



Wi-Fi Capacity Analysis for 802.11ac and 802.11n: Theory & Practice

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Introduction – Why capacity matters with Wi-Fi

Just a few years ago, enterprise Wi-Fi networks were planned with coverage and perhaps interference in mind. The number of wireless devices and the amount of transmitted data was small and users could tolerate an imperfect Wi-Fi network. Today, 802.11 networks should be designed primarily for capacity. The key drivers of improved network capacity and reliability are:

- More devices are joining the network
- End users and business-critical applications rely on a Wi-Fi network that works 24/7
- The amount of data transmitted wirelessly has significantly increased thanks to:
 - Voice calls made over Wi-Fi
 - HD video streaming over Wi-Fi
 - File access and storage in the cloud
- Thanks to the Bring Your Own Device (BYOD) trend, personal devices are allowed on enterprise networks

When modeling the capacity of a single Access Point (AP) and client, the capacity limits of each transmission technology are well known. Unfortunately, it is not a one-AP, single client world. As a Wi-Fi network engineer, managing multiple access points on different floors serving different types of client devices from different generations running various applications, is a reality. Network management becomes incredibly complex unless administrators have the right tools and some basic Wi-Fi knowledge.

There are two scenarios in which the estimation of network capacity is important:

- **When designing a completely new network**, it is beneficial to evaluate the coverage and capacity of the network without actually installing it. Installing either too few or too many APs will lower the capacity of the network. Too few APs will cause low signal strengths and adversely impact data rates whereas too many APs will result in interference.

- **Capacity estimates can be useful when assessing installed networks as well.** However, measuring network capacity can be very difficult in practice. This is because all normal network usage causes interference which skews measurements and a complete analysis would require controlling all the traffic in the network, which is practically impossible in large networks. However, advanced tools such as Ekahau Site Survey™ (ESS) allow quick and comprehensive analysis of network capacity and even simulation of various traffic loads.

The rest of this whitepaper is organized as follows:

1. **Understanding capacity:** An overview to the operation of IEEE 802.11 Wireless Local Area Network (WLAN) [1] and how capacity can be estimated in 802.11 Wi-Fi networks. Understanding network operations is crucial for understanding how ESS estimates the capacity of the network.
2. **How Wi-Fi capacity can be seen and optimized:** A high level overview to the Ekahau Site Survey tool that allows you to design and maintain enterprise Wi-Fi networks.

Part 1: Modeling the IEEE 802.11 WLAN Capacity

The IEEE 802.11 WLAN consists of a set of APs and clients as presented in Figure 1. Each AP and the clients associated to it form a Basic Service Set (BSS). Multiple BSS can be connected via a Distribution System (DS) and usually they are connected to the Internet [1].

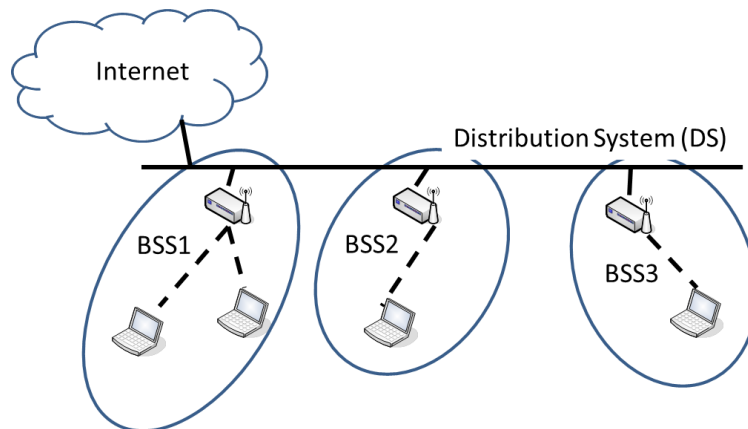


Figure 1 Topology of an IEEE 802.11 Wireless Local Area Network

The modern IEEE 802.11 WLANs operate in the 2.4 GHz and 5 GHz frequency bands. The basic channel is 20 MHz wide but 802.11n and 802.11ac allow usage of wider channels by bonding several channels together. The number of available 20 MHz channels in the 2.4 GHz and 5 GHz frequency bands are 11-13 and 19-25 respectively, depending on the regulatory domain. All devices that are within the transmission range and share the same, or overlapping, channel also share the channel transmission capacity.

IEEE 802.11 specifies operations in two layers of the Open Systems Interconnection (OSI) model, namely in the data-link and physical layers as presented in Figure 2. The data-link layer contains the Medium Access Control (MAC) protocol, which is responsible for controlling transmissions in the BSS. The physical layer is responsible for modulating and transmitting data. Each transmitted data packet goes through each layer and is encapsulated with the layer specific framing. Finally the corresponding layer in the receiver decodes the frame. The framing in each layer is needed for the operation of the layer but this overhead decreases the effective capacity of the network.

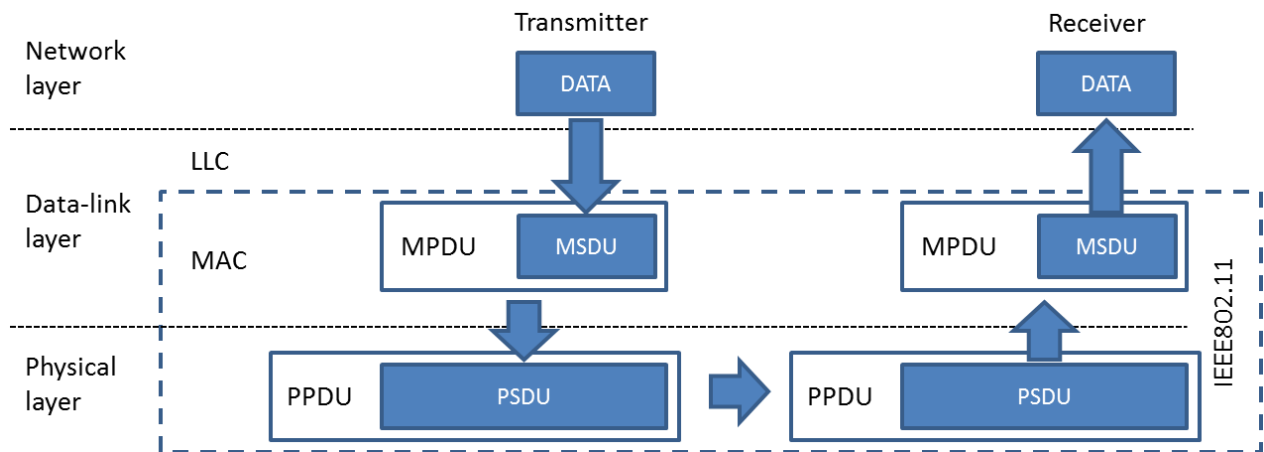


Figure 2. Simplified view of OSI model and packet encapsulation.

IEEE 802.11 MAC operation

The 802.11 MAC protocol uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) method [1] illustrated in Figure 3. The basic principle in channel access is that before sending, each station must listen to the channel and send only when the channel is sensed free. Detection of collisions is difficult in a wireless environment and the following additional method is used to avoid collisions. When the channel is sensed as 'free' and available, first the station waits for the duration of an InterFrame Space (IFS). The time between the IFS and the next transmitted frame is called a contention window, which is divided into transmission slots. After the IFS period has passed, the station starts a backoff counter. The initial value for this counter is selected randomly between zero and contention window minus one slots. When the counter reaches zero and the channel is still idle, the station starts transmitting. If another station starts to transmit before that the counter is stopped and the counting continues when the channel has been idle again for longer than the IFS. When the counter reaches zero, the transmission can start.

In the MAC layer the transmitted data packet is called a MAC Protocol Data Unit (MPDU). It starts with the MAC header followed by a MAC Service Data Unit (MSDU), which is the actual payload data of the packet. The payload is followed by a Frame Check Sequence (FCS), which is used for detecting transmission errors in the packet. Each correctly transmitted packet is acknowledged with an ACK packet

and retransmitted if no ACK packet is received. Each transmitted MAC layer packet is wrapped inside a physical layer packet.

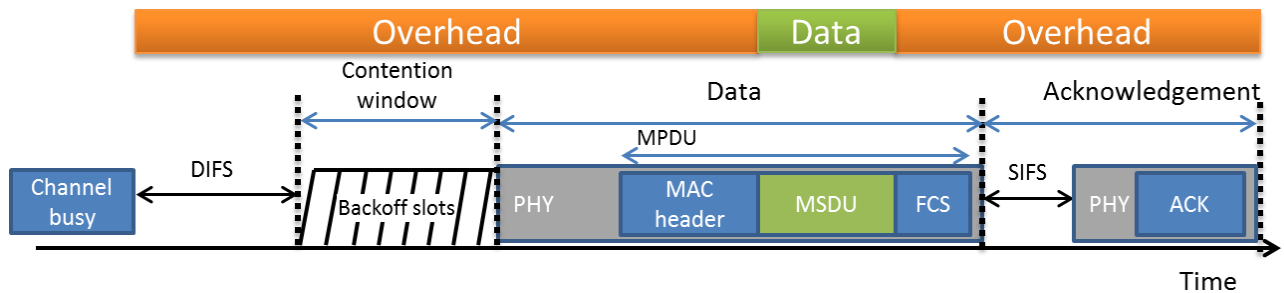


Figure 3 CSMA/CA access cycle

Several additional methods are used to avoid collisions. These are a dynamically changing contention window, as well as Request to Send (RTS), Clear to Send (CTS) packets [2]. RTS and CTS packets are omitted from the figure for simplicity.

The channel access method described above enables controlled usage of the transmission channel simultaneously by several stations. However, as shown in the figure, it also requires a considerable overhead before each sent frame and this causes problems, especially with high loads and small packet sizes [3]. Distributed channel access also makes capacity estimation very difficult.

Packet aggregation was introduced with 802.11n to reduce overhead in the MAC layer [4]. It allows transmission of several network layer packets in a single MAC layer packet. Packet aggregation increases packet delay because the transmitter must wait until all packets are collected before a MAC frame can be transmitted. Thus, the method has its limits with delay sensitive applications, such as voice and video.

IEEE 802.11 Physical Layer

The IEEE 802.11 standard defines several physical layers. The latest new physical layer is called VHT (Very High Throughput) and it is defined in the IEEE 802.11ac standard amendment [5]. The support of VHT Physical layer was introduced to ESS in version 6.0. The physical layer packet starts with a preamble, which is different for each physical layer. The preamble is needed to synchronize transmission and control physical layer operation. Figure 4 shows examples of the physical layer frame formats for High Rate / Direct Sequence Spread Spectrum (HR/DSSS) defined in 802.11b, High Throughput (HT) mixed format defined in 802.11n and VHT format defined in 802.11ac. As can be seen in the picture, the overhead required in the preamble has decreased from 192 μ s to a minimum of 40 μ s.

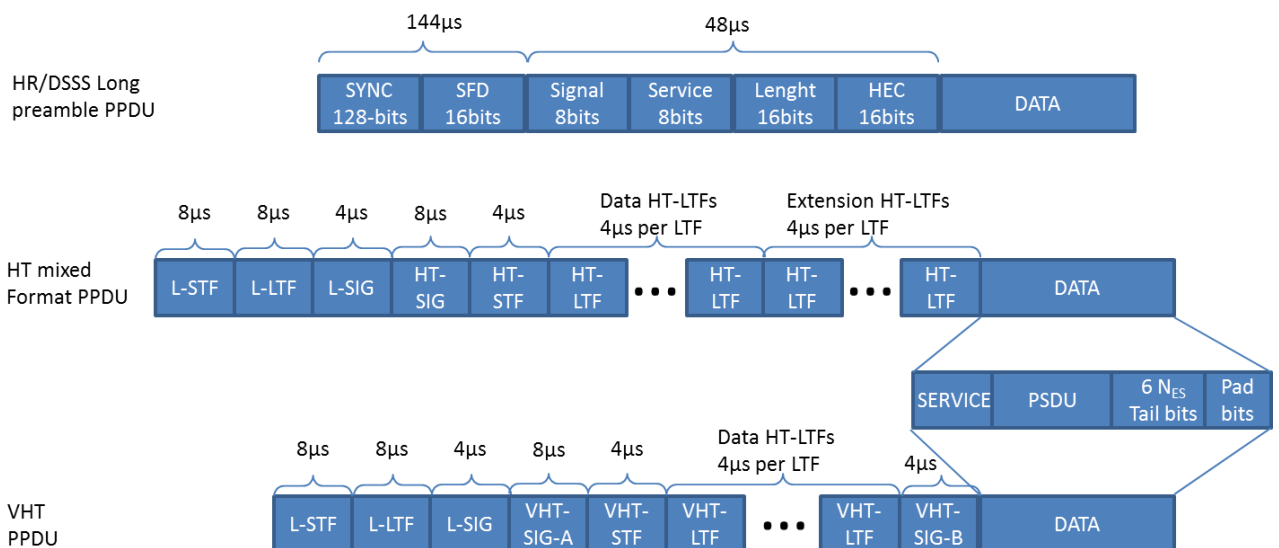


Figure 4. Example physical layer frame formats with 802.11b, n and ac.

After the physical layer preamble, the data itself is transmitted using a selected Modulation and Coding Scheme (MCS). Each physical layer defines a set of possible MCSs depending on the quality of the signal between the transmitter and receiver. The MCSs differ on the amount of error coding and density of data. This makes different MCSs suitable for different signal conditions.

In the latest physical layers (802.11n and 802.11ac), data is transmitted using several possible channel bandwidths. The normal channel bandwidth in 802.11 WLANs is 20 MHz, whereas the 802.11n supports a 40 MHz bandwidth and the

802.11ac can utilize also 80 MHz and 160 MHz bandwidths. This allows transmission of much more data during the same time period. The 802.11n and 802.11ac also support spatial multiplexing by using several antennas to transmit multiple streams between the transmitter and receiver simultaneously. This technology is called Multiple-Input and Multiple-Output (MIMO). If interference conditions allow, the efficiency can be increased by reducing the guard interval between the symbols from 800 ns to 400 ns. Using the short guard interval, the symbol length becomes 3.6 μ s. These parameters are presented in Figure 5, which provides a simple equation to calculate the physical layer data rate. As can be seen, the physical layer data rate may differ significantly based on the properties of the AP and the client device as well as the signal conditions.

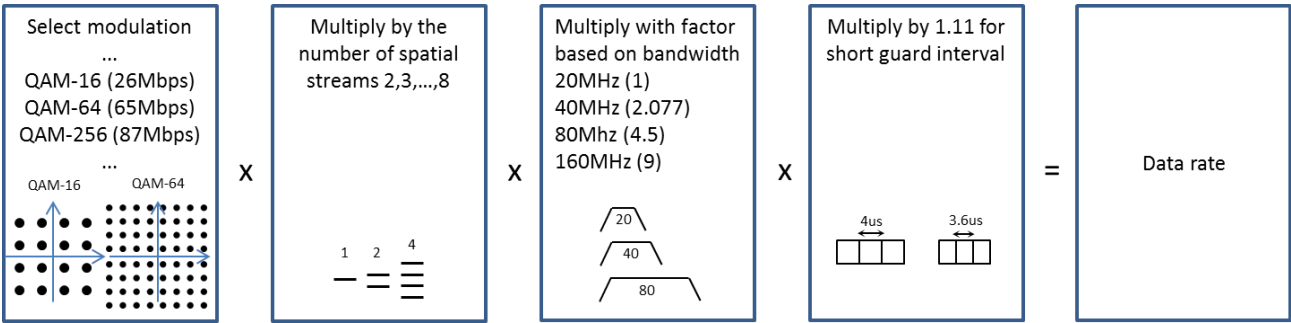


Figure 5. Key parameters of determining the IEEE 802.11 data rate.

How to estimate 802.11 capacity

The transmission time of an end user packet can be calculated based on the factors described in the previous sections. For IEEE 802.11ac, the standard amendment [5] provides equation 1 for the purpose, which is further described in the following section. When the transmission time of the signal packet is known, the channel utilization of a data stream can be calculated based on packet transmission time and packet rate. Although this may sound simple, there are still several key parameters that must be estimated by ESS:

- Packet error rate
- Number of streams
- Channel bandwidth
- Additional overhead caused from multiple clients sharing the same channel
- The amount of background traffic caused, for example, by beacons, probes and management applications

Example

This section presents an example of the VHT physical layer transmission time calculation with a full HD video stream application. The application is assumed to have a 1000 byte packet size and a 10 Mbps transmission rate. Equations 1-4 can be used to calculate the transmission time of a single data packet. The equations and the included variables are described in detail in the 802.11ac standard amendment chapter 22.4.3 [5].

$$T_{XTIME} = T_{LEG_PREMABLE} + T_{L-SIG} + T_{VHT-SIG-A} + T_{VHT_PREMABLE} + T_{VHT-SIG-B} + T_{SYML} \times \left[\frac{T_{SYMS} \times N_{SYM}}{T_{SYML}} \right] \quad (1)$$

$$T_{LEG_PREMABLE} = T_{L_STF} + T_{L_LTF} \quad (2)$$

$$T_{VHT_PREMABLE} = T_{VHT_STF} + N_{VHTLTF} \times T_{VHT-LTF} \quad (3)$$

$$N_{SYM} = m_{STBC} \times \left\lceil \frac{8 \times DATA_LENGTH + N_{SERVICE} + N_{tail} \times N_{ES}}{m_{STBC} \times N_{DBPS}} \right\rceil \quad (4)$$

First, the number of symbols (N_{SYM}) needed to transmit the packet is calculated using equation 4. The equation has the significant parameter N_{DBPS} , which defines the number of data bits per symbol that are encoded with the selected modulation and channel bandwidth. For example with a QAM-64 modulation, 5/6 coding rate, 40 MHz bandwidth and 2 spatial streams the standard defines that N_{DBPS} is 1080. When a MAC frame is added to the data packet, the $DATA_LENGTH$ is 1034 bytes. Assuming that a Space-Time Block Code (STBC) is not used, the equation becomes

$$N_{SYM} = 1 \times \left\lceil \frac{8 \times 1034 + 16 + 6 \times 1}{1 \times 1080} \right\rceil = 8.$$

When a short guard interval is used, the transmission time can be calculated using equation 1. Consequently, in the physical layer, the transmission of a single 1000 byte packet takes

$$T_{XTIME} = 8\mu s + 8\mu s + 4\mu s + 8\mu s + 4\mu s + 2 \times 4\mu s + 4\mu s + 4\mu s \times \left[\frac{3.6\mu s \times 8}{4\mu s} \right] = 76\mu s$$

Similarly, the transmission of the 14 byte MAC layer ACK frame takes 48 μs . Most of the transmission time is consumed by the overhead, which causes that the transmission of the ACK packet takes almost the same time as the transmission of

the data packet. When we add the MAC layer overhead including DIFS, estimated backoff time, and SIFS, the transmission time of a single packet increases to approximately 200 μs, depending on the active contention window.

With a 10 Mbps rate, the application must send 1250 packets during one second. This is further increased to 1375 packets/s by assuming that 10 % of the packets are retransmitted on the MAC layer, which is not uncommon. Based on the single packet transmission time and the amount of packets transmitted, the channel utilization caused by the single HD video stream in the example is 27.5 %. High level presentation how the transmission time is consumed is presented in Figure 6 a).

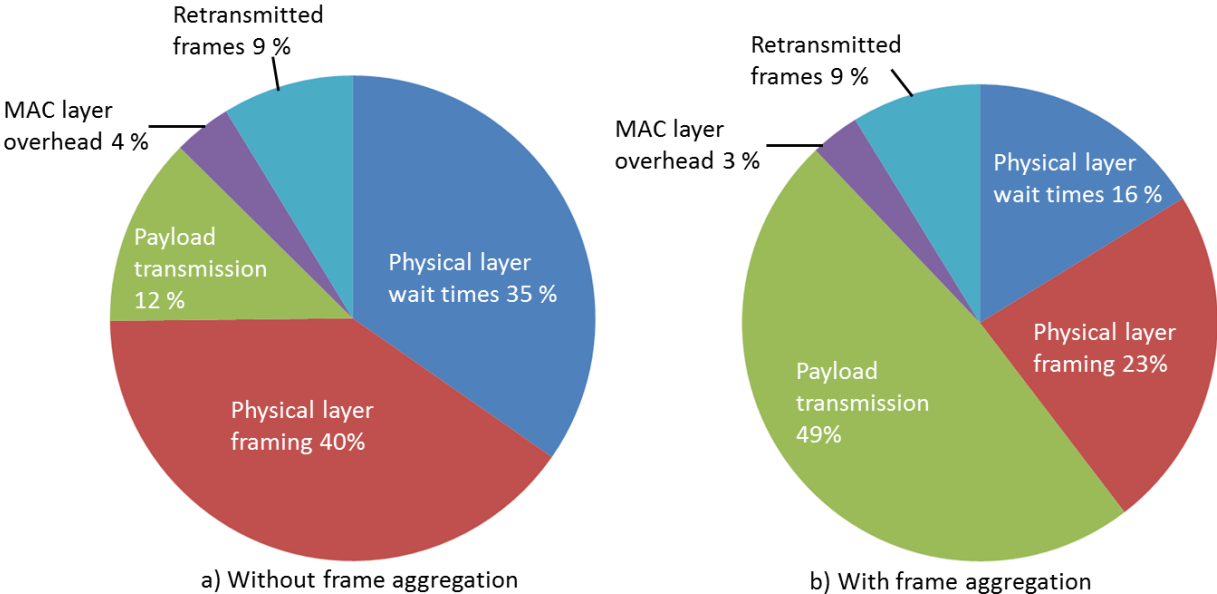


Figure 6. Transmission time distribution in the example.

MAC efficiency can be calculated by first calculating the theoretical maximum end-user throughput (with 100 % channel utilization) and then dividing the maximum throughput by the physical layer data rate as presented in [6]. In the example, the 10 Mbps throughput caused 27.5 % channel utilization so the maximum throughput is $10 \text{ Mbps} / 0.275 = 36 \text{ Mbps}$. The physical layer rate is defined in the standard for the selected modulation and coding rate. In the example, the rate is 300 Mbps. Consequently, the efficiency is only 12 %, which is mainly caused by the lack of frame aggregation. The efficiency of 802.11ac MAC depends heavily on how many packets can be aggregated into a single frame in order to limit transmission

overheads. To compare efficiency with frame-aggregation, the Figure 6 b) shows transmission time distribution when 10 packets are aggregated into a single frame using A-MPDU mechanism. This increases MAC efficiency to 49 %. Selecting right number of packets aggregated into single frame is a key parameter in capacity estimation because with latency sensitive applications such as voice and video, aggregating a large number of packets may cause unacceptable delay.

Part 2: Capacity Analysis in Ekahau Site Survey

Ekahau Site Survey (ESS) displays capacity metrics on the floor plan as visualizations. The ESS capacity visualizations are based on detailed modeling of capacity related parameters. Capacity modeling can be divided into three distinct layers as shown in Figure 7. These are the network modeling layer, the capacity estimation layer and the presentation layer.

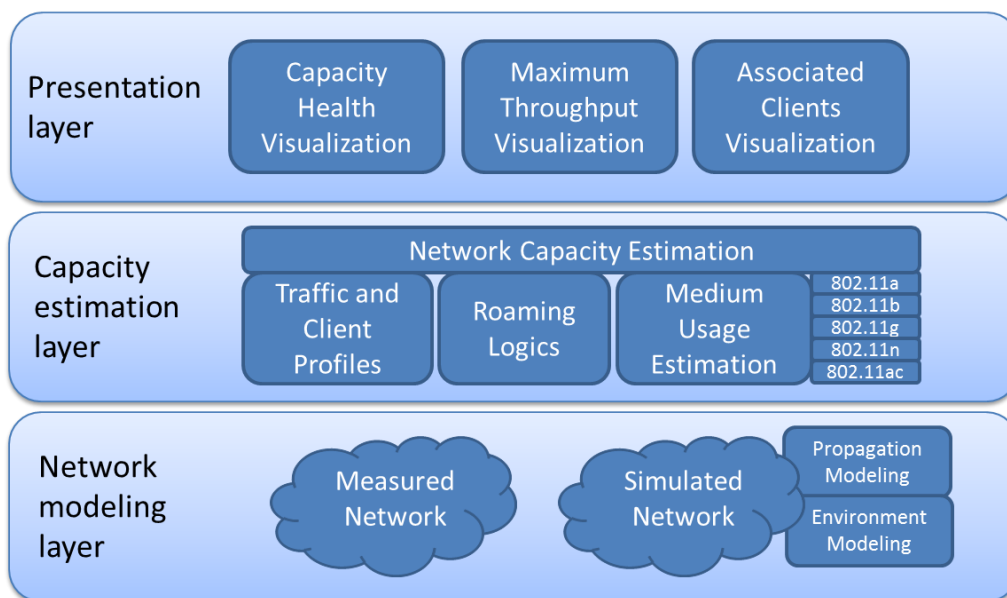


Figure 7. Capacity modeling layers in Ekahau Site Survey

The network modeling layer

For measured networks, the key information for capacity modeling is taken from beacons, probe responses and their information elements. This includes operational parameters such as utilized channels, channel bandwidths, and the number of utilized streams.

For simulated networks, ESS models the WLAN capacity starting from a detailed definition of APs, and the 3D environment. AP antennas as well as buildings, floors and walls are modeled in 3D. Together, this allows a detailed estimation of the client signal in different locations in the network using commonly available signal

propagation models. Based on this configuration, ESS also estimates the client interference based on 3D signal propagation modeling. Interference estimation can also be done for measured networks when noise information is not available from the utilized WLAN network interface card.

The capacity estimation layer

Client devices and client applications are modeled similarly for both simulated and measured networks. The differences between various client devices are modeled by allowing the user to select his own devices, including laptops, tablets, and mobile phones from different vendors. Figure 8 shows how devices joining to the network can be configured.

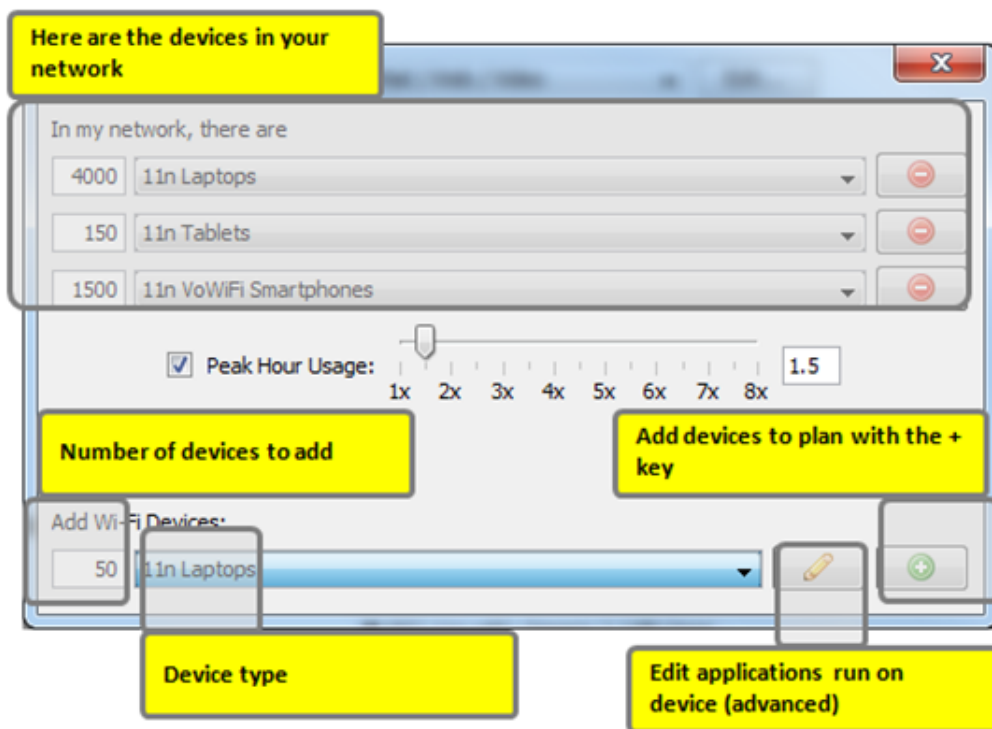


Figure 8. Configuring devices that will be joining to network

The set of client devices in the network can be configured by the user and each application is configured in detail by specifying packet types, lengths, packet transmission rates and protocols as shown in Figure 9. This allows detailed modeling of different applications including voice and video streams. Interactive applications such as voice and video are sensitive to transmission delay. The maximum possible delay within each packet type is taken into account based on the configured access category (IEEE 802.11e). This has an effect on how many packets are aggregated into a single MAC layer packet.

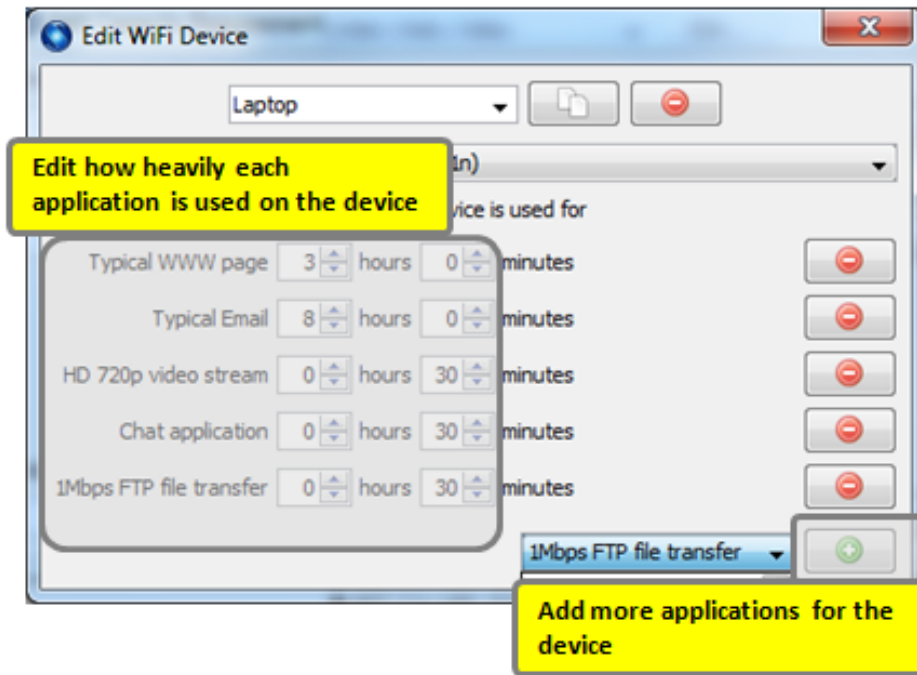


Figure 9. Configuring how the average user behaves will improve the capacity estimation accuracy

Data rates are calculated based on client device configurations and received signal strengths and the Signal-to-Noise Ratios (SNR). The capacity of the network is modeled based on selected client devices and their applications. For each packet stream on the network, ESS calculates transmission time estimates based on the specifications in the IEEE 802.11 standard. This includes modeling of the 802.11 MAC protocol packet transmission process as well as timings and modulations used in physical layers. Channel usage of the network is modeled based on CSMA/CA method [1] used in IEEE 802.11 together with roaming logics, which select APs each client device associates to. As a result, the algorithm gives the channel usage estimates for each AP in the network.

The presentation layer

The capacity health visualization presented in Figure 10 shows the user if the capacity requirement caused by client configurations are fulfilled in the network. The capacity requirement is fulfilled when channel usage in the network is below 100% for all APs. The algorithm also takes into account that part of the capacity is consumed by network management applications including WLAN beacons, probes,

association requests and so on. The number of associated clients for each AP as well as the number of each type of application is also compared to configured limits. This allows modeling of situations where too many client devices are associated with a single AP although the data transmission would be minimal.

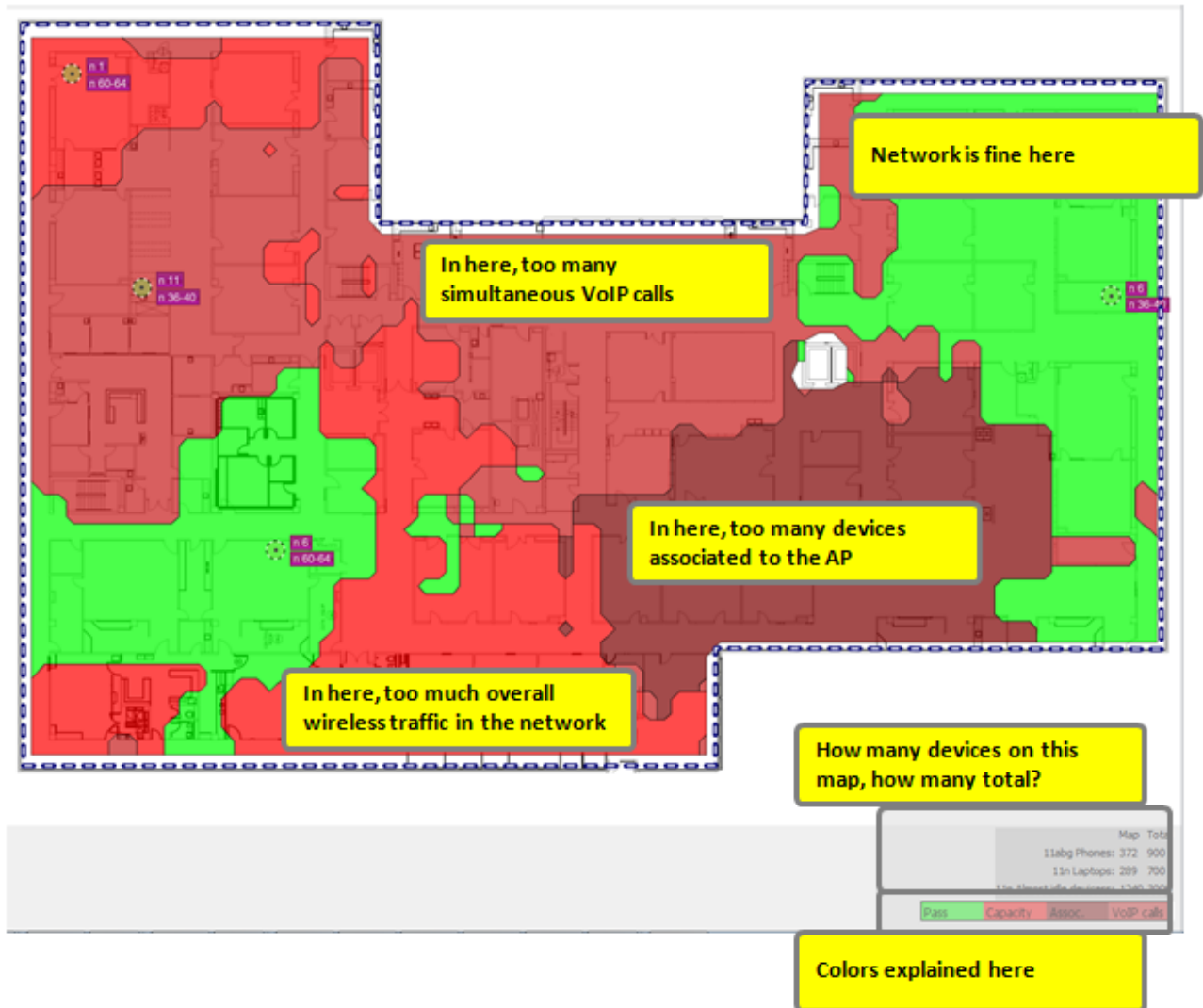


Figure 10 Capacity health visualization shows if the network contains too much traffic, too many voice calls or associations

The maximum throughput visualization presents the maximum possible throughput available for a selected client device in a particular location when there is no other traffic in the network. Because in a real network the capacity is shared between all users, this throughput cannot be normally reached. However, the visualization gives valuable information about the performance limits of the network.

The associated clients visualization presented in Figure 11 shows how clients are distributed between APs based on the roaming logic used by ESS. The roaming logic selects the best APs based on their data rate and SNR. It allows the user to see if some of the APs in the network would be overloaded based on commonly used roaming logics.

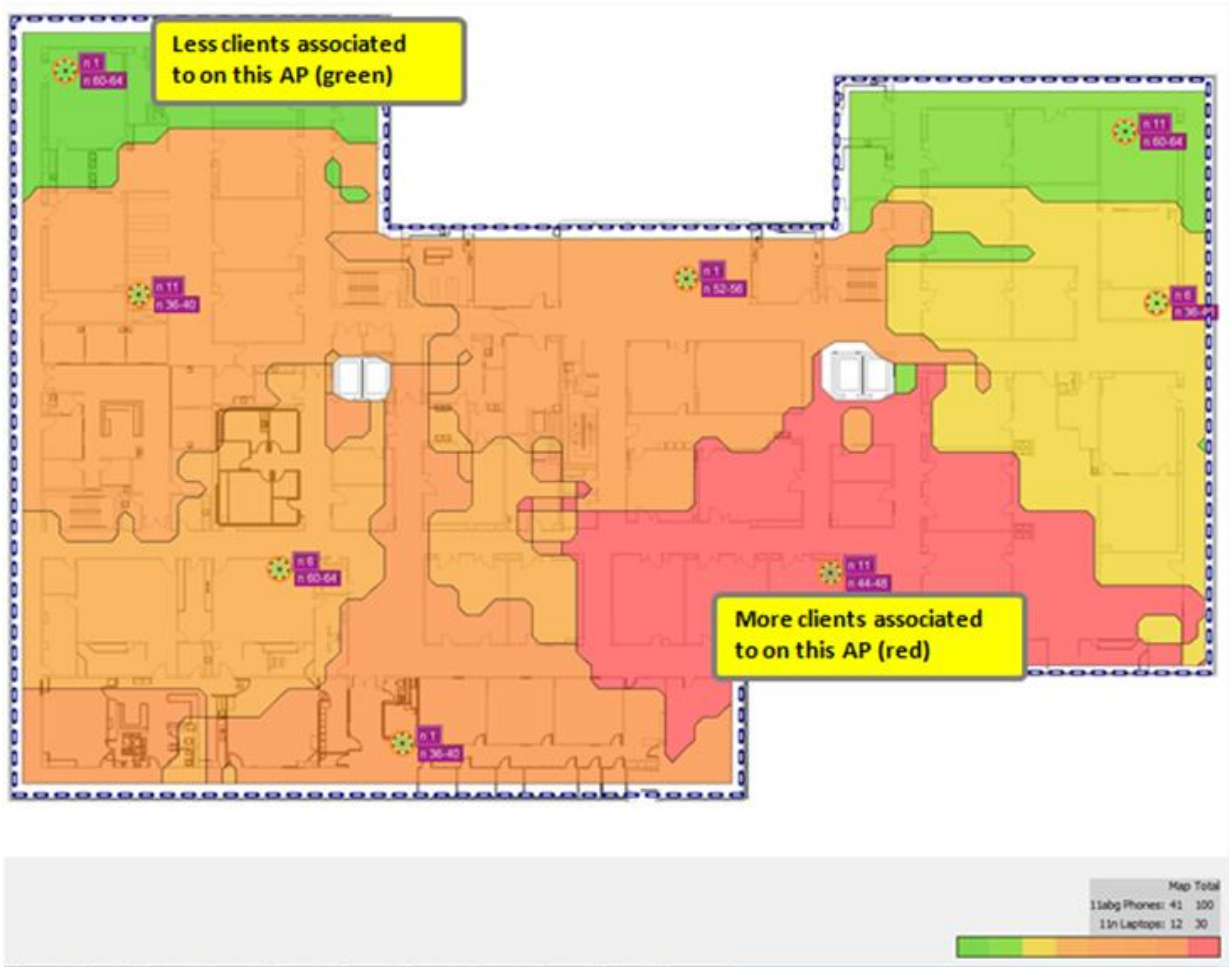


Figure 11. Associated clients visualization shows how clients are distributed between APs.

The accuracy of the capacity estimation of the network relies heavily on how exact the configuration of network applications and devices the user creates. The 802.11 specific channel usage algorithms are modeled on a level which is detailed enough to take into account the differences of capacity requirements of different applications (data, voice, video) as well as the specifics of WLAN physical layers defined in the standard amendments (802.11g, n) The latest physical layer integrated into ESS is IEEE 802.11ac. It includes support for wide channel

bandwidths (80, 160 MHz). The modeling is never a perfect image of the real world but gives estimates that are reasonably accurate. This allows network planning and modeling of the network capacity without actually installing the network.

Planning networks with capacity requirements

Network planning with ESS can be done in two ways:

1. Manually, by placing simulated APs on the map by hand or
2. Using Auto-Planner, where optimal AP placement and channel assignment are suggested based on user requirements for capacity and coverage.

Both methods support capacity requirements and allow analysis using capacity visualizations. If manual planning is chosen, the capacity visualizations can be used to monitor when the capacity requirements are fulfilled. With automatic planning, the Auto-Planner selects the number of APs in such a way that the capacity requirements are fulfilled.

Sometimes the capacity requirements cannot be fulfilled with the selected AP type and configuration. For example, there can be simply too many devices are streaming HD video in a small area. In such cases, ESS selects the number of APs, which fulfill the requirements as closely as possible. When the capacity requirements cannot be fulfilled, the user should explore the following possibilities to increase the capacity:

1. Increase the amount of channels used
2. Use dual-band 802.11n/ac APs
3. Move as many clients to 5GHz as possible
4. If possible, get rid of legacy client devices
5. Lower the AP transmission power to decrease interference.
6. Use 802.11n and 802.11ac specific features, such as wider channels, to increase capacity

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About the Author



Dr. Vanhatupa received M.Sc. '1998 in Software Systems, and Ph.D. '2008 in Digital and Computer Systems from Tampere University of Technology. He worked several years as a software engineer in a company developing network management solutions. His Ph.D. research topics included performance management and network planning in Wi-Fi networks. He joined Ekahau in 2007 and currently he acts as a senior research scientist in Wi-Fi tools team. His work includes developing algorithms for network planning and analysis for Ekahau Site Survey.