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Assessment of the Power Saving Potential in Dense Enterprise WLANs

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Abstract

Due to the requirements to provision a proper Quality of Service level in enterprise WLANs, supporting both voice and data services, the typical densities in the deployment of access points (APs) may exceed 4000 APs per square kilometer. While such density is necessary under heavy traffic conditions, it is obviously superfluous during the time of lower load - and dramatically excessive in night periods, with only marginal traffic intensity. In this report we present a novel, very aggressive scheme for adaptation of the AP density to the actual traffic. We claim that inactive APs can be powered off to the extent that the APs remaining in the operation provide the coverage required to detect user connectivity initiation. We suggest that the user connectivity initiation can be detected by receiving at least one, of possible several copies, of a single Probe Request frame within a given maximum tolerable delay. Once the user is detected, additional AP can be powered on to provide the required service.

In this report, we initially evaluate the power saving potential of the proposed algorithm. Using two simplified propagation models we calculate the minimum density of APs required to detect the user with a given probability and delay of detection. We translate this result into the power saving figures, applying the data from commercially available APs. Moreover, we relate our results to the best approaches presented so far in the literature.

Contents

1 Introduction

Recently, power consumption of radio access networks has become a key economic and environmental concern. Although the power consumption of each radio, i.e., access point (APs) and base stations (BSs) is lower than the power consumption of other network infrastructure components, e.g., switches and routers, the radio access networks are usually dimensioned for the peak user demand through a dense deployment of the radio components. It has been forecasted that the increase in traffic stemming from the increase in number of wireless devices will further lead to even more dense radio access networks. During the peak demand period, users benefit from the capacity provided by this radio density, however, it has been shown that the peak user demand seldom occurs [1, 2]. Therefore, it is clear that dense deployment of the radios causes a significant amount of power wastage during time periods when the user traffic is marginal.

To overcome the problem of power wastage in dense radio access networks, different approaches have been proposed. Whereas micro-level approaches aim to save power by designing a more power-efficient radio components, e.g., power amplifier, macro-level approaches are developed to save power through a power-aware management of the network. In other words, radio access network can be reconfigured using macro-level approaches to reduce the power consumption. One of the most promising macro-level approaches is the switching on/off strategy aiming at power saving by reducing the number of inactive radios, providing the excessive capacity. To keep the user performance, it is crucial that the radios remaining in operation can provide the coverage. It is also important that sufficient number of radios will be again powered on within a desired delay in case of an increase in the user demand for data rate.

In cellular networks, micro-level approaches aiming at saving power by switching some of the components of a BS have been studied in the literature [3]. For instance, it has been reported that 50% of the total power of the radio in the BS is consumed by the power amplifier [3]. Based on this fact, different time- and frequency activity scheduling is developed to reduce the power wastage caused by inactive BSs. In contrast, in wireless local area networks (WLANs) it has been demonstrated that 80-90% of the power consumption is attributed to the cooling and processing circuits [4]. Therefore, macro-level approaches have much more potential for power saving.

In this report we focus on dense WLANs and propose a novel strategy based on switching the inactive APs off to address the problem of power wastage in these scenarios.

1.1 Power wastage in dense WLANs

Popularity of WLAN stems from its particular features like availability (especially in campuses, cities and metropolitan areas), high data rates, low cost per bit and wide deployment of user terminals. Dramatic growth of users' demand provokes a further increase in number of deployed WLAN and consequently in their power consumption [5]. WLANs infrastructure consist of APs, switches and routers. Despite the fact that a single AP consumes less power (in order of 10 W, see [6]) than the other WLANs infrastructure components, it is the large number of APs that mainly accounts for the power consumption growth [2]. As shown in [7, 8], typical densities of dense WLANs are nowadays in the range of 2000-3500 AP/km^2 for data networks, and 4350 AP/km^2 for VoIP, being dimensioned to meet the peak user demand.

WLANs deployed in university campuses and enterprise networks are usually provisioned to carry these close-to-the-peak user traffic values. This leads to a rather *dense* deployment of the APs (i.e., dense WLAN features typically thousands of APs), and obviously, to an excessive power consumption in case of lower user traffic. Such situations are to be observed especially at nights, when user traffic is marginal, and the whole set of APs does not need to be powered on. Therefore several strategies have been proposed that aim at dynamic reduction of WLAN AP density to the minimum needed for the *full coverage* of a given area. In this report we go one step further and propose a novel, more aggressive, strategy for reducing the density of WLAN APs. We suggest that inactive APs can be powered off, as long as APs remaining in operation provide the coverage sufficient to *estimate the presence* of potential users, but not necessarily for their service. To meet the communication demand of the discovered users, additional APs will be powered-on. Both the discovery of users and the adaptation of the APs density are provided *entirely* within WLAN and do not require support of any additional technology.

The report is further organized as follows. In Section 2 approaches for reducing WLAN power consumption presented so far in the literature are shortly summarized. In Section 3, the system under study as well as proposed power saving strategy is explained. In Section 4, we present system model used to provide an analytical evaluation of the proposed strategy. Then, in Section 5, a numerical evaluation follows, together with the discussion of the results in context of the earlier presented solutions.

2 Related work

Two fundamental types of approaches to dynamically reduce the power consumption of dense WLANs in periods of very low demand can be distinguished in the literature.

In the approaches of the first type, multiple radio interfaces available nowadays in the mobile devices are exploited. Among several possible technologies, cellular is most often used in this context. It is assumed that the mobile terminal (station) has all the time the Internet connectivity using its cellular interface, and its position is roughly known. Under these assumptions, a WLAN AP in the proximity of the station can be waken up when needed to provide the required WLAN connectivity [9]. An interesting approach is presented in [10], where IEEE 802.15.4 rather than cellular network is used as a supporting technology. WLAN APs are additionally equipped with IEEE 802.15.4 narrow-band radios used as 2.4 GHz band spectrum sensors, whereas stations do not need any additional radio equipment beyond the WLAN interface. While not being able to receive the active discovery packets transmitted by the mobile stations, AP can sense radio activity via the IEEE 802.15.4 interface, using much less power that the WLAN equipment would. Once a potential user is discovered, the WLAN equipment is activated. Let us note here that the IEEE 802.15.4 sensors are not WLAN-technology-selective and might “wake up” WLAN APs if any other radiation is present in a channel. In [11] Bluetooth is used as the supporting technology. In this approach both the APs and the mobile devices have to be Bluetooth-equipped. It is assumed that mobile devices will be able to provide multi-hop connectivity via Bluetooth to the “multi-radio” APs. This multi-point connectivity could be sufficient in case of low-bit-rate applications, and only if the observed demand exceeds the Bluetooth capacity (or Bluetooth connectivity becomes weak) the WLAN part of the APs will be activated.

In the approaches of the second type, the transmission coverage over the entire area is assured by the WLAN all the time (a sufficient density of APs has to be assured at any time!). Possibly required “excessive” capacity, beyond the full coverage is provided on a “by-demand” basis. An example of such an approach is presented in [2], where results of traffic measurements (performed once a day) are used to ensure the coverage and sufficient bandwidth to meet the required performance. If a low user activity is measured in the vicinity of an AP, the AP might - coverage permitting - be powered off and its associated users would be served by the neighboring APs. Meanwhile, the neighboring APs could even increase their transmission power to strengthen their coverage. When the required capacity exceeds the capacity available with the set of APs being currently powered-on, additional APs would be activated. Similarly, Marsan et al. [12] investigate a cluster-based power saving scheme applicable in dense WLANs. All potential users are provided with coverage and required capacity. Authors propose to adjust the density of powered-on APs taking into account the number of users associated with an AP and the amount of user-generated traffic. Another approach [1], tunes the activity of APs to the demand following an assumption that possible positions of the users are known (for a given prediction period), and the coverage and capacity are then needed only for these predefined user positions rather than the full area. While the work presented in [1] is intended to be implemented in a centrally-managed system, Capone et al. [13] modify this approach for an application in decentralized systems. To deal with temporal variation of operation, system parameters addressed in [1] are modified. It is also enforced to have some powered-on APs at particular positions to cope with coverage and capacity provision problem.

Summarizing, solutions following purely WLAN-based approach, as described above, can not reduce the density of the APs as aggressively as the ones based on the heterogeneous technologies. In that case, however, usage of multiple radio interfaces is required, which further complicates the system.

Looking more closely into the strategies discussed above, there are two key aspects for all of them: the assessment of the area covered by a given set of APs and the assessment of the user demand. To that end two issues are of merit: coverage model and AP placement pattern (referred also in the literature as *the area coverage problem*). For the coverage models used in the literature an exhaustive survey of different approaches is given in [14] and reader is referred there for further discussion. As for the area coverage problem, APs can be placed either deterministically, what simplifies the calculations, or randomly [14]. Placing the APs in a random fashion, the overlapping area between any two neighboring signal emitters varies drastically and leads to a non-homogeneously covered area, which has been proven (in computational geometry) to be a NP-hard problem. Possible solutions include either tile-based approximation, as shown in [15], or use of computationally expensive (and not easily scalable) optimization algorithms to approximate the coverage [16].

3 Proposed approach

3.1 System considered

The system considered in this report is a dense high-capacity WLANs deployed typically in university campuses or enterprise networks, i.e., we assume that the available APs are not only able to provide full coverage for the target area, but can also provide high capacity by excessive density, as compared to the one needed just for the coverage. We assume that the above mentioned dense deployment of APs will be possible via careful frequency planning and power control - which will not be discussed here. Nowadays, the typical densities of dense WLANs are in the range of 2000-3500 AP/km^2 for data networks, and 4350 AP/km^2 for VoIP, as shown in [7, 8].

The APs are IEEE 802.11b/g devices (2.4 GHz band, with 13 channels) equipped with an omni-directional antenna. It is assumed that all the APs are powered by Power over Ethernet (PoE). We will consider that a device has WLAN connectivity, if it can associate with an AP with an expected bit rate higher than B, at the bit- error rate lower than R, within a waiting time T.

3.2 Strategy for reducing the density of the WLAN APs

To achieve power-efficient operation of the system described above we develop a strategy for aggressive reductions of the APs activity. In that we make the following observation: to assure that the permitted waiting time for an user connection establishment is not exceeded, it is *not necessary* to keep alive APs providing the coverage over the entire target area with the desired bit-rate B. In contrary, we need only to *detect* the user connectivity initiation, and switch proper APs on within a desired time. Hence, the following aspects should be considered:

1. a criterion for reducing the density of the WLAN APs
2. an algorithm to determine the required density
3. a criterion for increasing the density of the WLAN APs
4. an approach to select and power on additional APs

The first and the last of the mentioned aspects are addressed in numerous research studies (see Section 2) and will not be further discussed here. Instead, this work focuses on the second and third issue, as being crucial and the most innovative in the proposed scheme.

To determine the required density of the APs, we define a *detection coverage of an AP* as the area where the transmission (with low bit rate!) is detectable, but due to the high error rate, the connectivity cannot be established. We claim that it is only sufficient that the channel condition is good enough, so that at least one Probe Request frame is correctly received by an AP within a desired time. We further suggest that a user can be detected as long as the transmission attempts can be distinguished from the noise floor, although the Probe Request frames cannot be decoded properly. In such a case, the number of false positives (detection of non-WLAN transmissions) increases, meaning that a single AP may be waken up unnecessarily. In order to address the criterion for increasing the density of APs, the probability of a successful detection within a given time can be increased by sending *several* copies of a single Probe Request frame, transmitted with the lowest bit rate. When the user presence is detected, additional AP can be powered on to provide the required service. The ability to provide such discovery can be assured with *smaller* density of the APs than the density needed for a coverage with the lowest transmission bit rate, and *significantly smaller* than the density needed to assure a connectivity at a higher (or, as in currently deployed dense WLAN scenarios the highest) bit-rate. The schema (Fig. 1) illustrates the proposed strategy. As it can be seen, the transition between the minimum density of APs required for detection and the minimum density of APs required for transmission occurs when the powered-on APs cannot provide the user with the required capacity. During the time periods with marginal traffic, the AP density is reduced to the minimum AP density required to detect the user connectivity initiation with a given quality, i.e., bit error rate and tolerable delay. On the other hand, an increase in the required capacity leads to an increase in the AP density up to the minimum APs transmission density. In other words, upon deciding that a user is present in the detection area, we can power on the AP(s) needed to provide the required service to the user.

In what follows we will show that the presented solution has the potential of providing significant power saving that will be quantified further in this report.

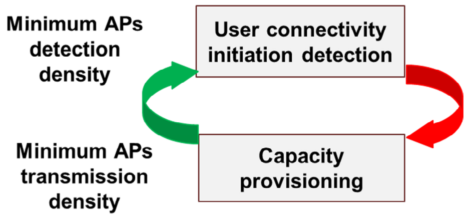


Figure 1: Proposed strategy

4 Coverage analysis

In order to quantify the power saving potential of the proposed algorithm we now present a short analytical study, in which for the suggested user detection scheme and the system model described below, we derive the minimum required density of the APs, as well as probability of a successful user detection.

4.1 System model

In order to provide a model for a dense WLAN scenario described in Section 3.1, we use a square area with deterministic, grid-based AP placement that, as mentioned in Section 2, facilitates coverage computation. In our model, the APs are placed in the top right corner of the grid, as shown in Fig. 2 for different densities of the WLAN. The distance between two adjacent APs in each row and each column is equal and denoted by $d_i = d_j = d$, and n is the number of APs placed in each row and column. We further assume that stations do not move - they simply pop-up in some location and abandon activity after having completed their connectivity objectives (terminal mobility is not discussed here). Moreover, we assume that any AP not needed to support currently active stations will be immediately switched off (we do not discuss the details of the possibly necessary hand-off policies and overheads). We assume that the user connectivity initiation can be detected when at least one Probe Request from number of sent Probe Requests is received by the AP.

To model the AP coverage area we use a truncated attenuated disk model. In our model, border of each disk is identified by desired received signal level. The radius of the AP coverage area achievable for a given quality of packet reception (for a given time, packet error rate and bit error rate, consequently) is denoted as r. To calculate the radius of the AP coverage area, two different models are adopted:

1. The calculation is performed by means of a path-loss prediction algorithm and fade margin, taking into account the applicable data rate (modulation) and receiver sensitivity. In outdoor scenario, path-loss is modeled using Obaidat-Green model [17], whereas for the indoor scenario the ITU model [18] is used. Fading is approximated only by introduction of a fade margin to assure the proper receive quality in indoor and outdoor scenarios.

2. To make our model more realistic, we consider an approximation of the effects of slow fading represented by the log-distance model [19]. In case of a stationary user assumed here, due to

the relation between symbol duration (4 μs for IEEE 802.11g [20]) and coherence time of the channel [21], the user signal would not be subject to fast fading. Therefore, we only consider the slow fading.

For each model the noise level is assumed to be -96 dBm. Based on random effects of shadowing causing slow fading, the received signal level can be less than the particular threshold at some points within the coverage disk. In each coverage disk, to calculate percentage of coverage with a desired received signal level, we follow the procedure defined in [19] (see Sec. 4.1.3). Computing the total coverage percentage, we take the AP coverage disk, within which, the received signal level is equal to, or greater, than the desired received signal level at 99.999% of the points.

Comparing these two approaches, the main differences between them are twofold:

1. Different path-loss exponent and different approximation of fading result in different sizes of the AP coverage area.
2. Based on random effects of shadowing, we assume that AP coverage area is a disk within that received signal level is equal to, or greater, than the desired received signal level at 99.999% of the points.

Following, we describe in more details path loss models that were used in our calculations.

4.1.1 Obaidat-Green model

For outdoor scenario, path-loss prediction is done by means of the Obaidat-Green model, an empirical radio propagation model for outdoor scenarios in 2.4 GHz frequency band. Following is the Obaidat-Green model formula,where the path loss (L_{FS}) can be expressed as:

$$L_{FS} = 40 \log d + 20 \log f - 20 \log h_t - 20 \log h_r \tag{1}$$

In the above formula d (the distance between AP and user) and f (frequency) are expressed in km and MHz, respectively. h_t and h_r are transmitter and receiver antenna height in meters [17]. Obaidat-Green model is used to calculate the free space loss. To provide a reliable link between the user and the AP, the impact of fading caused by several objects, e.g., building, foliage, etc., can be approximated by means of the fade margin. Different levels of fade margin are suggested in the link budget calculation/measurement studies conducted for different scenarios (outdoor/indoor area, different frequency bands and etc.), e.g., in [22, 23]. To take into account the impact of fading in our calculation, we feed the path loss prediction algorithm with the fade margin. To compute d, we have:

$$\begin{aligned} L_{FM}[dB] &= P_{rx}[dBm] - S_{rx}[dBm] \\ &= P_{tx}[dBm] - L_{FS}[dB] - S_{rx}[dBm] \end{aligned} \tag{2}$$

where L_{FM} is the applicable fade margin, P_{rx} is the received signal level, S_{rx} is the receiver sensitivity, P_{tx} is the transmitted signal level. S_{rx} for different data rates are taken into account, according to the data provided in datasheets (e.g., [24]). Also, maximum transmission power regulated by European Union (20 dBm) is used to calculate the maximum radius of the AP coverage area. Other possible losses (cable loss, etc.,) are assumed to be negligible.

4.1.2 ITU model

For indoor scenario, we use the ITU model for indoor attenuation [18]. This model is widely used in 2.4 GHz band for different indoor scenarios (office, residential, commercial area). Eq. (3) shows the ITU indoor path loss model expression for an office environment, in which we assume that the transmitted signal can penetrate two floors.

$$\begin{aligned} L_{FS} &= N \log d + 20 \log f + P_f(n) - 28 \\ &= 30 \log d + 20 \log f - 9 \end{aligned} \tag{3}$$

where L_{FS} (dB) is the path loss, d (the distance between AP and user) and f (frequency) are expressed in m and MHz, respectively. Also, N is the distance power loss coefficient, n is the number of floors between the transmitter and receiver ($n = 2$), and $P_f(n) = 15 + 4(n - 1)$ is the floor loss penetration factor [18]. Furthermore, d can be calculated as shown in Eq. (2).

4.1.3 Log-normal model

Here, we consider the impact of the slow fading, represented by the log-distance model. In the log-normal model, the fluctuation of the signal around its mean attenuation has zero-mean Gaussian distribution (X_σ, in dB) with standard deviation σ (in dB as well). Therefore, the total path-loss (mean attenuation and impact of slow fading) is [19]:

$$L_{SF} = L_d + X_\sigma = L_{d_0} + 10n \log (d/d_0) + X_\sigma \tag{4}$$

where L_{SF} is the total path-loss, L_d and L_{d_0} are the mean attenuation of the signal at user location (d is the distance between AP and user) and reference location, respectively. To calculate the percentage of the AP coverage area with a received signal level that is equal to, or greater, than the desired received signal level ($U(\gamma)$), we follow the procedure defined in [19]:

For a circular coverage area, having radius R from the AP, let there be the desired received signal level γ:

$$\begin{aligned} U(\gamma) = 0.5 \cdot (1 - erf(a) + \exp((1 - 2ab)/b^2)) \cdot (1 - erf((1 - ab)/b)); \\ a = (\gamma - P_{tx} + L_{d_0} + 10n \log(R/d_0))/(\sigma\sqrt{2}) \\ b = 10n \log(e)/(\sigma\sqrt{2}) \end{aligned} \tag{5}$$

where P_{tx} is transmitted signal level and e is the Euler's number. Therefore, for a given γ and $U(\gamma)$, the R can be calculated.

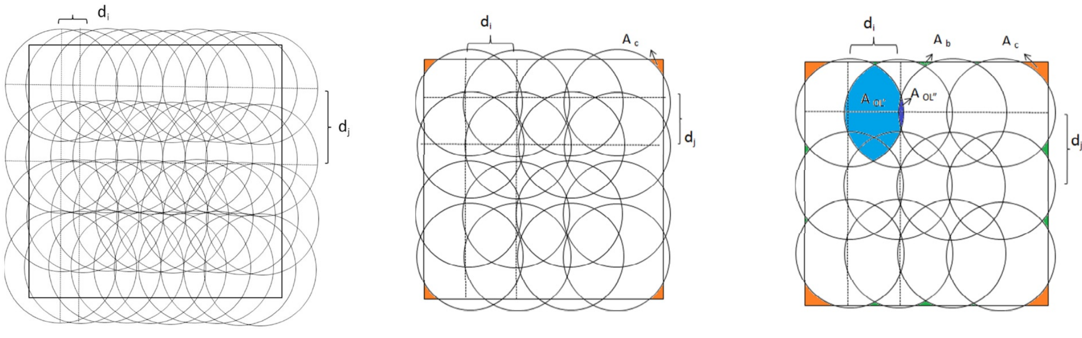
4.2 Coverage computation

With a high enough density of the APs all the area is covered (Fig. 2(a)), but if the density is reduced, some uncovered areas (A_{unc}) start to appear (Fig. 2(b) and 2(c)). Let us compute the surface of these uncovered areas. For the case shown in Fig. 2(b) , there are uncovered areas in each corner (A_c):

$$A_c = r \cdot (r - d) - 0.5 \cdot (r^2 \cdot \arccos (d/r) - d \cdot r^2 - d^2) \tag{6}$$

Thus,

$$A_{unc} = r^2 \cdot (4 - \pi) - 2A_c + (r - d)^2 \tag{7}$$



(a) $0 < d_i < d_j < r; d_j \leq \sqrt{r^2 - d_i^2}$ (b) $0 < d_i < d_j < r; d_j \geq \sqrt{r^2 - d_i^2}$ (c) $0 < d_i < d_j < r;$ $d_j \geq \sqrt{r^2 - 0.25 \cdot d_i^2}$

Figure 2: WLAN area- uncovered area is colored in orange and green for different cases.

For the case shown in Fig. 2(c), the overlapping areas between the circles should be computed ($A_{OL'}$ and $A_{OL''}$, respectively):

$$\begin{aligned} A_{OL'} &= 2r^2 \cdot \arccos{(d/2r)} - (d/2) \cdot \sqrt{4r^2 - d^2} \\ A_{OL''} &= 2r^2 \cdot \arccos{(d/r)} - 2d \cdot \sqrt{r^2 - d^2} \end{aligned} \tag{8}$$

Additionally, we have to compute the area between the circles and the boarder of the WLAN area (A_b):

$$\begin{aligned} A_b = (2 \cdot A_c + (n-1) \cdot B + n \cdot C - (s_{wlan} + \\ +2r - 2d) \cdot (r - d))/(n-1) \\ B = ((s_{wlan} + 2r - 2d) \cdot 2r - n \cdot \pi \cdot r^2 + \\ +n \cdot A_{OL'} + 0.5nA_{OL''} - (4 - \pi) \cdot r^2)/(2n-2) \\ C = r^2 \cdot \arccos{(d/r)} - d \cdot \sqrt{r^2 - d^2} \end{aligned} \tag{9}$$

Therefore, the uncovered area is computed as follow:

$$A_{unc} = 4(n-1) \cdot A_b + 4 \cdot A_c \tag{10}$$

Computation of the coverage percentage (cvg) is done for each case shown in Fig. 2, according to the formula: $cvg = 1 - (A_{unc}/A_{wlan})$. It can be seen that the complexity of our method is $O(N)$, where $N = n^2$ is the number of APs. Also, from Eq. (6)-(10), it can be understood that for a given cvg and r, the minimum number of APs (*the minimum density of APs* in A_{WLAN}) providing coverage over the WLAN area can be computed. Thus, based on the definition of r, there is a dependency between the quality of packet reception (for a given re-transmission time, packet error rate and bit error rate) and the minimum density of APs providing either transmission or detection coverage. We calculate APs detection density as a ratio of the number of APs providing detection coverage (with a given quality, i.e., bit error rate and tolerable delay) to the area of the entire WLAN.

4.3 Probability of successful packet reception

Now, we aim to analyze the relation between successful packet reception probability, r and the minimum APs detection density. We first calculate the probability of successful packet reception, and we will use the achieved result to calculate the probability of Probe Request reception $P_{b.rtx}$ in the next subsection.

For a given packet reception delay t_p, we can calculate the number of transmission attempts to successfully transmit a packet n_p as follows:

$$t_p = n_p \cdot \Delta t = n_p \cdot (t_{pro} + t_{tx} + t_{btw.ps}) \tag{11}$$

where Δt is the required time to transmit the packet, t_{pro} is propagation delay of packet, t_{tx} is the transmission delay of a packet and $t_{btw.ps}$ is the time between two packets. In addition, for a given bit error rate p, the probability of at least one erroneous bit within the frame is:

$$P_{pl} = 1 - (1-p)^n \tag{12}$$

where n is the number of bits in a frame and P_{pl} is packet loss. When $p \ll n$ then $P_{pl} \simeq n \cdot p$. Also we have:

$$\begin{aligned} E_b/N_0 &= \left(erfc^{-1}(2p)\right)^2 \\ SNR &= (E_b/N_0) \cdot Datarate/BW_{Channel} \end{aligned} \tag{13}$$

where SNR is signal to noise ratio and $BW_{Channel}$ is channel bandwidth. Thus, for a given noise level we can calculate minimum signal level required to achieve the required P_{pl}. Therefore, for a given P_{pl}, t_p, the maximum distance between user and AP (r) can be computed using path-loss model for a given fade margin or path loss exponent and slow fading standard deviation. For the calculated r and given cvg, the minimum density of AP providing coverage with a given probability of successful packet reception can be computed from the Eq. (6)-(10).

4.3.1 Probe Request receiving probability $P_{b.rtx}$

For a given maximum tolerable user detection delay (t_{det}), i.e., a delay that user may experience to be detected, number of Probe Request transmission attempts (n_b) can be calculated from Eq. (11). It is worth mentioning that t_{pro} and t_{tx} are in the order of μs and are thus negligible in comparison to the $t_{btw.bs} = 100\,ms$. Now, we introduce the $P_{b.rtx}$ as a probability that the user connectivity initiation can be detected when at least one, out of possibly several copies, of a single Probe Request frame is received by the APs. The probability of receiving at least one Probe Request from n_b attempts is given by the binomial distribution, then:

$$P_{b.rtx} = 1 - P_{bl}^{n_b} \tag{14}$$

Hence, for a given $P_{b.rtx}$, we can calculate P_{bl} (probability of Probe Request loss), p and SNR from Eq. (12)-(13) and r and the minimum APs detection density from Eq. (6)-(10) (for a given cvg), consequently.

4.3.2 User detection probability

For the assumed model, the probability of detecting the user that attempts to connect to a powered-on APs can be calculated as: $P_{det} = P_{b.rtx} \cdot cvg$.

5 Potential power saving

Following theoretical considerations, we now evaluate numerically our proposed strategy for power saving, using two propagation models mentioned in the previous section. The most important parameters to conduct these computations are shown in Table 1. In addition, S_{rx} for any data rate is derived from [24, 25].

Table 1: Simulation parameters

Parameter name	**Value / Range**
Outdoor/Indoor WLAN area	square, $s_{wlan} = 1000\,\mathrm{m}$
Fade margin	20 dBm (Outdoor) 8 dBm (Indoor,commercial area)
Max. transmission power	20 dBm
Frequency band (IEEE 802.11a)	5.2 GHz
Frequency band (IEEE 802.11b/g)	2.4 GHz
Transmitter and receiver antenna height	1 m
Slow fading standard deviation (IEEE 802.11a)	Indoor : 5.7 dB [26] Outdoor : 8 dB [27]
Slow fading standard deviation (IEEE 802.11b/g)	Indoor : 6.8 dB [26] Outdoor : 8 dB [27]
Path loss exponent (IEEE 802.11a)	Indoor : 2.6 [26] Outdoor : 2.7 [27]
Path loss exponent (IEEE 802.11b/g)	Indoor : 2.5 [26] Outdoor : 2.7 [27]

We use an iterative method to compute the number of APs required to cover WLAN area with a given coverage percentage, as illustrated in Fig. 3. We suggest that for a given t_{det}, we can calculate n_b, the number of Probe Request transmission attempts (the first transmission plus all retransmissions) required to receive at least one copy, out of possibly several copies, of a single Probe Request frame. Then, the Probe Request loss (P_{bl}) and the bit error rate (p) can be calculated consequently. For the calculated p, we calculate the SNR and translate it to the maximum distance (r) between the user and the AP where the user can be detected for a given t_{det} and $P_{b.rtx}$. To perform this calculation, we use path-loss models described in Section 4.1. The minimum AP density is calculated following the coverage computation method described in Section 4.1.

5.1 Metrics

In order to evaluate the performance of our power saving strategy, the following parameters will be used:

1. Power saving: the difference in terms of power consumption between the number of APs typically deployed in dense WLAN (e.g., as reported in [7]) and the number of APs foreseen by the proposed strategy.
2. maximum user tolerable detection delay (t_{det}): as defined in Section 4.3.1.
3. user detection probability (P_{det}): as defined in Section 4.3.2.

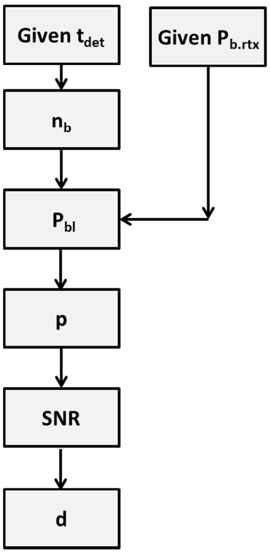


Figure 3: Proposed algorithm

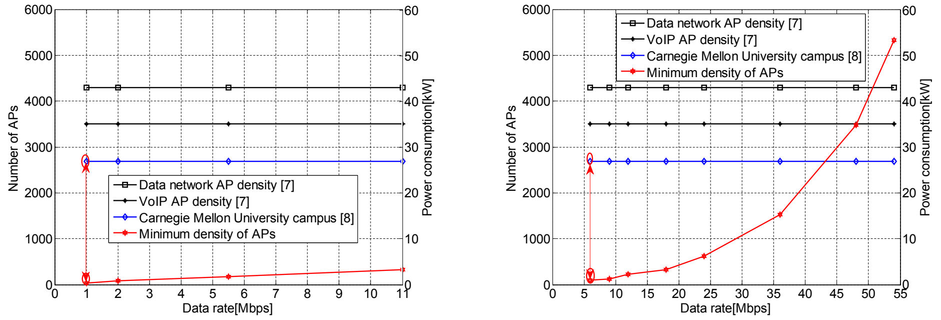
5.2 Main result: achievable power saving in dense WLANs for 802.11b/g

The densities reported in Section 3 as a reference for dense WLAN scenarios are not related to any particular traffic application. Thus, we have to consider their upper bounds for the estimation of the power saving potential offered by our strategy (minimum density of APs). In Fig. 4 we show the results in function of the data rate in indoor VoIP and data network scenarios (for IEEE 802.11b/g) for the ITU model and a given fade margin. In Fig. 5, the depicted results are for the log-distance model. Additionally, the number of APs is translated into the consumed power. Based on the power consumption data collected in [6], we approximate that a single AP consumes 10 W. For a given data rate, the difference between power consumption of deployed APs (in both VoIP and data network scenarios) and the minimum density of APs demonstrates the potential power saving, which can be achieved by deploying the minimum density of APs. This significant difference can be explained by the fact that an increase in r (decrease in the probability of a successful packet reception) leads to a decrease in the minimum density of APs. As it can be seen, providing just the detection coverage ($P_{det} = 1$), with $t_{det} = 0.2s$ and the minimum data rate (depending on the standard, 1 Mbps or 6 Mbps, respectively), leads to the maximum potential power saving.

Comparing the results obtained for the log-distance model and the path-loss model, the minimum density of APs is greater in the latter case due to a smaller size of the AP coverage area.

5.3 Main result for IEEE 802.11a

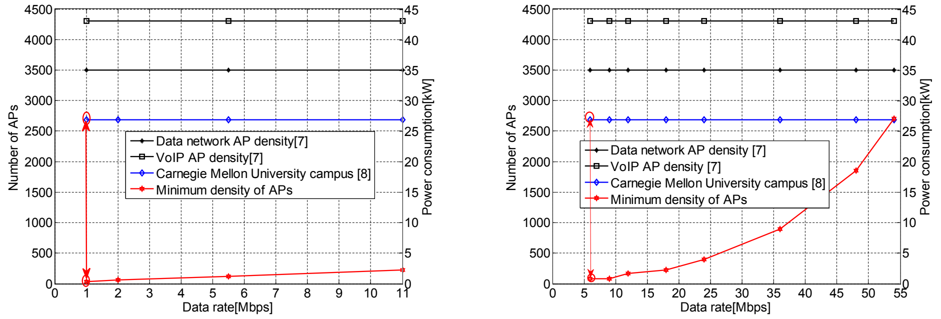
We conduct the same analysis for IEEE 802.11a. Comparing the results shown in Fig. 6(a) and 6(b) with these achieved for IEEE 802.11b/g, it can be concluded that both AP detection and transmission densities are greater for IEEE 802.11a. This can be explained by the fact that IEEE 802.11a devices operate in the higher frequency band which leads to a higher mean signal attenuation and higher path loss exponent. As it can be seen in Fig. 6(a) and 6(b), for the higher data rates (more than 36 Mbps),



(a) IEEE 802.11b

(b) IEEE 802.11g

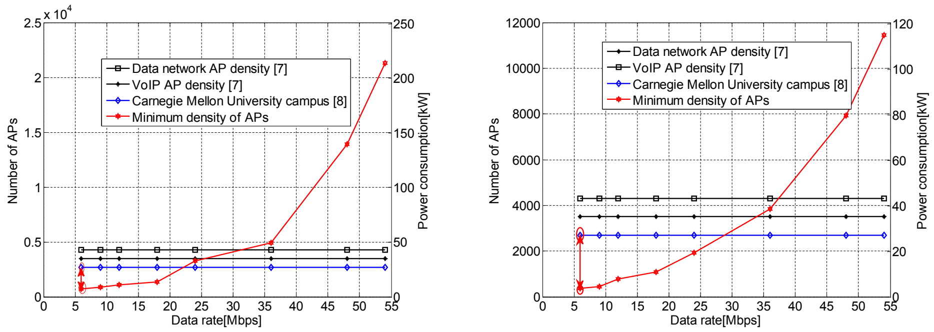
Figure 4: Number of APs in deployed networks and minimum density of APs vs. data rate ($L_{FM} = 8\,\text{dB}$):



(a) IEEE 802.11b

(b) IEEE 802.11g

Figure 5: Number of APs in deployed networks and minimum density of APs vs. data rate (log-distance model):



(a) $L_{FM} = 8\,\text{dB}$

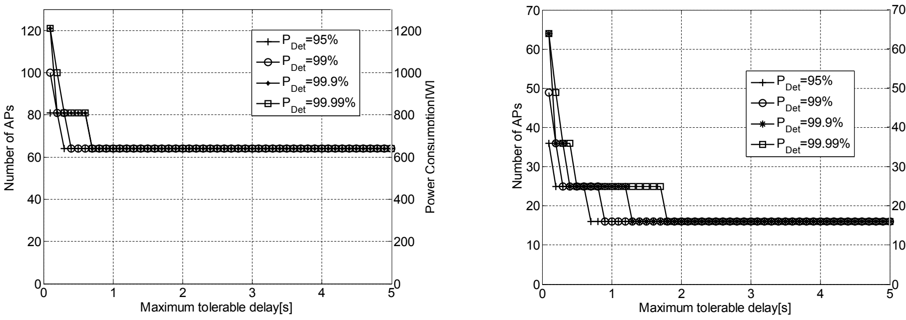
(b) Log-distance model

Figure 6: Number of APs in deployed networks and minimum density of APs vs. data rate (IEEE 802.11a)

the minimum density of APs calculated based on our assumption exceeds the number of the deployed APs demonstrated in [7, 8]. This can be explained by the fact that in [7, 8] there is no evidence given that the APs deployed in reference scenarios are IEEE 802.11a devices. Under this circumstance, we can conclude that the densities demonstrated in the reference scenarios are are most probably for IEEE 802.11b/g.

5.4 Improvement #1: number of APs vs. t_{det}, $cvg = 100\%$

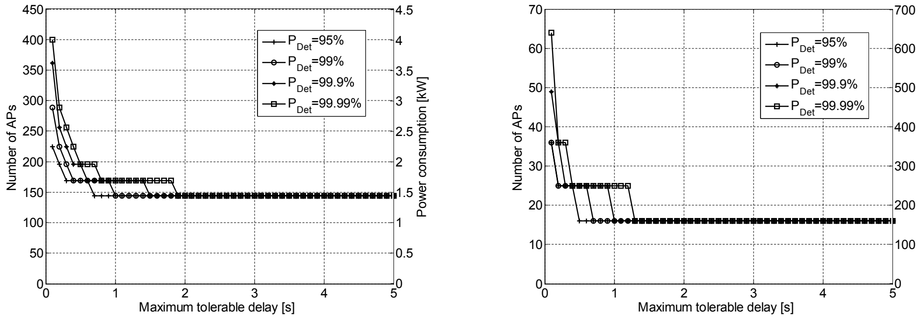
As a further step to achieve possible power savings, we examine the impact of increasing t_{det} on the minimum density of APs for a given probability of detection, when $cvg = 100\%$. Fig. 7 illustrates the relation between the number of APs and t_{det} for a given detection probability in indoor and outdoor scenarios for data rates of 6 Mbps (for 802.11g) or 1 Mbps (for 802.11b). As it can be seen, the increase in probability of detection leads to an increase in the number of APs, for a given t_{det}. Similarly, increasing t_{det}, the number of APs is decreased. Also, when the t_{det} is more than either 0.7 s (1.9 s for the log-distance model) for outdoor scenario and more than 1.8 s (1.3 s for the log-distance model) for indoor scenario, all curves converge to the minimum density of APs. As can be seen, the range of



(a) outdoor scenario

(b) Indoor scenario

Figure 7: Number of APs vs. t_{det} $cvg = 100\%$



(a) outdoor scenario

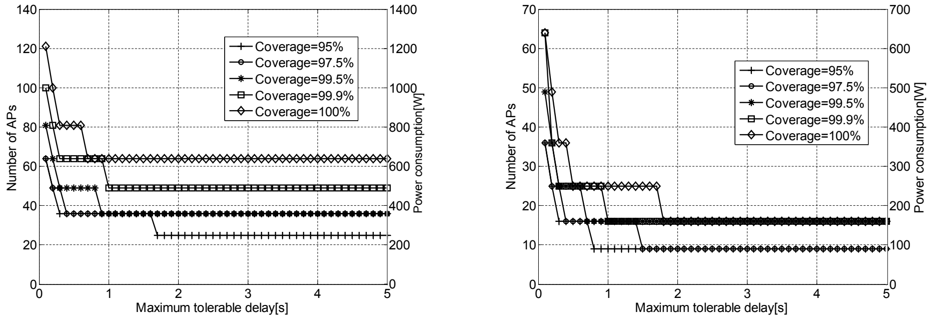
(b) Indoor scenario

Figure 8: Number of APs vs. t_{det} $cvg = 100\%$ (log-distance model)

achievable power saving is lower than what has been shown as the main result (Fig. 4), but still there is a considerable potential for power saving, which can be achieved by just an 0.6 s increment in t_{det}, for a given detection probability. The same conclusion can be drawn from the results shown in Fig. 8, in which the log-distance model is used.

5.5 Improvement #2: number of APs vs. t_{det} for $cvg < 100\%$

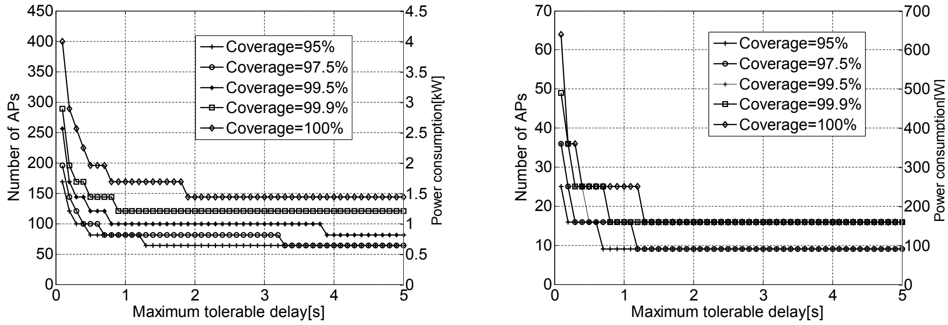
Last, we study the relation between the minimum density of APs and t_{det}, when slightly less than the detection coverage ($cvg < 100\%$) is provided, with a given probability of detection. Fig. 9 and Fig. 10 (log-distance model) show the impact on the user-tolerable delay, for a given detection probability, in indoor and outdoor scenarios. From our experiment for $P_{b.rtx} = 0.9999$, it can be seen that even 0.1% decrease in detection coverage leads to a further power saving. The power saving is greater for lower t_{det} due to a smaller size of AP coverage area. It can be concluded that a fair amount of power can be further saved, when provided detection declines slightly.



(a) outdoor scenario

(b) Indoor scenario

Figure 9: Number of APs vs. t_{det}, $P_{b.rtx} = 0.9999$



(a) outdoor scenario

(b) Indoor scenario

Figure 10: Number of APs vs. t_{det}, $P_{b.rtx} = 0.9999$ (log-distance model)

5.6 Comparison with related work

The task of comparing results of this work with the other strategies proposed so far (that were presented in Section 2) is relatively challenging. The reason is twofold: first, it is difficult to precisely reproduce the experiment scenarios and, second, only few experiments consider the dense WLAN settings. In an effort to relate the potential power saving offered by the proposed algorithm, we refer to the work presented in [2]. For the studied setup (indoor scenario with 15 APs in the area of 2000 m^2 and the resulting density of 7500 APs/km^2), assuming that the entire WLAN area is covered, Jardosh et al. report that 53% power saving can be achieved for the low traffic case, and 16% in the high traffic time interval. Our aggressive strategy yields much higher power savings, reducing the number of APs from 7500 to 81 for IEEE 802.11g (and to 36 APs for 802.11b, respectively), if the 1 km^2 area is considered (Table 2). Nevertheless, one has to be very careful when interpreting these results, especially taking into account our simplified system model, as described in Section 4.1.

Table 2: Comparison with related work

Proposed algorithm	**Number of APs**	**WLAN area**	**Density**	**Power saving**
[2]	15	0.002 km^2	7500	53.33%
Our strategy	7500	1 km^2	7500	98.92%

6 Conclusion

In this report we suggest a novel, purely WLAN-based and very aggressive strategy to reduce the density of WLAN APs that may result in switching off up to 98% of the inactive APs in campus and enterprise environments. We claim that it is not necessary to provide the coverage over the entire target area with the desired bit rate but, in contrast, any AP can detect the user connectivity initiation by receiving at least one Probe Request frame, transmitted with the lowest possible bit rate, within a tolerable waiting time. We suggest that for a given probability and delay of user detection, the maximum distance between the user and AP, i.e., radius of the detection coverage of an AP, can be calculated. From that we obtain the minimum density of APs covering the WLAN area with a given percentage.

On the basis of theoretical analysis and numerical evaluation for the provided system model, we initially assessed how significant amount of power can be actually saved with the proposed scheme. We show that in comparison to the other purely WLAN-based approaches we are able to drastically reduce the power footprint of dense WLAN networks. Moreover, we study the impact of increasing delay of user detection on the minimum density of APs for a given probability of detection. It is shown that a reasonable increase in delay of user detection can lead to a considerable power saving. Last but not least, the relation between the minimum density of APs and the delay of user detection is studied when slightly less than the full detection coverage is provided. It can be concluded from the results that a fair amount of power can be further saved in this case.

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