

**Sittin’ On the Dock of the (WiFi) Bay:**
On the Frame Aggregation under IEEE 802.11 DCF

Ricardo J. Rodríguez*, Member, IEEE, José Luis Salazar, and Julián Fernández-Navajas

Abstract—It is well known that frame aggregation in Internet communications improves transmission efficiency. However, it also causes a delay that for some real-time communications is inappropriate, thus creating a trade-off between efficiency and delay. In this paper, we establish the conditions for frame aggregation under the IEEE 802.11 DCF protocol to be beneficial on average delay. To do so, we first describe the transmission time in IEEE 802.11 in a stochastic framework and then we calculate the optimal value of the frames that, when aggregated, saves transmission time in the long term. Our findings, discussed with numerical experimentation, show that frame aggregation reduces transmission congestion and transmission delays.

Index Terms—Wireless communication, Multiplexing

I. INTRODUCTION

WiFi protocols have evolved to achieve higher and higher transmission speeds, giving rise to different standards, such as 802.11a/b/g/n/ac. Older standards are superseded by newer standards and must coexist in the same implementation to ensure backward compatibility. Those with a lower rate provide greater coverage, while those with a higher rate force the terminals to be closer. When the terminals are far away, there is a lower transmission rate, so the aggregation of frames in WiFi has been seen as an improvement in efficiency (less bandwidth overhead), but it increases the risk of causing delays. For instance, this situation can be problematic in real-time services such as VoIP, video conferencing, or online gaming, where the transmission delay must not exceed certain limit values to satisfy the user experience. In this paper, we study how frame aggregation causes delays and how this deterioration can be quantified, especially for those standards (or lower rate situations) where it is more relevant to give a correct solution (e.g., 802.11b/g).

IEEE 802.11 DCF (Distributed Coordination Function) is the medium access control used by WiFi [1], which is based on Carrier Sense Multiple Access/Collision Avoidance and operates at layer 2 of the OSI model. CSMA/CA is a network arbitration protocol which regulates communication between multiple nodes communicating through a single channel.

CSMA/CA works as follows. When a node wants to transmit, it first checks if the channel is free. When the node detects that the medium is continuously free for a time defined by the DCF Interframe Space (DIFS), then it is allowed to transmit its data frame. The receiving node will send an acknowledgment (ACK) frame after a time, specified by SIFS (Short Interframe Space), when the sent frame is successfully received. Conversely, when the node detects that the medium is busy, it postpones its transmission until the end of the current transmission. After an additional DIFS interval, the node generates a random backoff period for an additional deferral time before transmitting. That is, the node generates an integer $i$ uniformly distributed in the interval $\{0, 1, ..., CW\}$, where $CW$ is an integer within the range of $aCW_{min}$ and $aCW_{max}$, i.e., $aCW_{min} \leq CW \leq aCW_{max}$. The $aCW_{min}$ and $aCW_{max}$ values are the minimum and maximum time for the content window and depend on the characteristics of the physical layer. Then, the node waits for the $i$ SLOT intervals before transmitting. The SLOT value also depends on the characteristics of the physical layer.

When another node transmits before the backoff period ends, the countdown stops, and the remaining time is used on the next transmission attempt. When two nodes have the same backoff period (or the remaining backoff values), they will transmit at the same time and therefore their transmissions collide. The station detects the collision as it will not receive the ACK frame from the receiving node. When this happens, an exponential backoff algorithm is applied, i.e., $CW$ is doubled up to $aCW_{max}$ for the next transmission attempt.

In [2] a complete study of IEEE 802.11 DCF performance is presented considering throughput, fairness, and delay. As the authors indicate, CSMA/CA supports long-term fairness by achieving the best performance for a small number of nodes, although it suffers short-term unfairness when the number of nodes exceeds the optimal value, as nodes whose transmission collides will increase their content window and then they will be less likely to access the medium.

Note that CSMA/CA exhibits some randomness as a random integer is computed to calculate the backoff period and the data payload of each frame (although it is limited to a maximum of 1500 bytes, it is likely to be different in each frame). In this work, we want to show that under certain conditions, frame aggregation can reduce the average delay. In this regard, we first consider this randomness to better characterize the transmission time of a frame under IEEE 802.11, which allows us to obtain an analytical solution to our problem. Then, we calculate the optimal value of the frames that, when aggregated, saves transmission time in the long term. Finally, we present and discuss some numerical experiments.

This paper is organized as follows. Section II reviews related
work. Section III details the characterization of frame transmission time by means of random variables. Then, Section IV establishes the formulae to calculate the optimal number of aggregated frames which, on average, saves transmission times. Finally, Section V concludes the paper.

II. RELATED WORK

Most of the published works study the performance of IEEE 802.11 under different conditions, such as [3]–[5], to name a few. Other works closer to ours are [6], where a packet aggregation scheme is proposed to maximize network performance, and [7], where the frame delay is studied under stochastic terms.

Other works have studied the savings achievable when using 802.11 aggregation for packets from one application (or different applications) to the same destination [8]. In [9], a central-controlled aggregation mechanism is proposed that limits the maximum aggregation size in applications with real-time constraints that share the medium with background traffic. This mechanism enables the provision of a low latency service for applications with real-time constraints and maximum throughput for the other applications. As an alternative, the authors also consider permanently setting a low value for the maximum A-MPDU size. An adaptive machine learning-based approach to adjusting the maximum length of A-MSDU per user is presented in [10]. In this context, the authors of [11] propose an algorithm for dynamically adjusting the maximum size of aggregated frames in 802.11 WLANs, which allows a network administrator to find an optimal balance between performance and latency in these networks.

As far as we know, we are the first to mathematically study when delaying frame transmissions saves transmission time, and how much time it saves, across all IEEE 802.11 protocols.

III. STOCHASTIC TRANSMISSION TIME

In this section, we present a stochastic interpretation of the transmission time that we then use in our calculations.

Figure 1 shows the timing diagram involved in a successful single frame transmission under IEEE 802.11 (adapted from [2]). Some of these times are overhead, such as DIFS and SIFS intervals, ACK transmission, and the Physical Layer Convergence Protocol (PLCP) preamble and header that precede each frame. These values depend on the characteristics of the physical layer. The MAC header and CRC transmission times are also dependent on the physical layer bit rate.

The time boxes depicted with a dashed line in Figure 1 indicate that there is some randomness and therefore, we cannot define them as a concrete value: $t_{\text{backoff}}$ refers to the backoff time, which is equal to a discrete random value uniformly distributed in the interval $\{0, CW\}$, multiplied by SLOT units of time; and $t_{\text{data}}$ refers to the data payload transmission, which is equal to a discrete random value that expresses the size of the data (in bytes) multiplied by the time required to transmit a byte, considering the underlying physical characteristics.

Let us first denote $t_{\text{backoff}}$ in terms of random variables. Let $X \sim U(0, 1,..., CW)$ be a discrete random variable following a discrete uniform distribution $U$ in the interval $\{0, 1,..., CW\}$. Therefore, $Y = \text{SLOT} \cdot X \sim U(0, \text{SLOT},...,\text{SLOT} \cdot CW)$. Let the time $t_{\text{backoff}}$ for a frame $i$ be denoted as $Y_i$. Although this model does not closely match reality (since when the medium is congested and collisions are generated, the backoff times are redefined to $\{0, 1,..., 2CW\}$), our final goal is to compare the times of the standard model with those of our proposal (see Figure IV-A), where there is no probability of collision since we have grouped all the sources in a single buffer, which cannot collide. Therefore, to assume that there are no collisions in a system without frame aggregation is to give it an additional advantage when comparing its performance with our proposal of frame aggregation.

Now, let us denote $t_{\text{data}}$ similarly to $t_{\text{backoff}}$. Let $P$ be a discrete random variable that describes the size distribution (in bytes) of the data payload of the frames. Let $Z = \frac{X}{P}$ be the dependent variable that represents the time required to transmit a data payload, where $br$ is the physical layer bit rate, in units of bits per second. Let the transmission time $t_{data}^i$ for a frame $i$ be denoted as $Z_i$ seconds.

Putting everything together, the total time $tx_i$ for a successful transmission of a frame $i$ under IEEE 802.11 is defined as $tx_i = \gamma + Y_i + Z_i$, where $\gamma = \text{DIFS} + 2t_{\text{pr}} + t_{\text{MAC}} + t_{\text{crc}} + t_{\text{SIFS}} + t_{\text{ack}}$ is a real constant whose value depends on the underlying physical characteristics defined in IEEE 802.11.

IV. ON THE OPTIMAL NUMBER OF FRAMES AGGREGATED

This section first describes our proposal to aggregate frames intuitively and then details the assumptions and derivation of the mathematical formulae to calculate the number of aggregated frames that, on average, will allow us to improve the transmission time. Finally, we present a series of numerical experiments and provide our final observations.

A. Description of the Intuitive Idea

Figure 2(a) depicts the standard model of a node that receives $N$ transmission sources, each with a distribution rate of $A_i, 1 \leq i \leq N$. Each destination frame $f_i$ is queued, assigned a backoff time $t_{\text{backoff}}^i$ and sent accordingly when the backoff time expires and the medium is free, in accordance with IEEE 802.11.

Our proposed frame-aggregation model is outlined in Figure 2(b). Unlike the standard model (without frame aggregation), the destination frames are queued together. Upon the arrival of $k$ frames, they are aggregated and sent as a single multicast frame $g$ following the IEEE 802.11 specification (i.e., a backoff time $t_{\text{backoff}}^g$ is calculated accordingly and the frame $g$ is sent when the backoff time expires). Thus, through multicast transmission, downlink efficiency is increased by aggregating packets from different applications and various origins and destinations. Security mechanisms can be put in place to prevent group members from reading data that is not intended for them.

Our aggregation proposal, via multicast frames, is implementable in all IEEE 802.11 standards, thus improving the efficiency achieved regardless of the chosen standard. The use of multicast frames also has some drawbacks. For instance,
A transmission service. Let us focus on one of these sources, the distribution rate resulting from adding all of them is also a Poisson distribution whose rate is the sum of the rates, denoted as $\lambda$. We assume a payload size for each source, which follows a distribution (usually exponential), denoted as $P$. In any event, the payload size distribution is left open, because we are primarily interested in the mean.

Our scenario is the following:

1) The frames enter and wait for a buffer of size $k$. Since they enter with a Poisson distribution, the waiting time for the arrival of $k$ packets follows an Erlang distribution of mean $k\lambda$. Then, the mean waiting time of the $j$th frame in the buffer will be $\frac{k-j}{\lambda}$, on average $E[r] = \frac{k-1}{2\lambda}$.

2) With a time that we will consider negligible, an aggregated frame $f$ of size $kE[P]$ is built that will wait for a mean backoff time $t^f_{\text{backoff}}$ where $P$ is the random variable that determines the payload size of the frames that will be transmitted.

3) The aggregated frame will then move to a queuing system with a Poisson input rate $\lambda_A(k) = \lambda/k$. The service time for each frame will be $\frac{1}{\mu(k)} = \frac{8 \cdot kE[P]}{br} + \gamma + t^f_{\text{backoff}}$, where $\mu(k)$ is the system throughput, measured as bits per second (bps). We consider that the average time of stay of the frame in the system is $W(k)$. As it is a $M/G/1$ queue, hence $W(k) = (\lambda_A(k))^2(\sigma(k))^2 + (\rho(k))^2$, where $\rho(k) = \frac{\lambda_A(k)}{\mu(k)}$. Another formulation (Pollaczek-Khintchine [13], [14]) can be $W(k) = \frac{2\lambda_A(k)(1 - \rho(k))}{\mu(k)}$.

4) The mean time of the frame in the system will be $F(k) = Er(k) + \frac{1}{\mu(k)} + W(k)$.

Therefore, we can evaluate the gains of our proposed model (shown in Figure 2(b)) by evaluating $G(k) = F(k) - F(1)$. When $k \in \mathbb{Z}_{>1}$ and $G(k) > 0$, then the aggregation of $k$ frames causes, on average, that the delay in receiving all frames in the destination is less than sent individually.

C. Numerical Experiments

To appreciate under what circumstances our proposal on frame aggregation will be most beneficial, we need to calculate $G(k)$ with network traffics that have different $\lambda$ distribution rates (measured in pps) and varying the value of $k$.

Figure 4 shows the value of $G(k)$ and $\lambda$ calculated for a WiFi transmission under IEEE 802.11b with a rate of 11Mbps, for different values of $k(k \in \{2, 3, ..., 10\})$. The other IEEE 802.11b parameters remain the same for all experiments.
(\(CW = 16, t_{\text{backoff}} = 20\mu s, t_{\text{DIFS}} = 50\mu s, t_{\text{pr}} = 96\mu s\), and \(E[P] = 800\) bits). To better understand what the values of \(\lambda\) mean, remember that they are proportional to the input rate values following the expression \(\lambda E[P]\), measured in bps.

We can observe that, regardless of the number of frames aggregated, \(G(k)\) takes positive values up to a certain value of \(\lambda\). A positive value indicates that a delay in the transmission will appear if we aggregate frames. From that value of \(\lambda\), \(G(k)\) takes negative values, which indicates that the aggregation no longer causes delay. Furthermore, the graph also indicates that if the value of \(\lambda\) continues to increase, the values of \(G(k)\) tend to \(-\infty\). This means that if no aggregation is done, the transmission becomes impossible because there is a situation of unacceptable congestion.

Figures 3 and 4 show the value of \(\lambda\) that makes \(G(k), k \in \{2, 3, ..., 20\}\), a negative value for different rates of an IEEE 802.11b transmission (\(CW = 16, t_{\text{backoff}} = 20\mu s, t_{\text{DIFS}} = 50\mu s, t_{\text{pr}} = 96\mu s\) and \(E[P] = 800\) bits).

**Final Remarks.** In summary, we have found that the delays caused by the aggregation of frames are compensated by the decrease in transmission congestion, which is a recommended practice to allow a better use of the radio medium in WiFi. To conclude, frame aggregation not only improves congestion situations, but also improves transmission delays. The mathematical expression proposed in this work is useful to discriminate when to use frame aggregation and save transmission time, on average. This expression can be used as a step prior to transmission, but the final decision of the value \(k\) chosen must be adapted to each case.

V. CONCLUSIONS

We have described the transmission time of a frame under the IEEE 802.11 protocol in a stochastic way and then we have obtained a formula to calculate the number of frames that can be aggregated to save transmission time, on average. Our numerical experiments demonstrate that WiFi frame aggregation improves the efficiency under certain IEEE 802.11 traffic conditions saving transmission time and reducing transmission congestion, and can be even proposed in those standards that do not have an aggregation mechanism defined. This formula can be used as a configuration criterion for a traffic regulator node (for instance, a router) with frame aggregation capability, to decide when frame aggregation should occur.

REFERENCES

[1] "IEEE Standard for Information Technology - (…) - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Spec-
[2] A. Duda, “Understanding the Performance of 802.11 Networks,” in Proc. 2008 IEEE 19th Int. Symp. on Personal, Indoor and Mobile Radio Commun., Sep. 2008, pp. 1–6.

[3] G. Bianchi, “Performance analysis of the IEEE 802.11 distributed coordination function,” IEEE Journal on Selected Areas in Communications, vol. 18, no. 3, pp. 535–547, 2000.

[4] Y. Xiao and J. Rosdahl, “Throughput and delay limits of IEEE 802.11,” IEEE Commun. Lett., vol. 6, no. 8, pp. 355–357, Aug. 2002.

[5] J. W. Tantra and C. H. Foh, “Achieving near maximum throughput in IEEE 802.11 WLANs with contention tone,” IEEE Commun. Lett., vol. 10, no. 9, pp. 658–660, Sep. 2006.

[6] P. Teymoori, A. Dadlani, K. Sohraby, and K. Kim, “An Optimal Packet Aggregation Scheme in Delay-Constrained IEEE 802.11n WLANs,” in Proc. 2012 8th Int. Conf. Wireless Communications, Networking and Mobile Computing, Sep. 2012, pp. 1–4.

[7] Y. W. Kuo, W.-F. Lu, and T. L. Tsai, “A framework to approximate the delay distribution for IEEE 802.11 DCF protocol,” in Proc. 2009 IEEE 9th Malaysia Int. Conf. Commun. (MICC), Dec. 2009, pp. 874–879.

[8] T. Selvam and S. Srikanth, “A frame aggregation scheduler for IEEE 802.11n,” in 2010 National Conference On Communications (NCC), 2010, pp. 1–5.

[9] J. Saldana, J. Ruiz-Mas, and J. Almodóvar, “Frame Aggregation in Central Controlled 802.11 WLANs: The Latency Versus Throughput Tradeoff,” IEEE Commun. Lett., vol. 21, no. 11, pp. 2500–2503, 2017.

[10] E. Coronado, A. Thomas, and R. Riggio, “Adaptive ML-Based Frame Length Optimisation in Enterprise SD-WLANs,” Journal of Network and Systems Management, vol. 28, no. 4, pp. 850–881, Oct 2020.

[11] J. Saldana, O. Topal, J. Ruiz-Mas, and J. Fernández-Navajas, “Finding the Sweet Spot for Frame Aggregation in 802.11 WLANs,” IEEE Commun. Lett., vol. 25, no. 4, pp. 1368–1372, 2021.

[12] “IEEE Standard for Information technology— (...) – Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: MAC Enhancements for Robust Audio Video Streaming,” IEEE Std 802.11ax-2012, pp. 1–163, 2012.

[13] F. Pollaczek, “Über eine Aufgabe der Wahrscheinlichkeitsrechnung,” Mathematische Zeitschrift, vol. 32, no. 1, pp. 64–100, Dec 1930.

[14] A. Khintchine, “Mathematical theory of a stationary queue,” Matematicheski Sbornik, vol. 39, no. 4, pp. 73–84, 1932.