. Markov chain model for the PbP-DCF channel access method.

This latter can be determined by imposing the normalization condition, as follows:

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

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 $1-(1-\tau_1)^{n-1}$ [8].

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 PbP-DCF ($N_c = 2$), 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 secondary channel.

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

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

In turn, the normalized system throughput S is defined as the fraction of time used to successfully transmit payload bits in the overall spectrum within B_w. In the proposed PbP-DCF, S is given by the throughput simultaneously achieved in the primary plus secondary channels. They are asymptotic bounded by S_1 (10) and S_2 (11), respectively.

$$S_1 = \frac{P_{s1}P_{tr1}E[P]}{P_{s1}P_{tr1}T_s + P_{tr1}(1-P_{s1})T_c + (1-P_{tr1})\sigma} \qquad (10)$$

$$S_2 = \frac{P_{s2}P_{tr2}E[P]}{P_{s2}P_{tr2}T_s + P_{tr1}(1-P_{s2})T_c + (1-P_{tr2})\sigma} \qquad (11)$$

In (10) and S_2 (11), $E[P]$ 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:

$$T_s = H + E[P]_t + SIFS + \delta + ACK + DIFS + \delta \qquad (12)$$

$$T_c = H + E[P]_t + DIFS + \delta \qquad (13)$$

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.

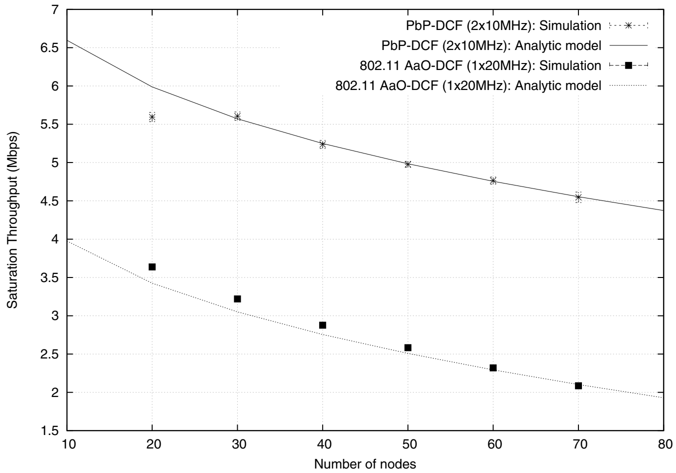

Fig. 3. PbP-DCF × AaO-DCF: Saturation throughput for the IEEE 802.11a basic access mode with $m = 3$ and $W = 16$.

TABLE I
SATURATION THROUGHPUT: ANALYTIC × STEADY-STATE SIMULATION

n	DCF:N_c×MHz	S(Mbps)	$\overline{X}$(Mbps)	H	s	d^*
20	PbP (2×10)	5.98	5.59	0.0603	1482	247
	AaO (1×20)	3.42	3.63	0.0044	1506	251
30	PbP (2×10)	5.57	5.60	0.0543	1530	255
	AaO (1×20)	3.05	3.21	0.0052	1548	258
40	PbP (2×10)	5.24	5.23	0.0520	1500	250
	AaO (1×20)	2.75	2.87	0.0062	1500	250
50	PbP (2×10)	4.98	4.97	0.0384	1494	249
	AaO (1×20)	2.50	2.58	0.0046	1566	261
60	PbP (2×10)	4.75	4.76	0.0466	1632	272
	AaO (1×20)	2.29	2.31	0.0048	1446	241
70	PbP (2×10)	4.55	4.54	0.0684	1530	255
	AaO (1×20)	2.10	2.08	0.0045	1452	242

IV. RESULTS DISCUSSION AND FUTURE DIRECTIONS

To validate the model and evaluate the PbP-DCF protocol, we performed infinite-horizon simulations [9] on the Network Simulator 3.14.1 [10]. We compare PbP-DCF under $N_c = 2 \times 10$ MHz against the AaO 802.11a DCF (20 MHz) for the basic access mode. The common parameters are reported on table II while the channel-width related ones are as specified in [5]. Particularly, the data modulation scheme set for AaO-DCF is BPSK 1/2 ("6 Mbps"), which requires a receiver sensitivity of -82 dBm [5]. 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 S and its 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 I for n nodes.

Fig. 3 shows the model accurately follows the performance of MAC the protocols. Regarding comparison, PbP-DCF clearly outperforms throughput of AaO-DCF. The key reason behind that is twofold: *lower contention*, since PbP-DCF can keep up to N_c collision-free simultaneous transmissions within B_w, and *efficient spectrum usage*, since individual nodes can take advantage of all subchannels of B_w after winning a contention in the primary channel. These results make a strong case for PbP MACs, especially where design of advanced hardware to sustain SNR requirements of wide channel leads to higher cost and is limited to the constraints of mobile devices. Further, we also believe that the PbP MAC paradigm represents an important advance for the emerging generation of full duplex radios e.g. [11][12], where a single-card node could manage multiple independent simultaneous transmissions based on a single PbP MAC instance. In this sense, we leave deeper researches for future work.

TABLE II
COMMON PARAMETERS VALUES.

Packet Payload	1436 bytes
Application Layer Data Rate	10 Mbps
MAC Header and FCS	224 bits [5]
ACK Length	112 bits [5]
Minimum Contention Window Size W	16 slots
Number of back-off Stages m	3
Control Modulation Scheme	BPSK 1/2
Propagation Delay	1 μs

ACKNOWLEDGEMENTS

The author wishes to thank prof. Michele Nogueira for her comments to the first version of the manuscript.

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