

A Simple Method for Determining an Optimal Number of Access Points in Distributed WLAN Networks

K. Staniec¹, M. Kowal¹

¹*Department of Electronics, Chair of Radiocommunications and Teleinformatics,
Wrocław University of Technology,
Wyb. Wyspiańskiego 27, 50-370 Wrocław, Poland
kamil.staniec@pwr.wroc.pl*

Abstract—In large wireless installations based on WLAN systems, mechanisms governing their operation other than just those related to the radio coverage may play a crucial role in the customer experienced quality of service (EoS). In particular, two factors have been identified as having a particular impact on the final efficiency of the distributed WLAN network. The first one is the IEEE 802.11x protocol overhead (assisted with the choice of the preamble length) which is largely dependent on the kind of WLAN standard used – ‘b/g’, ‘a’ or ‘n’. The other factor is the MAC protocol scheme, the CSMA/CA, developed for the IEEE 802.11x family, identical for all its sub-standards. A simple formula has been developed that accounts for both these aspects and provides an easy-to-implement method allowing deployment of the minimum number of access points as a function of the expected number of users, assuring a guaranteed effective throughput per user at optimal utilization of the total available capacity.

Index Terms—CSMA/CA, overhead, throughput, 802.11.

I. INTRODUCTION

The technology addressed in the paper grounded on the IEEE 802.11x family of standards started off as a wireless extension to home local area networks; however, its usability has quickly been appreciated in other applications. Nowadays, the range of applicability reaches network connectivity services in shopping malls, airports, town squares, campuses, etc. Unlike cellular technologies that involve intensive research prior to deployment, the development of WLAN-based wide coverage networks has followed an trial-and-error path with very little theory on effective planning of such networks (let alone security aspects which are still given far too little attention by WLAN administrators). Although keeping pace with such a rampant growth of application space is an uneasy task, some efforts have been made on developing methods for optimal planning; either regarding the determination of optimal locations for a group of cooperating access points or evaluating their number based on the adaptive channel selection or the radio coverage (e.g. [1]–[7]). In this paper another aspect will be addressed associated with the

throughput efficiency to be achieved with WLAN systems and its impact on the prospective number of access points (APs). As a result, an optimal number of access points will first be found and on this basis further investigations may proceed (such as propagation and channel selection issues).

II. IEEE 802.11X – GENESIS AND THE STATE OF THE ART

The WLAN (Wireless Local Area Network) systems have been present in the customer market since 1997. As the first release, i.e. IEEE 802.11 [8], did not offer impressive performance (i.e. merely 1 Mb/s - and 2 Mb/s of throughput), it was soon replaced with two other offspring: 802.11b [9] and 802.11a [10], offering the maximum data rate of up to 11 Mb/s and 54 Mb/s, respectively. In 2003 another WLAN version was released: 802.11g [11] being a 2.4 GHz equivalent in performance to its 802.11a counterpart operating in 5 GHz UNII band. In 2009 a breakthrough 802.11n [12] generation was launched with the maximum offered throughput of 600 Mb/s due to the use of some innovative techniques such as: MIMO technology (up to 4×4), increased number of subcarriers (now 52 compared to 48 used in previous releases), the channel width (up to 40 MHz versus former 20 MHz) together with enhanced frame-aggregation techniques improving the transmission effectiveness. The market adoption of WLAN systems has led to a veritable boom in the customers' and vendors' interest which is best expressed in the 30 % growth in the Access Points sales per year – a figure maintaining for the past few years. At present, yet another WLAN generation is being strongly promoted, although still in the draft 3.0 stage accepted in May 2012, offering data rates up to 7.2 Gb/s, with the first equipment already available for purchase. Such a momentum could not be left unnoticed by the cellular technologies carriers, vendors as well as scientific communities [13]–[25]. Owing to its ubiquitous presence at the customers' premises and public institutions, WLAN is now recognized as a serious candidate serving as a technology for offloading the cellular 4th generation LTE (Long Term Evolution) system from a significant amount of the indoor-originated user traffic.

III. ON TRAFFIC SCENARIOS IN LARGE PUBLIC SPACES

The ideas presented in this paper come from the

experience acquired during deployment of WLAN systems in some public places in Poland, mainly shopping plazas where the telecom traffic generated by users shows a similar profile as that of customers visiting stores. Hence, after the site opening there is a linear growth that stabilizes at c.a. 11 a.m. and continues till evening hours (c.a. 7 p.m.) to decline steadily till the facility close-up late night. In peak hours, however, the number of simultaneous users may reach up to 200 or more – mostly customers in café's, fast-food bars or entertainment and meet-up sections. Since the wireless access in a commercial area is an effective attractor, an adequate quality of services must also be guaranteed to end-users. It will be reasonable, therefore, to prepare the complex system for efficient operation even during rush hours. Moreover, the system configuration must be such as to allow users nomadic access if not mobile between access points (APs). Mobility, however, still presents some problem during hand-off procedures which – so far – require the connection with the current AP to break before authentication and/or authorization procedures with another AP take place. During this switch time some frames may be inevitably lost which may, in turn, cause some real-time applications to close sessions. To alleviate the situation a specification IEEE 802.11r has been ratified in 2008 which manages the hand-off procedures in the entire system assuring seamless roaming between APs (although no on-the-market products are known to implement it yet except firmware solutions that claim to operate just as well as the 802.11r specification).

IV. ON THE IEEE 802.11X TRANSMISSION EFFICIENCY

Users nowadays are accustomed to some level of service provided by network service providers. Albeit in public places the expectations are lower, however that which is considered as ‘satisfactory’ is still on the order of at least 1 Mb/s. A simple, yet unrealistic solution for a WLAN designer would consist in dividing the physical rate offered by an AP (e.g. 54 Mb/s in 802.11g) by the expected data rate per client to obtain the number of users enjoying this assumed data rate. This paper will explain why such an approach is faulty and how to calculate the required number of access points in order to provide users with guaranteed data rates for their improved satisfaction. Since our investigations are best suited to wide-area scenarios, it is assumed that individual access points are spaced from each other at distances assuring non-interference operating conditions (which also assures the most efficient radio coverage).

Since IEEE 802.11x standards are only defined in the physical (PHY) and the MAC (Medium Access Control) sublayer of the ISO/OSI stack, the throughput calculated here will be one achieved “on top” of MAC, i.e. including the overhead due to the multi-access procedures but neglecting upper OSI/ISO layers.

A. The Upper OSI/ISO-layers overhead efficiency (η_1)

As was first indicated in [26], each WLAN type bears some intrinsic features that set an upper bound on the achievable throughput (just above the MAC layer), referred to in this paper as the MAC-layer data rate R_{MAC1} (see also [26]–[28]). The ratio of this achievable throughput (R_{MAC1})

related to the data rate at the physical layer (R_{PHY}) will be termed as transmission efficiency of the first type η_1 , as given by (1). The index ‘1’ in the subscript of R_{MAC1} means that only the effect of the first efficiency on the resultant R_{MAC} will now be studied (as opposed to R_{MAC2} in Section IVB), remembering that in reality both efficiencies should be considered simultaneously.

$$\eta_1 = R_{MAC1} / R_{PHY}. \quad (1)$$

The reasons for R_{MAC1} being much lower than R_{PHY} throughput are the following:

- Each frame preamble is transmitted at constant data rates (i.e. 1 or 2 Mb/s as in 802.11 b/g/a) or for a defined fixed period of time (for 802.11/n). The same rule applies to the frame header. Depending on the standard the preamble duration T_{PRE} varies from 16 μ s to 144 μ s whereas that of the PLCP header T_H lies between 4 μ s to 48 μ s;
- WLAN devices need to compete for access to the wireless medium. In CSMA/CA algorithm – native to IEEE 802.11x family – the transmission cycle is shown in Fig. 1. Before any transmission starts, each device waits for a DIFS (Distributed Interframe Space) period of time T_{DIFS} equal to $2 \cdot T_{SLOT} + T_{SIFS}$, that depending on the standard, lasts for either 28 μ s or 50 μ s. In this type of efficiency (η_1), however, it is assumed that there are no other competitors except the investigated one;
- The coding rate between $1/2$ and $5/6$.

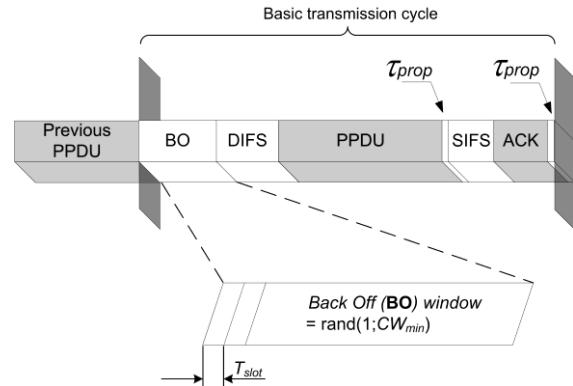


Fig. 1. CSMA/CA algorithm used in WLAN devices.

As one can see in Fig. 2 the achievable throughput is very dependent on the payload size with the maximum performance for the largest packets. In most practical situations this means packets of about 2 kB, although it is a matter of the operating systems restrictions regarding the MTU parameter (Maximum Transmit Unit). Nevertheless, even with these packet sizes the achievable data rate (R_{MAC1}), limited by the transmission efficiency η_1 given by (1), is only a fraction of the nominal PHY data rate R_{PHY} , as presented in TABLE I. Equations (2) and (3) define R_{MAC1} for WLAN ‘a/g’ and ‘n’, respectively, where T_{SYM} – the OFDM symbol duration, L – the user data length, L_{ACK} – the acknowledgement frame length, N_{DBPS} – the number of usable bits per OFDM symbol, N_{SS} – number of antennas in the MIMO scheme (see [9]–[12] for more information).

This feature, in turn, is attributed to the fact that the preamble and the PLCP header transmission as well as the

multiple access procedures are only performed for a single spatial data stream – all the other streams are free from this overhead and contribute to the steep increase rate for even small or moderate packets:

$$R_{MAC1} = \frac{[8L \cdot 10^{-6}]}{\left[T_{DIFS} + T_{SIFS} + 2T_{PRE} + 2T_H + T_{SIG} + T_{SIG-EXT} + \right.} \quad (2)$$

$$\left. + T_{SYM} \cdot \frac{8L_{ACK} + 8L}{N_{DBPS}} + \frac{C_{W\min} \cdot T_{SLOT}}{2} \right]$$

$$R_{MAC1} = \left[\frac{8L \cdot 10^{-6}}{N_{SS}} \right] / \left[T_{DIFS} + T_{SIFS} + 2T_{PRE} + 2T_H + \right. \quad +$$

$$\left. + T_{SYM} \cdot \frac{8L_{ACK} + 8L/N_{SS} + 22}{N_{DBPS}/N_{SS}} + \right. \quad +$$

$$\left. + \frac{C_{W\min} \cdot T_{SLOT}}{2 \cdot N_{SS}} \right] +$$

$$+ \left[\frac{8(N_{SS}-1)L \cdot 10^{-6}}{N_{SS}} \right] / \left[T_{SYM} \cdot \frac{8L_{ACK} + 8L(N_{SS}-1)/N_{SS} + 22}{N_{DBPS}(N_{SS}-1)/N_{SS}} \right], \quad (3)$$

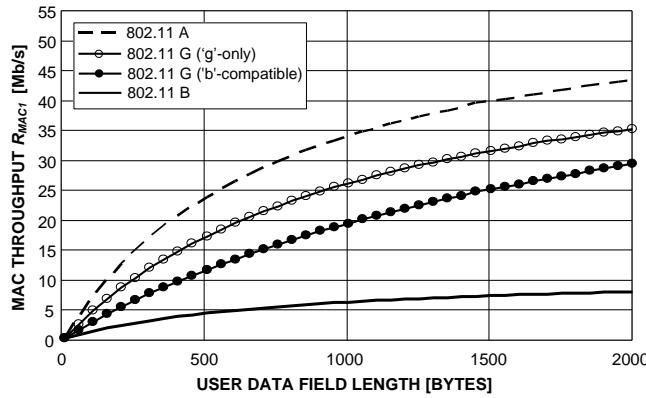


Fig. 2. Throughput performance for WLAN 'b/a/g' vs. user data length.

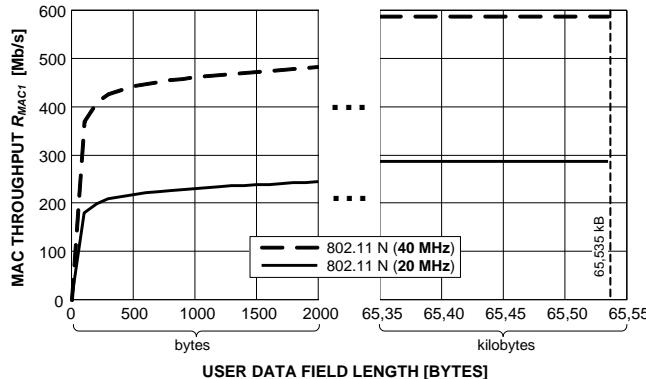


Fig. 3. Throughput performance for WLAN 'n' vs. user data length.

TABLE I. WLAN TRANSMISSION EFFICIENCY.

IEEE 802.11 type	b	g		a	n	
		'b'-comp.	'g'-only		20 MHz	40 MHz
R_{PHY} [Mb/s]	11	54	54	54	288.9	600
R_{MAC1} [Mb/s]	6.82	29.2	42.4	43.4	285.7	587.3
η_1 [%]	62%	54%	79%	80%	99%	98%

B. The CSMA/CA multi-access efficiency (η_2)

The other type of efficiency (η_2) is strictly associated with the multiple access mechanism defined for WLANs. In Section IV A it was deliberately assumed that no competition exists and therefore CW_{min} parameter was set to the absolute possible minimum, i.e. a single T_{slot} . However, if many

stations are competing for access to an AP, collisions may (and do) occur. If one takes place, the colliding devices double their CW_{min} and repeat this multiplication upon each consecutive collision occurrence until $CW_{min} = 1023$ in which case CW_{min} is reset to the minimum value (i.e. 15 or 31) during the next collision. Intuitively, as the number of competing stations grows, so does the probability of two or more colliding upon access attempt, which results in increased average back-off in the network during which no device is transmitting. These backoffs, in turn, cause the access point to operate even beneath its transmission capacity (or throughput performance) discussed in Section IV A. In [17] the CSMA/CA efficiency η_2 was found to exponentially depend on the number of users N_{US} (or WLAN cards) contending for access to the medium as shown in Fig. 4. One curve in the figure represents the simulated η_2 whereas the other shows the best-curve approximation with $R^2 = 0.993$. As one can observe, even with five stations per a single AP ($N_{US/AP}$), the transmission efficiency is declines to c.a. 80 % and further down to a little above 60 % for $N_{US/AP} = 50$. It is also worth noticing that $N_{US/AP}$ in fact equals N_{US}/N_{AP} , where N_{US} is the total number of users that need to be provisioned with network services in a given site and N_{AP} is the number of access points.

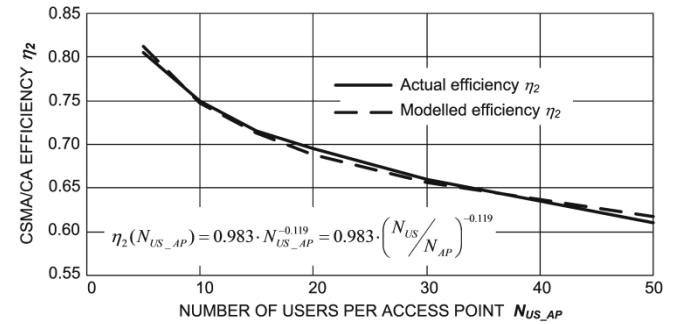


Fig. 4. CSMA/CA transmission efficiency vs. the number of users per AP.

V. ESTIMATION OF THE OPTIMAL NUMBER OF APs

In the previous section two kinds of transmission efficiency were discussed. As was stated there, simply dividing R_{PHY} by N_{US} will lead to a great overestimation of the user's real achievable throughput above MAC. Therefore in a general form, the MAC-layer data rate per a single user is defined as a ratio of R_{MAC} and the number of users per AP ($N_{US/AP}$), as in (4), whereas the number of users per a single AP by (5).

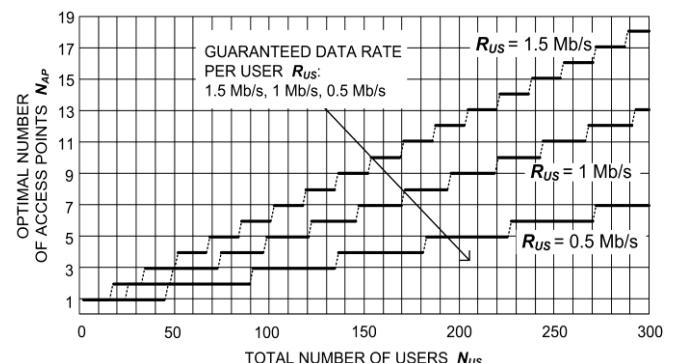


Fig. 5. Optimal number of APs vs. the total number of users and the guaranteed throughput above MAC layer.

Finally, substituting (6) and (5) to (4) and then substituting the formula for η_2 from Fig. 4 into (6) we may easily factor out the required number of access points N_{AP} (7) necessary to provide each of the total N_{US} users with a guaranteed MAC throughput R_{US} . The simple formula allows one to quickly estimate the number of APs of a certain kind (say WLAN ‘a’, ‘g’ or ‘n’), specifying on the input the total expected number of users N_{US} , the physical data rate R_{PHY} offered by the APs (usually put explicitly on the product box) and the throughput R_{US} one wishes to guarantee the end user, above MAC layer.

For the estimation of the available data rates at higher OSI/ISO layers refer to [14] for example:

$$R_{US} = \frac{R_{MAC}}{N_{US_AP}}, \quad (4)$$

$$N_{US_AP} = N_{US} / N_{AP}, \quad (5)$$

$$R_{MAC} = R_{PHY} \eta_1 \eta_2, \quad (6)$$

$$N_{AP}(N_{US}) = \left[N_{US} \cdot \left(\frac{R_{MAC}}{0.983 \cdot R_{PHY} \cdot \eta_1} \right)^{0.894} \right]. \quad (7)$$

In plots shown in Fig. 5, three curves are drawn in accordance with (7), where each user’s guaranteed data rate R_{US} is used as a parameter. For instance, with $N_{US} = 200$ users, five APs are necessary to provide R_{MAC} of 0.5 Mb/s whereas providing R_{MAC} of 1.5 Mb/s would require twelve APs.

VI. CONCLUSIONS

Two sources of reduced user throughput (above MAC) in WLANs were analyzed and treated as efficiencies: one occurs due to the constant lag caused by the protocol overhead and the other due to the CSMA/CA contention protocol. Their combination allowed the authors to derive a concise formula for the necessary number of access points required to assure a fixed level of throughput to each user (out of all N_{US} users), which may be of easy use to WLAN designers at commercial sites.

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