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High density multi-cell

wireless networks

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Contents

1 Introduction

Mobile internet usage has become a daily activity for many people. It is mainly used to access news and information on the internet. According to *comScore*, the number of people using mobile devices has doubled between 2008 and 2009 to 63.2 million. 35% of them did so daily [12]. In most cases those mobile devices include wireless network (WLAN) capabilities. The number of devices shipped with embedded wireless is expected to surpass one billion units in 2011 and will be doubled in 2015 [28]. Also the *Federal Communications Commission lab* reports the number of authorized wireless transmitters has grown to nearly 12000 in 2010. Compared to a decade ago, that is an increase of 400% [19].

It is a challenge to provide reliable wireless connectivity for the ever growing demand, especially in dense environments like conference halls and events. Because of the high penetration rate of the wireless enabled devices, the air (shared medium) is extremely vulnerable for congestion. The greatest challenge is interference, mainly by neighboring devices, followed by the other more common wave deformations (absorption, reflection and diffraction).

This document is mainly focussed on the *physical* (PHY) layer and *Medium Access Control* (MAC) layer aspects of the IEEE 802.11 standard. It is organized in three parts. The first part (Section 2) lists some of the major problems that needs to be solved with regard to high density wireless network deployments. In the next part (starting from Section 3) background information is provided on the wireless standard (IEEE 802.11), common interference problems and some interference mitigation techniques. Part 3 (starting from section 6) lists some of the most popular enterprise wireless solutions provided by both commercial and non-commercial entities. Section 8 compares and discusses those solutions. Finally this thesis is concluded in section 9.

2 The problem

It is not trivial to setup large scale wireless networks serving massive amount of users in dense environments. This is mainly imposed by the nature of radio waves and the medium access scheme. Because the medium is shared across all neighbouring devices, transmissions are extremely sensitive to signals tampering.

How would one optimize the wireless network such that it can deliver reliable connectivity in a dense environment? This question can be decomposed into smaller ones:

1. What are dense environments?
   Conference halls, large class rooms and open air events are examples of dense environments. In general an area where massive amount of users use wireless devices in a condensed space.

2. What architecture is best suited?
   Multi-cell is needed to segment the coverage. By dividing the coverage area into cells, more concurrent transmissions can take place and thus increases network throughput. See section 3 for more details.

3. What are the problems with multi-cell?
   The biggest problem is how to mitigate interferences. Because multiple devices can transmit data at the same time, they can interfere with each other.

Above questions will be answered in more details throughout the subsequent sections.

3 Wireless network

A *wireless network* (WLAN) interconnects two or more devices with each other without wires. In the network there is at least one special node called *access point* (AP). This AP announces the presence of the network by periodically broadcasting messages. An AP is identified by its *Basic Service Set Identifier* (BSSID). The network on the other hand is identified by a *Service Set Identifier* (SSID). If there are different BSSIDs announcing the same SSID, then the network is of type *multi-cell*. A cell is essentially the coverage area of one AP. The characteristic of this type is that clients can distinguish between cells themselves. The coverage area can be extended using additional APs (Section 3.6) or equip existing AP with higher gain antennas (Section 3.1). Communication between nodes in a WLAN is only possible if they adhere to the same communication protocol; Wireless LANs implement one or more standards from the IEEE 802.11 family. The first widely accepted was 802.11b followed by 802.11g and recently 802.11n. In the rest of this section light is shed on the basics of the IEEE 802.11 standard and how performance is affected in certain situations.

3.1 Physical Layer

Each device is equipped with one or more radio interfaces. A radio interface can transmit and receive radio waves, but not simultaneously. Radio waves are a type of electromagnetic wave. Electromagnetic signals are converted into electrical current and vice versa by antennas. The physical construction of an antenna determines how energy is beamed out or received. The *Law of Antenna Reciprocity* [30] causes an antenna to receive signals with the same ability as it can send signals. This means that a high-gain or directional antenna both transmits and receives with increased *gain*. So the device's coverage area can be increased with a high-gain antenna. The coverage can also be changed by varying the transmit power. However the reception capability remains the same. The response sent by a client may not be received correctly by the device with high transmit power.

There are two fundamental types of antennas with reference to a specific two dimensional plane, usually horizontal:

1. Directional: a narrow beam is focussed in a single specific direction or a sector. It essentially radiates more in one direction than in the other, thus higher gain.

2. Omni-directional: all directions are radiated equally, but most antennas really have some gain by improving horizontal range at the expense of reception above or below the antenna. Typically applied in a portable computer.

A *channel* in which radio waves are generated is a range of electromagnetic frequencies. The radio interface translates the waves into bit sequences forming a data stream. Subsequences of this data stream are called *frames* in *Data link* layer.

3.2 Data Link Layer

For stations to communicate with each other, various frames are defined in the 802.11 standard[14]. Frames can be categorized into three main types: management, control and data frames. In the next sections some relevant subtypes are briefly introduced.

3.2.1 Management frames

Management frames allow stations to establish and maintain communications. Some of these subtypes are:

- *Authentication frame* – Frame containing its identity is sent to the AP. The AP replies indicating acceptance or rejection.
- *Association request/response frame* – The request carrying supported data rates and the SSID is sent to the AP which in turn responds with either acceptance or rejection. If the request is accepted, resources are allocated and the response frame includes information regarding the association: association ID and supported data rates.
- *Re-association request/response frame* – The request is sent by the client to another AP with stronger signal when it roams away from the current associated AP. The new AP replies with rejection or acceptance containing an association ID and supported data rates. Data remaining in the buffer of the previous AP is forwarded to the new AP.
- *Beacon frame* is sent periodically by an AP to announce its presence.
- *Probe request/response* – A station can probe other stations for information. The response contains capability information, supported data rates and among others.

3.2.2 Control frames

Exchange of data frames between stations are facilitated by control frames. RTS/CTS frames (Details in section 3.4) are introduced to solve the hidden terminal problem (Section 3.5.2).

- *Request to Send (RTS) frame* – A station sends a RTS frame to another station as the first phase of a two-way handshake necessary before sending a data frame.
- *Clear to Send (CTS) frame* – A station responds to a RTS with a CTS frame, providing clearance for the requesting station to send a data frame.
- *Acknowledgement (ACK) frame* – The receiving station will send an ACK frame to the sending station if no errors are found. If the sending station doesn't receive an ACK after a period of time, the sending station will retransmit the frame.

3.2.3 Data frames

In the body of a data frame a packet is encapsulated and transported. A packet is a package of data that exists at Layer 3 (network layer). For example an Internet Protocol packet. Packets can be fragmented into multiple frames depending on the *Maximum Transmission Unit* (MTU) size.

3.3 Distributed Coordination Function (DCF)

The DCF access mechanism employs a *Carrier Sense Multiple Access with Collision Avoidance*(CSMA/CA) mechanism to control access to the wireless medium. CSMA/CA is similar to the access scheme used in the Ethernet standard (IEEE 802.3). There is also PCF (Point Coordination Function), because the majority of clients do not support it, it is not considered any further.

Figure 1 illustrates how DCF medium access works: If the medium is free for one DIFS (Data Inter Frame Spacing), go ahead and transmit. Otherwise if the medium is busy, wait for the DIFS duration and enable the back-off procedure:
A random number of timeslots is chosen from the range [0,CW], where CW is the *Contention Window* maintained by every terminal[1] individually. For each newly transmitted frame the CW is set to a minimum value and increases with the number of retries. As CW becomes greater, the likelihood of terminals choosing the same back-off duration decreases.

During back-off, if the medium is free, decrement the back-off counter and freeze the timer when it becomes busy. Once the counter reaches zero, go ahead and transmit.

On the receiver: After receiving a data frame, wait for a SIFS (Short Inter Frame Spacing) and immediately send an ACK (Acknowledge) frame back to the sender.

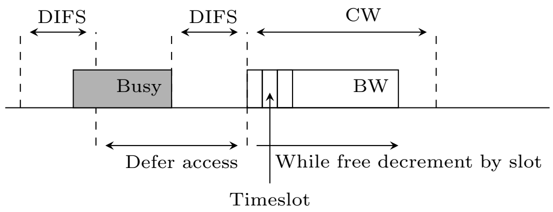

Figure 1: DCF access procedure

Note that there is no carrier sensing or backing-off for an ACK. In a heavily loaded network collision is very likely to occur causing frames to be dropped. As a result the throughput is affected negatively. End-users will experience higher latency and decrease in usable bandwidth because of retries.

3.4 DCF with RTS/CTS

The carrier sense mechanism not only implements physical carrier sense but also virtual carrier sense in this mode. After winning contention the station sends a special frame called RTS (Request to Send) to its destination node. The destination waits for a SIFS then replies with a CTS (Clear to Send) to indicate permission to send. Each station has a Network Allocation Vector (NAV) predicting how long the medium will be busy. The RTS and CTS include fields that specify the time to be taken for sending the data frame and the ACK, which follows this RTS-CTS pair. The NAV value is updated based on the duration field in the frames it overhears. A node will only try to win contention when its NAV value is zero. Figure 2 shows the RTS-CTS frame exchange sequence. RTS/CTS handshake gets triggered only if the packet being sent is larger than the RTS/CTS packet size.

3.5 Classical Radio Frequency problems

The most common problem in the wireless world is signals emitted by entities unrelated to the network. Because they are not to be influenced, a well designed system try to workaround them. Further more in highly dense WLANs it is very likely for other 802.11 devices to cause interference to each other. The performance will be vastly degraded as a result of collisions. These

[1] Device capable of sending and receiving radio signals

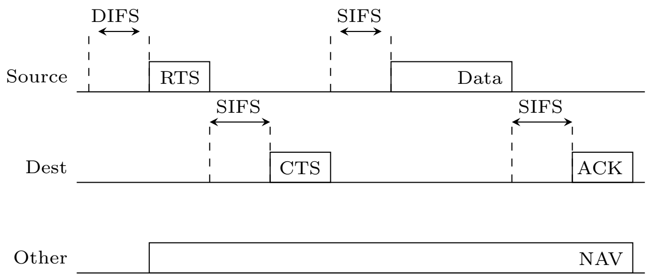

Figure 2: RTS-CTS frame exchange sequence

scenarios are known as the *hidden* and *exposed terminal* problems.

3.5.1 Uncontrollable RF sources

Besides the active interferences among neighbouring nodes, there are others uncontrollable sources like rogue nodes belonging to different networks. At least those signals can be intercepted and decoded. So decisions can be made based on those informations. However there are other more trouble some sources that emit non-decodable signals, also known as noise. The problem with noise is its unpredictability and therefore difficult to filter out.

3.5.2 Hidden terminal problem

A well known problem in WLANs is the hidden terminal problem. For instance there is an AP α and two clients, CL_1 and CL_2 such that they are out of each others range, associated with it (see figure 3). If CL_1 starts sending a frame to α while CL_2 also sends its payload, collision will occur. Because CL_1 and CL_2 cannot sense each other, according to the CSMA/CA mechanism, the channel was idle and hence safe to use the medium.

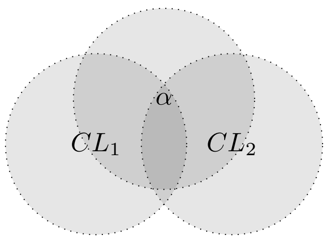

Figure 3: Hidden terminal problem: CL_1 and CL_2 cannot sense carrier

Extending CSMA/CA with RTS/CTS described earlier helps alleviate above problems at a certain degree. Recently Manitpornsut et al [20] concluded if the majority of traffic is downstream traffic in a densely deployed WLAN, the RTS/CTS mechanism together with strategic channel assignment can augment the system performance for both best-effort and delay-sensitive applications under the hidden node scenario.

3.5.3 Exposed terminal problem

Another problem that might occur is the exposed terminal problem where a client's transmission is interfered by another client. Figure 4 shows that while CL_1 is transmitting to α and CL_2 wants to send to β, CL_2 must back-off as it senses the carrier is busy. But in fact it could send to β as its transmission is out of range of α. Given that they operate in the same frequency.

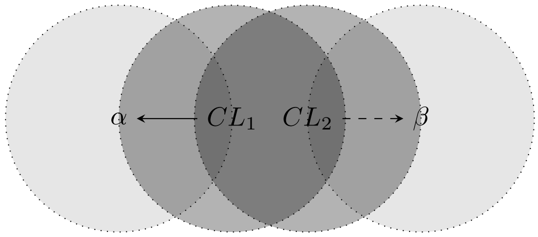

Figure 4: Exposed terminal problem: CL_1 is interfering CL_2 from transmitting

3.6 Architectures

The most simple architecture consists of a single cell. That is the building block used to create larger networks called *multi-cell* networks. A cell is the coverage area of an AP. This AP in turn can be equipped with multiple radios together with directional antennas segmenting its coverage even further. This is desirable because it increases the capacity per AP, ideal in dense environments where connections between APs are expensive (e.g. cabling).

When multiple radios are involved they can cooperate with each other creating a single large cell. Some companies consider multi-cell networks of which all APs operate on the same channel also to be single cell. In such a case clients are still aware there are multiple APs involved. Another approach is by *virtually* merge multiple radios located at distinct geographic locations into one, this technique is called *macro diversity*. Macro diversity is a diversity scheme where several receiver and/or transmitter antennas are used to transfer the same signal. Radio signals can be centrally processed as opposed to distributed processing in individual APs. Ouachani et al [26] concluded that macro-diversity is proportionally more useful in situations where receivers and transmitters are far away than when they are closer. Such a setup requires a fast connection between the radios and the central controller. Also there is overhead of higher protocols needed to transport the raw signals. This diversity scheme has its own share of complexity of which is discussed partially in section 4.

3.7 Control And Provisioning of Wireless Access Points Protocol

Control And Provisioning of Wireless Access Points (CAPWAP) protocol specification is developed by the Internet Engineering Task Force(IETF) defining the communication between lightweight APs and a controller. The protocol specification is described in RFC5415 [16] and the IEEE 802.11 binding in RFC5416 [15]. It is based on Lightweight Access Point Protocol (LWAPP) initially proposed by Airespace as a standard, now property of Cisco. Aruba Networks (Section 6.2) also contributed to this protocol, they even sponsored an open source implementation of CAPWAP called openCAPWAP. This interoperable protocol enables an access controller

	Split	Local
Function		
Distribution Service	AC	WTP/AC
Integration Service	AC	WTP
Beacon Generation	WTP	WTP
Probe Response Generation	WTP	WTP
Power Mgmt/Packet Buffering	WTP	WTP
Fragmentation/Defragmentation	WTP/AC	WTP
Assoc/Disassoc/Reassoc	AC	WTP/AC
IEEE 802.11 QoS		
Classifying	AC	WTP
Scheduling	WTP/AC	WTP
Queuing	WTP	WTP
IEEE 802.11 RSN		
IEEE 802.1X/EAP	AC	AC
RSNA Key Management	AC	AC
IEEE 802.11 Encryption/Decryption	WTP/AC	WTP

Table 1: Differences between Split and Local MAC mapping of 802.11 functions

(AC) to manage a collection of Wireless Termination Points (WTPs, or simply Access Point). Its goals are:

- Centralize authentication and policy enforcement functions
- Shift higher-level protocol processing from WTPs
- Extensible protocol not bound to a specific wireless technology

3.7.1 Split and Local MAC

CAPWAP supports two modes of operation: split and local MAC. Layer 2 wireless data and management frames are encapsulated and exchanged between AC and WTP in split mode. Local MAC mode allows the data frames to be either locally bridged or tunneled as 802.3 frames (Ethernet). In both cases Layer 2 wireless management frames are processed locally by WTP and then forwarded to AC. The specific architecture differences are listed in Table 1.

3.7.2 Control parameters

Several types of control messages are defined in CAPWAP like discovery. We're interested in the *Configuration Status Request/Response Message* and *Configuration Update/Request Message* in particular. The first types allows the AC to collect per WTP information elements like:

1. QoS: Best effort, video, voice or background
2. Supported rates: rates supported on the WTP
3. Radio: Type of sectorization, omni or MIMO
4. Current channel: current operating frequency channel

Above data can be used by an optimizer in the AC to generate feasible and optimal configurations for the network. These configurations can then be assigned to each WTP individually. The most important settings are:

1. Tx Power: radio power level
2. QoS: change policy per station
3. Supported rates: which rates are allowed

Frame statistics may also be retrieved from WTPs like:

1. Failed count: Failed transmissions
2. Retry count: Transmit retries
3. Frame duplicate count: duplicate frames received
4. RTS and ACK failure count: failed transmitted RTS and ACK
5. Associated station count: number of associated stations

These may aid the optimizer in finding better solutions.
It should also be noted that *Frame Info* field, optional CAPWAP header field for data messages in *split mode* from WTP to AC include the following information:

1. RSSI: Received signal strength indication
2. SNR: Signal-to-noise ratio
3. Data rate: Data rate of the packets received by the WTP

4 Interference mitigation

Several methods can be applied to mitigate interferences in single RF multi-cell networks. Because of the fact there are masses of radios transmitting and receiving signals, it is very likely collisions will occur, known as Co-channel interference. Collisions should be avoided as it decreases the network throughput. When a collision occurs, the transmission is dropped, thus wasted resource. In this case *free-air time*. Free-air time is time slices of which a transmission occurs. The slices can be divided evenly across clients, *Time Division Multiple Access* (TDMA). TDMA, not supported on general consumer products, has been applied to long distance and rural environments [27, 13, 18]. It is less predictable in case of CSMA/CA (See section 3).

4.1 Channel Assignment

To minimize co-channel Radio Frequency (RF) interferences, neighbours of AP α operate in different channels. However not all 11 available channels should be used because there is only 5 MHz separation between the center frequencies, and an 802.11b signal occupies approximately 30 MHz of the frequency spectrum. The signal falls within about 15 MHz of each side of the center frequency. So there are 3 non-overlapping channels (1, 6, 11) that will guarantee neighbouring nodes won't be interfered. Sometimes partially-overlapped channels (1, 4, 7, 11)[2] could be used in case 3 isn't enough [24].

4.2 Spatial diversity

802.11n NICs (Network Interface Cards) exploit *spatial diversity* using MIMO (Multiple-Input Multiple-Output) systems with multiple antennas [17]. The aim is to combat fading and increase received signal strength and quality by combining the signals from local antennas received/transmitted at slightly different phases. Antenna diversity is especially effective at mitigating multipath situations common in urban and indoor environments. Although spatial diversity does not exactly mitigate interferences, it helps reduce those effects by improving the signal reliability at the cost of redundancy.

4.3 Back-off override

A powerful technique is to coordinate the APs in order to maximize the free-air time usage while minimizing interferences. Take for instance the exposed terminal problem discussed in section 3.5.3. In that case, it is perfectly fine for CL_2 to ignore the back-off. This is possible if the distances across APs and between clients are known. A controller can override the back-off if it is certain transmissions will not result in collisions. To be practical, this can only be done on the APs because the CSMA/CA needs to be modified. The requirement to change clients is not realistic unless the feature gets accepted in future standards.

[2] Europe allows channel usage from 1 through 13, so they could be further apart which in turn reduces interferences

5 Coordination

There are numerous resources involved in a wireless network. Some of those resources are discussed in this section together with techniques used to optimize them in order to improve performances.

5.1 Load distribution using cell breathing

A dense network of APs can be modelled as a multi-cell system model [29]. Each cell is represented as a hexagon with one AP in the center. Figure 5 is a network consisting of 6 cells. Note that a cell is defined by its size. The relation of the channel with regard to its neighbours are irrelevant. Depending on the number of clients associated with an AP in a cell, some cells may become congested. In order to improve the Quality of Service (QoS), the load could be distributed to neighbouring under-loaded cells.

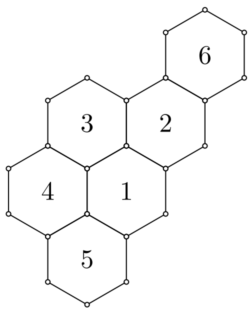

Figure 5: A multi-cell system

Bein et al [5] proposed some algorithms to vary the transmission radii of selective sensor nodes to lower the energy spent in broadcasting. The sensor nodes are analogue to the connected set of APs where load balancing can be applied. Brickley et al [8] proposed a cell breathing concept in cellular WLAN that performs active load balancing with the aim to improve QoS for real-time services. Two operations can be applied to a cell: expansion and contraction. In figure 6 two unbalanced cells (dashed lines) become balanced (dotted lines) by contraction (left arrow) and expansion (right arrow) of respectively α and β. During this procedure one client has swapped cell, the dashed line shows its previous association. Because the cell-sizes has changed, zero or more neighbours' cell sizes might also need to be adjusted to mitigate interference, this continues recursively until no cell has to be adjusted to restore coverage.
Note that cell breathing does more than forces clients to switch to a different cell. By contracting a cell, its interference zone also shrinks down. Recall from section 3.2.1 reassociation is initialized by the client, thus the order of cell-manipulation does matter: first expand *then* contract cells.

5.2 Optimal Coverage

The optimality of a coverage mainly depends on the cell-overlap percentage. Greater overlap can result in better handover because the client decide for itself when to swap base station. By increasing the cell size, clients could perceive better signal strength and negotiate higher data rate; thus increases overall throughput. However the interference zone also grows along. This is undesirable if adjacent cells are on the same channel.

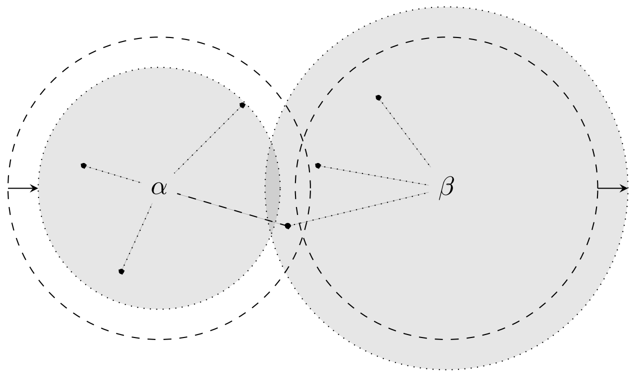

Figure 6: Load distribution between two cells by expanding β and contracting α, in that order

5.3 Online load distribution

It is crucial for the system to distribute load without service interruption. Some permissible parameters that may be changed transparently are:

- Transmit power: there are strings attached to modifying the transmit power of a particular radio. If the power were to be lowered, the coverage area shrinks which may result in connection loss for one or more clients. Section 5.1 describes how cell breathing should be applied effectively.
- Contention coordination: medium access fairness can be enforced and avoid resources starvation by managing available *free airtime*.

6 Proprietary solutions

There are numerous proprietary enterprise wireless solutions. This section sheds some light on those solutions from 6 most popular companies in this market. Most of the solutions provided by those companies consist of multiple components that make up an actual deployment. This is known as *vendor lock-in* because for instance hardware purchased at *company1* is probably not compatible with software sold by *company2* making the vendor switching economically uninteresting.

6.1 Meru Networks

Meru networks operate in one channel resulting in one large *Virtual Cell*[23] allowing seamless roaming while a client moves between physical access points. Uninterrupted roaming is possible because from the client's point of view, it is still associated to the old AP. This can be accomplished using a single channel deployment with virtual cells. Furthermore Air Traffic Control Technology and cellular-like coordination algorithms across cells are applied to mitigate co-channel interference.

6.1.1 Virtual Cells

Meru's *Air Traffic Control* architecture uses the *Virtual Cell* to eliminate co-channel interference by placing all APs on one channel span and letting the controller control a fully-coordinated and distributed architecture. All APs are placed in the same channel with the same BSSID, creating an illusion there is just one AP while in fact there are multiple. Such an approach can be advantageous because:

- Some decision makings are moved from the client to the controller like hand-offs. Because the controller is better informed about the network state, resources are utilized more efficiently.
- Seamless hand-offs, even applicable to legacy clients that do not support it.
- Effective load balancing is possible because the controller is free to choose the best AP to transmit to and receive from a client.
- Capacity can be increased with additional APs or a new network in a non-overlapping channel.

6.1.2 Intra- and inter-cell coordination

The *Air Traffic Control* architecture [22] is capable of coordinating all of the individual clients' data streams. Traffic coordination algorithms allow the Air Traffic Controlled AP to ensure independent service fidelity for each client accessing the network. Each AP is coordinated by *Airtime Fairness*, *Density Control* and *Quality of Service*. Airtime fairness prevents clients with low data rates from dominating the air. As a result airtime is evenly distributed among the clients. Density control ensures that overhead imposed by stations interfering each other in high density environments does not dominate the network. This problem is overcome by intelligently control each AP's channel access. Traffic is classified by type and prioritized. The Quality of delay sensitive services like video and audio can therefore be assigned higher priorities over others.

6.2 Aruba Networks

Aruba Networks delivers complete enterprise solutions consisting of controllers running the *ArubaOS* and Access Points in a mesh network. Remarkably, *Airwave 7*[3], a network management software used in the controllers is sold separately as a product or SaaS (Software as a Service) similar to Meraki (Section 6.5). Aruba APs support distributed and centralized traffic forwarding modes, and offer RF management through *Adaptive Radio Management* (ARM) technology.

6.2.1 Adaptive Radio Management

ARM[3, 4] ensures low-latency roaming, consistent high performance and maximum client compatibility in a multi-channel environment. Unlike single-channel architectures, Aruba's architecture is designed to squeeze maximum efficiency and performance out of all available RF spectrum, RF airtime to be allocated fairly, and co-channel interference to be avoided or mitigated. And it does so without compromising interference resistance, scalability, or interoperability – common problems of single-channel architectures.

- Adaptive Power and Channel Assignments: Automatically assigns channel and power settings for all APs in the network.
- Coordinated Access to a Single Channel: Allows nearby APs on the same channel to share spectrum without increasing co-channel interference; similar to Meru
- Channel Load Balancing: Ensures the even distribution of clients across available channels in a given area to avoid overloading a single channel or AP.
- Airtime Fairness: Provides equal access to the wireless medium for all clients, regardless of client type, capability or operating system.
- Airtime Performance Protection: Delivers uniform performance for all clients by preventing clients, especially slower ones, from monopolizing resources.

6.2.2 Airwave Management Platform

The *AirWave Management Platform* gives an accurate picture of everything that affects service quality for users – from wired infrastructure, to the RF environment, to controllers and access points. AMP communicates with and controls all of this infrastructure using standard protocols (SNMP, SSH, and so on) across a LAN or WAN. Some of its main features are:

- Real-time monitoring: devices connected to the network are automatically tracked with regard to their relations
- Automated configuration management: configure APs, controllers and edge switches.

6.3 Cisco Systems

Cisco Unified Wireless Network (Figure 7) is composed of *Aironet Access Points* connected to a *Wireless LAN Controller* with *Mobility Services Engine* into the management platform *Wireless Control System.* With the *Cisco CleanAir Technology* Cisco claims it can intelligently avoid the impacts of interference by detecting them while improving wireless performance. While *M-Drive* aims to improve signal quality by taking advantage of multiple antennas among other optimizations.

[3] http://www.airwave.com

Figure 7: Cisco Unified Wireless Network [9]

6.3.1 CleanAir

Cisco CleanAir technology[9] creates a spectrum-aware, self-healing and self-optimizing wireless network that mitigates the impact of wireless interference and offers performance protection for 802.11n networks. CleanAir has the ability to detect and classify RF interference, identify the source, locate it on a map and then automatically re-optimize the wireless coverage. The detection system can distinguish between Wifi and non-Wifi interference. Based on the classified severity of the interference, CleanAir may change channels to protect the performance.

6.3.2 M-Drive

Cisco M-Drive[11] technology helps the transition of business with existing 802.11a/g equipment to the 802.11n standard by providing a set of tools. Cisco M-Drive has the following major components:

- Cisco ClientLink[10]: higher performance for 802.11 a/g clients can be reached by processing three received signals (spatial diversity) into one reinforced signal using *Maximal Ratio Combining* (MRC). The adjustments calculated by MRC is used to optimize the reciprocal signal transmitted back to the client.
- Automated RF management: Establish channel plan and output power of each access point to optimize coverage and automatically re-adjusts them as physical conditions of the facility changes or coverage holes are observed.
- Consistent connections: Quality of service policies are applied on the type of traffic. Reliability is imposed by ensuring APs don't become oversubscribed.

6.4 Xirrus

Unlike many other manufacturers, Xirrus introduces multiple radios with directional antenna systems in a single device. Other features include automatic channel assignment, interference and load optimization of the RF environment. A key selling point in Xirrus' solution is each Array is composed of 4, 8, 12 or 16 radios which can operate in different channels independently[33]. Each radio equipped with a directional antenna allowing greater amount of sectors (Figure 8), minimizing co-channel interference. Also the amount of interference received from other directions are limited while receive sensitivity is improved and thus reduces packet errors. It essentially reduces multipath[4] issues. Furthermore Xirrus Arrays support Load balancing, auto cell, auto channel assignment, traffic shaping, broadcast & multicast control and station to station blocking.

[4]Multipath propagation occurs when an RF signal takes different paths when propagating from a source to a destination node

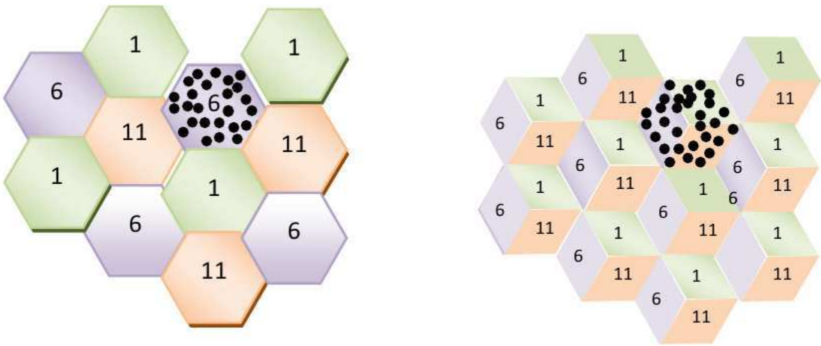

Figure 8: Single omni-directional and triple directional antennas per device [33]

6.4.1 Load balancing

The Xirrus Wi-Fi Array supports automatic Load Balancing to distribute Wi-Fi stations across multiple radios. In 802.11, it is the station that decides to which radio it will associate. The Array cannot actually force station association to a specific radio, however the Array can *encourage* stations to associate in a more uniform fashion across all of the radios of the Array. The Array decides if a particular radio is over utilized and should not allow any more associations. This decision process is based on a load-balancing algorithm that takes 3 key factors into account:

- Fewer stations on a radio is preferable
- The strength of the signal
- 5GHz channels preferred over 2.4GHz channels

6.4.2 Auto Cell

Auto Cell[32] is an automatic, self-tuning mechanism that balances cell size between Arrays to guarantee coverage. It uses communication between Arrays to dynamically set radio power so that complete coverage is provided to areas, yet at the minimum power level required. This helps to minimize potential interference with neighbouring networks. Arrays running Auto Cell automatically detect and compensate coverage gaps caused by system interruptions like radio failures. In such an event, only a subset of the directional antennas facing the failed Array is adjusted. As a result the coverage overlap can be kept under control more accurately. Several parameters can be defined including minimum cell size, scheduled RF assessment/adjustment and the ability to define coverage overlap percentage for roaming.
The Auto Cell process can be described as follow:

1. Every Array generates broadcast probes on all channels every 250msec at full power.
2. All Arrays respond to the probe at full power with:
   - Loudest Array in each channel including its MAC address, RSSI (Received Signal Strength Indicator) and TX power of the probe.
   - Maximum power setting of the radio.

  - Current power level setting of the radio.

3. Each Array keeps track of loudest responses by channel in a table (included in step 2). Using the gathered data the closest Array is determined by the highest RSSI.

4. Auto Cell tuning: For each response, if current Array occurs in the response calculate the *path loss* (also known as path attenuation, is reduction in power density of an electromagnetic wave as it propagates through space) and adjust TX/RX power settings based on the required coverage overlap.

5. Repeat on all Arrays at scheduled interval in both directions, possibly simultaneously.

6.4.3 Auto channel assignment

The automatic channel assignment system used in an Array optimizes the network for best overall performance. The tuning process may be executed manually or scheduled to respond dynamically to environmental changes. Radios in the same Array and between multiple Arrays are automatically set to different channels that have enough frequency spread between them so they do not interfere with each other.

In order to derive an optimal channel plan the external RF environment around the Array must be evaluated. During this process all radios on the Array tune to the same channel and listen for RF signals for a period of 250msec. Based on the perceived signals, a *signal score* is determined. The signal score is calculated based on signal strength of valid 802.11 and non-802.11 traffic, noise floor and SNR.

When the channel scanning procedure is completed, channel usage information is stored in a spectrum usage matrix. This matrix is compared to a predefined *Channel Allocation Map* containing potential channel configurations to optimize channel allocation.

As the scan is done passively, clients will not experience disruption in services. If Array radios must be reassigned to a new channel, associated stations are informed via 802.11h packets.

6.4.4 Other features

Xirrus also introduces higher-level improvements to their system. With *Traffic Shaping* traffic is classified and prioritized for delay sensitive applications. It also allows rate limiting on *User Group* where specific stations are forced to associate at a predefined rate. To minimize broadcast and multicast packets all traffic is routed through the wired network where ARP traffic is filtered and passed to a Proxy on the Arrays replying on behalf of the stations to which they are associated.

6.5 Meraki

In the Meraki architecture[21], there is only one hardware component: the multi-radio access points. All control, configuration, optimization, and mobility control is centralized in a *Cloud Controller* located in Meraki's data center. In case of local Internet connectivity issues, each network operates autonomously until connectivity is restored. Figure 9 illustrates the Meraki architecture and the arrow shows data traffic remains within the local network without bypassing the remote controller.

On start up a node labels itself as a *gateway device* if it has internet connectivity, otherwise it is a *repeater* to extend the mesh network. Nodes are loaded with a proprietary operating system called *MerakiOS* that handles routing decisions, RF channel planning and power management.

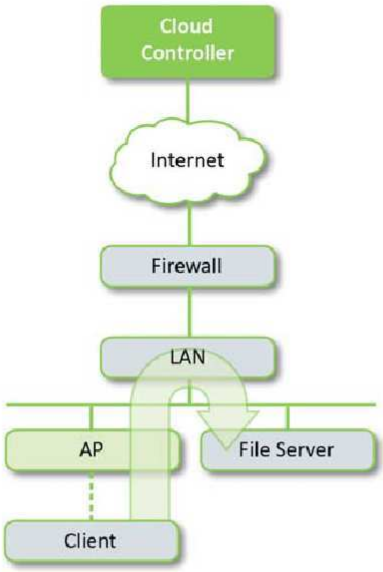

Figure 9: Overview of the Meraki architecture [21]

6.5.1 Multi-Radio Routing

Meraki routing protocols (SrcRR[2] and ExOR[7]) are designed to measure the data capacity of each link and determine the best routes for traffic through the network. By constantly measuring frame reception rates on all available links, across a wide range of modulations, Meraki's proprietary routing protocols are able to determine which paths deliver the highest throughput. These measurements also account for the many forms of interference or link failure seen in wireless networks, such as multi-path fading, link asymmetry from interference and environmental changes.

6.5.2 RF Planning

The Meraki Cloud Controller also provides built-in RF planning capabilities, which operate on a continuous basis to ensure access points avoid interference from nearby devices and maximize client throughput. Each Meraki AP reports statistics about channel utilization to the Cloud Controller, which then builds a global view of spectrum utilization. Networks automatically adapt to changing conditions in the spectrum by re-planning on a nightly basis when traffic is at a minimum, or on-demand through the online interface.

6.6 Aerohive

Aerohive Networks has developed an new class of wireless infrastructure called *Cooperative Control Access Point* (CC-AP) [1]; similar to the Internet architecture. This cooperative control functionality enables multiple HiveAP – an implementation of CC-AP – equipped with dual radios (2.4 GHz and 5GHz) to be organized into groups called *Hives*. A HiveAP has the *Portal* role if it is directly connected to the wired LAN via Ethernet that provides default MAC routes within the Hive. Otherwise it is a *Mesh Point* where one of the radios is used to associate with another HiveAP as data and control link. Multiple portals can be installed to improve network performance and availability. See figure 10 for a graphical representation of the devices.

Control information is shared among neighbouring HiveAPs enabling functions like coordinated radio channel, power management, native mesh networking and secure/fast layer 2/3 roaming. In the following subsections three cooperative control protocols are outlined covering aforementioned functions.

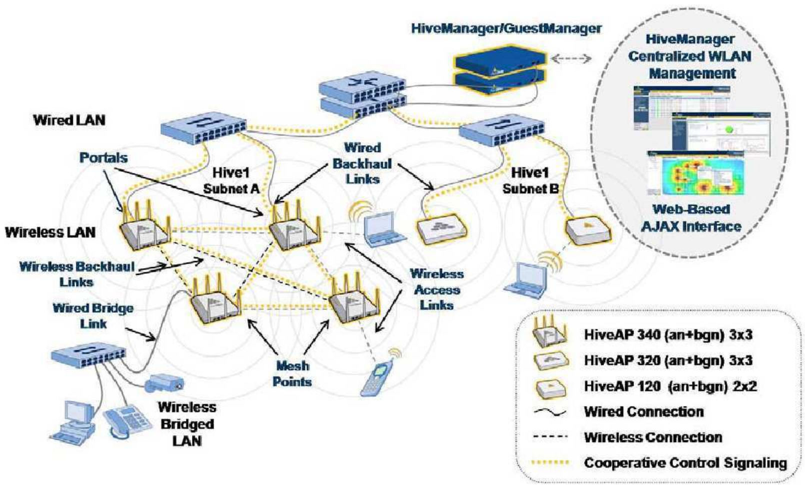

Figure 10: Overview of the Aerohive components[1]

6.6.1 Aerohive Mobility Routing Protocol (AMRP)

AMRP enables HiveAPs to perform automatic neighbor discovery, MAC-layer best-path forwarding through a wireless mesh (Figure 11) and seamless roaming between HiveAPs (Figure 12). Deployment of HiveAPs is simplified by enabling them to automatically discover one another over both wired and wireless. Whether connected via the wired LAN or wireless mesh, HiveAPs cooperate with each other using AMRP to predictively exchange client authentication state, identity information, and encryption key information with neighbouring HiveAPs, allowing clients to perform fast/secure layer 2 roaming. HiveAPs can make decisions to offload stations from one radio to another within the same HiveAP or adjacent HiveAP. The load is determined by:

1. Overall load of the system, e.g. traffic being processed locally
2. Load in a specific area on a specific channel

3. Total attached stations
4. Signal quality of attached stations

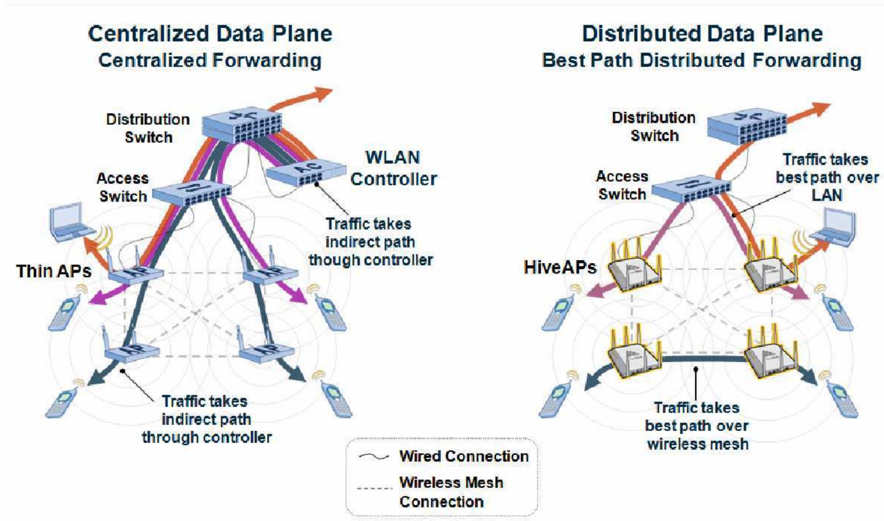

Figure 11: Centralized and distributed data forwarding[1]

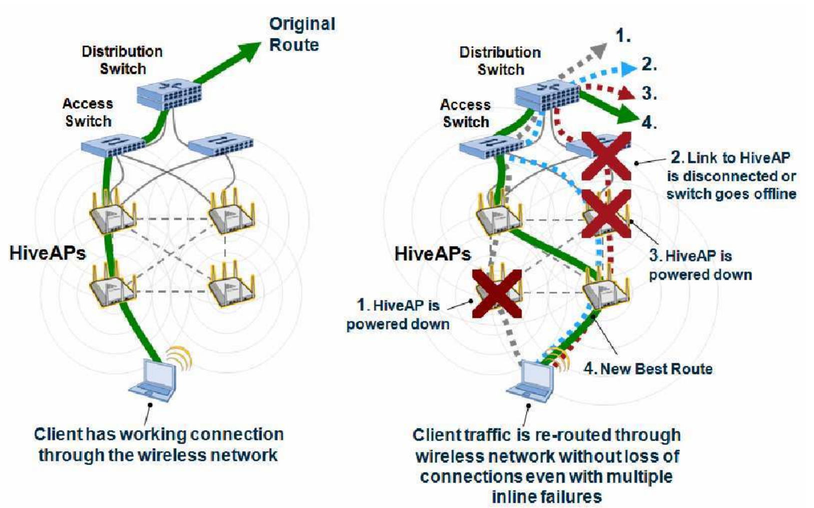

Figure 12: Automatic re-routing[1]

6.6.2 Dynamic Network Extension Protocol (DNXP)

DNXP allows users to maintain their IP settings and network connections while roaming across subnets throughout a WLAN. Layer 3 tunnels between HiveAPs in different subnets are created dynamically. Based on a configurable idle time or number of packets per minute, HiveAPs can be set to disassociate these wireless clients so that they can reconnect and receive an IP address in their new subnet allowing traffic to be locally forwarded.

6.6.3 Aerohive Channel Selection Protocol (ACSP)

The RF environment on each channel is analysed in conjunction with each other to determine the best channel and power settings for wireless access and mesh. ACSP minimizes co-channel and adjacent channel interference. HiveAPs use ACSP to scan channels and to build tables of discovered wireless devices. Additional RF information such as channel utilization and retry counters are used to identify and classify interference types and sources. This state information is distributed among the HiveAPs. ACSP will select a channel and power level to maximize coverage while minimizing interference with its neighbors. Neighboring APs are constantly monitored for availability. In the event of a failure neighbouring APs automatically adjust their power to the optimum state. Recalibration of the radio channels can also be scheduled.

7 Open source solutions

Unlike proprietary solutions there is currently no feature complete open source solutions. There are however projects focussed at components that enables the creation of wireless networks. In this section, some of those projects are listed together with brief overview of their features.

7.1 OpenCAPWAP

Aruba Networks is quite a prominent contributor to the CAPWAP protocol. Aruba Labs supported the openCAPWAP [6] project, an open source implementation of CAPWAP with *local MAC mode* proposed by Bernaschi et al. They concluded their implementation can be used effectively in real world scenarios. As pointed out by Bernaschi et al, openCAPWAP can be used as a basic platform to test efficient algorithms for control applications on the AC and smart methods of estimating wireless state.

7.2 Hostapd

Hostapd is an user space daemon for access points. It creates the possibility to turn any device running BSD or Linux with a supported wireless card into an AP. Together with small inexpensive embedded devices it is possible to deploy large networks. There are three versions:

- *Jouni Malinen's hostapd*[5]implements the IEEE 802.11 access point management and other high level features such as RADIUS authentication. It is supported on Linux, FreeBSD and DragonFlyBSD.
- *OpenBSD's hostapd*[6] helps improve roaming and monitoring on OpenBSD wireless networks. It implements the *Inter Access Point Protocol* (IAPP) for exchange station association information between access points.
- *Devicescape's hostapd*[7], also known as *Open Wireless Linux* (OWL) hostapd is still in its early stage.

7.3 WRT54G

The *WRT54G* consumer wireless router released by Linksys (Acquired by Cisco in March 2003) in 2003 is probably the most popular hobby router among tweakers around the world. Because the original firmware used Linux components, Linksys was forced to release the source code with the *GNU Public License* (GPL) [31].
Developers could study the source code and soon after derivations of the original firmware surfaced on the internet. Among them the most popular ones are *DD-WRT* and *OpenWrt*. They are both full fledge router Operating Systems equipped with a wide variety of features comparable enterprise products. Their successes are also evident as they are being used by other projects like *Freifunk*[8] and *Coova*[9].
Tomato is also quite popular. It is based on *HyperWRT*. The notable features are its AJAX based web interface and graphical bandwidth monitor. *X-Wrt*[10] also targets end users with improved interface based on OpenWrt.

[5]http://hostap.epitest.fi/hostapd/
[6]http://www.openbsd.org/cgi-bin/man.cgi?query=hostapd
[7]https://devicescape.org/projects/hostapd/
[8]http://www.freifunk.net
[9]http://wwww.coova.org
[10]http://www.x-wrt.org

8 Comparison & Discussion

	Meru	*Aruba*	*Cisco*	*Xirrus*	*Meraki*	*Aerohive*
Architecture	Virtual Cells, Controller-APs	Mesh, Controller(also SaaS)-APs, distributed& centralized	Controller-APs	Arrays, Mesh	Cloud controller-APs	Mesh: Portals and Mesh points (based on Internet)
Interference Mitigation	Density control, Virtual Cell	ARM: power settings, channel assignment, coordinated access to single channel	CleanAir: detect and classify RF interferences, M-Drive: power settings, spatial diversity	increased coverage segmentation, channel assignment	spectrum analysis, replanning	ACSP: power settings, channel assignment
Channel Assignment	single	multi	multi	multi	multi	multi
Roaming/ Hand-off	seamless	yes	-	yes	-	yes
Airtime management	Airtime fairness, QoS	Airtime fairness	QoS	QoS (traffic shaping)	-	-
Recurring optimization	yes	-	yes	Auto Cell, Auto channel assignment	scheduled replanning	yes
Load balancing	Density control	yes	QoS	yes	-	-
Vendor lock-in	yes	yes (Airwave 7)	yes	yes	yes	yes

Table 2: Comparison of commercial wireless enterprise solutions

Table 2 shows the comparison of the different enterprise solutions between the different companies listed in section 6. The dash (-) indicates their was no clear evidence found in the sources (references). Otherwise a short summary is given where possible for each category listed on the left.
As stated in section 7, currently there is no comparable open source alternatives. Hence this comparison does not include any.

8.1 Architecture

Perhaps the most notable property of those solutions is the wide variety of architecture types. It is extremely hard to argue which is best. First they are all designed to scale. Second the mesh architecture is more superior than its counterparts if wired connection between APs are expensive and if the majority of the network traffic are local. That is because centralized traffic processing can become a bottleneck. A great advantage of the *Virtual Cell* approach is that legacy clients are supported to roam across the network. Xirrus with its Arrays is very suitable for high density deployments. The arrays are more than multiple APs because each radio is equipped with directional antennas. This makes the system very flexible and efficient in recovering from failed nodes as the coverage area of an Array is not of circular form any more. Recently the Arrays have proven to be successful at Microsoft events [25].

8.2 Interference Mitigation & Channel Assignment

In multi-channel networks the most common techniques to mitigate co-channel interferences is intelligently assign channels with proper power management. Cisco and Meraki try to improve interference detection by incorporating spectrum analyzers. Such an addition is crucial in dynamic environments with high interference chances. It is useful to detect rogue clients and other non-IEEE 802.11 devices. This information can be fed to the optimizer to aid interference prediction and thus resulting in more optimal decisions.

Meru's *Virtual Cell* and Aruba's *ARM* support single channel with a coordination layer. This implies a centralized architecture where control over the APs are handled by a controller. In terms a scalability such a system should be able to support hierarchies of controllers to distribute the load.

8.3 Roaming/Hand-off

Roaming has become a requirement in corporate environments as users tend to move around quite often. Although from Table 2 it is not entirely clear that all solutions support roaming it is safe to assume they do. There are different ways to support roaming capability.

Seamless roaming is the capability for a client to switch between physical AP without noticeable transmission interruption. In the case of *Virtual Cell*, associated clients are unaware of the underlaying network structure. This abstraction moves the complexity of hand-offs from the interaction between client and AP to the controller. Other more common roaming method is to let the client decide for itself. Then it must be able to distinguish between APs and in most cases it tries to connect to the terminal with the strongest signal.

8.4 Airtime management

Most solutions have some sort of QoS support. Traffic shaping is mostly applied to prioritize delay sensitive applications like voice-over-IP. Such policy is acceptable in most cases because not all applications require low latency access. For example peer-to-peer traffic is often classified as very low priority.

As all stations compete for medium access on a single AP together with the different bit-rates, slower clients can dominate usable airtime. Therefore, Meru and Aruba apply low level coordination on medium access by regulating airtime. This way all clients get their fair share of resources. It is quite remarkable only a few supports this.

8.5 Recurring optimization & Load balancing

Wireless environments are extremely dynamic. RF interferences can come and go or vice versa. Other problems like failing AP also affects the network coverage. So a good system should be able to adapt itself to those changes. There are two ways to do it:

- *Scheduled* – Depending on the severity of the change, sometimes the network may become unusable. Therefore such a transition needs to be planned.
- *Online* – Other less drastic changes like load balancing using passive cell-breathing can be done on-line. Effectively, any change in the network that could lead to better performance or reliability without introducing service interruptions.

All solutions support one form and/or the other except Aruba. Evidence was found they do load balancing. So they *might* also do recurring optimizations, otherwise it doesn't make sense to load balance, say, once a day.

8.6 Vendor lock-in

All solutions are suspect to vendor lock-ins. It is understandable it is not very feasible or economically interesting to support third party hardware from the vendors point of view. However once the customer chooses one vendor it is almost impossible to reuse the same equipments with a different vendor. At least the Airwave 7 management software by Aruba can be used in conjunction with other popular products from vendors like Cisco.

9 Conclusions

Wireless access is becoming increasingly important in modern world. Large-scale networks are very common in corporate environments nowadays. In this document the basic principles of wireless networks were discussed together with a comparison of 6 popular commercial enterprise solutions. The open source community is not very active in that regard. However there are promising projects when combined with standards like IAPP and CAPWAP could aid in producing a competitive open source alternative.

The choice of an architecture greatly influences scalability and reliability. A good system should not fall apart when any component directly related to the wireless network fails. This can be realized with a distributed mesh network of Access Points together with one or more independent controllers. Independent such that when controllers are unavailable, services delivered by the APs are not interrupted. Stronger yet, when a component fails, say an Access Point, the system should take immediate action to relief the impact on accessibility of the network by readjusting the cell sizes. A well designed system should support the capability to expand an operational network without disruptions. It is also possible to comply with those requirements with a centralized system by adding redundancy.

In dense environments *Airtime* must be managed carefully to avoid starvation yet respect *QoS* rules. Some proprietary solutions introduce multiple radios with directional antenna which increase coverage segmentation. This will however increase the cost.
Co-channel interference is very likely to occur and therefore should be mitigated. This is best done with a multi-channel cellular system as all permissible resources can be used. Single channel is only interesting if local policies require it.
Finally it is crucial for the system to do periodic health checks, recovery and optimizations. Those can be done with proper airtime management, load balancing and channel replanning.

In conclusion, wireless connectivity has become part of our daily lives. It becomes a real challenge to deploy and manage reliable and robust wireless networks. In dense environments like conferences, co-channel interferences is the greatest threat in degrading network performance. There is a wide range of enterprise solutions to deploy large scale wireless networks. However there is no open source alternative that can be considered to be a competitor.

10 Future research

- Fundamental MAC problems like *Hidden Terminal* are solved in the IEEE 802.11 standard. But the impact of *Exposed Terminal* could still be reduced or rather exploited with proper coordination scheme.
- Even though a standard like CAPWAP exists, vendors still use their proprietary solutions. That is probably because of the late introduction of CAPWAP. Also vendors try to stand out from the crowd by promoting their own methods. Such act can also be seen as *vendor lock-in* which obstructs interoperability and innovation. In short, why exactly are vendors avoiding CAPWAP?
- Currently there is no viable open source enterprise wireless alternatives. openCAPWAP has been discontinued but it can used as a base for a new framework to do experiments on interference mitigation theories, coordination schemes and even routing. From there full-fledged solutions could be derived.

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Some figures used in this document were taken from referenced scientific publications and white papers. They are property of their respective owners.

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