CHAPTER 7

Radio Resource Allocation for Interference Management in IEEE 802.11n WLANs

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I. Introduction

In Wireless Local Area Networks (WLANs) Radio Resource Allocation techniques may affect network reliability, availability, performance and deployment characteristics [1].

- **Reliability and Availability**: The radio propagation environment changes in the time and frequency domains and thus affects connection speeds, error rates and the Quality of Service. In an indoor environment, due to multipath propagation as the receiver is moving, it is possible for a link to fail completely. Also, the number of users being served by an Access Point (AP) may vary considerably. In this case, an overload may occur resulting to congestion that degrades the services provided by the specific AP.
- **Performance**: A WLAN should be capable of providing high throughput with low latency. Users and APs share the same bandwidth resource, and congestion is likely to happen in areas of high user density, which causes user throughput reduction.
- **Deployment characteristics**: In a WLAN deployment, the AP locations and the radio channels assignment strategies must be selected carefully. In a coverage-oriented design, the APs are placed as far apart as possible in order to minimize installation costs and to avoid overlapping between the coverage areas of APs operating on the same radio channel. Additionally, proper channel assignment minimizes the co-channel interference.

We consider the gains that can be achieved by a cross layer approach for a wireless network design, where the knowledge of the wireless medium in the PHY layer is shared with MAC and higher layers in order to provide efficient methods of allocating network resources [2]. Channel-state-dependent techniques can lead to improved network throughput. The radio propagation environment may change dynamically, so one cannot be sure about the reliability of the channel estimates and the sub-channel assignments that are based on those estimates. With cross layer radio resource management, the WLAN 'senses' the propagation conditions from time to time and then dynamically adjusts the allocations in the frequency and time domains. The optimal channel allocation minimizes the overlap between the coverage areas of co-channel APs. There are also other factors that influence the selection of the optimal set of frequency assignments. These other factors include noise and interference (co-channel and adjacent channel) from other networks. Additionally, an AP may transmit only occasionally and cause less interference to other APs using the same channel. Moreover, adaptive beamforming techniques can improve the results of the frequency assignment procedure by taking into account the changes in the propagation environment and the generated interference from neighboring WLANs.

By allocating sub-channels in a dynamic manner among various data users with smart scheduling mechanisms, the resource utilization may be improved efficiently, based on the instantaneous user demand and the instantaneous channel states for each user. The achieved gain due to channel-state-dependent scheduling algorithms is called multi-user diversity gain. Various real-time algorithms have been designed that achieve this gain and also support diverse Quality of Service requirements. Since an AP and its associated users share a limited bandwidth resource, APs can become overloaded, leading to congestion and poor performance in terms of provided throughput per user. A user may be able to communicate with two or more APs. Network resources might be allocated using methods that rely on information received from a set of APs. The AP my either accept the request from a user or deny the request and advise the user to handover its connection to another AP.

Numerous papers have addressed optimal resource allocation in wireless networks. Proper channel assignment may minimize the overlapping between coverage areas of co-channel APs. The problem of assigning channels to APs can be characterized as a graph-coloring problem. The nodes at this graph represent APs, the edges correspond to coverage overlaps between APs and the weights associated with the edges give the amount of measured overlapping. The goal is to cover APs with the minimum number of channels (colors) such that there will not be a case of adjacent APs using the same channel. In [3] the overlapping coverage weights are calculated taking into account co-channel interference as well as interference between overlapping channels. In [4] centralized channel selection and user association algorithms are proposed. The problem of channel selection and user association is solved in [5] by using a centralized approach. The problem of the joint determination of transmit power and MAC parameters in a distributed way is investigated in [6].

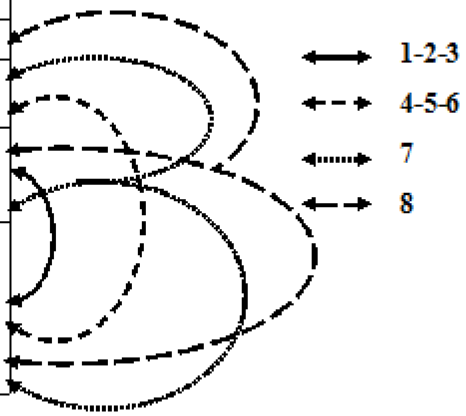
The aim of this chapter is to study some representative cross-layer (CL) proposals and approaches for IEEE 802.11n WLANs focusing on radio resource management schemes. In section II, we describe the schemes covered in this chapter. Section III gives a brief overview of IEEE 802.11n WLANs while section IV analyzes the problem of the unlicensed and uncoordinated environments of WLANs. Sections V - XII describe different cross-layer schemes for unicast scenarios whereas section XIII is oriented towards multicast scenarions. Finally, section XIV concludes this chapter.

II. Classification Method for Cross- Layer Design

Among the different CL schemes for radio resource management that can be found in the literature, we focus on eight CL strategies. Table 1 illustrates these schemes with the related (tunable) parameters belonging to different OSI layers.

Table 1 Cross-Layer interactions

Layer	Tunable Parameters
Application	•QoS constraints
Network	•Admission control •Routing load
Link	•Medium access •Sub-carriers assignment •Scheduling
Physical	•Band selection •Power control •Beamforming •Space Division Multiple Access •Modulation and Coding scheme •Channel estimation



The CL interactions are explained in the following list:

1. Channel allocation is made taking into account the total traffic load on each channel due to the contention nature of the asynchronous MAC protocol.
2. Channel state detection is used for scheduling in MAC layer, which requires a MAC-PHY cross-layer interaction. Scheduling decisions are made by the MAC layer and are optimized through cross-layer interaction with PHY layer.
3. Beamforming schemes reduce interference to the other APs and conserve energy. Adaptive modulation schemes select the most appropriate transmission rates depending on channel conditions. The feedback information of eigen-steering vectors and the related acknowledgements (ACK) in the uplink direction after successful reception may enhance downlink throughput.
4. Power control reduces interference. A cross-layer scheme can operate between the PHY and network layers and user association is taken into consideration. The traffic load may be balanced across the different WLANs.
5. The proposed PHY-networking cross layer scheme allows a user to be associated at the appropriate AP and the AP selects the operating frequency that minimizes co-channel interference.
6. In this cross-layer scheme the information about routing passes to the PHY layer in order to select the appropriate channel.
7. PHY, link and network cross-layer interactions allow a number of spatially separated users to share the same frequency and time resources by applying Space Division Multiple Access (SDMA) techniques. The goal is achieved by tuning MAC layer parameters.

8. The proposed CL scheme is targeted for multimedia applications in which specific Quality of Service (QoS) is required. Beamforming, frequency assignment and scheduling take into account QoS requirements in order to reduce interference and enhance performance in terms of throughput and fairness.

III. IEEE802.11n WLANs

The most notable advantages that will be offered by the IEEE 802.11n standard compared to previous WLAN technologies are substantial improvement in reliability and greater application data throughput. The IEEE 802.11n standard is expected to deliver data rates of up to 300 Mbps per radio link [7]. The IEEE 802.11a/g solutions can achieve a maximum data rate of 54 Mbps, while the IEEE 802.11b delivers a maximum data rate of 11 Mbps. The operating frequencies of IEEE 802.11n are within the 2.4 GHz and 5 GHz radio bands, thus it is backward compatible to all IEEE 802.11a/b/g variants. The introduced solutions in IEEE 802.11n employ several techniques to improve throughput and reliability. The most representative innovations are:

- Multiple Input Multiple Output (MIMO)
- Packet aggregation
- Channel bonding (40 MHz channel band)

Also, the PHY layer design is based on orthogonal frequency-division multiplexing (OFDM) with MAC layer support, closed loop control of the PHY data rates and QoS handling. The following sub-sections describe the main features of IEEE 802.11n that are used in the proposed schemes, namely Orthogonal Frequency Division Multiplexing (OFDM) modulation, Multiple-Input-Multiple-Output (MIMO) transmission and Medium Access Control (MAC) techniques .

A. OFDM modulation

Two main transmission schemes exist for IEEE 802.11 at the PHY Layer: Direct Sequence Spread Spectrum (DSSS) and Orthogonal Frequency Division Multiplexing (OFDM). The IEEE 802.11a uses OFDM that supports high bit rates (54 Mbits/s maximum physical rate) while IEEE 802.11b employs DSSS with lower bit rates (11Mbits/s). IEEE 802.11g is compatible with IEEE 802.11b and supports transmission with both OFDM and DSSS.

OFDM is well suited for wideband transmission when the propagation channel effects include frequency selective fading. In IEEE 802.11n the OFDM modulation is used in the 20 MHz band as in IEEE 802.11 a/g. It's composed of 64 sub-bands out of which a total of 48 sub-bands are used for data and 4 as pilot. In the lower (DC) sub-band no modulation is applied and it is used to estimate the noise power whereas the remaining sub-bands are used as guard sub-bands. The 40 MHz band contains 128 sub-carriers (108 data tones and 6 pilot tones) [8]. Fig. 1 illustrates the tone design for 20 and 40 MHz channelization. The employed technique that combines two adjacent frequency sub-bands of 20 MHz into a single 40 MHz band is called bonding and is most effective in the 5GHz frequency band, where there are much more available sub-channels. A Cyclic Prefix (CP) having duration equal to 800ns is used to maintain the orthogonality among the sub-bands against the delay spread of the channel. Taking into account that the OFDM symbol is 3.2 μs long, the CP overhead occupies 20% of each transmitted symbol. For indoor applications with lower delay spreads, the CP can be reduced down to 400ns.

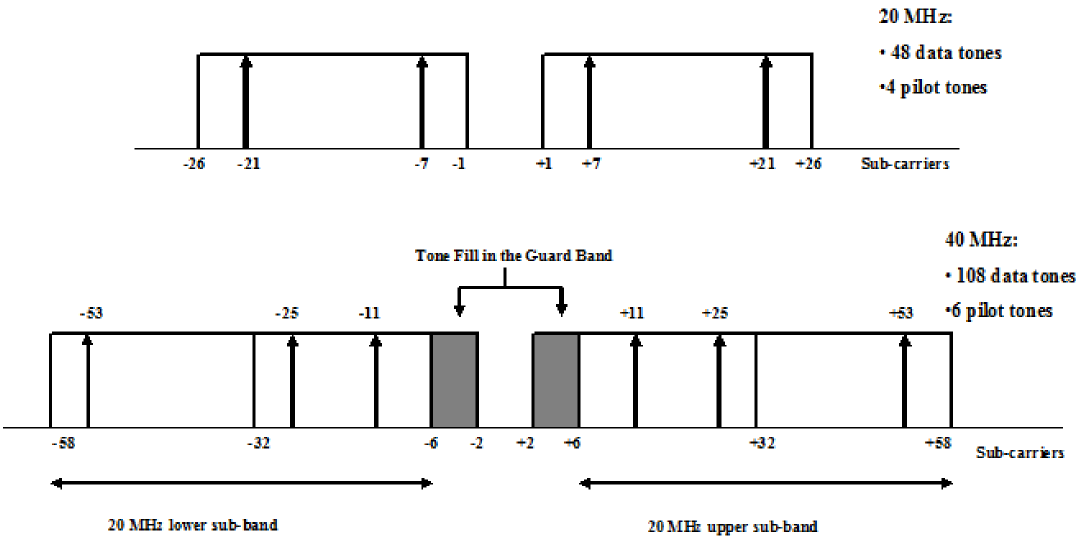


Figure 1 Tone design in IEEE 802.11n

B. MIMO

In IEEE 802.11 a/b/g a point-to-point communication through a single spatial stream over a single antenna is established between APs and users. In IEEE 802.11n, APs transmit up to four spatially separated streams and the mobile terminals employ multiple antennas (two or four) to recover the multiple transmitted data streams. MIMO technology enables the transmission of different bits of a message over separate antennas providing much greater throughput and reliability. In contrast to the previous WLANs technologies, IEEE 802.11n with MIMO exploits multiple transmitted paths and their reflections that effectively increase the range of an AP and reduce “dead spots” in the wireless coverage area.

The MIMO channel response can be represented in matrix form as

$$H_n = \begin{bmatrix} h_{11}^n & h_{12}^n & h_{13}^n & h_{14}^n \\ h_{21}^n & h_{22}^n & h_{23}^n & h_{24}^n \\ h_{31}^n & h_{32}^n & h_{33}^n & h_{34}^n \\ h_{41}^n & h_{42}^n & h_{43}^n & h_{44}^n \end{bmatrix} \qquad (1)$$

where h_{ij}^n is the channel response between receiver antenna element i and transmitter antenna element j, n is the OFDM sub-band index which characterizes the wideband channel at the discrete frequency n belonging to a set of $\{1, 2, \cdots, N\}$ sub-channels. Assuming 20 MHz channelization the value of N is 52. H_n has dimensions equal to N_r x N_t , where N_r is the number of receiver antenna elements and N_t is the number of transmitter antenna elements. When sufficient scattering exists, the maximum number of available spatial transmission channels is limited by the rank of H_n. A trade-off between the diversity gain and the number of spatial streams over a MIMO channel is selected. Additionally, beamforming was proposed for exploiting the full capacity benefits of MIMO [9,10]. Two categories of design may be used:

- Eigen vector steering (ES) when full Channel State Information (CSI) or complete knowledge of channel H_n is available at the transmitter.
- Spatial Spreading (SS) when either partial CSI or the statistical knowledge of channel matrix H_n is available at the transmitter.

I. Eigenvector steering (ES)

When full CSI is available at the AP, the optimum transmit and receive steering vectors may be obtained from the Singular Value Decomposition (SVD) of the channel. The MIMO channel can be decomposed into orthogonal spatial channels that are commonly referred as eigenmodes.

$$H_n = U_n D_n (V_n)^H \quad (2)$$

U_n and V_n are unitary matrices representing the left and right eigenvector of H_n respectively. D_n is a diagonal matrix, representing the transmit power at each eigenmode. The columns v_{ni} of V_n with $i = \{1, 2, \cdots, N_t\}$ are used as transmit steering vectors and the rows u_{nj} of U_n with $j = \{1, 2, \cdots, N_r\}$ as receive steering vectors. D_n is a diagonal matrix so that there is no cross talk between the estimated symbols at the receiver. Finally, up to min(N_t,N_r) parallel channels can be transmitted. Fig. 2 depicts the ES transmission and reception scheme for a 2x2 MIMO channel.

The larger eigenmodes have substantially less frequency selectivity than the smaller ones.

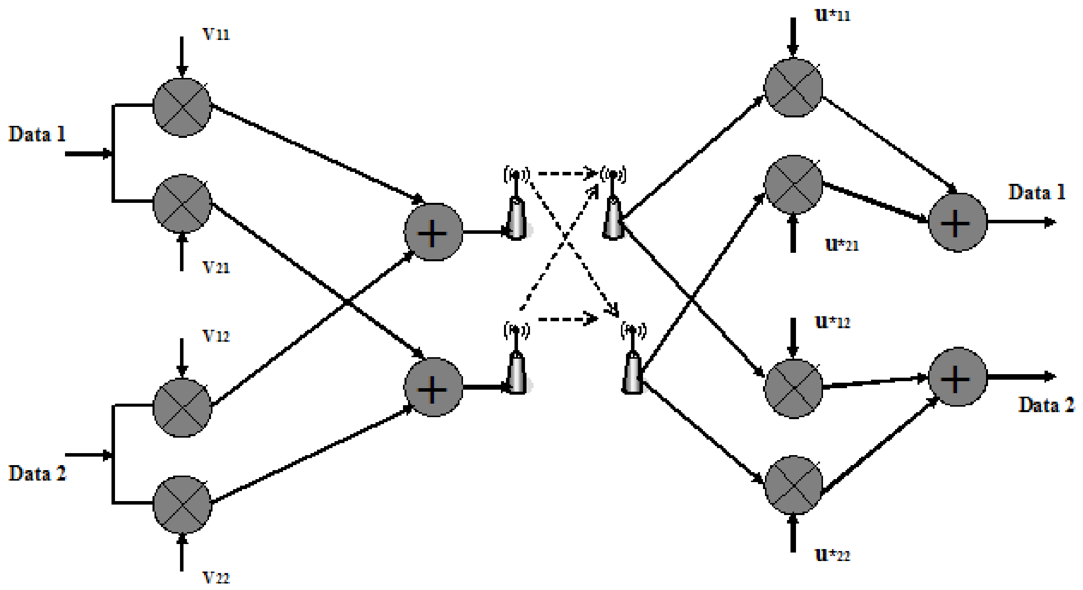


Figure 2 ES mode for a single OFDM sub-carrier with 2 antennas at the transmitter and the receiver

II. Spatial Spreading (SS)

When full CSI is not available at the transmitter, it is desirable to achieve maximum diversity while transmitting on some or all spatial channels. The receiver spatial processing is responsible for isolating the independent transmitted data streams. The receiver can spatially filter the received signal by using linear processing based on Zero Forcing (ZF) or Minimum Mean Squared Error (MMSE) algorithms. SS uses a generalized space - frequency code over the OFDM sub-carriers. The transmitted signal is multiplied by an orthonormal spatial spreading matrix W_n that varies among sub-carriers in order to maximize the transmit diversity. We may construct matrix W by using a fixed unitary spreading matrix $\hat{W}$ combined with a linear phase shift across the OFDM sub-carriers per transmitted stream.

$$W_n = C_n \hat{W} \quad (3)$$

The transmitter spreads the data streams across the min(N_t,N_r) spatial channels by using $\hat{W}$, which can be a Hadamard matrix or Fourier matrix. The number of data streams may be determined from statistical feedback. C_n is an N_t x N_t matrix which represents the linear phase shift in the frequency domain and may be implemented by having a fixed cyclic time shift per transmit antenna.

C. MAC Operation

In the IEEE 802.11 MAC protocol operation, the fundamental mechanism to access the medium is based on the Distributed Coordination Function (DCF) and is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. Binary exponential backoff rules manage the retransmission of collided packets. The default mechanism is a two

– way handshaking technique. After the successful reception, the user immediately sends an Acknowledgement (ACK) back to the AP. An optional four way hand-shaking mechanism, known as Request–To–Send/Clear–To–Send (RTS/CTS) could be used along with the default CSMA/CA scheme. In the commercial WLAN deployments, the default setting for RTS/CTS operation is 'off'. When a station operates in the RTS/CTS mode it has to send a special Request-To-Send short frame before transmitting a packet. The destination station acknowledges the receipt of the RTS frame by sending back a Clear-To-Send frame. Thereafter, the data packets can be transmitted following the acknowledgement mechanism that was previously described. This scheme increases system performance by reducing the duration of a collision when long messages are transmitted. The RTS/CTS scheme can effectively resolve the 'hidden terminals' issue, according to which two terminals cannot hear each other. The hidden terminal problem appears when two transmitters are far apart from each-other and attempt to transmit to a common receiver. The transmitters sense the channel as idle because they are away from each-other and thus their transmissions will collide. These two transmitters are considered as 'hidden terminals' by each other and the collisions of the data packets may lead to long recovery times (proportional to the size of the transmitted data packets) and the initiation of an exponential back-off stage. In [11] a simple analytical model computes the performance of the 802.11 DCF scheme. For the default mechanism, the performance strongly depends on the system parameters, and on the number of users in the wireless network. Fig. 3 illustrates the operation of the legacy IEEE 802.11 schemes. This mechanism is shown in [12] to have an upper limit on throughput and a lower limit on delay. Thus, it is necessary to reduce overhead in order to achieve better performance.

The MAC layer receives a MAC Service Data Unit (MSDU) to transmit. It adds MAC headers and forms the MAC Protocol Data Unit (MPDU). The PHY layer adds PHY headers and forms a PHY Protocol Data Unit (PPDU). A station waits for a fixed time interval before transmitting a PPDU. First, it monitors the channel and if the channel is idle for a period of time, equal to a Distributed Interframe Space (DIFS) value, the station transmits. If the channel is sensed as busy, the station continues to monitor the channel until it is determined as idle for a DIFS period. At this point, the MAC layer enters a random backoff procedure which is determined by a Contention Window (CW). If the channel is still idle after the backoff procedure, the station can initiate its transmission. In this way, the problem of collision with packets by other stations is minimized. The DCF scheme adopts an exponential backoff scheme and the backoff time is randomly selected based on a discrete uniformly distributed random variable that ranges from 0 to CW-1. The value of CW depends on the number of packet transmission failures. At the first transmission, CW takes a minimum value CW_{min}. The station listens to the channel and for every idle time slot, the back-off counter decreases by one unit. When the back-off counter expires, the station attempts its transmission. After each unsuccessful transmission, the value of CW is doubled, and this is repeated after each packet failure while CW is less or equal that a maximum value CW_{max}. The values CW_{min} and CW_{max} are PHY layer specific. After successful packet reception the ACK is immediately transmitted after a period of time called Sort Interframe Space (SIFS).

We observe that DCF may be inefficient since the introduced overheads (DIFS, CW, SIFS, ACK, PHY and MAC headers) may limit the data throughput.

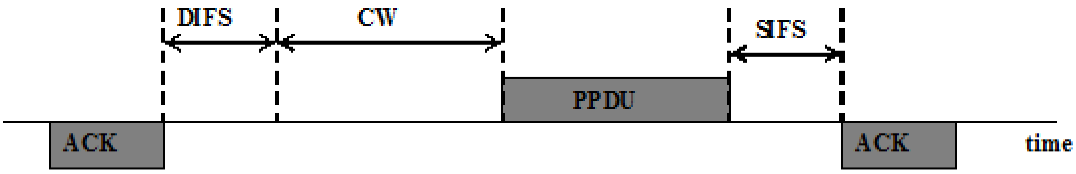


Figure 3 Basic access mechanism

In order to understand better the state of the art mechanism of IEEE 802.11n, which aims at achieving high data throughputs, we describe shortly the previous version IEEE 802.11e which partly achieved higher data rates compared to the 'legacy' standards IEEE 802.11a,b,g. In IEEE 802.11e, the notions of differentiated QoS support and Enhanced Distributed Channel Access (EDCA) were introduced [13]. The QoS support is provided in four different access categories. Each access category sets an independent backoff mechanism and different CW parameters as CW_{min}, CW_{max}, SIFS in order to provide differentiated QoS priorities. Additionally, the IEEE 802.11e MAC scheme introduces the Transmission Opportunity (TXOP) mode. The TXOP mechanism defines a period of time during which a station may transmit multiple data frames without entering a backoff mode. The station waits for a SIFS period to transmit the next PPDU. A 'block ACK' mechanism can be used to further enhance the medium access efficiency. A station transmits multiple PPDU frames in TXOP mode and accepts only one 'block ACK' regarding all these PPDUs instead of using a 'legacy ACK' for each PPDU.

Apart from this overhead reduction, that provided a solution for increased throughputs in IEEE 802.11e, aggregation can further enhance the efficiency and channel utilization. The IEEE 802.11n technologies improve the MAC layer efficiency by aggregating multiple data packets from the upper layers into one larger aggregated data frame for transmission. Aggregation is more beneficial for non-real-time applications such as the File Transmission Protocol (FTP) than real-time applications because the packet aggregation scheme may introduce latency that exceeds the delay constraints of the service. For the case of real-time applications (voice, multimedia, etc) the IEEE 802.11n benefits are related mainly to the PHY and MAC layer enhancements. The block ACK mechanism in 802.11n is modified to support multiple MPDUs. When some aggregate MPDUs (A-MPDUs) are received with errors, a block ACK is sent that only acknowledges the specific MPDUs that have been correctly received. Thus, the non-acknowledged MPDUs only need to be retransmitted. The original block ACK message in 802.11e contains a block ACK bitmap field with 64x2 bytes. These two bytes record the fragment number of MSDUs to be acknowledged. Fragmenting of MSDUs is not allowed in an A-MPDU. Therefore, these two bytes can be reduced to one byte. Finally, in IEEE 802.11n the reverse direction mechanism enhances the efficiency of TXOP for bi-directional traffic applications like VoIP and on line gaming. The reverse direction mechanism allows for the unused TXOP time to be allocated at the reverse direction. The major gain with the reverse direction mechanism is the latency reduction in the reverse link traffic.

IV. Unlicensed and Uncoordinated Wireless Environments

The WLAN market is growing exponentially due to low cost and high data rate capabilities. The unlicensed frequency bands offer an attractive alternative to the high cost of the licensed spectrum. The unlicensed 2.4 GHz ISM (Industrial, Scientific and Medical) band covers from 2.4 to 2.4835 GHz with relatively large available portions of available spectrum (i.e. 75 MHz). The U-NII (Unlicensed National Information Infrastructure) bands that cover the 5.15-5.35 GHz, 5.47-5.725 GHz and 5.725-5.85 GHz bands have been preferred due to the higher throughput and greater diversity they may offer but these frequencies overlap with the C band military radar frequency that ranges between 5.25 and 5.925 GHz. This can lead to degraded performance in the WLAN networks and also may cause interference problems to military radar systems.

Interference is defined by the International Telecommunications Union (ITU) as "the effect of unwanted electromagnetic energy on reception of radio communications, manifested by any performance degradation or loss of information that could otherwise have been avoided in the absence of the unwanted energy". In the ISM band, users can experience significant interference in some locations from ambulances, police cars, citizen's band radios as well as from other unintentional or intentional electromagnetic radiation such as microwave ovens, cordless phones, Bluetooth systems, etc. These devices are called 'selfish interferers' since they run their own protocols for their own benefit without any coordination. WLANs must be robust to interference caused by devices that co-exist with them in the ISM band. Another RF challenge of U-NII band operation is the increased isotropic loss for the 5 GHz frequency bands, that is about 7 dB higher than the loss calculated in the 2.4 GHz frequency band for the same distance between the terminal and the AP, since the isotropic loss is proportional to the square of the carrier frequency.

WLAN deployment is not planned as in the case of cellular systems. The uncoordinated placement of APs (all sharing the same bands within the ISM region) may result in a highly variable density of individually managed APs. These deployments are characterized in [14] as 'chaotic' deployments or networks. This chaotic and uncoordinated nature of WLANs may cause unpredictable network performance and may lead to unfair resource usage among neighboring APs. In such scenarios we must consider additional constraints on the nature of the radio resource management problem as well as on the possible practical solutions:

- It's not possible to improve performance in outdoor environments through careful AP placement or site surveys. This approach can be used only in indoor environments.
- The proposed solutions should not assume any coordination between co-existing WLANs because there is no explicit way of interaction between APs and users of different networks.

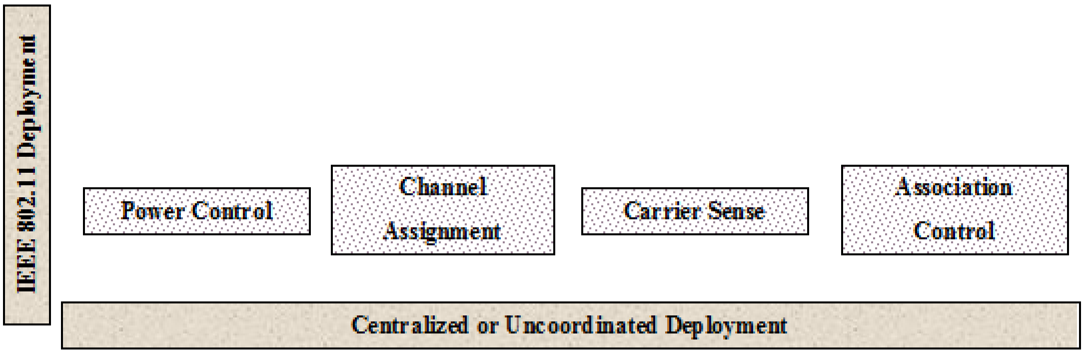


Figure 4 Methods of improving 802.11n performance.

In [15] multiple ways of dealing with the aforementioned issues are summarized. Fig. 4 illustrates the multiple complementary ways of addressing performance issues in IEEE 802.11 networks. Power control, via the dynamic management of transmit power reduces interference. This technology is referred as Transmit Power Control (TPC) and manages the transmit power of the APs (cell size) while the receiver eliminates interference with CSMA/CA mechanism. Additionally, with careful channel assignment, the idea of channel hopping for improving fairness is exploited. According to this, the APs spend a fixed amount of time in a single channel and switch to a subsequent channel. This technique is of the same nature as Dynamic Frequency Selection (DFS) that is used if airport radars (operating in Europe in the 5 GHz band) or military radars (operating in the C band) are in use in the same area. The association control may balance the client-load across a set of APs. An AP may become overloaded since the bandwidth resources that are allocated from the AP to its associated users are limited. An AP that is heavily loaded might not be the candidate to associate to it a new user. The WLAN distributes client associations among APs so that one loaded AP may deny the association request and the client may be associated to a lightly loaded AP. The methodology by which a client decides from which AP to request association is not specified in the standard.

. V *Frequency Assignment considering traffic loads at the MAC layer*

Conventional frequency allocation methods for typical cellular networks cannot be applied directly to IEEE 802.11 networks. A channel allocation technique should consider the traffic load at the MAC layer [16]. In IEEE 802.11 networks, the same physical channel is shared and its access is coordinated by the CSMA/CA protocol. Co-channel interference can be avoided at the expense of increased delay when the channel is busy. Frequency allocation methods are applicable to WLANs by combining the effects of the physical channel and the MAC protocol. Optimal allocation methods cannot be applied directly due to the coupling between the physical and MAC layers.

We focus on the interactions among the APs. Let's assume that the network has B APs. According to the CSMA/CA protocol the AP transmits if it senses the channel and finds that it's idle, e.g. the AP detects that the received power is lower than a threshold P_{th} (typically around -76 dBm or lower). Otherwise the channel is considered as busy. Co-channel interference may be caused due to the co-existence of multiple APs. For each AP $i \in \{1, 2, \cdots .B\}$, we denote with C_{ib} the set of interfering APs which cause enough co-channel interference for AP i to detect the channel as busy. The index b defines the "class" of interferers for AP i. If b = 1, only one AP is assumed to interfere with AP i (*class-1* interferer). When b = 2, two interfering APs cause AP i to sense the channel as not idle (*class-2* interferers). Similarly, *class-3* or higher classes of interferers may be defined. Due to the contention, the probability of having 3 interfering APs simultaneously transmitting without sensing each other is small and therefore, we consider only *class-1* and *class 2* interferers. Let P_j denote the transmitted power from AP j and A_{ij} be the path loss of the link between AP i and j. In general, the wireless channel is characterized by three effects: path loss, shadowing and fast fading. Each one contributes a power loss factor for the received power. The shadowing and fast fading are usually modeled as random variables with zero-mean distributions such as the log-normal distribution for shadowing and Rayleigh distribution for the fast fading component. For simplicity, we assume that in the long term these random effects are averaged out. We only consider the path-loss effect which is defined as:

$$A_{ij} = (\frac{d_0}{d_{ij}})^{\gamma} \quad (4)$$

where d_0 is the breakpoint distance and depends on the channel model, d_{ij} is the distance between the AP i and j and γ is the path loss factor which varies from 2 to 6 , depending on the environment. We assume that P_j is fixed (i.e. channel assignment is performed without dynamic power control). If AP j belongs to C_{i1}, the channel is busy when the received co-channel interference from AP j is greater than the threshold P_{th}:

$$A_{ij} P_j \geq P_{th} \quad (5)$$

Similarly, if the AP pair l and k belong to C_{i2}, the 'channel busy' condition is:

$$A_{il} P_l + A_{ik} P_k \geq P_{th} \quad (6)$$

Due to the contention nature of the CSMA/CA protocol, the traffic load on each channel (related to the probability of transmission for an AP) cannot be too high. Therefore we only consider up to 2 interfering APs (b = 1,2) for the set of C_{ib}. We define ρ_i as the offered traffic load of AP i assuming channel utilization without interference and N the total number of non-overlapping channels. We assume that each AP is assigned with only one channel and X_{in}=1 if AP i allocates the channel $n \in \{1, 2, \cdots N\}$ otherwise X_{in}=0. If the effective channel utilization U_i is defined as the fraction of time at which the channel can be sensed as busy then we have:

$U_i = \rho_i$ + {total traffic load of *class-1* interferers} +{total traffic load of *class-2* interferers}

, therefore we can state the following expression:

$$U_i = \rho_i + \sum_{n=1}^{N} X_{in}[\sum_{j \in C_{i1}} \rho_j X_{jn} + \sum_{l,k \in C_{i2}} \rho_l \rho_k X_{ln} X_{kn}] \quad (7)$$

The objective function for the channel assignment is to minimize the utilization of the most 'stressed' (also characterized as 'bottleneck') APs:

$$minimize\ Max\{U_1, U_2, \cdots, U_B\}$$

over the assignment indicator { X_{in} }. The optimal assignment is feasible if its objective function value is less than 1

$$U_i < 1 \quad (8)$$

The optimization problem is NP complete [11]. Therefore, heuristic algorithms for the optimal channel assignment can be studied. The following heuristic algorithm is proposed to minimize the effective channel utilization for the bottleneck AP:

1. Generate a random initial channel assignment with maximum effective channel utilization V=max{Ui}.
2. Identify the AP i with the highest effective channel utilization.
3. For AP i identify its current assigned channel k. For the available channel n≠k that ranges from 1 to N and co-channel AP j in C_{i1}, reassign AP j with channel n. Re-compute Wjn, the maximum effective channel utilization for the new assignment. Let W be the minimum of all Wjn's.
4. Compare W with V a) if W<V then replace V by W and go to step 2 b) if W=V replace V by W with a pre-specified probability 0<δ<1 (in order to avoid infinite loops within the algorithm) and go to step 2 c) if W>V, a local optimum exists, therefore go to step 5.
5. Repeat steps 1 to 4 with a number of random, initial assignments and choose the best solution.
6. Test if constraint (8) is satisfied for the final assignment to check the feasibility of the final solution.

VI Distributed Queues and Cross-Layer Mechanisms

The use of distributed queues and cross-layer information improves radio channel utilization, by eliminating backoff periods and collisions in data packet transmissions and achieve thus a performance that may be independent of the number of stations transmitting [17]. We define as Virtual Transmission Time (VTT) the period that is required to successfully transmit a packet, taking into account ACK transmissions, contention periods in which backoff mechanisms are applied, inter-frame spaces and the possibility of multiple retransmission attempts due to collisions or erroneous packet receptions. Contention periods and possible periods of collisions are wasted intervals that limit the achievable throughput. In this section, a reference scenario - utilizing a set of parameters taken from the IEEE 802.11b standard- is considered. Fig. 6 illustrates the variation of system throughput versus the number stations when assuming a constant packet length (2312 bytes) and 11 Mbps transmission rate. The scenario is evaluated for two cases: with and without RTS/CTS.

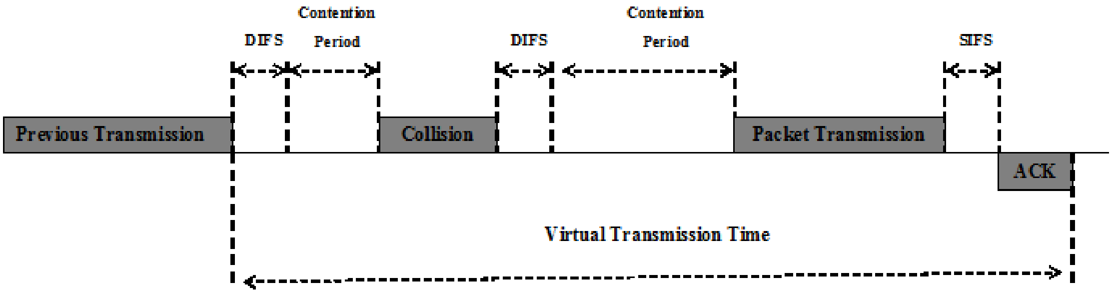


Figure 5 Virtual Transmission Time in CSMA/CA protocol

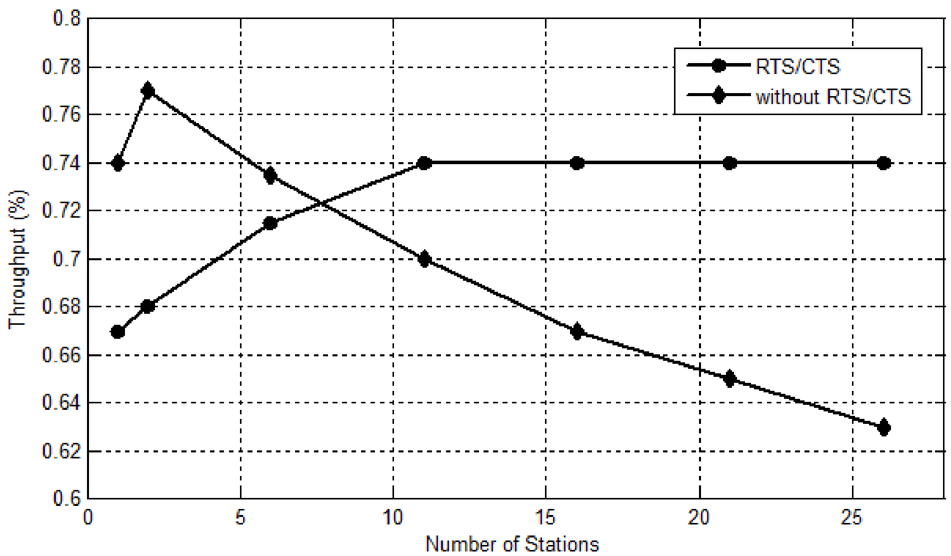


Figure 6 Analytical bounds for achievable throughput in 802.11b system with a constant packet length equal to 2312 bytes (based on results from [17]).

As it is observed, without using RTS/CTS, if the number of stations increases, throughput is reduced due to the effect of contention and collision. On the other hand, when RTS/CTS is applied , the throughput is maintained constant to around 73% when the number of stations increases but it is degraded as the number of stations drops, due to the overhead of the RTS/CTS mechanism.

If it was possible to eliminate contention periods and collisions, the maximum achievable throughput would be increased for any number of stations without using RTS/CTS. A MAC proposal called Distributed Queuing Collision Avoidance (DQCA) that may operate over the IEEE 802.11 PHY layer will be described. The protocol is based on two distributed queues. A Data Transmission Queue (DTQ) devoted to the data packet transmission scheduling and a Collision Resolution Queue (CRQ) devoted to the collision resolution algorithm. These two queues are represented by four numbers: TQ which represents the number of messages waiting for transmission in the DTQ, RQ which represents the number of collisions waiting for resolution in the CRQ, pTQ which is the node position within the DTQ and pRQ that is the node position within the CRQ. TQ and RQ represent distributed queues and their values have to be always the same for all nodes. A short time interval is reserved for user accesses and collisions while the rest of the frame is devoted to collision – free data transmission. A node checks the state of both distributed queues, in order to attempt either a system access request (if there are pending collisions that need to be resolved) or a transmission of data by randomly selecting a control slot and transmitting an access request. After an access request transmission, two cases are possible:

1. No other node has transmitted an access request. The accessing node will enter the DTQ obtaining value for its pTQ. When pTQ gets a value equal to 1, the data packet in the next frame will be transmitted.
2. One or more other nodes have transmitted access requests. The access requests will collide and the node will enter the CRQ getting a valid value. When pRQ gets a value equal to 1, an access request will be transmitted in the next frame.

An ALOHA – like data access transmission is performed when the DTQ is empty. This feature allows the presence of collisions in data transmission but also improves the delay performance for light traffic conditions. Fig. 7 shows the frame structure which includes 3 parts:

- A contention window divided into m control mini-slots. The nodes, that have data ready to transmit, request access to the channel by sending an access request sequence (ARS).
- A collision-free transmission part.
- The feedback packet (FBP) part that is broadcast by the AP and contains: a) feedback information on the state of all access mini-slots. This state has three possible characterizations (empty, success or collision) and is the physical information used for scheduling in the MAC layer (cross – layer concept).b) An ACK to verify the correct

reception of data packets c) A final message bit (1 or 0) that shows if the last packet has been received.

A cross-layer mechanism for enhancing the first-in-first-out (FIFO) data transmission order is shown in [18], where the transmission order is determined by a virtual priority function (VPF) from feedback information (FBP). The AP at the downlink transmission enables all nodes to calculate the VPF associated to every node in the DTQ. The VPF establishes a cross-layer interaction using PHY, MAC and QoS parameters. The node with the highest VPF is enabled to transmit.

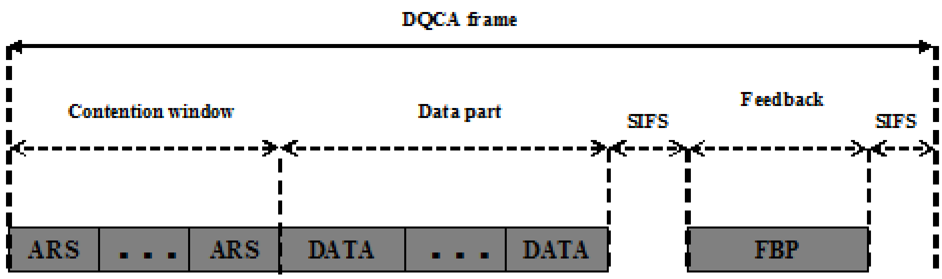


Figure 7 Frame of DQCA frame structure

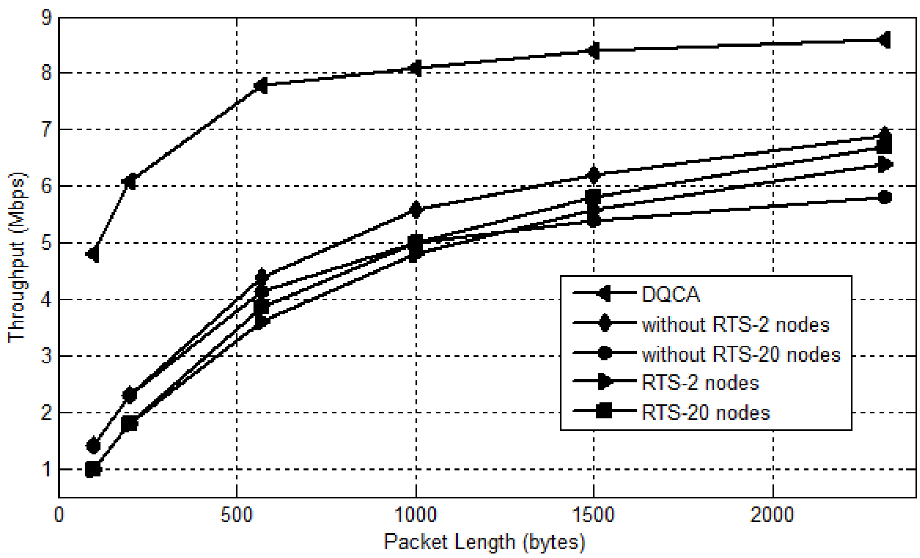


Figure 8 Throughput improvement for DQCA scheme (based on results from [17])

Together with the access request detection state, the CTS packet may include the appropriate selection of the PHY layer transmission mode in order to maximize performance. This selection will be based on channel state detected in the RTS transmission. Fig. 8 shows the significant improvement in throughput when the DQCA scheme is used. For reasons of comparison, different schemes with and without RTS/CTS when the number of stations is 20 and 2 were used. Focusing in the DQCA scheme, throughput is constant for any number of nodes but packet delay will be increased when the traffic load exceeds the PHY layer capacity. Finally, it is evident that system efficiency is improved when packets grow in size.

VII. Joint Adaptive Beamforming and Adaptive Modulation with ACK Eigen-Steering

Co-channel interference occurs when the CSMA/CA mechanism fails to detect collisions due to the hidden nodes in the different collocated WLANs. CSMA/CA is a MAC layer interference avoidance mechanism and therefore is not effective at densely deployed WLANs in urban areas. Co-channel interference needs to be suppressed in order to maintain high data transmission rates in co-existing WLANs. A method of using adaptive multiple antennas and adaptive modulation with ACK eigensteering was investigated to reduce interference, maximize data rate and eliminate the channel feedback requirements [19]. First, the optimum transmit beamforming weights for the AP and the receive beamforming weights for the terminal station are calculated for each sub-carrier. Second, the initial allocation of sub-carriers, power and modulation mode is done taking into account power and BER constraints. Third, the optimum transmit weights, power allocation and sub-carrier allocation are obtained by the minimum square error (MSE) receiver at the AP based on the up-link ACK.

We consider a system that consists of a terminal station and two non-cooperative co-existing APs within the same coverage area. The block diagram of the MIMO-OFDM system is shown in fig. 9

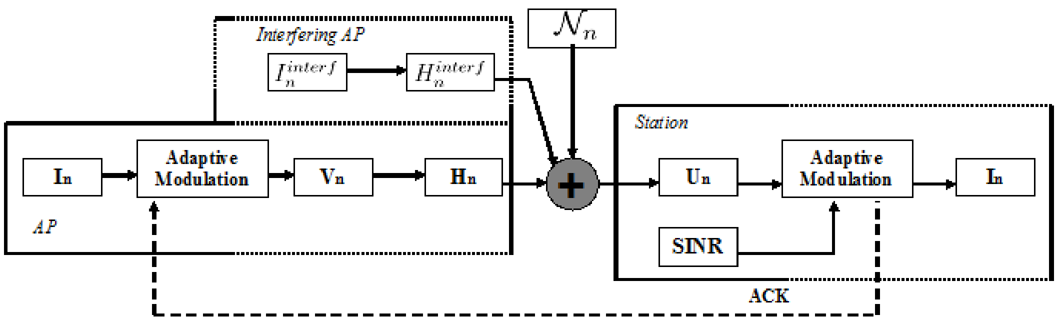


Figure 9 System model

In the downlink direction, we assume N_r receiver antenna elements, N_t transmitter antenna elements and N sub-carriers. For the nth sub-carrier, the SINR module at each station estimates the channel matrix H_n for the desired information signals and the interfering channel matrix H_n^{interf}. Then, the optimum transmitter and receiver weights V_n and U_n for each sub-carrier n are calculated with the objective of maximizing the SINR. This information is passed to the adaptive modulation module at the station where power allocation, sub-carrier allocation and modulation mode are performed. The uplink ACK is transmitted in the Eigenvector Steering (ES) mode (described in section III.B) using optimum receiver weights $U_n \in C^{N_r,x}$ where x is the number of spatial channels used for sub-carrier n. The allocation of power, sub-carriers and modulation rate are then based on the uplink ACK that is received by the AP. The symbol I_n is then transmitted by the AP and received at the station using these parameters. In fig. 9, $\mathcal{N}_n$ denotes additive Gaussian noise at the receiver and I_n^{interf} the interfering symbol.

I. Adaptive Multiple Antennas

The system is analyzed in the frequency domain for each sub-carrier and for simplicity the nth sub-carrier notation is omitted. The interference power plus noise correlation matrix is defined as

$$R = E[H^{interf}(H^{interf})^H] + [\mathcal{N}\mathcal{N}^H] = R_{interf} + R_N \quad (9)$$

$$\sigma = E[II^H] \quad (10)$$ and

$$\sigma_{interf} = [I^{interf}(I^{interf})^H] \quad (11)$$

σ and σ_{interf} are normalized to 1 for all modulation modes since the chosen mode can adaptively change. For suppressing co-channel interference and maximizing SINR, the interference power plus noise is minimized at the receiver while the amplitude of the desired signal is kept unchanged.

$$\mathcal{A} \quad \min_U U^H RV$$

$$\text{s.t.} \quad U^H HV = 1$$

The problem $\mathcal{A}$ is solved using the Lagrange method. The optimum receiver weights are given by

$$U = \frac{R^{-1}HV}{(HV)^H R^{-1} HV} \quad (12)$$

In (12), U requires knowledge of the transmitter weights. Singular Value Decomposition (SVD) is applied in the downlink, therefore $SINR = H^H R^{-1} H$ and V is the eigenvector which corresponds to the best spatial channel gain with the largest eigenvalue.

II. Adaptive Modulation

We calculate the downlink SINR

$$\gamma_n = U^H H^H R^{-1} HV \quad (13)$$

Taking into account (12) and after simplification

$$\gamma_n = V^H H^H R^{-1} HV \quad (14)$$

Let $M = \{0, 2, 4, 16, 64\}$ be the selection of the M-ary modulation that corresponds to {no-transmission, BPSK, QPSK, 16 QAM and 64 QAM}. The minimum SINR γ_M for each M with a given target of BER $\mathcal{B}$ is given by:

$$\gamma_M = \begin{cases} \frac{2(M-1)}{3}[\text{erfc}^{-1}\{\frac{\mathcal{B}\sqrt{M}\log_2\sqrt{M}}{\sqrt{M}-1}\}]^2 & M \neq 0 \\ 0 & M = 0 \end{cases} \quad (15)$$

Adaptive modulation selects the values of M, n and $P_{n,M}$ ($P_{n,M}$ is the power of the nth sub-carrier for modulation M) that give the maximum data rate for each M, C_M.

$$\max_{P_{n,M}} C_M$$

The optimization problem can be written as:

$$\begin{aligned} \mathcal{A}' \quad & \max \sum_n \log(1+\gamma_n P_{n,M}) \\ \text{s.t.} \quad & \sum_n P_{n,M} \le P_{tot} \\ & P_{n,M} \ge \frac{\gamma_M}{\gamma_n} \\ P_{n,M} = 0 \quad & \text{for} \quad P_{n,M} < \frac{\gamma_M}{\gamma_n} \end{aligned}$$

P_{tot} is the total power available for all N sub-carriers. The second and third constraints in $\mathcal{A}'$ imply that $P_{n,M}$ is allocated only if with this allocation it will be feasible to reach γ_M that satisfies the BER target. $P_{n,M}$ is found by using the Largange method.

III. ACK Eigen-Steering

The AP needs the definition of V_n and $P_{n,M}$ for its downlink transmission with an optimum transmit vector $\sqrt{P_{n,M}}V_n$ and the optimum receiver U_n given in (12). Let U_n be the transmit vector used by the station to eigen-steer the uplink ACK and V_n^H be the received weights at the AP. MSE at the receiver is used to detect the uplink ACK:

$$\text{MSE}_n = E[|Y_n - I_n|^2] \quad (16)$$

where Y_n is the received signal for sub-carrier n. If we minimize MSE_n with respect to V_n^H, we obtain

$$P_{n,M} = |(I+R_n)V_n^*|^2 \quad (17)$$

where I is the identity matrix. We can see from (17) that by using ACK eigen-steering V_n, $P_{n,M}$ can be extracted at the AP without recalculating the eigenvalue decomposition therefore there is no need for using additional channel feedback.

Fig. 10 and 11 illustrate simulation results (spectral efficiency (SE) versus signal to interference ratio SIR) for a target BER=10^{-3}. For different antenna configurations in the downlink direction, the notation $M_t + M_r$ is used (e.g. M_t transmit antennas and M_r receiver antennas). The eigenvector with the best eigenvalue is selected. Fig. 10 shows that adaptive modulation is useless for low SIR since the spectral efficiency is very low for very small SIR values (SIR≤ 0).

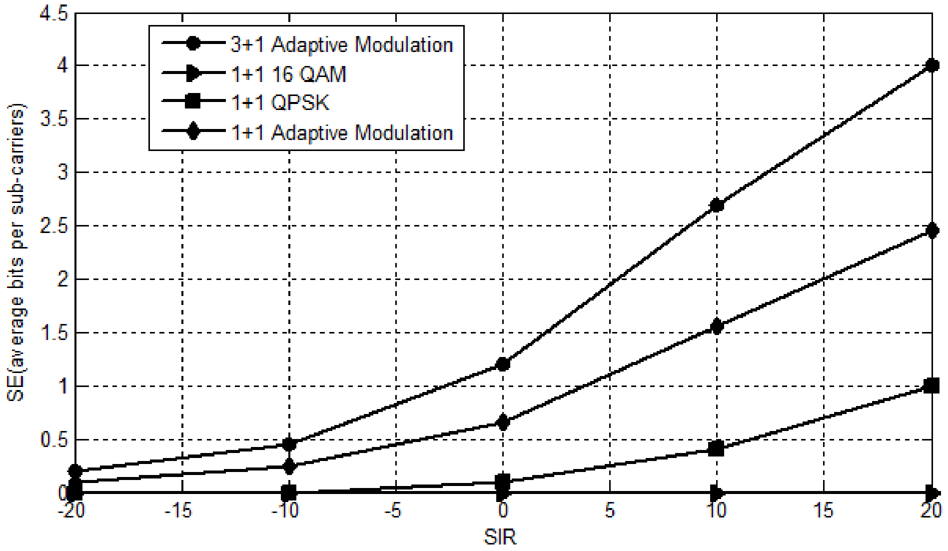


Figure 10 Effect of adaptive modulation and transmit beamforming (based on results from [19])

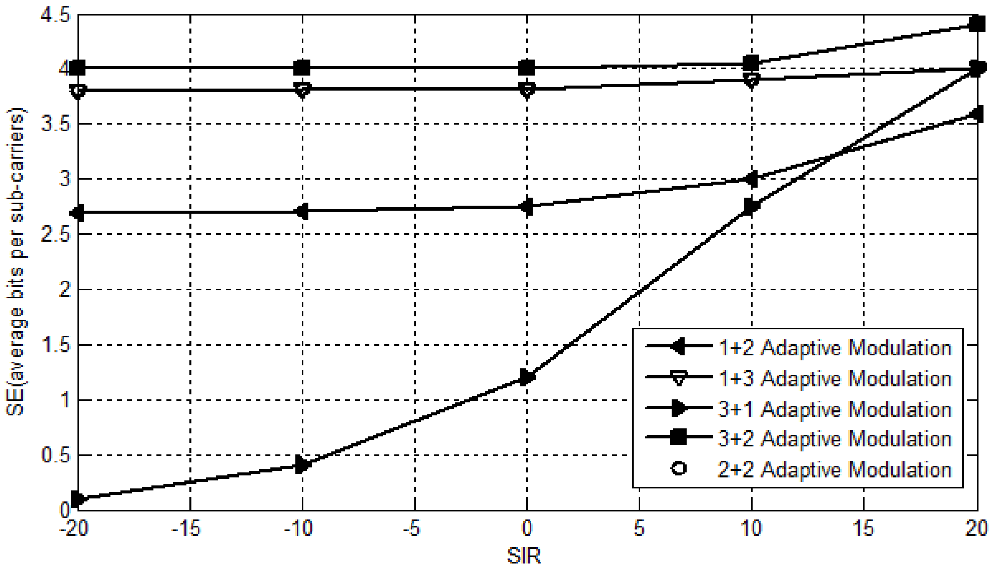


Figure 11 Effect of adaptive modulation and transmit/receiver beamforming (based on results from [19])

Fig. 11 shows that the benefit of transmit beamforming can only be realized if receiver beamforming is also implemented. This is evident as the '3+1' scheme has average SE≈0.5 in strong co-channel interference environment (SIR≤0) and the '3+2' scheme has SE≈4. Also, if we compare the '1+2' transmission mode to the '2+2' transmission (we add one antenna element at the transmitter) the benefit of SE is (3.75-2.65)/2.65=41.5%. We conclude that with joint receiver beamforming and adaptive modulation, we improve performance in the co-existing WLANs.

VIII. Joint User Association and Transmission Power Control

In IEEE 802.11 WLANs each user scans the channel to detect its nearby APs and initiates a connection with the AP that has the strongest Received Signal Strength Indicator (RSSI). This approach that is based on RSSI measurements doesn't take into account the interference conditions on the uplink and downlink channels. With DFS, a user performs channel measurements of the surrounding interference levels. The user monitors the medium and records the RSSI (quantized into 8 levels) and the time periods over which the particular strengths are observed. The medium is periodically examined by passive scanning in order to find if there exists a "better" AP for association. If such an AP exists, then the user triggers a Re-association/Handoff phase to switch from the current AP to a new one. An association procedure has to be based on the SINR measurement on both uplink and downlink directions [20]. The SINR that is computed by user k and is related to AP b is given by:

$$\mathrm{SINR}_{k,b} = \frac{\mathrm{RSSI}_{k,b}}{\mathrm{RSSI}_k^{mean}} \quad (18)$$

where $\mathrm{RSSI}_{k,b}$ is the signal strength received from AP b and RSSI_k^{mean} is the mean estimated interference in the neighborhood of user k. $SINR_{k,b}$ estimations are made for the uplink and downlink transmissions. Each user calculates the Packet Error Rate (PER) or the probability of success of a packet Pb_u on the uplink and Pb_d on the downlink direction. The user selects the AP that provides the maximum Pb_uPb_d, e.g. minimizes the number of frames required for a successful transmission.

Power control could reduce the interference levels and, in conjunction with the association procedure, the load could be balanced across the WLAN cells. For simplicity we describe a system with two cells with labels 1 and 2. We have four cases represented by 'dd', 'du', 'uu', 'ud', where the index 'd' represents a downlink transmission and 'u' represents an uplink transmission. For example, du represents a downlink transmission in the first cell and an uplink transmission in the second. The two cells are assumed to be circular with radii r_1 and r_2 ($r_1 + r2 \geq D$). In the general case, the cells are overlapping and in the extreme case, they are simply adjacent to each-other $r_1 + r_2 = D$. The optimal power level is derived for no overlapping cells. If there are uncovered areas, the cells are expanded for some time (the largest cell first) until the area is completely covered. The basis for this policy is to increase the radii of as few cells as possible. Let k_1 and k_2 be the users in cell 1 and 2 respectively. We compute the PER in a particular slot

$$Pb_I = \frac{Ib_{dd} + Ib_{du} + Ib_{ud} + Ib_{uu}}{4} \quad (19)$$

where $Ib_{dd}, Ib_{du}, Ib_{ud}$ and Ib_{uu} represent the probability that a collision occurs (assuming that the channel is free of interference and with negligible channel errors) in the smaller cell in each of the four cases. The model assumes that the uplink and the downlink traffic are equal in volume. Fig. 12a depicts the case 'uu'. The users of cell 2 that affect the reception at the AP of cell 1 are the users located in the area A (intersection of two circles):

$$A = 2r_2^2 \cos^{-1}(\frac{D}{2r_2} - \frac{1}{2}D\sqrt{4 - D^2}) \quad (20)$$

Similarly, we can analyze the cases 'du', 'dd' and 'ud'. In case of 'dd', no collision is observed. In the case of 'du', 64 numerical computations have to be done since there are 8 possible power levels.

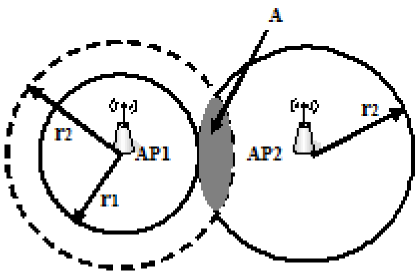


Figure 12a Intersection area in the case 'uu '.

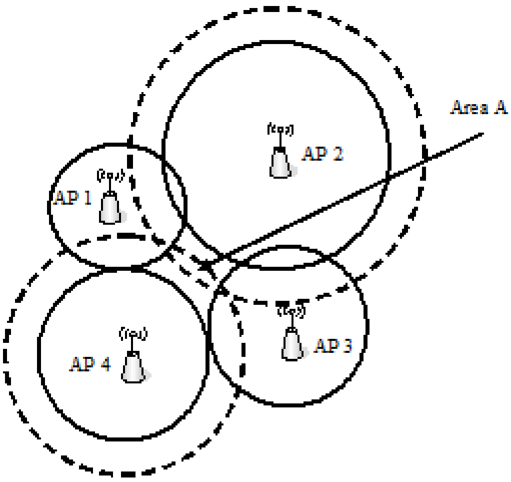


Figure 12b Area A is covered due to the extension of cells 2,4 with the power control algorithm

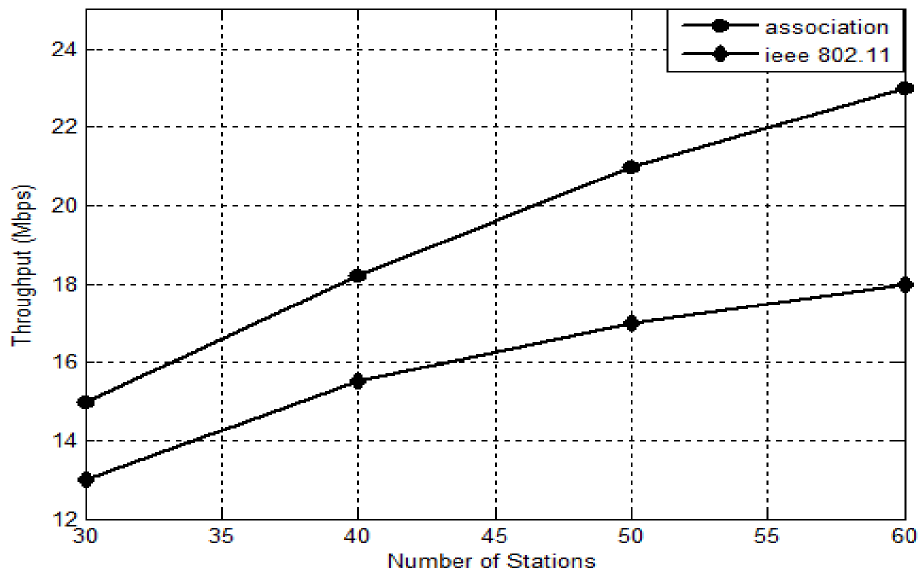


Figure 13 Throughput in the association procedure ((based on results from [20])

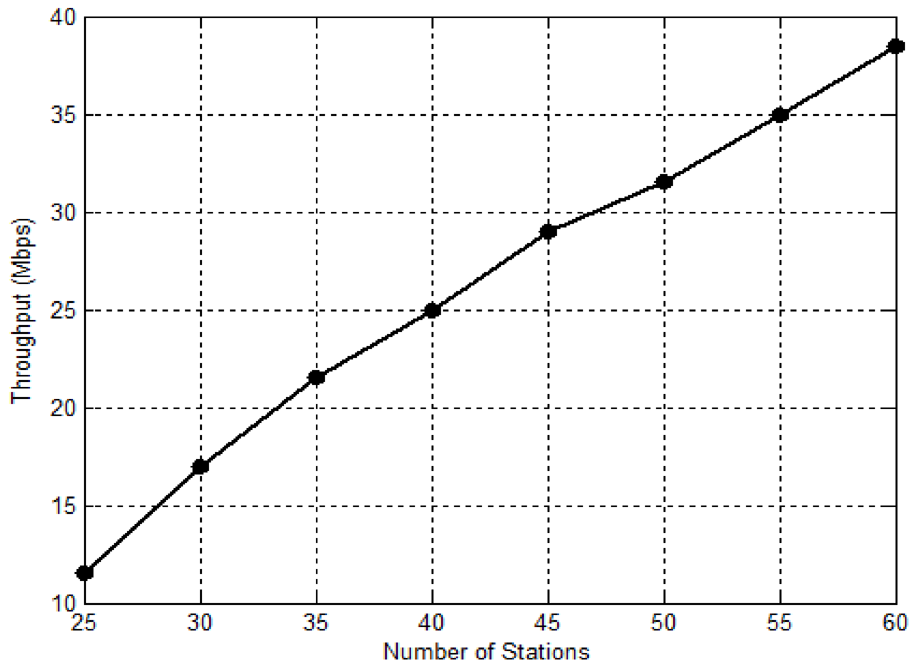


Figure 14 Throughput when power control is applied (based on results from [20])

If, for example, we assume the cellular layout of Fig.12b and that the users are uniformly distributed in cell 2, we obtain the following:

$$Ib_{uu} = k_2 * \frac{A}{\pi r_2^2} \quad (21)$$

and the power level of the APs is computed in the following steps:

Step 1: The AP calculates Pb_1 for each particular neighbor cell. The maximum of these power levels is computed.

Step 2: The radius of the cells from the largest cell to the smallest is extended (to the next possible level) until full coverage is achieved. In fig. 12b, the area A is covered due to the extensions of power control in cells 2 and 4.

Simulation results were performed in a 6-cell environment. Fig. 13 compares the throughput achieved by the proposed association policy with that in IEEE 802.11b. Under heavy load (large number of users per WLAN), the users make more accurate association decisions taking into account the interference levels. Fig. 14 demonstrates the effectiveness of the power control scheme especially when the number of users increases due to interference management and load balancing between the cells. The additional gain comes from the ability of every AP to control the maximum transmit power (i.e.the coverage of the cell) in response to interference patterns. This coverage modification minimizes the interference and balances the load between cells.

IX. Channel Selection and User Association using Gibbs Samplers

A geographical area where multiple APs are available to users is considered. All antennas are considered to be omni-directional. A completely distributed method for an AP to optimally select its operating frequency by minimizing global interference and for a user to select an AP in order to lead to globally optimal bandwidth sharing was proposed in [21]. The wireless access network that is considered is described by

- A set of APs $b \in B$
- A set of users $k \in K$
- A set of available distinct channels $c \in C$.

Let $c_b \in C$ be the channel that is chosen by AP $b \in B$. We introduce the function $I(b, i)$ that is equal to 1 if b and i are operating on the same channel (co-channel interference) and 0 if they are orthogonal (this function is considered as the interference factor or the I-factor). We introduce $K_b \subseteq K$ the subset of users associated with b. We denote as U_b the number of users (belonging to the set K_b) that are associated with b. For all pairs of users k and v, let $s(k, v)$ be the function whose value is equal to 1 if k and v are associated with the same AP and 0 in all other cases. Within a traffic scenario featuring a saturated AP, the bandwidth is shared equally among all users of the same cell as all users are supposed to aim at achieving the same long term throughput. The information is transmitted to each user in data units of the same length, so that the propagation delay that is related to a data unit sent from AP b to user k is given by

$$d(k) = \frac{1}{f(SINR(k))} \quad (22)$$

where $f(SINR(k))$ represents the instantaneous transmission rate. The function $f()$ adapts the modulation and coding rate of the transmitter to the channel conditions. If the AP b has other APs in its contention domain, its channel access time $M(b)$ will not be equal to 100%. The max-min fair allocation of bandwidth in the cell implies that the long term throughput obtained by each user k associated with b is given by

$$r(k) = \frac{M(b)}{\sum_{v \in K_b} d(v)} = \frac{M(b)}{\sum_{v \in K} s(k,v)d(v)} \quad (23)$$

For simplicity we assume $M(b)$=1. The SINR received by a user k on the downlink is given by:

$$\mathrm{SINR}(k) = \frac{P_b(k)}{\mathcal{N}_k + \sum_{i \in B, i \neq b} I(i,b)P_i(k)} \quad (24)$$

where $P_b(k)$ is the useful power received by user k from AP b and $\mathcal{N}_k$ is the thermal noise in the receiver of user k. In the previous relationship, only the interference from neighboring APs is considered. Uplink traffic from users is neglected. We define the potential function V for all subsets A of B by:

$$V(A) = \begin{cases} \mathcal{N}_b \quad \text{for} A = \{b\} \\ I(b,i)(P_b(i) + P_i(b)) \quad \text{for} A = \{b,i\} \\ 0 \quad \text{for} |A| \geq 3 \end{cases} \quad (25)$$

The local energy of an AP b is defined as:

$$\mathcal{F}_b = \sum_{b \in A} V(A) = \mathcal{N}_b + \sum_{i \neq b} I(b,i)(P_b(i) + P_i(b)) \quad (26)$$

Assuming that each AP uses the same nominal power to transmit and following the terminology of Gibbs fields, where the energy function $\mathcal{F}$ is equal to:

$$\mathcal{F} = \sum_{b \in B} (\mathcal{N}_b + \sum_{i \in B, i \neq b} I(b,i)P_i(b)) \quad (27)$$

we obtain the following:

$$\mathcal{F}_b = \mathcal{N}_b + \sum_{i \neq b} 2I(b,i)P_i(b) \quad (28)$$

A user would always try to associate with the AP that offers the best long-term throughput. The optimization criterion for such an allocation is the minimal potential delay. The potential delay of a user is defined as the inverse of its rate $\frac{1}{r_k}$ and may be interpreted as the delay for the network to transmit one unit of information for this user. We follow the same Gibbs methodology [22]. The set of nodes in the Gibbs framework is the set of users. The state of the users is considered to be the AP they associate with. The potential delay can be expressed as an energy function:

$$\mathcal{E} = \sum_{\forall k} \frac{1}{r_k} \quad (29)$$

and can be shown to derive from a potential function V defined on the subsets of U :

$$\mathcal{E} = \sum_{\mathcal{U} \subseteq K} V(\mathcal{U}) \quad (30)$$

The local energy of a user k is:

$$\mathcal{E}_k = \sum_{k \in \mathcal{U}} V(\mathcal{U}) = \sum_{v \in K_b} \frac{1}{f(\mathrm{SINR}(v))} + U_b \frac{1}{f(\mathrm{SINR}(k))} \quad (31)$$

The second term can be seen as the sum of the additional potential delay experienced by other users due to user k associating with this AP. This may be considered as the 'social cost'. The first term consists of the sum of the data unit delays of all users affiliated with the AP and may be seen as the delay experienced by user k because of the other users. We can consider it as the 'self cost'.

I. Algorithms for AP channel selection

The idea is to trigger the AP to find a state that minimizes energy and thus converges to the optimal channel selection. If the energy function $\mathcal{F}$ is derived from the potential V, then the minimization can be achieved by using a Gibbs sampler. The Gibbs sampler is a procedure where each AP b updates its own state according to the following algorithm:
Given the state of all APs , AP b computes the following probability on the state of the graph $\forall c \in C$

$$\mu(c) = \frac{\exp\left(-\mathcal{F}_b(c)/T\right)}{\sum_{c \in C} \exp\left(-\mathcal{F}_b(c)/T\right)} \quad (32)$$

The transition of all the nodes can occur in an asynchronous way. When the parameter T >0 (T is equivalent to the Temperature) decreases to 0 with time t >0 like $\frac{1}{\log_2(1+t)}$, we achieve convergence to a collection of states of minimal global energy $\mathcal{F}$. The probability distribution $\mu(c)$ is a Markov random field. This means that the state of AP b is independent of the states of all non-neighboring APs.

Each AP maintains an exponential timer with mean t_a (an exponential timer is a timer which expires as a random variable that is exponentially distributed). Whenever this timer expires, it follows the following transition:

Probabilistic AP transition algorithm

1. Compute the temperature parameter : $T = \frac{T_0}{log_2(2+t)}$.
2. $\forall c \in C$ compute $\mathcal{F}_b(c)$.
3. $\forall c \in C$ compute $\mu(c)$.
4. Sample a random variable with low μ and choose a channel according to this random variable.

Here, t is an 'age variable' that represents the time that elapsed since initialization of the network and T_0 is the parameter that determines the speed of convergence.

The previous probabilistic algorithm is rather complex as it needs to maintain the value of t (synchronization). In practice, the following deterministic algorithm could be used:

Deterministic algorithm

$$c = \arg\min_{c \in C}(\mathcal{F}_b(c))$$

This deterministic algorithm may be seen as a limit case of the probabilistic algorithm when the temperature goes to zero. State updates are not randomized but are always chosen to minimize the local energy. The difference between the performances of the two algorithms is that the first can be shown to converge eventually to a state of minimal interference for any fixed topology. The second however can get blocked in local minima. Simulations have shown that these local minima provide excellent approximations of the optimum obtained by the first scheme [21].

II. Algorithms for users association

The algorithm for user association is very similar to the channel selection c from AP b. Additionally, the algorithm assumes that each AP has selected its channel. After collecting the number of users and load from APs, for each channel, each user can compute the local energy that it would experience when associated with AP b for all $b \in B$. Following the same steps as in the algorithm in section IX.I, we start with an initial value for temperature T and choose to associate with the AP b with probability μ defined from the local energy in (31). The deterministic algorithm may also be defined as follows:

$$\text{Choose } b = \arg\min_{b \in B}(\mathcal{E}_k(b))$$

X. Channel Selection Based on Airtime Cost Metric

A Load Aware Channel (LAC) allocation scheme has been proposed for WLANs. It considers the load that is carried by APs along with the channel conditions, the number of affiliated users as well as traffic load [17]. Through the airtime cost metric, the most appropriate channel for every AP (aiming a maximum throughput) is derived in a distributed fashion by measuring: a) both the downlink and uplink channel conditions and b) the number of affiliated clients/users with every AP.

The airtime cost metric reflects the 'multi-user environment' conditions in terms of interference and contention. It is proposed in the IEEE 802.11s wireless mesh networking standard as a default routing metric (RM-AODV routing protocol) [24]. This metric reflects the load on a wireless router (average delay when a unit size packet is transmitted) in order to provide the minimum end to end path. Let's assume a user $k \in K_b$ that is associated with the AP b and uses channel $c \in C$. The airtime metric is given as:

$$\mathcal{C}_{b,c}^{k} = [O_{cb} + O_p + \frac{B_t}{r_k^{b,c}}]\frac{1}{1 - e_{pt}^{c}} \quad (33)$$

O_{cb} is the channel access overhead, O_p is the protocol overhead and B_t is the number of bits in the test frame in order to compute the airtime cost. For IEEE 802.11b we have $O_{cb} + O_b$ = 1.25ms and B_t = 8224 bits. $r_k^{b,c}$ represents the current transmission rate in Mbps and e_{pt}^{c} is the Frame Error Rate, both parameters corresponding to the test frame size B_t in channel c. The average airtime cost of one direction (uplink or downlink) for K_b users is given by:

$$\overline{\mathcal{C}_{b,c}} = \frac{1}{K_b}\sum_{i=1}^{K_b}[O_{cb} + O_p + \frac{B_t}{r_k^{b,c}}]\frac{1}{1 - e_{pt}^{c}} \quad (34)$$

It has been shown that the average airtime cost in the uplink and the downlink direction is an approximation of the average per-packed delay in both directions [23]. Therefore, the average airtime cost is a representative metric that reflects the uplink and downlink channel performance and can also be used to approximate the maximum throughput in the cell. The proposed algorithm measures the average airtime cost for both uplink and downlink for all channels $c \in C$.

$$\mathcal{C}_b^c = \overline{\mathcal{C}_{b,c}^{up}} + \overline{\mathcal{C}_{b,c}^{down}} \quad (35)$$

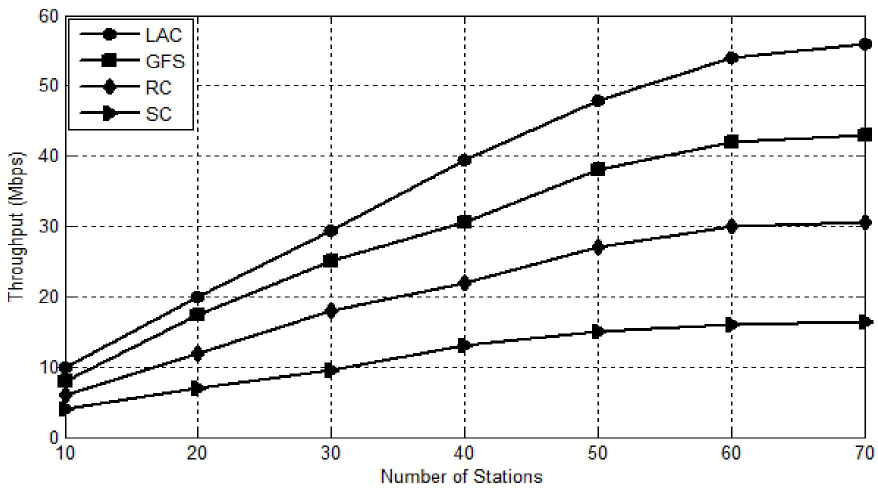


Figure 15 Total network throughput versus number of users (based on results from [23])

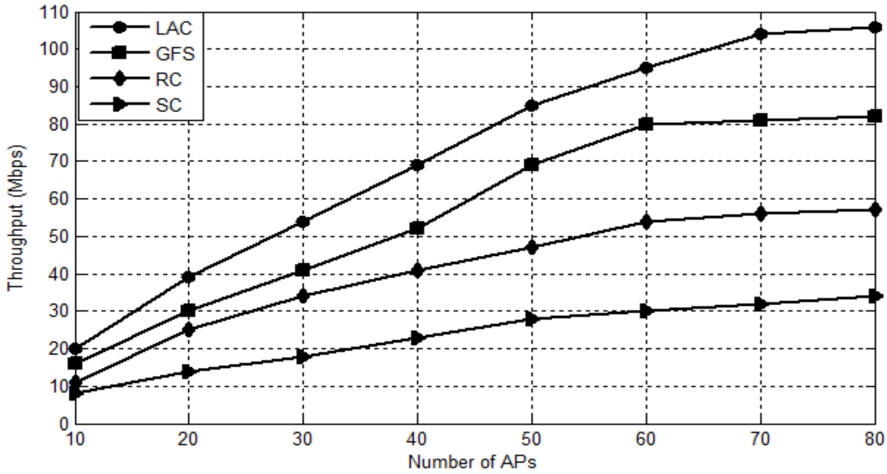


Figure 16 Total network throughput versus number of APs (based on results from [23])

The channel with minimum $\mathcal{C}_b^c$ is chosen:

$$\mathcal{C}_b = \arg\min_{c \in C} \mathcal{C}_b^c \quad (36)$$

Therefore, the channel selection policy determines the frequency with the minimum average per-packet delay, i.e. the maximum throughput.

Simulation results are illustrated in fig 15 and fig. 16. The network performance of LAC is compared to Single Channel assignment (SC) (where APs are assumed to operate on the same channel), Random-Channel allocation (RC) and for the Gibbs sampler Frequency Selection (GFS) strategy described in section IX.I. Fig. 15 depicts the throughput as the network density increases in terms of the number of clients and it is apparent that the LAC strategy provides much higher throughput when the load increases. Fig. 16 depicts the total throughput gain of the tested strategies as the number of APs increases, once again the LAC outperforms the other three strategies.

XI. Time-Offset Space Division Multiple Access (SDMA)

Space Division Multiple Access (SDMA) is the technique that uses multiple antennas at the transmitter in order to allow a number of spatially separated users to share the same time-frequency channel. Time Division Duplex (TDD) systems are especially suitable for SDMA applications since the uplink channel information may be used in the downlink transmission. As the number of transmit antennas increases, the number of simultaneous users which communicate with an AP in SDMA mode increases. This conclusion does not take account of channel latency, data and ACK slot structures, channel estimation, transmission/reception algorithms, etc. The application of SDMA mode in a WLAN based on the IEEE 802.11a/g standard was studied in [25], assuming that only the AP (equipped with multiple antennas) may be modified while the terminals cannot be changed (single antenna terminals).

We assume K users that communicate with an AP equipped with N_t antennas. In the general case $K > N_t$. In fig. 17, h_k is an M_t x 1 vector representing the propagation channel from the M_t AP antennas to the single antenna at the kth user. Each user is specified by its partial 'signal signature' h_k. The signal signature generated over the transmitted signal acts like spreading code in a CDMA system. Therefore multi-user detection techniques known from CDMA can be applied in SDMA-OFDM [18]. We formulate the downlink scenario on a per sub-carrier basis. The transmitted signals for different users are linearly combined and are then multiplied by a weight matrix W of size M_r x K at the transmitter. In the Least Squares solution, the signal transmitted for user k can be fully separated from the signal destined to other users at the receiver.

$$HW_{LS} = I_{KxN_t}$$

$$W_{LS} = H[H^H H]^{-1} \quad (37)$$

where I_{KxN_t} is the K x N_t identity matrix and H is the K x N_t channel matrix of rows:

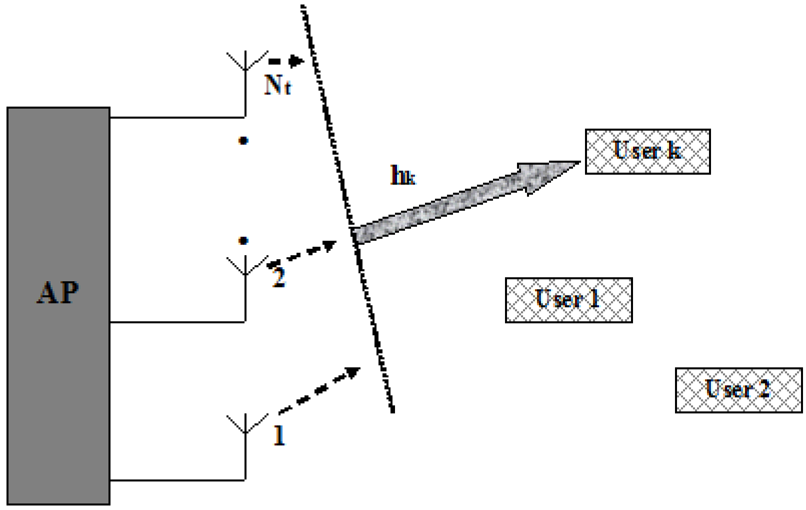


Figure 17 SDMA model

$h_1^T \cdots h_K^T$. In the Minimum Mean Squared Error solution, the expected variance of the error on each transmitted signal is minimized. The W_{MMSE} weight matrix achieves a balance between the recovery of the transmitted signals and the suppression of AWGN noise:

$$[HH^H + \mathcal{N} I_{KxN_t}] - H = 0 \quad (38)$$

In the above equation the total transmit power is normalized to 1.

In the CSMA/CA protocol, after no ACK reception, the backoff interval is increased because of the assumption that co-channel interference is the main reason for packet errors. In the SDMA environment, packet errors mainly occur due to the cross-correlation between the data transmitted towards different users (non-ideal SDMA) rather than co-channel interference. In this case the backoff interval doesn't have to be increased but it is required to update the channel estimation h_k for all users. Direct application of a downlink SDMA transmission scheme to an IEEE 802.11a/g WLAN is difficult due to the characteristics of the CSMA/CA protocol.

(S) Synchronization	(P)Pilot	Signal	Data
160 samples	160 samples	80 samples	80 samples
12 QPSK sub-carriers	52 BPSK sub-carriers	52 BPSK sub-carriers	16 QAM sub-carriers

Figure 18 ACK slot structure

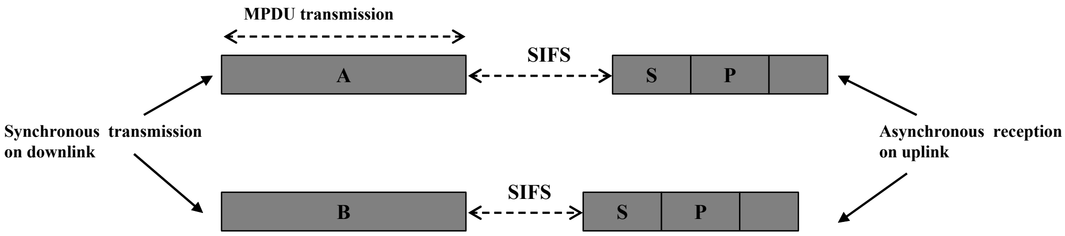


Figure 19 Downlink SDMA slot structure

We consider the ACK slot structure shown in fig. 18 and the SDMA transmission for two users in fig. 19. Simultaneous transmission of two MPDUs A, B to two users will result in each terminal responding after a SIFS period (16μs) with an ACK. Upon arrival at the AP, the two ACKs almost completely overlap in time and mutually interfere with each other. Each ACK slot consists of synchronization, pilot and data segments which confirm the successful reception. Pilots of ACKs may be used to derive up-to-date estimates of the propagation channel in order to transmit the next MPDU burst in the downlink direction. The overlapping of pilot and synchronization segments severely degrades channel estimation and synchronization. Pilot and synchronization segments are the same for all ACKs. This precludes the use of any form of joint channel estimation. A proposed solution is to impose a time offset between transmitted MPDUs, which results in a similar (within some finite accuracy) time-offset in the two ACK bursts as is illustrated in fig. 20:

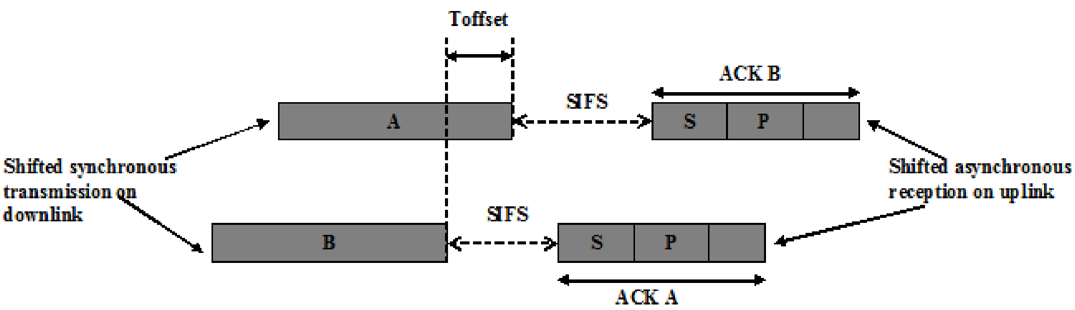


Figure 20 Time-offset SDMA slot

The co-channel interference is reduced particularly for critical synchronization and pilot intervals. The maximum value of this offset is T_{offset}=16 μs. The SDMA technique is applicable in cases of contentionless access. The SDMA initialization process (e.g. refresh of channel estimation) has to take place after every interruption. This overhead impacts the achievable throughput gain. The Time –Division Multiple – Access (TDMA) protocol was proposed in order to partition the radio resources across SDMA and conventional modes of operation for APs as is illustrated on fig. 21

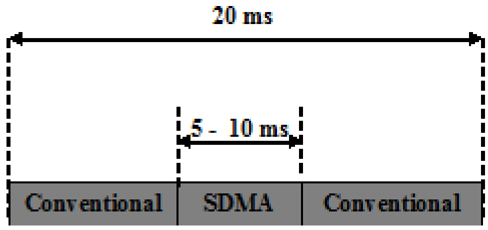


Figure 21 The proposed TDMA frame structure for SDMA

In the conventional 802.11a/g mode, the AP contends using the CSMA/CA scheme. In SDMA mode, the AP reserves a channel with an adaptive interval of 5-10 ms depending on the mix of traffic.

XII. Joint Beamforming and Sub-carriers assignment

Distributed algorithms in a dense WLAN node deployment for channel selection and user association based on the Gibbs sampler are probabilistic. These algorithms require continuous synchronization and are long-term efficient. Mechanisms such as automatic frequency selection and CSMA/CA are based on interference avoidance. In a 'crowded' WLAN environment, the above solutions will result in low or no transmission to suppress interference. The transmit power and channel bands are often set without consideration of the occupancy of the cell and the position of the users with respect to the AP. A great improvement for frequency utilization and minimization of co-channel interference for overlapping WLAN networks is proposed in [26], that achieves to simultaneously keep QoS at an acceptable level for all users. In order to guarantee a specific SINR for all users (QoS), contention periods and collisions within 802.11 MAC operation (as well as the RTS/CTS mechanism) are eliminated.

In order to increase throughput, SDMA is used. According to their locations, the users are divided into g sets. The SDMA technique accommodates the g groups using the same frequency c within the same cell simultaneously, by constructing a spatially independent channel to each group and transmitting the respective signals in parallel. Therefore, frequency utilization can be greatly be improved. Afterwards, downlink beamformers are designed for the co-channel sets of users to achieve the Quality of Service targets (minimum attained signal to interference plus noise ratio at each receiver). The goal is to minimize the total transmission power and thus 'contain' the interference leakage to neighboring co-channel groups and cells. The beams are designed in the same way for the whole channel band by considering as channel matrix H_k^c the average channel matrix for all sub-carriers:

$$H_k^c = \frac{1}{N}\sum_{i=1}^{N} H_k^i \quad (39)$$

From the set of the fixed number of available channels $c \in C$ used by AP b we select the channel that gives the minimum transmit power after beamforming optimization. This is not a link-by-link optimization problem and therefore does not have a large computation cost. For each set of users, multi-user diversity can be exploited to find a subset (from the 48 total data sub-carriers) of good sub-carriers that meet the Quality of Service (QoS) requirements. Following the optimal beamformer calculations at the AP, the different sub-carriers of each set can be allocated to different users (OFDMA). By adaptively employing different AMC modes on the sub-carriers according to SINR, the system performance may be enhanced. The drawback in such a design is that the receivers are found at different locations, near or away from the AP and the constraint of minimum guaranteed SINR must be satisfied for all receivers. By using multiple antennas at the receiver and coherent combination of the diversity paths (in a scattering environment), the SINR is increased compared to the case of just a single antenna receiver. The AP b and the user k exploit the CSI to form beamforming weights in a short-range environment with low mobility. This combination of MIMO, SDMA, OFDMA technologies has the following characteristics:

- The MAC layer takes full advantage of the OFDMA-TDD (Time Division Duplex) delivery mechanism. There is no contention based access, ensuring fast retransmission over the link and a large number of active users.
- Each sub-carrier is allocated only to one user-group. There is no problem of mutual interference between the uplink ACKs.
- In IEEE 802.11a/b/g/n WLANs interference on the same channel can be directly detected through the contention mechanism. But adjacent channel interference often contributes to background noise and cannot be handled in an explicit manner. The design takes account of adjacent channel interference.

Each user listens to every channel for a specific period of time and performs channel measurements that reflect the interference level in the neighboring cells. We introduce again the notion of interference factor or I - factor $I(c_i, c_b)$ where $c_i, c_b \in C$ are frequencies at the center of band for AP $i, b \in B$. The I - factor is the normalized fraction of power which is transmitted at the interfering frequency c_i and is captured from receiver that works at the useful frequency c_b. Fig. 22 illustrates a method for measuring the interference factor:

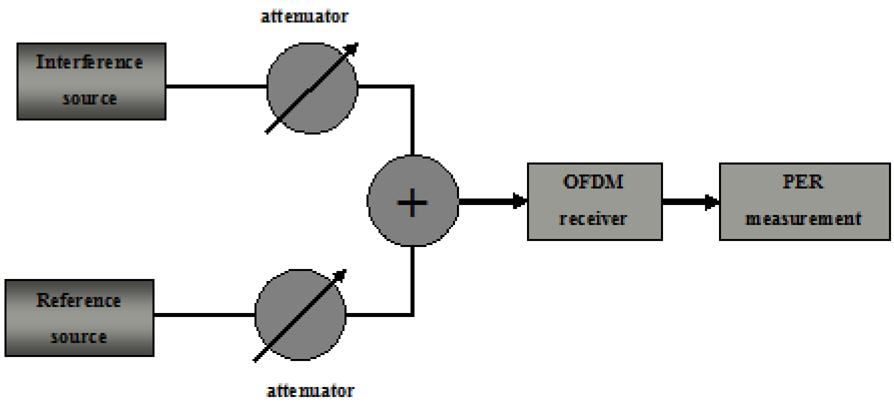


Figure 22 Lab set-up for adjacent channel rejection

In fig. 22, the interference signal is an OFDM signal, unsynchronized with respect to the reference signal. The SINR is calculated for a PER less than 1% and for PSDU equal to 4095 bytes according to the IEEE 802.11n standard. We measure the SINR at the receiver with operating frequency c_b when the transmitted frequencies are c_b and c_i. The ratio:

$$I(c_i, c_b) = \frac{SINR(c_i)}{SINR(c_b)} \quad (40)$$

is the interference factor. When $c_i = c_b$, co-channel interference is assumed to be present and $I(c_b, c_b) = 1$.

Assuming $P_{c_b}(k)$ as the average - over all sub-carriers - power measured from receiver k at frequency c_b when AP b is silent, the total interference power is:

$$I_{c_b} = \sum_{i \neq b} P_{c_b} I(c_i, c_b) \quad (41)$$

The formation of the user groups doesn't require any knowledge of the user's position. In LoS environments, the Angle-of-Arrival (AoA) for the LoS component from the incident signal at the antenna of the AP is estimated. Users concentrated on the same direction are assumed to belong to the same group. In an environment of many scatterers, the LoS component rarely is the dominant one. Up-link waves arrive at the AP predominantly from a few directions. In that case user groups are constructed according to the AoA of the NLoS component with the higher strength. If the formulation of co-channel groups in an environment with rich multipath scattering is not possible, broadcast transmission can be realized. In such a case, the beamforming optimization matches the transmission to more possible eigenmodes of the channel, derived from Singular Value Decomposition (SVD) of the MIMO channel Matrix. The user mobility is likely to be very low and the channel can be viewed as quasi-static, which means that the channel remains fixed during the transmission of a data block. The most critical assumption is the availability of CSI at the transmitter and at the receiver. Accurate CSI may be easy to obtain when the channel changes slowly, as mentioned above.

In the PHY layer, the synchronization, pilot and signal segments are added to the MPDU. Each user estimates the propagation channel from the pilot segments. The CSI is known at the AP by using an uplink channel to send channel measurements that are collected during the transmission of the downlink training sequences at 48 data sub-carriers. In IEEE 802.11n, explicit feedback is proposed in the TDD mode, i.e. each user sends to the AP the MIMO channel coefficients. A CSI matrix report is depicted in table 2, where N_c denotes the number of columns in each CSI matrix and N_r the number of rows. The explicit feedback format field is structured into Grouping (N_g=1 to 4) and Coefficients Size (N_b=4 to 8 bits) fields. The feedback of CSI Matrix can be instantaneous or aggregate. The structure of the CSI Matrix Report includes all sub-carriers. In the case where the beamforming vector V_n is applied at the transmitter and the matrix U_n^k is applied at the user k, the combined channel matrix $(H_{eff})_n^k = (U_n^k) H_k^n V_n$ is estimated from the receiver. U_k^n is known at the receiver side and therefore $H_k^n V_n$ is derived by multiplying the combined channel matrix with $((U_k^n)^H)^{-1}$. The equivalent channel $H_k^n V_n$ is still assumed to be smooth across the sub-carriers belonging to the same set of users because these sub-carriers are multiplied by the same vector V_n. So, we may efficiently estimate the channel by interpolating and smoothing over the pilot tones.

Table 2 CSI MATRICES REPORT FOR 20 MHZ

Field	**Size**
SNR in Rx channel 1	8 bits
……………..	
SNR in Rx channel N_r	8 bits
CSI Matrix for Carrier -28	$3+2xN_bxN_cxN_r$ bits
CSI Matrix for Carrier -28+N_g	$3+2xN_bxN_cxN_r$ bits
………………..	
CSI Matrix for Carrier -1	$3+2xN_bxN_cxN_r$ bits
CSI Matrix for Carrier 1	$3+2xN_bxN_cxN_r$ bits
CSI Matrix for Carrier 1+ N_g	$3+2xN_bxN_cxN_r$ bits
……………….	
CSI Matrix for Carrier 28	$3+2xN_bxN_cxN_r$ bits

The proposed transmission protocol operates in the following way:

Step 1: The AP broadcasts an MPDU containing a CSI feedback Request to each of the users $1, \ldots K$ sequentially.

Step 2: The users $k = 1, \ldots K$ receive the MPDU using an omni-directional antenna pattern and perform channel estimation $\hat{H}_k^n$ with $n = 1, \ldots N$. Upon successful reception of the MPDU, each user calculates the matrix U_k^n , quantizes the CSI and sends an ACK containing the CSI feedback.

Step 3: The AP collects the radio channel matrices $\hat{H}_k^n$ and groups users according to the strategy mentioned above.

Step 4 : The matrix $H_k^n V_n$ is estimated by each user and is sent to the AP as feedback. The receiver channel matrix calculated in *step 2* is used (assuming that it is still reliable due to the channel low variability).

Step 5: If all K steering ACKs are received from the AP at the allocated frequencies, then *step 4* is repeated.

Step 6: If all K steering ACKs are received from the AP at allocated frequencies and the optimization problem of constructing beams has a feasible solution, then *step 3* is repeated.

Step 7: If one of the ACKs is not received from the AP or the specified SINR at each receiver cannot be achieved, then the procedure is interrupted and we begin from *step 1* to estimate the full dimension of channel matrix $\hat{H}_k^n$.

The receiver antenna arrays steer the beams to enhance the total received power in all reflected paths within the scattering environment. The array gain is achieved via coherent combining of the signal paths. The calculation of U_k is based on Singular Value Decomposition SVD.

$$H_k = U_k D_k (V_k)^H \quad (42)$$

The columns of U_k (u_{ki}) are the optimum vectors of the receiver antenna array for the ith eigenmode. Therefore, the receiver antenna arrays form beams using eigenvectors and capture all possible spatial streams derived from scatterers which are within the vicinity of both the transmitter and the receiver. SVD is evaluated at the receiver. At the AP, the beamformers V_g are designed simultaneously for several co-channel groups with central frequency c.The goal is to minimize the total transmit power $\sum_{g=1}^{G} \left\| V_g^c \right\|_2^2$ (G is the total number of groups) guaranteeing at the same time a predefined SINR constraint γ_k for all users K.

$$\mathcal{Q} \quad \min_{\{V_g^c \in C^{M_t}\}_{g=1}^{G}} \sum_{g=1}^{G} \left\| V_g^c \right\|_2^2$$

$$\frac{\left|(U_k^c)^H\, H_k^c\, V_g^c\right|^2}{\sum_{l\neq g}\left|U_k^c H_k^c V_l^c\right|^2+(\mathcal{N}_k^c)\left\|U_k^c\right\|^2+\sum_{i\neq b} P_k^i(i,b)} \geq \gamma_k$$

$$\|U_k\|^2 = 1, \quad \forall k \in \{1,2,\dots K\}, \quad \forall g \in \{1,2,\dots G\}, \ \forall c \in \{1,2,\dots C\}$$

The problem $\mathcal{Q}$ takes into account co-channel interference from other groups in the same cell (intra-cell interference) and co-channel or adjacent channel interference from neighboring cells (inter-cell interference). This problem was found to be NP-hard for the general channel vector. It can be formulated as a convex optimization problem and may be solved by any Semi Definite Programming (SDP) solver.

Finally, we select channel $c \in C$ that minimizes the total transmit power of AP b for all possible operating channels. Therefore

$$c = \arg \min_{\{c \in C\}} \sum_{g=1}^{G} \left\|V_g^c\right\|_2^2 \quad (43)$$

In the following, the problem which has to be solved is how to assign N=48 OFDM data sub-carriers to each co-channel group. A sub-carrier is only allocated to one user. The solution is developed in two steps.

a) Resource Allocation

The number of sub-carriers m_k to be allocated to each user is computed. If group g has K_g users ,

$$\sum_{g=1}^{G} K_g = K \quad (44)$$

$$\sum_{k=1}^{K_g} m_k = N \quad (45)$$

The calculation takes into account

a) The SINR_k calculated from problem $\mathcal{Q}$
b) The minimum rate required R_k^{min} and
c) The maximum BER required

R_k^{min} and BER are related to different QoS. For M-QAM modulation with $M = 2^{b_k}$, the throughput of user k is:

$$T_k = W_{subchannel} \log_2(1 + \alpha \mathrm{SINR}_k) \quad (46)$$

where,

$$\alpha = \frac{1.5}{-\ln(5\mathrm{BER})} \quad \text{and} \quad \alpha = \frac{1.5}{0.2/\mathrm{BER} - 1} \quad (47)$$

for AWGN and Rayleigh fading respectively. Each sub-channel occupies 312.5 KHz and therefore $W_{subchannel}$ = 312.5/2 KHz. When α=1, the relationship (46) is the Shannon

Capacity. We have assumed that $SINR_k$ is constant for all sub-carriers, $m_k = \lceil \frac{R_k^{\min}}{T_k} \rceil$, where $\lceil x \rceil$ denotes the smallest integer that exceeds x. We distinguish two cases:

a) $\sum_{k=1}^{K_g} m_k > N$: The user with maximum m_k is the user who requires high bit rate but has small T_k i.e. bad $SINR$. Fair allocation rules impose the removal of one subcarrier.

b) $\sum_{k=1}^{K_g} m_k < N$: in order to achieve maximum throughput, we add one sub carrier to the user with minimum m_k and high $R_k^{\min}$.

b) Sub-carriers Allocation

The hypothesis that the channel is constant over the whole band is acceptable only for resource allocation. The channel matrix is approximately constant over the narrow band of each sub-carrier, therefore the users don't observe the same SNR_k^n on all sub-carriers. We normalize $SINR_k^n$ relative a to maximum value $SINR^{\max} = \max_{\forall k,n} SINR_k^n$.

$$w_k^n = \frac{SINR_k^n}{SINR^{\max}} \quad (48)$$

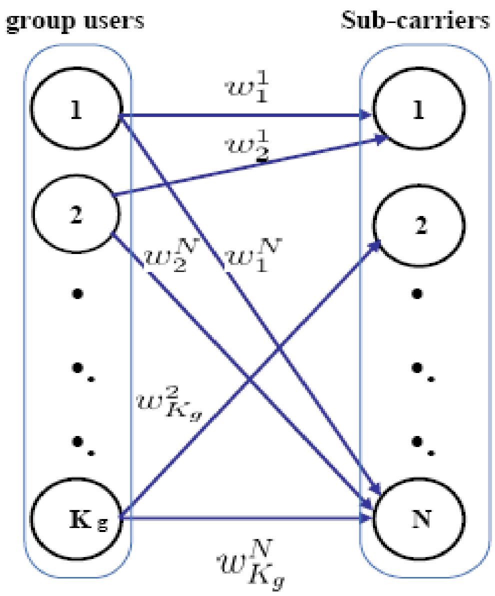


Figure 23 Graph of N sub-carriers allocated to K_g users

If we consider two disjoint sets of vertices, one representing the K_g users and the other representing the N sub-carriers, then the problem of sub-carriers allocation is transformed into a weighted bi-partite matching as is illustrated in fig. 23.

The maximum augmenting path may correspond to the maximal weighted matching. A second method is via integer programming. Let's assume p_k^n to be a binary variable which is constrained to take value 1 if (k,n) is a matching edge and 0 if (k,n) is not a matching edge. We formulate our problem in the following way:

$$\mathcal{I} \quad \max \sum_{k=1}^{K(g)} \sum_{n=1}^{N} w_k^n \; p_k^n$$

$$\text{s.t.} \quad p_k^n \leq 1$$

$$\sum_{k=1}^{K_g} p_k^n = 1$$

$$\sum_{n=1}^{N} p_k^n = m_k$$

The problem can be solved by Linear Programming (LP) .We assume deployment with 5 partially overlapped cells as in fig. 24. Channel 1 is assigned to AP 2, channel 2 to AP 4, channel 3 to AP 3 and channel 4 to AP 5. AP 1 is assumed to enable self-configuration when the total number of operating frequencies is 4. Within the cell of AP 1, 10 users are assumed to be allocated into 4 groups as in fig. 25. The first cluster consists of 4 users, the second of 3 users, the third of 2 users and the fourth contains one user. We make a list of operating frequencies with random order $\mathcal{F} = \{1, 2, 4, 3\}$. The radiation pattern of the neighboring cells is illustrated in fig. 26. The calculated transmit power of AP 1, according the list $\mathcal{F}$, is shown in fig. 27. Each run corresponds to different random locations of users. In the 1st run, the difference between the transmitted power in frequencies 2 and 4 is 0.235 W. The transmitted powers corresponding to frequencies 1 and 3 are greater than 250 mW and therefore they are rejected. In the 3rd run, only frequency 2 can be used. The average PHY data rate for AP 1 without inter-cell interference is calculated assuming that the same number of sub-carriers is allocated to each user. The number of users is 4 and the users are placed in the 4 groups of fig. 24. The results are compared to the SVD technique, the IEEE 802.11a standard and are shown in fig. 28 . At the first 5 runs, the angular width of the 4 groups is 20°, at the next 5 runs it becomes 40° and at the final 5 runs it is equal to 60°. The figure shows that the proposed SDMA technique outperforms the other 2 techniques and that in all cases the throughput drops as the user group covers a bigger area.

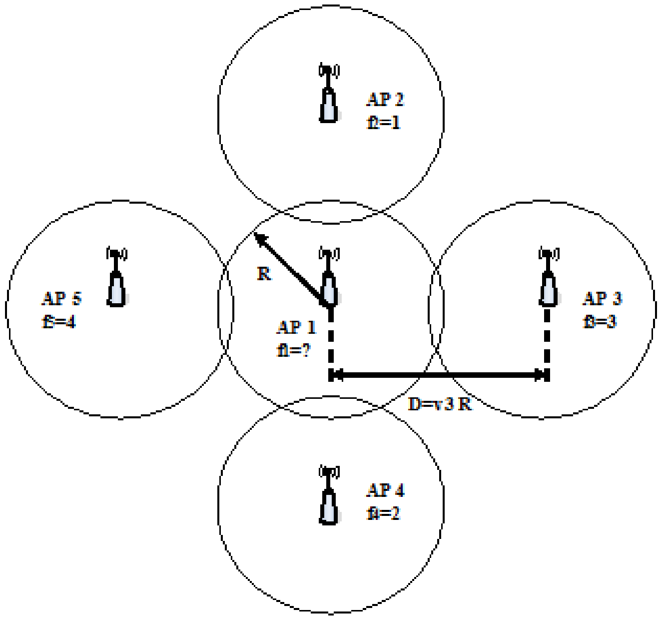


Figure 24 5 cells partially overlapped.

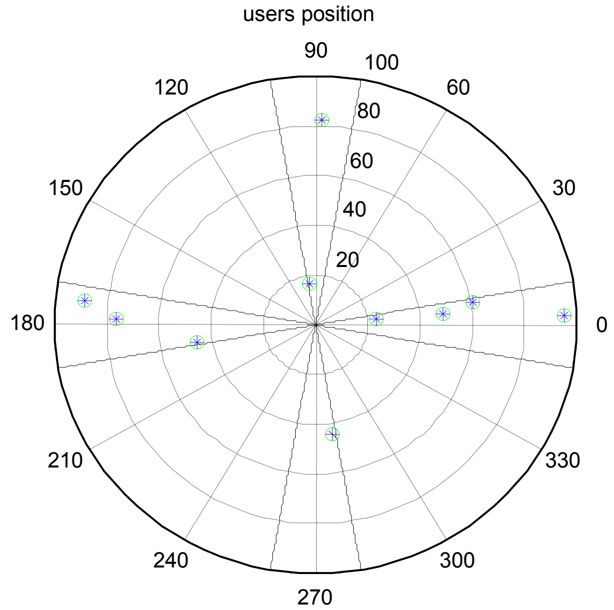


Figure 25 Location of 10 users in 4 groups

XIII. Joint Beamforming and Channel Selection for Multicast Transmission

Multicast is a method that allows transmission and routing of a single application to multiple recipients at different locations using minimum network resources. Many emerging mobile applications – including group oriented mobile commerce, on line gaming, distribution of television content and distance education, requires multicast support. The wireless delivery of such multimedia content requires high throughput and low end-to-end latency for supporting QoS. Due to bandwidth limitations, point to point communication cannot be accommodated for each user assuming a large number of terminals. Multicast transmission can be done at the

PHY layer [27]. The streams are transmitted only once and the scheduler doesn't duplicate the transmitted data. This efficient method supposes that the CSI is processed at the network layer. Only the users with good channel are scheduled with dynamic rate adaptation. The PHY throughput is limited from the MAC layer. Increasing the PHY layer data rate will result in even lower MAC efficiency. Multicast minimizes excessive contention when the number of users increases. IEEE 802.11 a/b/g/n does not support a reliable handshaking for multicast transmission. If we guarantee a minimum SINR for all receivers, we can achieve a reliable data exchange. A downlink beamformer may be designed for minimizing the total transmit power and thus reducing the interference leakage in the user's vicinity. To do that we need to specify a minimum received SINR that has to be attained at each intended receiver. The antenna arrays may form beams to transmit signals towards directions of interest (spatial filter). Adaptive beamforming can be employed for different sub-carriers by only changing the gains of the antenna weights in the case of each subcarrier, according to the required attenuation factor. The total transmit power is minimized for the sub-channel with the minimum gain. In the same time this power can fulfill the constraints for all other sub-carriers with grater gain. If q is the rank of the channel matrix(the number of parallel channels) , the transmit power for each sub-carrier n after the SVD of H_k^n is:

$$P_k^n = \sum_{i-1}^{q} (D_k^n)^2[i,i] \quad (49)$$

The sub-carrier n_k^{min} which corresponds to weakest gain at each user is:

$$n_k^{min} = \arg\min_{\forall n} P_k^n \quad (50)$$

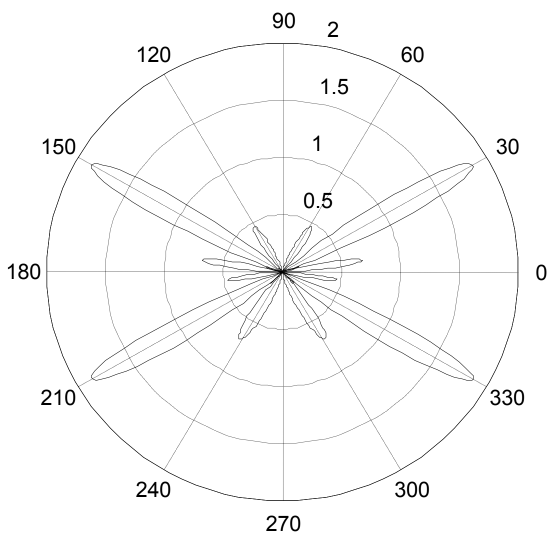


Figure 26 Beamforming of AP 2,3,4 and 5

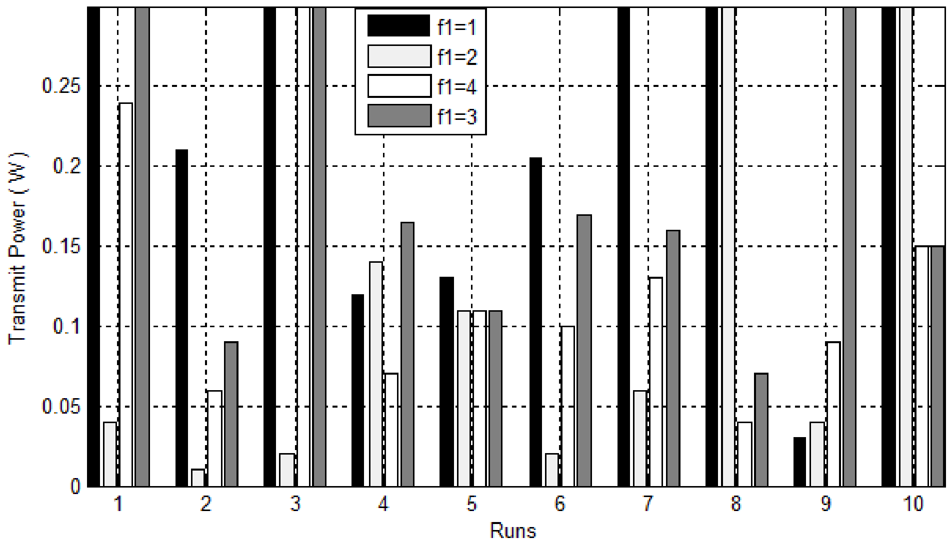


Figure 27 Calculated transmit power [26]

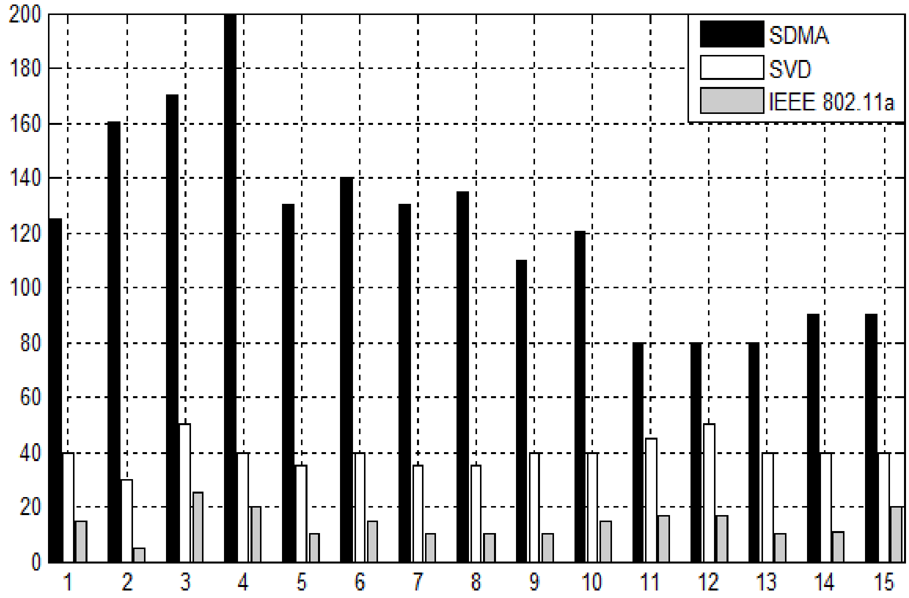


Figure 28 Average PHY data rate for different users location [26]

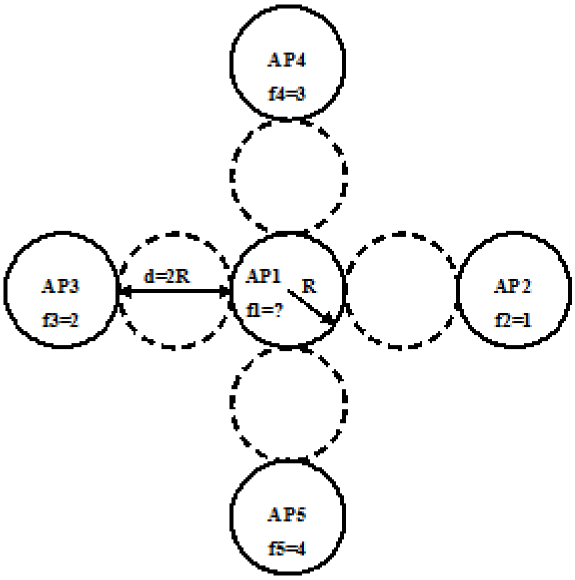


Figure 29 Deployment of a configuration for multicast application

We define the set $I_{min} = [n_1^{min}, n_2^{min}, \cdots, n_k^{min}]$ with the minimum sub-carriers for each user. The problem is solved not for all n and k but for $n \in I_{min}$.

A network that consists of 5 non-overlapping cells is considered as in fig. 29. The distance between two APs is $D = 4R$, where R=200m is the radius of the cell. At each cell, 16 users are randomly distributed. In a rich scattering environment a single multicast group is assumed to be formed. Channel 1 is assigned to AP 2, channel 2 to AP 3, channel 3 to AP 4 and channel 4 to AP 5. Fig. 30 shows the average transmitted power in Watts as a function of active users for channels 1 to 6. If only 4 channels are supported, channel 3 requires the minimum power (0.5 Watts) for 12 and 16 users.

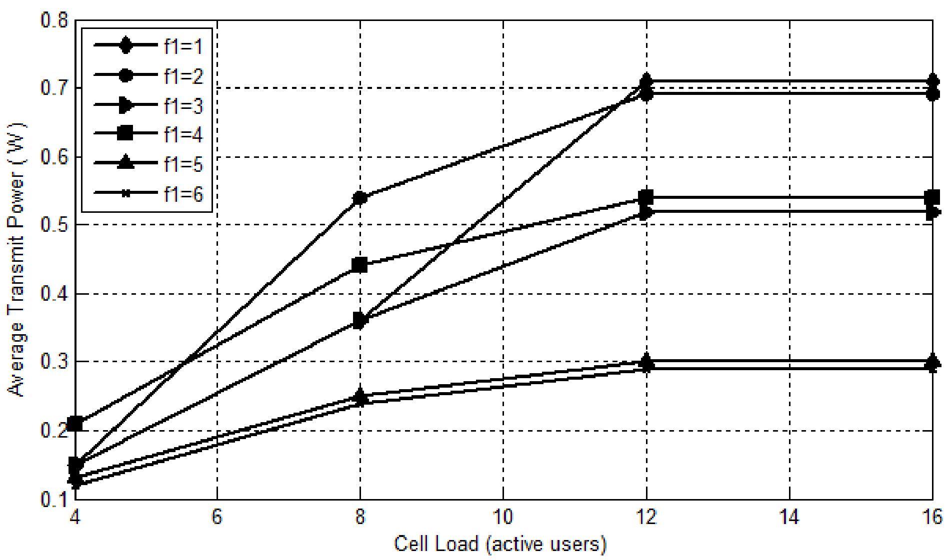


Figure 30 Transmit power for 6 channels vs the number of multicast users [27]

XIV. Conclusions

In a densely deployed WLAN environment, APs may cause significant inter-cell interference, which reduces the spectral efficiency and the offered QoS. The use of CSMA/CA mechanism has contributed to the success of IEEE 802.11 but suffers from throughput and latency degradation in an environment with variable (independently managed) AP densities. By exploiting the advantages beamforming, MIMO, SDMA and OFDMA techniques, distributed algorithms may suppress interference among collocated WLANs by minimizing the transmitted power and allowing APs to select the appropriate channels for their associated users. These techniques provide high throughput in densely deployed environments but may have high implementation complexity. The cross-layer design between PHY, MAC and network layers, could lead to solutions that ensure the efficient allocation and usage of the wireless resources by trading off performance for complexity..

The proposed cross-layer strategies adapt the wireless systems to the frequency-time channel variations without increasing the overhead or causing instability from the interconnection of independent OSI layers. A large part of the presented techniques has been focused on beamforming and frequency assignment since the availability of multiple transmitting and receiving antennas, combined with the use of the OFDMA technique that is proposed in IEEE 802.11n offer new challenges. By using channel state information the link adaptation schemes may dynamically select the best transmission rate. This is combined with an opportunistic scheduler that leads to optimized transmission taking also into account QoS information from the application layer in order to support multimedia applications. Other strategies exploit channel state information from PHY layer in order to permit users to select the AP to connect to. Some of the presented schemes perform joint user association and transmission power control or dynamic channel selection. Finally, we presented cross-layer schemes where the time of packet transmission in the MAC layer is adjusted in order to transmit simultaneously to more than one users. The presented algorithms have been summarized in Table 3.

Table 3 Summary of the presented cross-layer algorithms

Section	Scheme	Mechanism
V	Frequency assignment considering traffic loads at the MAC layer	Channel assignment considering the traffic load at the MAC layer
VI	Distributed MAC protocol	The resolution of collisions and the scheduling of data transmissions are separated into two logical queues. A virtual priority function is employed for rescheduling

		transmissions according to a cross-layer design.
VII	Joint adaptive multiple antennas and adaptive modulation with acknowledgement and eigen-steering feedback.	• Optimum transmitted and received beam weights are calculated. • Adaptive modulation performs allocation of OFDM sub-carriers, power and modulation mode. • Optimum transmitted weights, power and subcarrier allocations are obtained from the uplink acknowledgment.
VIII	Joint user association and power control	• Each user is associated with the best AP by considering the quality of channel. • Every AP controls the maximum transmitted power in its cell to minimize co-channel interference and to balance the load between cells.
IX	Channel selection and user association	Fully distributed algorithms that rely on Gibbs samplers
X	Channel selection based on minimum end-to-end path metrics	The frequency channel with the minimum average air time cost for uplink-downlink directions is selected
XI	Application of SDMA mode in WLAN	A time offset between transmitted packets is imposed. TDMA is proposed to partition the radio resources using SDMA and conventional modes.
XII	Joint beamforming and sub-carrier assignment	• Beams are designed by considering the average channel matrix of all sub-carriers • Sub-carriers are assigned taking account QoS constraints
XIII	Joint beamforming and channel selection for multicast applications	Transmit power is minimized for the sub-channel with the minimum gain.

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