Optimization of Dense WLANs: Models and Algorithms

Vasilios A. Siris
Institute of Computer Science (ICS)
Foundation for Research and Technology - Hellas (FORTH)
P.O. Box 1385, GR 711 10, Heraklion, Crete, Greece
vsiris@ics.forth.gr


The goal of this report is to investigate the optimization of dense WLANs under various control mechanisms that include MAC layer parameter control, Access Point (AP) coverage control through beacon power control (also referred to as cell breathing), AP assignment, and channel assignment. This is important for projects, such as BT's Wireless Cities, whose goal is to achieve a blanket WiFi coverage across a whole city. To achieve such coverage, APs need to be deployed in a dense manner, hence there will be areas of overlapping coverage from more than one APs. If the APs are operated in an ad hoc manner, with no planning of the channel assigned to each AP or of the area covered by each AP, then there can be significant interference in the overlapping areas. This will result in reduced performance not only for wireless clients located in the overlapping areas, but for all wireless clients. The mechanisms mentioned above exist, in some basic form, in current generation wireless AP devices. However, the vendors and subsequently managers of dense AP networks either disregard them or use them in a suboptimal manner.

Until today, there is no systematic investigation of the joint optimization of all the aforementioned mechanisms. There are only a few works that look at the combined optimization of at most two mechanisms, and most focus on physical layer performance metrics, such as the signal-to-noise-and-interference ratio (SINR) or the aggregate throughput, which does not account for how resources are shared among different clients. This work tried to understand key aspects of the problem, and developed a modelling framework that allows the combined investigation of the various control mechanisms. The modelling framework developed allows the analysis of simple scenarios that help in understanding of how various wireless network parameters affect performance, it incorporates important features of WLANs, such as 802.11’s MAC layer sharing model and multi-rate nature, and 802.11e’s service differentiation parameters, it allows the encoding of different fairness or provider policy objectives for resource sharing, and it can be subsequently extended with more realistic models for path loss and client distribution or utilize measurements of the channel activity for accurate estimation of an AP’s load. The eventual target of this research, and further ones that follow from this report, is to develop algorithms and procedures to efficiently utilize the wireless resource and adapt to changes of the client distribution or the external interference due to the use of unlicensed spectrum, and provide practical guidelines for increasing the performance of dense WLANs, while taking into account user requirements and provider policies.

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1 Introduction

It is widely accepted that wireless networks will play an increasingly important role in providing ubiquitous broadband access in both local and metropolitan environments. In this direction, there are a number of efforts in deploying dense wireless networks based on WiFi (IEEE 802.11) technology for blanket coverage of metropolitan areas. One such project is BT's Wireless Cities. Additionally, there are efforts for dense deployment of WLANs in enterprise environments. In both of the above cases, Access Points (APs) need to be deployed in a dense manner in order to achieve high coverage, hence there will be areas of overlapping coverage from more than one APs. If the APs are operated in an ad hoc manner, with no planning of the channel assigned to each AP or of the area covered by each AP, then there can be significant interference in the overlapping areas. This will result in reduced performance not only for wireless clients located in the overlapping areas, but for all wireless clients. The latter is due to a well known property of 802.11's medium access protocol, whereby the throughput for all stations associated with an AP is the same, even if their transmission rates are different.

The goal of this work was to investigate the optimization of dense WLANs under various control mechanisms that include MAC layer parameter control, AP coverage control through beacon power control (also referred to as cell breathing), AP assignment, and channel assignment. This is important for projects, such as BT's Wireless Cities, whose goal is to achieve a blanket WiFi coverage across a whole city. The aforementioned mechanisms exist, in some basic form, in current generation wireless AP devices. However, the vendors and subsequently managers of dense AP networks either disregard them or use them in a suboptimal manner. The eventual target of this research, and further ones that follow from this work, is to develop algorithms and procedures to efficiently utilize the wireless resource and adapt to changes of the client distribution or the external interference due to the use of unlicensed spectrum, and provide practical guidelines for increasing the performance of dense WLANs, while taking into account user requirements and provider policies.

Until today, there is no systematic investigation of the joint optimization of all the aforementioned mechanisms in 802.11 WLANs. There are only a few works that look at the combined optimization of at most two mechanisms, and most focus on physical layer performance metrics, such as the signal-to-noise-and-interference ratio (SINR) or the aggregate throughput, which does not account for how resources are shared among different clients. A review of the state-of-the-art is presented in Section 7. The objectives of this work was to understand key aspects of the problem, and to develop a modelling framework that allows the combined investigation of the various control mechanisms. The modelling framework developed allows the analysis of simple scenarios that help in understanding how various wireless network parameters affect performance. Novel features of the modelling framework developed during this work include the following:

- It considers performance objectives that are a function of the MAC level throughput that wireless clients experience. Consequently, the models can capture the impact of the client distribution on the MAC level performance.

- The throughput model considered accounts for the multi-rate nature of WLANs and the 802.11 MAC wireless resource sharing, while taking into account the parameters for service differentiation supported by the 802.11e standard supplement.

- The framework can consider different optimization objectives, and is not restricted to simple measures such as the aggregate throughput. These objec-
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tives can characterise how the wireless resource (spectrum) is shared among different clients (fairness), and can encode different provider policies.

- It can be extended to more realistic path loss models, which account for actual interference from both the uplink and the downlink, but also interference originating from external sources. This is particularly important due to the use of unlicensed spectrum by the 802.11a/g family standards.

This report is structured as follows: In Section 2 we present an overview of resource control mechanisms in 802.11 WLANs, which include MAC layer channel access, coverage control (cell breathing), AP assignment, and channel assignment. In Section 3 we discuss the resource sharing mechanism in IEEE 802.11 networks, and present a simple expression for the throughput above the MAC layer. In Section 4 we discuss the optimization objectives we consider, which are functions of the MAC level throughput achieved by stations in the WLAN. In Section 5 we discuss in more detail the application of the previous optimization framework to coverage control (cell breathing), presenting a centralized and decentralized algorithm for beacon power control. In Section 6 we summarize the key results and findings of this work. Finally, in Section 7 we present a brief overview of other related work, and in Section 8 we conclude the report, identifying a number of important future research directions that can build on the work presented in this report.

## 2 Resource control mechanisms

In this section we provide an overview of resource control mechanisms for dense WLANs. The mechanisms include:

- MAC layer channel access
- Coverage control (cell breathing) through beacon power control
- AP assignment
- Channel assignment

Although the optimization framework presented in Section 4 can be applied to all of the above problems, in this report we investigate in more detail its application to coverage control (cell breathing). Additionally, in Section 5.2 we investigate the co-existence of coverage control and channel assignment, thus illustrating that the framework can be used to investigate the joint operation of various control mechanisms.

### 2.1 IEEE 802.11 MAC

IEEE 802.11’s DCF (Distributed Coordination Function) is based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). According to the collision avoidance mechanism of CSMA/CA, a station performs a backoff procedure before initiating a frame transmission. After detecting that the medium is idle for a DIFS (DCF interframe spacing) interval, the station selects a random backoff period from \([0, CW - 1]\), where \(CW\) is referred to as contention window. The station waits for the channel to be idle for a total time equal to this backoff period, after which it can transmit a data frame with the basic CSMA/CA procedure, or an RTS frame with the RTS/CTS procedure. The contention window \(CW\) has an initial value \(CW_{min}\), and is doubled when a collision occurs, up to the maximum value \(CW_{max}\). When a frame is successfully transmitted, the contention window is reset to its initial value \(CW_{min}\).
Control Mechanisms: MAC layer channel access

The IEEE 802.11e standard supplement addresses the issue of QoS support in WLANs. The MAC protocol of 802.11e is the Hybrid Coordination Function (HCF), which supports both contention-based and controlled channel access. The contention-based access of HCF is supported by the Enhanced Distributed Channel Access (EDCA) mechanism, which is an extension of the DCF mechanism that enables distributed differentiated access to the wireless channel with the support of multiple access categories (ACs). A higher priority access category has a smaller minimum contention window $CW_{\text{min}}$, thus has a higher probability to contend and eventually gain access to the channel. Additionally, different access categories can have a different maximum contention window $CW_{\text{max}}$ and interframe spacing interval ($IFS$). Finally, the 802.11e standard defines the transmission opportunity ($TXOP$) parameter, which determines the time duration a station can occupy the channel, once it has gained access through the channel access mechanism.

Recent work (e.g., see [26, 31, 37, 30, 11, 20] and the references therein), has been shown that the minimum contention window ($CW_{\text{min}}$) and the transmission opportunity ($TXOP$) are the most important for best-effort (elastic) traffic, while the maximum contention window ($CW_{\text{max}}$) affects resource sharing only in periods of high contention; the latter should be avoided in order to efficiently utilize the wireless channel. For real-time traffic, the interframe spacing ($IFS$) and the transmission opportunity ($TXOP$) are the most important.

Although the IEEE 802.11e standard identifies a number of parameters that can be used to achieve service differentiation, it does not define how these parameters should depend on the network load and traffic characteristics in order to efficiently utilize the shared wireless channel. Hence, the optimization of the MAC layer
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**2.2 Coverage control (cell breathing)**

Currently, wireless clients associate with the access point (AP) that has the largest received beacon power. Hence, control of the beacon transmission power can be used to control an AP’s coverage. A similar mechanism is used in cellular networks, where it is referred to as cell breathing. Coverage control or cell breathing can thus be used to balance the load among neighboring APs, Figure 2, and in doing so achieve some global resource sharing objective.

It is important to note that the intelligence for cell breathing can be implemented solely at the APs, without requiring any modifications to the wireless clients; the latter continue to associate with the AP that has the highest received beacon power.

**2.3 AP assignment**

Access Point assignment involves assigning to each wireless client the particular AP it should associate to. In comparison to cell breathing, AP assignment enables

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1. Actually, the optimization framework presented in Sections 4 and 5 is general, and can be applied to both elastic and real-time traffic with appropriate selection of the utility function. What is not so straightforward is to develop a simple throughput expression when both elastic and real-time traffic co-exist, and use the interframe spacing ($IFS$) parameter for prioritized channel access. However, in Section 3.1 we discuss a possible approximation, when the real-time traffic is not saturated and its aggregate traffic is a small percentage of the total traffic.
finer control of the distribution of clients to APs, Figure 3. On the other hand, it typically requires changes to the wireless clients. Finally, the intelligence or algorithm for selecting the AP for each client can reside on the client, the AP, or some management system (e.g., in the case of a network with thin APs); in the latter case, the AP or management system only requires to communicate the AP assignments to the wireless clients.

2.4 Channel assignment

Channel assignment involves assigning a particular channel to each AP, Figure 4. Channel assignment in cellular networks, as well as a significant amount of the work on WLANs, has focused on minimizing the total amount of interference. However, the MAC channel access mechanism in WLANs has a significant impact on resource sharing and the achievable throughput. One of the key points of this work is that the characteristics of the MAC should be taken into account for the channel assignment problem. Indeed, one of the effects of channel assignment in WLANs is to segregate the collision domain into smaller collision domains with fewer stations contending for channel access. This is similar to the role of bridging/switching in wired Ethernet networks.

It is possible to perform channel assignment in either a centralized or distributed manner. The former would be appropriate for small networks, or networks that are managed by the same organization. Moreover, the time scales over which channel assignment is performed are typically larger than the time scales over which cell breathing is performed. Moreover, cell breathing does not affect ongoing sessions or

2Nevertheless, we note that some form of crude AP assignment can be achieved using access control lists on the various APs.
clients already associated with an AP. On the other hand, when an AP changes its channel, all wireless clients associated with it must also switch to the new channel.

3 Resource sharing in IEEE 802.11 networks

In this section we investigate a simple resource sharing model and throughput expression for IEEE 802.11 WLANs that captures important characteristics of such networks, namely

- the MAC channel access model, hence the throughput above the MAC layer, and the MAC layer service differentiation parameters,

- the multi-rate nature of wireless networks, which is due to the path loss and channel characteristics, and

- the location-dependent nature of contention, which is due to the path loss.

3.1 A simple model for MAC layer sharing

Several analytical studies have approximated IEEE 802.11’s congestion avoidance procedure with a p-persistent model [10, 28]. In a p-persistent model, the probability \( p \) that a station tries to transmit in a time slot is independent of the success or failure of previous transmission attempts. The p-persistent model closely approximates the throughput of the actual congestion avoidance procedure when the average backoff is the same [10]; moreover, the saturation throughput has a small dependence on the exact backoff distribution [22].
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If $E[CW]$ is the average contention window, then the approximate p-persistent model has transmission probability $p = \frac{E[CW]}{E[CW]+1}$ [10]. If the probability of a frame being involved in more than one collision is very small, then $E[CW] \approx CW_{\text{min}}$ [28]. In IEEE 802.11e, different wireless stations can have a different minimum contention window, hence using the same arguments as above [28], the corresponding transmission probability of station $i$ in the p-persistent model is $p_i = \frac{CW_{\text{min},i}}{CW_{\text{min},i}+1}$.

The MAC operation of IEEE 802.11 can be viewed in time as involving three different types of time intervals: a successful transmission interval, a collision interval, and an idle time interval. We denote the length of each interval type as $T_{\text{suc}}$, $T_{\text{col}}$, and $T_{\text{idl}}$, respectively. The duration of each time interval depends on the physical layer encoding and the MAC layer operations. For basic CSMA/CA in 802.11b, $T_{\text{suc}}$ is given by

$$T_{\text{suc}} = 2T_{\text{PHY}} + T_{\text{SIFS}} + \frac{8(O + L)}{r} + T_{\text{ACK}} + T_{\text{DIFS}},$$

where $L$ is the frame length, $O = 34$ or 28 bytes is the MAC overhead, $r$ is the data transmission rate, and $T_{\text{PHY}}$, $T_{\text{SIFS}}$, $T_{\text{DIFS}}$, $T_{\text{ACK}}$ are the physical layer overhead, SIFS interval, DIFS interval, and ACK transmission time, respectively. The collision interval $T_{\text{col}}$ is

$$T_{\text{col}} = T_{\text{PHY}} + \frac{8(O + L)}{r} + T_{\text{DIFS}}.$$

When the RTS/CTS procedure is used, the successful transmission and collision intervals can be computed in a similar manner, taking into account that in 802.11b the ACK, RTS, and CTS frames are always transmitted at the basic rate (1 or 2 Mbps), hence their transmission times are independent of the data transmission rate $r$.

The average throughput for station $i$, considering a renewal assumption, can be expressed as the ratio of the average amount of data transmitted by that station in one time interval, over the average time interval. The average data transmitted by station $i$ in one time interval, considering a p-persistent model and assuming that the station always has a frame ready to transmit, is

$$E[X_i] = p_i \prod_{j \neq i} (1 - p_j) L,$$

where $L$ is the frame size, which for simplicity we assume is the same for all stations.

The average time interval is a weighted sum of the three types of intervals. If we assume that the intervals $T_{\text{suc}}$ and $T_{\text{col}}$ are normalized to the size of the idle slot time, and if all stations have the same transmission rate, then the average time interval is

$$E[T] = \sum_k p_k \prod_{j \neq k} (1 - p_j) T_{\text{suc}} + \left[ 1 - \prod_{j} (1 - p_j) - \sum_k p_k \prod_{j \neq k} (1 - p_j) \right] T_{\text{col}} + \prod_j (1 - p_j).$$

Combining the above two expressions, the average throughput $x_i$ for station $i$ is approximately

$$x_i = \frac{p_i \prod_{j \neq i, j \in I_i} (1 - p_j) L}{E[T]}.$$

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3We assume that the propagation delay is very small, hence do not consider it.

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where $E[T]$ is given by (3). Note that the above expression is valid under saturation conditions, when stations always have a packet to transmit, and can be applied to all versions of 802.11, provided all stations have the same transmission rate. The specific version of 802.11, and whether the CSMA/CA or RTS/CTS procedure is used, will determine the values of $T^{\text{succ}}$ and $T^{\text{col}}$, which we have taken to be normalized to the duration of the idle interval.

Next we consider the case where different stations have different transmission rates. In 802.11b with the RTS/CTS procedure, the transmission rate does not affect the collision interval, since the latter involves RTS frames which are always transmitted at the basic rate (1 or 2 Mbps). Hence, for 802.11b with RTS/CTS, the average time interval is

$$E[T] = \sum_{k} p_k \prod_{j \neq k} (1 - p_j) T^{\text{succ}}_k + 1 - \prod_{j} (1 - p_j) - \sum_{k} p_k \prod_{j \neq k} (1 - p_j) \prod_{j} (1 - p_j),$$

(5)

where the duration of the successful transmission interval $T^{\text{succ}}_k$ depends on the station’s transmission rate through (1).

In 802.11 with the basic CSMA/CA procedure, the collision interval also depends on the transmission rate. In this case the second term in (5) needs to be modified appropriately, to take into account the transmission rate of the stations involved in the collision.

The above model does not take into account the backoff procedure of the CSMA/CA mechanism. However, as noted in the beginning of this section, the saturation throughput has a small dependence on the exact backoff distribution [22]. Moreover, recall that our objective is to optimize resource usage. Both simulation [34] and actual experimentation [36] suggest that the above model is indeed accurate for parameter values that optimize resource usage; this result reflects the fact that the exponential backoff procedure should not be activated often in order to efficiently utilize the wireless channel.

The expression for the throughput of stations associated with an AP can be further simplified as follows, when all stations have the same MAC layer parameters:

$$x \approx \frac{1}{a \sum_{r} \frac{N_r}{r} + b},$$

(6)

where factors $a, b$ depend on the MAC and physical layer overheads, on whether the RTS/CTS mechanism is used, and the uplink/downlink traffic mix. Indeed, if there is only downlink traffic (which is similar to a random polling mechanism), the last expression becomes accurate and $a, b$ represent, respectively, the transmission rate-dependent overhead (e.g. the MAC layer overhead) and the transmission rate-independent overhead (e.g. the physical layer overhead and the overhead due to control packets - RTS/CTS and ACKs, which are transmitted at a basic transmission rate). A similar approximation is considered in [22, 23, 15], where it is noted that the factor $b$ depends on the number of clients. However, when the MAC layer parameters are optimized, both the number of collision and idle intervals will be minimized, hence factor $b$ will have a small influence on the throughput.

The last expression captures the multi-rate nature of wireless networks, which has a significant impact on the throughput. Moreover, the transmission rate $r$ depends on the signal-to-interference-and-noise-density ratio through a function of
the form $r = f(SINR)$, where $SINR$ takes into account the path loss, and the interference from other APs and clients that operate either on a different interfering channel (inter-channel interference) or on the same channel but outside the carrier sense range.

As noted in the footnote at the end of Section 2.1, deriving a throughput expression that considers the interframe spacing ($IFS$) parameter for channel access prioritization is not straightforward. However, if we assume that the high-priority traffic is non-saturated and their aggregate traffic is a small percentage of the total traffic, then a possible approach for considering the real-time traffic is to add to the denominator of (6) the total time the wireless channel is used for transmitting real-time traffic.

For the remainder of this report, we will use the last approximation, with $a = 1$ and $b = 0$. Note, however, that the methodology we follow is independent of this selection; for example, we can follow the same methodology, but approximate the throughput by (6) with the values of factors $a, b$ determined by empirical measurements.

If nodes do not always have data to send, and if we assume that each wireless node has an activity factor $u$, which denotes the percentage of time the node transmits data, then the average throughput can be approximated by

$$x'(u, N) = \sum_{K=1}^{N} q_K x(K),$$

where $q_K$ is the probability that $K$ stations out of the total $N$ are active:

$$q_K = u^K (1 - u)^{N-K} \binom{N}{K}.$$

The throughput expressions discussed in this section, can be used for analyzing various optimization objectives, and deriving algorithms for efficiently utilizing the wireless resource. Although we use simple throughput expressions for deriving the models and subsequently the algorithms, when implemented in practice the algorithms can rely on measurements of the channel activity to accurately infer an AP’s load, e.g., based on the number of active stations [10, 8, 39], the number of idle periods [10, 14], the slot utilization and frame size [9], and the percentage of success and idle intervals [35]. An advantage of such an approach is that it would enable the application of algorithms for efficient cell-breathing, AP assignment, and channel assignment, irrespective of whether the MAC layer is optimized or not.

### 3.2 Consideration of MAC layer parameters

Equation (6) assumes that all wireless stations have the same MAC layer parameters. The equation can be extended to the case where different stations have different MAC layer parameters. In particular, if we have different classes of stations, and the minimum contention window for stations belonging to class $c$ is $w_c$, then the average throughput for station $i$ is, assuming $a = 1$ and $b = 0$ in (6)

$$x_i = \frac{w_{c(i)}}{\sum_{i} w_{c(i)}} x,$$

where $c(i)$ is $i$’s class.

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4We note that this expression gives a rough estimate of the average throughput. For a more accurate estimation or to consider other performance measures, one needs to more accurately account for non-saturation conditions in the MAC channel access model, e.g., see [12, 21] and the references therein.
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In the case of the transmission opportunity $TXOP$, and if all stations have the same value of $TXOP$, then transmission time is equally shared among all stations and hence the average throughput for station $i$ with rate $r_i$ is

$$x_i = \frac{r_i}{N}.$$  

If we assume different classes, and class $c$ stations have transmission opportunity $TXOP$ proportional to $w_c$ (note that the absolute values of $TXOP$ are not significant for the modelling), then the average throughput is given by

$$x_i = \frac{r_i w_c(i)}{\sum_i w_c(i)}.$$

4 Optimization objectives

In this section we discuss two optimization objectives for efficiently utilizing resources in dense WLANs. Both objectives directly take into account the throughput at the MAC layer, based on the models discussed in the previous section. The first objective maximizes the sum of the utilities for all wireless clients, where the utility for each client is a function of the throughput it receives. The utility represents the valuation for a particular throughput, and can depend on the traffic type and provider policies in terms of the throughput the provider want to offer its customers. The second objective minimizes the maximum load of all APs, where the load is defined as the inverse of the throughput achieved by all clients associated with a particular AP.

4.1 Aggregate utility maximization objective

This objective is formulated as follows:

$$\text{maximize } \sum_i U_i(x_i(p, b, c))$$

over $p, b, c$, \hfill (7)

where $p, b, c$ are sets containing the MAC layer parameter, the beacon powers (or AP assignments), and the channel assignments, respectively. The throughput $x_i$ is given by (6). The above objective is generic, and different utility functions $U_i$ result in a different sharing of the wireless resource. Utility functions of interest include the following:

- $U_i(x) \propto x$: In this case the objective is to maximize the aggregate throughput, independent how the throughput is shared among the various wireless stations.
- $U_i(x) \propto \log(x)$: This objective achieves a proportionally fair sharing of the wireless resource. Unlike the aggregate throughput, with this objective increasing the throughput of low throughput stations yields a higher utility than increasing the throughput of high throughput stations.
- $U_i(x) \propto w_i \log(x)$: This objective extends the previous, by enabling differentiation of wireless clients according to the weight factor $w_i$. Moreover, such a utility can be applied in the case of class-based differentiation, where different weight factors can correspond to different classes.
- $U_i(x) \propto -\frac{1}{x}$: This objective minimizes the aggregate potential delay, since the inverse of the throughput gives the average packet delay.
A concave utility function is appropriate for elastic traffic, which can adapt to any throughput, a sigmoid function is appropriate for soft real-time traffic that has some minimum throughput requirements but can adapt to the available throughput, and a step function is appropriate for hard real-time traffic that only has minimum throughput requirements [33].

The aggregate potential delay is considered in [17, 16] for the AP assignment problem. A logarithmic utility function is considered in [23] for the AP assignment problem. Considering the AP assignment problem, and for a general definition of the utility function, one can derive bounds which enable the application of a branch and bound algorithm for exactly solving the corresponding optimization problem [19].

4.2 Load-based optimization objective

This objective is formulated as follows.

$$\minimize_{p, b, c} \max_j \frac{1}{x_j(p, b, c)} \text{ over } p, b, c. \quad (8)$$

The above objective tries to minimize the maximum load, defined as the inverse of the throughput that a station associated with a particular AP achieves. This definition of the load for an AP is justified by a key property of the IEEE 802.11’s MAC channel access model according to which all wireless stations associated with a particular AP achieve the same average throughput, independent of the physical layer data transmission rate.

The above optimization objective is interesting, because deriving simple bounds can be straightforward. For example, considering the problem of AP assignment, it is easy to see that for any partial assignment, the load $1/x_j$ for an AP $j$ is a lower bound for the load of AP $j$ under any extended assignment. Based on such bounds, one can apply a branch and bound algorithm for exactly solving the corresponding optimization problem [19]. The objective discussed in this section has been considered in [4] for the cell breathing problem.

5 Coverage control (cell breathing) optimization models and algorithms

In this section we apply and discuss in more detail the optimization framework presented in the previous sections, to the coverage control (cell breathing) mechanism in WLANs, which is achieved through beacon power control, assuming that all the other mechanisms are fixed. The formulation of the problem is based on (7):

$$\maximize_{b} F(b) = \sum_i U_i(x_i(b)) \text{ over } b. \quad (9)$$

The next subsection contains the analysis of the above optimization problem, for simple linear topologies and in the case of uniform client distributions. The analysis can be extended in a straightforward manner to grid topologies and non-uniform client distributions.

5.1 Analysis for linear topologies and uniform client density

In this section we first present the analysis methodology for linear topologies using a graphical representation for the case of two APs, Figure 5. In this figure note that
the interference (or collision) range depends on the transmission power of the data and control (e.g. RTS/CTS and ACK) frames and on the carrier sense threshold, but is independent of the transmission power of beacon frames. Another key property of the MAC layer mechanism is that it tries to minimize the probability that two stations inside the interference range transmit at the same time.

We focus on estimating the throughput for clients associated with the left AP in Figure 5. In the simple case where we have only one transmission rate, to estimate the throughput achieved by stations associated with an AP, we need to calculate the number of stations that are associated with the left AP ($N_{\text{STA}}$ in Figure 5) and the number of stations that are associated with the right AP, but are within the left AP’s interference (carrier sense) range ($N_{\text{INT}}$ in Figure 5). In the case of uniform client distribution, the number of stations $N_{\text{STA}}$ and $N_{\text{INT}}$ can be calculated based on the corresponding areas shown in Figure 5. All $N_{\text{STA}}$ stations associated with the left AP achieve the same throughput, which is approximated by

$$x = \frac{1}{N_{\text{STA}} + N_{\text{INT}}} \cdot \frac{r}{N_{\text{STA}} + N_{\text{INT}}}.$$

The aggregate utility is then

$$N_{\text{STA}} U(x).$$

The analysis in the case of multiple transmission rates can be performed in a similar manner as described above. Hence, if $N_{\text{STA},r}, N_{\text{INT},r}$ are respectively the number of stations that are associated with the left AP at rate $r$ and the number of stations that are associated with the right AP at rate $r$ but are within the interference (carrier sense) range of the left AP, then the average throughput can be approximated by

$$x = \frac{1}{\sum_r \left( \frac{N_{\text{STA},r}}{r} + \frac{N_{\text{INT},r}}{r} \right)},$$

while the aggregate utility is

$$\left( \sum_r N_{\text{STA},r} \right) U(x).$$

The analysis can be extended in a straightforward manner to grid topologies. Indeed, for uniform client distributions, the number of associated and interfering stations at different transmission rates can be calculated from the corresponding areas.

In the experiments of this and later sections, we consider the transmission rates for different distances shown in Table 1. The aggregate utility as a function of the beacon range (coverage) of each AP is shown in Figure 6. Since the client distribution is uniform, the optimal beacon range is the same for both APs. The two graphs in this figure show the aggregate throughput, which corresponds to a linear utility function $U(x) \propto x$, and the aggregate utility for a logarithmic utility $U(x) \propto \log(x)$. Note that neither the absolute values of each graph, nor the comparison of the two

<table>
<thead>
<tr>
<th>Transmission rate (Mbps)</th>
<th>Distance d (m)</th>
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<tbody>
<tr>
<td>11</td>
<td>$d \leq 35$</td>
</tr>
<tr>
<td>5.5</td>
<td>$35 &lt; d \leq 50$</td>
</tr>
<tr>
<td>2</td>
<td>$50 &lt; d \leq 120$</td>
</tr>
<tr>
<td>1</td>
<td>$120 &lt; d \leq 250$</td>
</tr>
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5.2 A greedy hill-climbing heuristic

In this section we present and investigate a greedy hill-climbing heuristic for beacon power control. The idea behind the heuristic is to start with all APs transmitting at their maximum power, and gradually decrease the APs’ beacon power in the order that gives the largest increase of the objective function $F$ in (9). The reduction of the beacon power is continued until no further improvements of the objective function can be achieved. The steps of the heuristic are summarized below:

1. All APs transmit beacon at maximum power.

2. Decrease power of AP that gives the largest increase of the objective $F$.

3. Repeat the previous step until no further reduction of an AP’s beacon power increases the objective $F$. 

Figure 5: Analysis for two APs and uniform client distribution, in the simple case of a single transmission rate.

graphs is of significance. Rather, the importance is the AP coverage for which the corresponding objective is maximized. Hence, Figure 6 shows that the maximum aggregate throughput is achieved for a small beacon coverage, in which case only a few wireless stations get associated. On the other hand, the maximum aggregate logarithmic utility is achieved for a higher beacon coverage, hence, more stations are associated to an AP. This is because maximizing the aggregate throughput is not concerned with how resources are shared among the different clients. On the other hand, due to the concavity of the logarithmic function, to maximize the aggregate utility it is more important to accept more clients with a low throughput, compared to fewer clients with a higher throughput.

Figure 7 shows the aggregate utility as a function of the beacon range, for different utility functions. This figure shows that when the utility has larger concavity, which indicates that there is higher a valuation for lower values of throughput, the optimum is achieved for a larger AP coverage.
Maximization of the aggregate throughput and aggregate logarithmic utility

- Figure 6: Aggregate utility as a function of beacon range for two APs and uniform client distribution. Maximization of the aggregate throughput corresponds to the utility $U(x) \propto x$, whereas the fair sharing objective corresponds to the logarithmic utility $U(x) \propto \log(x)$.

- Figure 7: Aggregate utility as a function of beacon range for two APs and uniform client distribution, and different utility functions.

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**Figure 8:** Linear topology considered in the investigations. The probability of wireless clients to be in the hotspot area (red/darker area) is $p_{\text{hotspot}}$, whereas the probability to appear outside the hotspot area is $p_{\text{normal}}$.

Next we investigate the above heuristic for the linear topology shown in Figure 8. In this section we have a given number of wireless clients, which are randomly placed in the area shown in Figure 8. For this reason, we will assume that a client is always associated with an AP, if it is in the range of at least one AP. This means that we do not reduce the AP coverage such that a client, that could have otherwise been accepted, is not accepted. We consider that the transmission rates for different distances are those given in Table 1. Additionally, to estimate the received beacon power we use the following path loss (in dB) expression:

$$L(d) = -40 - 2.8 \cdot 10 \cdot \log d,$$

where $d$ is the distance in meters. The range of the parameters we investigate, and their default values, are shown in Table 2. Finally, the results we present are an average of 200 runs, and also shown are the 99% confidence interval.

**Table 2:** Range and default values for parameters considered.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of clients, $N_{\text{cl}}$</td>
<td>10 – 70, default: 50</td>
</tr>
<tr>
<td>Hotspot length</td>
<td>50 – 500 m, default: 200 m</td>
</tr>
<tr>
<td>AP distance</td>
<td>200 – 500 m, default: 300 m</td>
</tr>
<tr>
<td>Ratio $p_{\text{hotspot}}/p_{\text{normal}}$</td>
<td>1 – 40, default: 30</td>
</tr>
<tr>
<td>Interference/carrier sense range</td>
<td>250 m</td>
</tr>
<tr>
<td>Beacon power levels</td>
<td>default: four levels, 0, 7, 13, 15 dBm</td>
</tr>
<tr>
<td></td>
<td>six levels, 0, 7, 13, 15, 17, 20 dBm</td>
</tr>
</tbody>
</table>
Figure 9: Aggregate utility for a different number of clients and ratio $p_{\text{hotspot}} / p_{\text{normal}}$.

- Small # clients and uniform distribution: exhaustive/heuristic close to default (max power)
- Performance of heuristic close to exhaustive search

Figure 9 shows the dependence of the aggregate utility (efficiency) on the number of clients and on the ratio $p_{\text{hotspot}} / p_{\text{normal}}$: the latter ratio depicts the intensity (i.e., degree of uneven client distribution) of the hotspot. This figure shows that for a small number of clients and a uniform client distribution, both the exhaustive search and the heuristic algorithm perform close to the default (maximum beacon power). Moreover, the figure shows that the heuristic performs close to the optimum (found through an exhaustive search). Figure 10 shows the dependence of the aggregate throughput on the number of clients and on the ratio $p_{\text{hotspot}} / p_{\text{normal}}$. This figure interestingly shows that maximizing the aggregate utility also results in maximizing of the aggregate throughput. In other words, the aggregate utility maximizing objective yields the same performance in terms of the aggregate throughput, as the aggregate throughput maximizing objective. As we will later see, this is not the case when we have ideal non-overlapping channel assignment.

Figure 11 shows the dependence of the aggregate throughput on the hotspot length and AP distance. The figure shows that the improvements that can be achieved with cell breathing are smaller for very small and very large values of the hotspot length and AP distance. Figure 12 shows that there are very small improvements of the aggregate utility when 6 beacon power levels (0, 7, 13, 15, 17, 20 dBm - which are typical for Cisco wireless interfaces) are used, compared to 4 beacon power levels (0, 7, 13, 15 dBm).

Figure 13 shows the performance of cell breathing, in the case where all APs are assigned the same channel and the case of ideal non-overlapping channel assignment. As expected, the aggregate utility is higher in the case of ideal channel assignment. Moreover, observe that with ideal non-overlapping channel assignment, the improvements that can be obtained using cell breathing are larger compared to the improvements in the case where all APs are assigned the same channel. Figure 14 shows the aggregate throughput in the case where all APs are assigned
Linear-4 AP: Aggregate throughput vs. # clients, $p_{\text{hotspot}}/p_{\text{normal}}$

- Exhaustive/heuristic increases performance in terms of both aggregate utility and aggregate throughput
- Performance of heuristic close to exhaustive search

Figure 10: Aggregate throughput for a different number of clients and ratio $p_{\text{hotspot}}/p_{\text{normal}}$.

Linear-4 AP: Aggregate throughput vs. hotspot length & AP distance

- Improvements smaller for very small or very large hotspot length and AP distance

Figure 11: Aggregate throughput for different hotspot areas (determined by the hotspot length in Figure 8) and AP distances.
Linear-4 AP: Aggregate utility vs. $p_{\text{hotspot}}/p_{\text{normal}}$ for 4 & 6 beacon power levels

Figure 12: Aggregate utility for 4 and 6 beacon power levels. Observe that no significant improvements are achieved with 6 beacon power levels, compared to 4 beacon power levels.

- No significant improvement of aggregate utility when # of power levels increases from 4 to 6

Linear-4 AP: Aggregate utility vs $p_{\text{hotspot}}/p_{\text{normal}}$, $N_c=50$ (Same CA & Ideal CA)

Figure 13: Aggregate utility for the same channel assignment (left graph) and for ideal non-overlapping channel assignment (right graph).

- Aggregate utility higher with non-overlapping CA
- With cell breathing, aggregate utility improvement over default (max-power) larger for non-overlapping CA
5.3 A distributed algorithm with local information

The heuristic algorithm for cell breathing discussed in the Section 5.2 is a centralized algorithm that requires complete information regarding the client distribution. This information is necessary to estimate the aggregate utility after a change of an AP’s beacon power.

To gain some intuition on constructing a distributed algorithm, consider the simple case where an AP $j$ has only one neighbor AP $k$. Without loss of generality, we also assume that all users have the same utility function. AP $j$ should decrease his beacon power if $U(x_k) > U(x_j)$, since this would result in some clients to associate to its neighbor AP $k$, hence yield a larger aggregate utility. In the case where $j$ has more neighbors, say $K$, then its decision on whether to decrease its...
beacon power can be based on the average utility of its neighbors $\sum_k U(x_k)/K$. Note that both rules require only local information, which can be obtained by having each AP $j$ broadcast to its neighboring APs the value $x_j$ or $U(x_j)$.

If according to the rule in the previous paragraph more than one APs should decrease their beacon powers, according to the rule presented above, then based on the greedy heuristic presented in the previous subsection, the AP for which a beacon power decrease yields the largest increase in the objective $F$ should perform the decrease first. However, the increase of the objective function $F$ is known only a posteriori. A reasonable estimate of the increase of the objective function $\Delta F_j$ is to consider both the number of clients currently associated to it, in addition to the average utility of its neighbors as follows:

$$\tilde{\Delta} F_j = \sum_r \alpha_r N_{j,r} \cdot \left( \frac{\sum_k U(x_k)}{K} - U(x_j) \right),$$

where $N_{j,r}$ are the number of clients associated with AP $j$ at rate $r$, and $\alpha_r$ is a factor satisfying $\alpha_{r'} \geq \alpha_r$ for $r' \leq r$; the latter represents the fact that a client associated with a lower rate is likely to be farther from the AP, hence more likely to switch to a neighboring AP.

Given the above estimate $\tilde{\Delta} F$, there are two approaches to achieve that the station with the largest $\tilde{\Delta} F$ decreases its beacon power first (in a probabilistic sense). In particular, if $\tilde{\Delta} F_j > 0$ for AP $j$, then

- assuming discrete (equal) time intervals, AP $j$ decreases its beacon power with probability $P(\tilde{\Delta} F_j)$, or
- AP $j$ decreases its beacon power after time $T(\tilde{\Delta} F_j)$.

The above discussion presents just an outline of the algorithm. The definition of the functions $P(\cdot)$ and $T(\cdot)$ are important, in order to avoid slow or fast changes. The investigation of this issue, in addition to the convergence properties of the algorithm are left for future study.

### 6 Key results

The key new results and findings from this research work include the following:

- The models developed can incorporate service differentiation at the MAC layer, where different clients can have different classes with different 802.11e MAC layer parameters (such as the minimum contention window and the transmission opportunity - TXOP).

- As a result of the MAC layer sharing mechanism (which is based on the CSMA/CA protocol), for an objective that is the sum of a function of the wireless clients’ throughput, the AP assignment problem can be solved exactly using a branch and bound algorithm.

- For channel assignment, the problem of minimizing the maximum load, defined as the inverse of the throughput that a client can achieve while connecting to a particular AP, can be solved exactly using a branch and bound algorithm.

- We developed both a centralized and a decentralized heuristic algorithm for controlling the beacon power, to maximize the aggregate system efficiency which is defined as the sum of a function (utility) of the clients’ throughput. Experiments show that the solution found by the centralized algorithm is very...
close to the true optimum, and the overall performance depends on various system parameters such topology, uniform or hotspot client distribution, size and intensity of hotspot.

- We found that the performance of beacon power control in terms of both efficient resource sharing and aggregate throughput did not differ significantly when 6 beacon power levels were used, compared to the case where 4 beacon power were used.

- We compared the performance for optimization objectives related to the aggregate system efficiency and to the aggregate throughput, when all APs are assigned the same channel and under ideal non-overlapping channel assignment. Our results show that the improvements in terms of efficient resource sharing are greater under ideal channel assignment. In general, the performance improvements depend jointly on both mechanisms, hence the mechanisms should not be investigated in isolation.

- Finally, our results show that cell breathing can be used to balance the load and share resources (wireless spectrum) more efficiently, while channel assignment alone cannot achieve such load balancing. Hence, both mechanisms are necessary to efficiently operate dense WLANs.

7 Related work

In this section we present a brief overview of related work. Channel assignment is investigated in conjunction with power control in [1, 2]. The work in [1] investigates the problem of interference in chaotic wireless 802.11 deployments using AP measurement data from several cities. Moreover, the paper investigates how channel assignment and power control can influence the interference among neighboring APs, and the resulting end-client performance. The paper concludes that intelligent channel assignment alone cannot minimize the interference among neighboring APs. In particular, the paper reports that intelligent channel assignment can improve performance by 150%, whereas intelligent channel assignment and static power reduction can improve performance by over 300%. The investigations in this paper considered 802.11b/g which supposedly has 3 non-overlapping channels. The work in [2] jointly considers power control and channel assignment, in order to achieve a coverage objective. This work finds that random channel assignment performs close to more sophisticated algorithms, when the AP density is high.

Cell breathing in WLANs is investigated in [3, 4]. The work in [3] investigates the cell breathing mechanism in WLANs, based on an aggregate throughput optimization model that assumes each client’s contribution to an AP’s load is always the same, and independent of its transmission rate. The paper reports performance (aggregate throughput) improvements of 50% in the case of uniform client distributions, and an order of magnitude in the case of non-uniform client distributions. The work in [4] investigates cell breathing in WLANs based on an optimization objective that seeks to minimize the maximum load over all APs, and propose algorithms for solving the corresponding problem in polynomial time.

Channel assignment in WLANs is investigated in a number of papers. The work in [25] considers the carrier sense mechanism in 802.11 WLANs and defines an optimization problem that minimizes the maximum utilization of of all APs, where the utilization considers the number of other APs that can trigger the carrier sense mechanism. Because the original problem in NP-complete, the paper proposes a heuristic algorithm. The work in [40] proposes an adaptive version of the previous
algorithm. The work in [39] considers a distributed algorithm for channel assignment based on an estimate of the utilization at various channels and the number of associated clients. The work in [24] proposes a distributed channel assignment algorithm, based on the level of interference in the various channels, estimated by each AP independently. The work of [29] presents a heuristic algorithm for channel assignment, where channels are assigned to the APs in decreasing order of the interference they experience. The work in [17] defines a channel assignment algorithm based on the Gibbs sampler, whose target is to minimize the total interference of all APs. According to the algorithm, each AP selects channels based on the interference and the Gibbs distribution, which contains a temperature factor that is adapted using a logarithmic cooling procedure. This work shows that a greedy version of the proposed algorithm performs close to optimum in most case. The work in [32] investigates traffic aware channel assignment algorithms, which are based on maximizing the sum of the separation between channels assigned to different APs. The work in [27] considers the problem of channel assignment based on a conflicting set coloring formulation that jointly performs load balancing and channel assignment by explicitly capturing the interference effects at wireless clients.

The work in [5] investigates the problem of assigning stations to access points in order to achieve max-min fairness. The approach considers the fact that in wireless networks different stations can connect at different physical layer transmission rates. The works in [15, 17, 23, 16] considers a simple model for the throughput that a station achieves, which takes into account the multi-rate operation of IEEE 802.11, and is similar to the expression considered in this report. In particular [15] considers a heuristic based on the linear combination of the transmission rate and throughput for access point selection. The work in [17, 16] considers an optimization objective based on minimizing the aggregate potential delay (Section 4.1), and proposes an algorithm based on the Gibbs sampler so that each client, in a decentralized manner, selects the AP to associate to. The work in [23] considers an optimization objective based on maximizing the sum of the logarithmic functions of the achieved throughput (Section 4.1), and investigate among others various special cases related to the clients’ transmission rates.

The work in [13] considers the packet error rate and the number of stations already associated to an access point as a metric for access point selection. The work of [18] proposes an access point selection scheme based on the quality of a link in both directions, in order to maximize the link rate. The work of [6] investigates various selfish algorithms, implemented at the wireless clients, to select the AP to associate to. In our prior work [35] we propose an online algorithm that can be implemented at the wireless client, to select the AP with the smallest expected packet delay; the algorithm achieves a fair allocation of the throughput among the various wireless clients.

8 Conclusion and future research directions

The work included in this report has progressed the understanding of various issues related to the joint optimization of WLANs across multiple control mechanisms, and has produced models that can be further extended in a number of directions. Future research directions include the following:

• Comparison of cell breathing with AP assignment. Assigning for each individual wireless client the AP to associate with, allows greater flexibility compared to cell breathing (beacon power control), but requires modifications to the clients. Hence, quantifying the performance improvements that AP assignment has over cell breathing is important to weigh its advantages against its additional complexity.
Our work has shown the performance of cell breathing with the same and with ideal channel assignment. In practise, channel assignment will not be ideal, hence understanding the interaction and performance improvements when cell breathing co-exists with realistic channel assignment is important. In this direction, it is necessary to consider the basic mechanisms for dynamic frequency selection and transmit power control which are supported by the new IEEE 802.11h standard, in addition to the reporting mechanisms supported by the IEEE 802.11k standard.

For cell breathing we have outlined a distributed algorithm which relies on local information that can be readily obtained by a node’s neighbors. An important issue is the convergence properties and performance of this algorithm.

Our work has compared two different optimization objectives: optimizing the aggregate system efficiency and the aggregate throughput. An interesting issue is to compare these objectives with others, such as minimizing the maximum load.

Our experiments have considered simple models for the path loss and for the client distribution. An interesting next step is to consider more realistic models for both, possibly based on actual measurements.

Another direction is to combine the algorithms and procedures based on the modelling framework presented, with actual measurements of the channel usage to accurately estimate the APs’ load. This would enable the application of the algorithms and procedures, irrespective of whether the MAC layer is optimized.

Another important research direction is to extend our models to include power control of data packets or adaptation of the carrier sense threshold [38]. Power control for data packets can both reduce the interference that wireless clients produce and can reduce their power consumption. Moreover, the new 802.11h standard supports a transmit power reporting scheme, which can be used for link quality estimates and power control.

Extension of models to other wireless LAN topologies and technologies, such as using sectorized or directional antennas. It is interesting to investigate the relative importance of the various mechanisms (beacon power control, AP assignment, channel assignment) in such network topologies, and to compare their performance to the case investigated during this report (onidirectional antennas).

Finally, another important issue is the placement of wired backhaul connections for dense WLAN deployments, and how this placement is influenced by factors such as client distribution.

References


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