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Wireless Local Area Network Performance Inside Aircraft Passenger Cabins

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May 2005

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Abstract

An examination of IEEE 802.11 wireless network performance within an aircraft fuselage is performed. This examination measured the propagated RF power along the length of the fuselage, and the associated network performance: the link speed, total throughput, and packet losses and errors. A total of four airplanes: one single-aisle and three twin-aisle airplanes were tested with 802.11a, 802.11b, and 802.11g networks.

1 Executive Summary

Wireless Local Area Network (WLAN) products have become increasingly popular technology solutions for truly mobile information sharing and Internet access. Wireless fidelity, or Wi-Fi, hotspots are being rolled out across the globe from hotels, airports and office complexes, to city streets, restaurants and cafes, college campuses, public schools and private residences. Wireless LAN technology has brought a revolution in personal accessibility and productivity, and has created new markets for products and services. Airline companies desire to expand their product and service offerings to passengers by offering WLAN connectivity onboard commercial airline flights for both enhanced passenger connectivity and for future revenue growth. Lufthansa is currently executing a pilot program called FlyNet, which offers wireless Internet connectivity using the Institute of Electrical and Electronics Engineers (IEEE) 802.11 standard on select European flight routes. The wireless Internet service is provided by Connexion by Boeing, and passengers can access the Internet for a flat fee per flight, or by pay-per-minute Internet access. Lufthansa has plans to roll out Internet service on all of their airplanes and flights in 2006.

Domestic air carriers also have a strong interest to provide Internet access to passengers onboard domestic airline routes. When adding new technology to the existing commercial airline fleet, several major issues must be addressed such as certification of the new technology and (especially in the case of wireless LANs) electromagnetic interference (EMI) concerns. The RTCA organization has recently formed a special committee, SC-202, to examine the effects of Portable Electronic Devices (PEDs) onboard airplanes, and the committee is considering a broad scope of PEDs, including WLAN enabled laptops and other devices which operate using the IEEE 802.11 standard. The SC-202 has a broad spectrum of participation from within the airline industry, from airframe manufacturers, avionics suppliers and cellular telephone companies to government regulatory bodies and other government agencies.

As the aircraft criticality of the information carried by wireless systems increases, the emphasis on robustness, security, availability, and maintainability of wireless systems will also increase. The propagation behavior of various radio frequencies, modulation schemes, and configurations will need to be well understood in order to design functional and reliable wireless networks within the aircraft. In critical aircraft systems, the potential for interference or system attacks from the passengers or the ground must be carefully considered – the price and technology advantages of using commercial off-the-shelf (COTS) equipment may be precluded by the robustness and security requirements of critical airborne systems. Prior to considering how to build robust and secure wireless networks, however, it is necessary to understand how well wireless networks operate within the fuselage.

This report provides an examination of IEEE 802.11 wireless network performance within an aircraft fuselage. This examination measured the propagated radio frequency (RF) power along the length of the fuselage, and the associated network performance – link speed, total throughput, and packet losses and errors. A total of four airplanes, one single-aisle and three twin-aisle airplanes, were tested with 802.11a, 802.11b, and 802.11g networks. The purpose of this test was twofold: first, to determine any problems or degradations in network performance that may be caused by the complex configuration of the aircraft cabin or multipath interference effects inside the aircraft cabin. Second, this test was designed to provide some experimental data that can be used to verify and validate electromagnetic modeling and simulation predictions for RF propagation inside aircraft passenger cabins using commercial COTS software packages.

Summary of Results and Conclusions

1. The results of this testing showed that not all WLAN 802.11 radios are equivalent. One obvious conclusion is: if multiple radios are expected to be used, attention must be paid to the quality of the spectral signature of the equipment.

2. The results show that the path losses in the cabin are in fact higher than the expected free space path loss. These results indicate that the cabin furnishings do block, shield or absorb a certain amount of the radiated energy.

3. The results of the network performance testing indicate that the WLAN performance would be easily within expectations for passengers within the same cabin segment as the access point (AP). Expecting a single AP to provide adequate performance throughput the cabin is, perhaps, an unrealistic expectation. The channel contention experimentation performed on the 802.11b WLAN system indicated that two co-channeled APs would contend for bandwidth, in spite of being installed at opposite ends of the airplane. However, it is probably safe to assume that crew, passengers, associated luggage, and cargo would significantly alter the propagation profile, and probably significantly increase the aircraft cabin path loss. In other words, frequency re-use may become feasible when the airplane is full of people, due to the lack of end-to-end propagation.

2 Introduction

High-speed computer networks are becoming increasingly common on modern aircraft. As processing power increases and costs decrease, more airborne devices are gaining a measure of computational capability, and a need to communicate with other systems. While this computational capability adds functionality and health awareness to the line replaceable units (LRUs), the additional weight and space required to provide the needed communications networks is generally undesirable. Wireless networks do not have these disadvantages, and thus are of significant interest to the aviation industry.

Wireless systems are being actively examined within the airframe and aftermarket industries. A number of terrestrial wireless local area network (WLAN) technologies are currently available, and improvements in technology are expected to continue. Current WLAN technology is led by the 802.11b standard, which operates at 2.4GHz and offers a nominal data rate of 11Mbps, and 802.11a, which operates in the 5GHz band and offers a data rate of 54Mbps. The recently approved 802.11g standard is an upgrade to 802.11b, which raises the data rate to 54Mbps. All of the technologies under consideration use spread spectrum modulation (SSM) methods. Consequently, there is a demand to understand how these products will operate within the fuselage of an aircraft.

As the aircraft criticality of the information carried by wireless systems increases, the emphasis on robustness, security, availability, and maintainability of wireless systems will also increase. The propagation behavior of various radio frequencies, modulation schemes, and configurations will need to be well understood in order to design functional and reliable wireless networks within the aircraft. In critical aircraft systems, the potential for interference or system attacks from the passengers or the ground must be carefully considered; the price and technology advantages of using commercial off-the-shelf (COTS) equipment may be precluded by the robustness and security requirements of critical airborne systems. Prior to considering how to build robust and secure wireless networks, however, it is necessary to understand how well wireless networks operate within the fuselage.

3 Test Procedure

3.1 Network Layers & Wireless Networks

A modern computer network can often be best analyzed via the Open Systems Interconnect (OSI) seven-layer model. This model starts at the bottom with layer one as the *Physical Layer*, which describes how data are sent over the physical media; and moves upward to layer seven, the *Applications Layer*, which describes how applications software can interact via the network. For the purposes of this testing, the details of layer one and layer two (the *Data Link Layer*) are of primary interest. The higher layers will generally be grouped together in this document. Note that the actual physical media such as cabling or radio waves are not part of layer one.

For wireless networks, the layer theory continues to be a valid model, with some additional requirements at layer one. Specifically, wired networks have little concern with bit rate changes, fading signals, or changing the entry point into the remainder of the network. For a wireless network, these issues are significant. An introduction to the nomenclature of wireless LANs may be useful.

- **Client Card:** An internal or external network card and radio that connects a mobile device (e.g. a laptop, personal digital assistant (PDA), or similar device) to the WLAN.

- **Access Point (AP):** The bridge point between the wired infrastructure, and the wireless network.
- **Associate:** For the client to have network connectivity, it must ask the AP to allow an *association*. The AP may approve or deny this request. At some point, when the signal becomes weak enough, the AP will consistently reject (or not receive) the association requests, in which case all network connectivity will be lost.
- **Connect Speed:** Due to the fluctuating quality of the signaling channel, the AP and client will negotiate a bit rate that is supportable by the channel. Standard bit rates in 802.11b networks include 11, 5.5, 2, & 1 Mbps. For 802.11a networks, standard bit rates are 54, 48, 36, 24, 18, & 9 Mbps.

3.2 Network Functional Tests

To test the networks, a wireless LAN was constructed within the cabin, consisting of one or more wireless network access points, and several laptop computers. One laptop computer acted as a server, connected to the AP. The other laptops acted as clients, monitors, and/or test points. In this configuration, the network layer one and layer two performances can be evaluated throughout the airframe using an evaluation tool such as the AirMagnet Wireless Network Analyzer [2]. Network and radio frequency (RF) power metrics such as data rate, dropped frames, signal-to-noise ratio (SNR), and received power were measured to gain a solid understanding of layer one/two network performance within the fuselage. To evaluate the performance of the higher-level network layers, NetIQ Chariot software Version 5 [5], which is a high-performance tool for assessing overall network throughput and error performance, was used to evaluate absolute network performance.

3.3 RF Propagation Tests

In addition to network performance, it is highly desirable to have a firm understanding of the actual RF propagation within the cabin. The aircraft fuselage acts very similar to a leaky reverberation chamber, which would have significant impact upon the propagation of radio signals. In addition, the cabin furnishings, passenger load with associated carryon items, movement of the beverage carts, etc., may have significant impact on both the standing wave electric fields and the radiated power delivered to a load at any point within the cabin.

The AirMagnet network analyzer has a power measuring capability, but is uncalibrated, and is of unknown accuracy. For relative measurements, and rough estimates of power propagation, the AirMagnet is considered adequate. The AirMagnet generates its own network traffic to estimate the received power. In addition, to more accurately test the propagation of the 802.11 spread spectrum signals in a repeatable calibrated method, a signal analyzer was used to measure the received power at various locations within the airframe. The network was configured as a multicast server, which transmits frames at a constant rate, to generate the WLAN traffic for RF measurement.

4 Experimental Results

4.1 Network Performance in Laboratory

WLANs are designed and intended for mobility and convenience. Absolute throughput performance is substantially lower than that for a wired network, and can be very erratic depending upon the propagation environment. To establish a baseline of performance for the WLANs, the experimental configuration was set up in a lab environment, and network performance and RF signatures were measured.

4.2 RF Power in Passenger Cabin

The RF power is essentially a secondary parameter for most of these experiments, since actual installed networks would have total power output tuned for optimum performance for the application. Of far more interest is the attenuation of power along the fuselage of the aircraft. Consequently the radiated power will be examined relative to the power received at one meter.

4.3 Spectral Signature

Also of interest is the specific spectral signature for each radio. To do this, the power spectral density (PSD) of each radio was measured using the spectrum analyzer. The examination of these signals produced some unexpected and interesting results depending on the quality of the unit. Four APs (three purchased for the project, and one privately owned) were used for testing. As noted in Appendix A, the purchased APs included an Orinoco, which is an enterprise-grade unit; and two units (LinkSys and NetGear) probably best described as intended for Small Office/Home Office (SOHO) use. An additional LinkSys 802.11b with router and switch was also available for certain experimentation.

To establish a wireless network link, it is necessary to have a client computer with a compatible client card. Thus, when measuring PSD the client cards impact the measurements. To minimize this effect, the same client cards were used in all AP PSD experiments with the exception of the NetGear 802.11g testing, which required the NetGear 802.11g card. For all other testing, the Orinoco a/b Gold client card was used. To further minimize the impact of the client cards upon the PSD measurements, a streaming media test was used, which does not require any response from the client after the initial association and circuit setup is completed.

Figure 1 shows the spectral signature of the Orinoco AP-2000, operating in 802.11b mode on channel six.

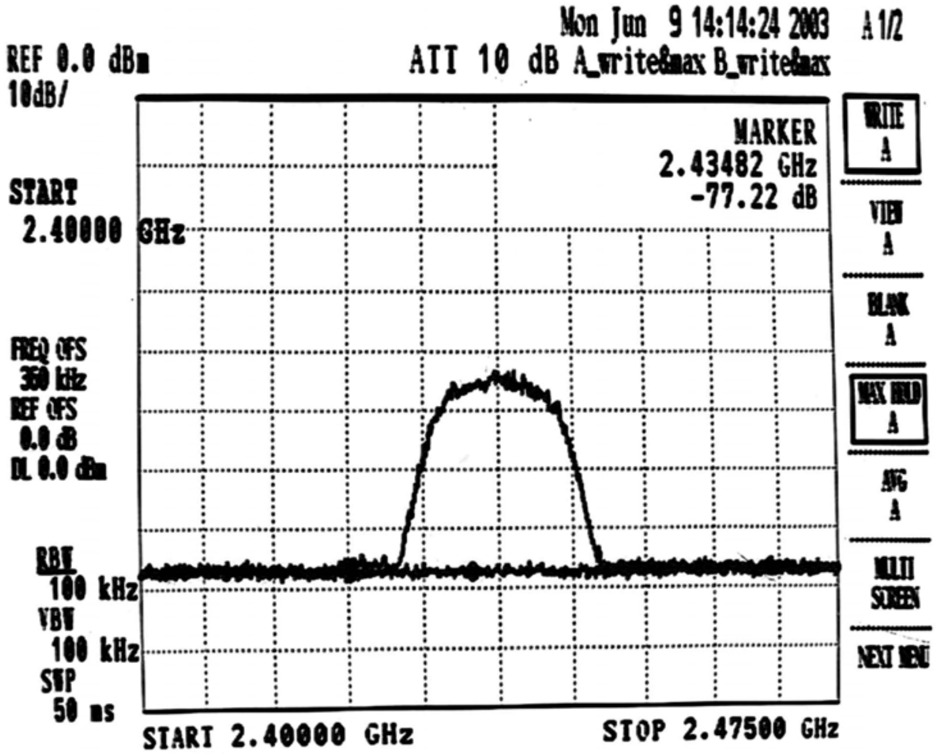

Figure 1: Orinoco model AP-2000 AP PSD while operating in 802.11b mode.

In Figure 1, note that the power distribution appears to be Gaussian in shape, and centered on channel 6 in the Industrial, Scientific and Medical (ISM) band (2.437GHz), with an amplitude of approximately -43 dBm (note that the marker position does **not** correspond to the channel center frequency; the marker is actually to the left of the main signal and cannot be seen on the graph). Recall that the receiving antenna in use was not calibrated, although the spectrum analyzer was. Particularly note the absence of any significant sidelobes in the spectral distribution. This is an example of a good spectral signature.

Figure 2 shows a similar PSD for an 802.11b-only LinkSys AP (the privately-owned LinkSys). Again, the smooth Gaussian shape, and lack of sidelobes is a desirable waveform. From Figure 2, it is noted that the power level for this signal is approximately -40 dBm. Thus, the LinkSys appears to output approximately 3dB more power than the Orinoco. None of the APs tested appeared to have any direct control of the output power. The difference in output power is likely attributed to the different antenna configurations on the two APs. The Orinoco AP-2000 uses the built-in antennas in the 802.11b client card, while the LinkSys has twin external dipole antennas.

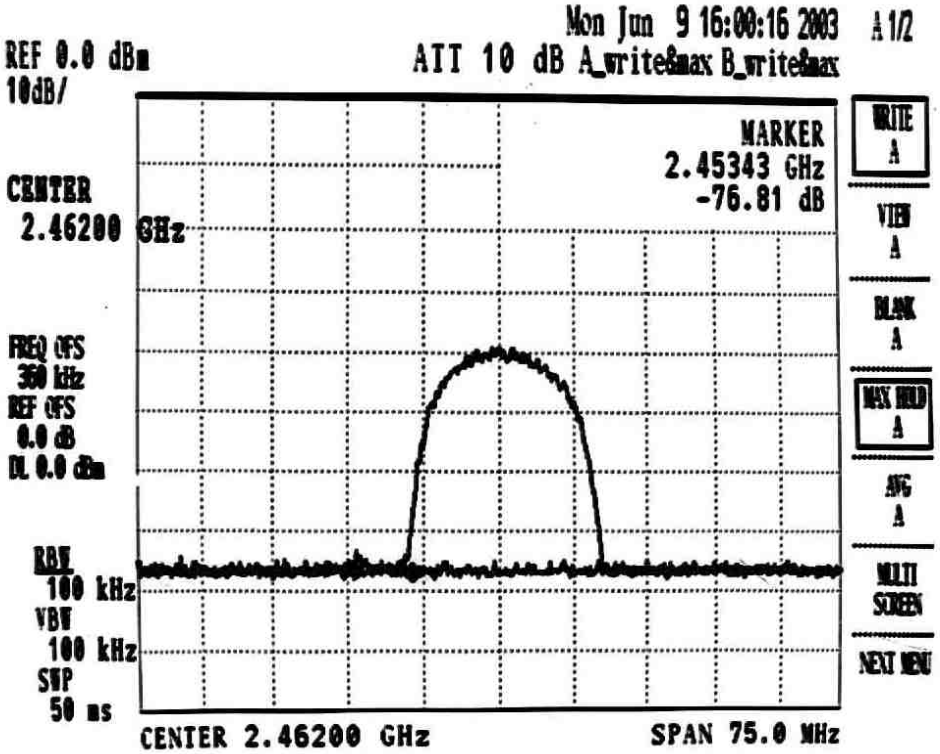

Figure 2: LinkSys Model BEFW 11S4 802.11b AP PSD while operating in 802.11b mode.

The NetGear AP PSD is shown operating in 802.11b mode in Figure 3. The PSD is clearly seen to have some problems with sidelobes that extend into the frequency space used by channels 1 and 11 in the ISM band. This interference was clearly noted as well in the network performance testing. Attempting to operate two 802.11b APs in adjacent channels (channel one with channel six, or channel six with channel eleven) resulted in a significant impact upon overall throughput.

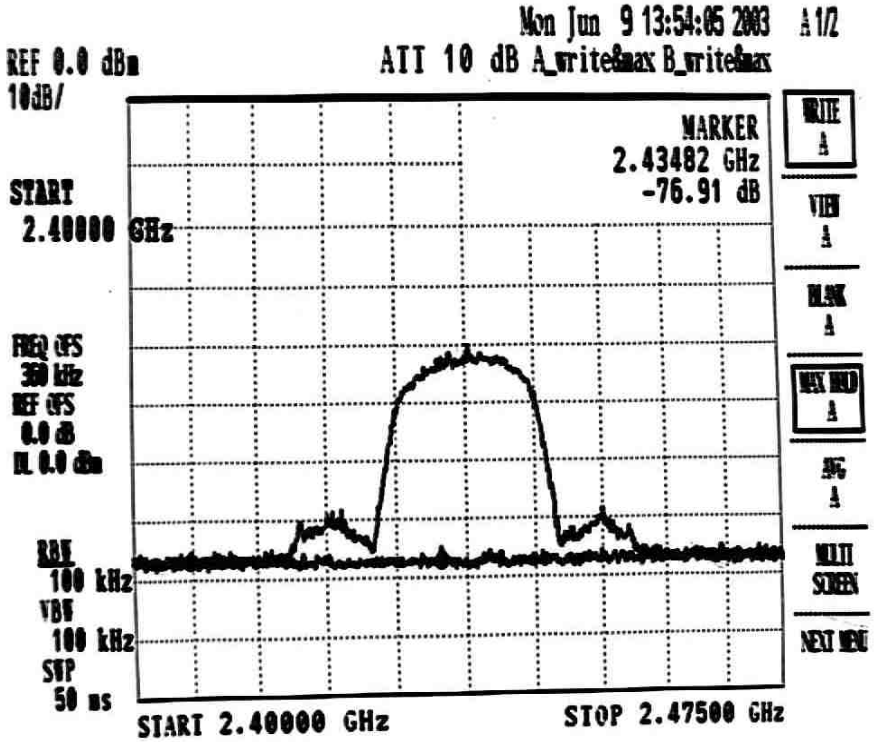

Figure 3: NetGear model WG-602 AP PSD while operating in 802.11b mode.

It is important to note that the NetGear AP is a pre-standard 802.11g unit, however. The NetGear documentation indicates that a firmware download will become available upon ratification of the new 802.11g standard, which may impact the PSD signature of the unit, although one might expect the impact to be primarily centered upon the 802.11g spectrum.

The last of the four 802.11b AP spectral signatures is shown in Figure 4. This is the LinkSys dual-mode AP purchased for this research project, and operated on channel six in the ISM band. The primary waveform is not only non-symmetrical and somewhat dispersed, but the sidelobes are significant and extend far into channels one and eleven, effectively negating any advantages of using multiple APs to improve total network capacity.

The ability of 802.11g APs to co-exist with 802.11b networks was also examined. When throughput tests were attempted with both systems, total throughput was essentially zero. A photograph of the spectral signature of the NetGear 802.11g system is shown in Figure 5, which explains the reason for the poor performance. Figure 5 shows that not only does the signal not stay inside a single 802.11b channel (as it should), but it appears to not even be confined to the ISM bands. Once again, this is a pre-standard chipset, and lapses in performance are not unexpected. Subsequent chip refinements and firmware enhancements will be forthcoming; improvement of this performance shortcoming may be anticipated.

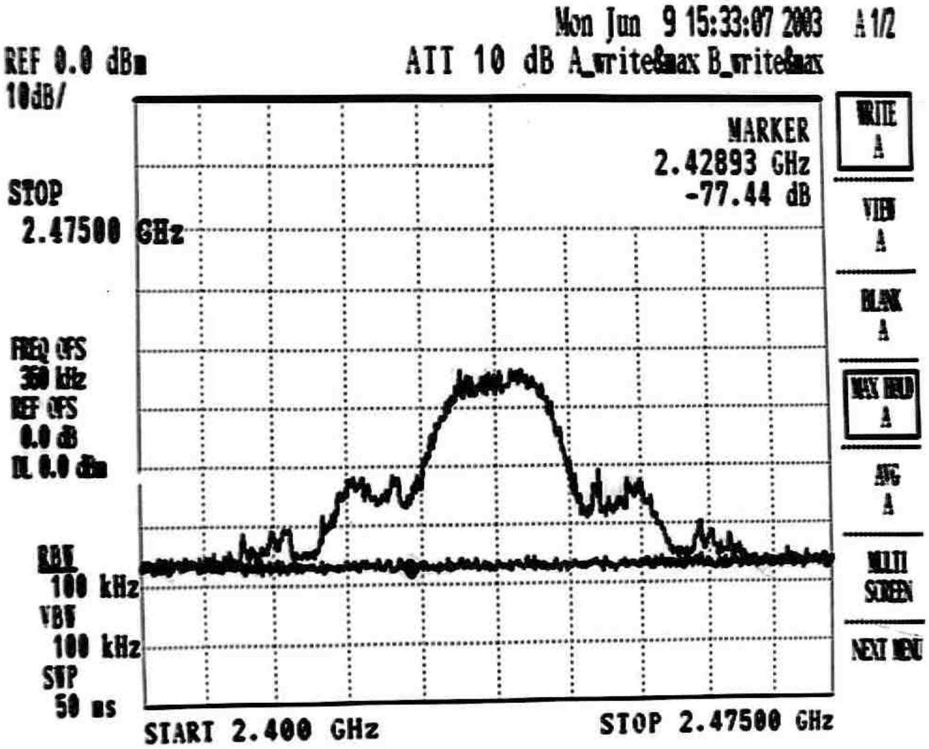

Figure 4: LinkSys model WAP51AB AP PSD while operating in 802.11b mode.

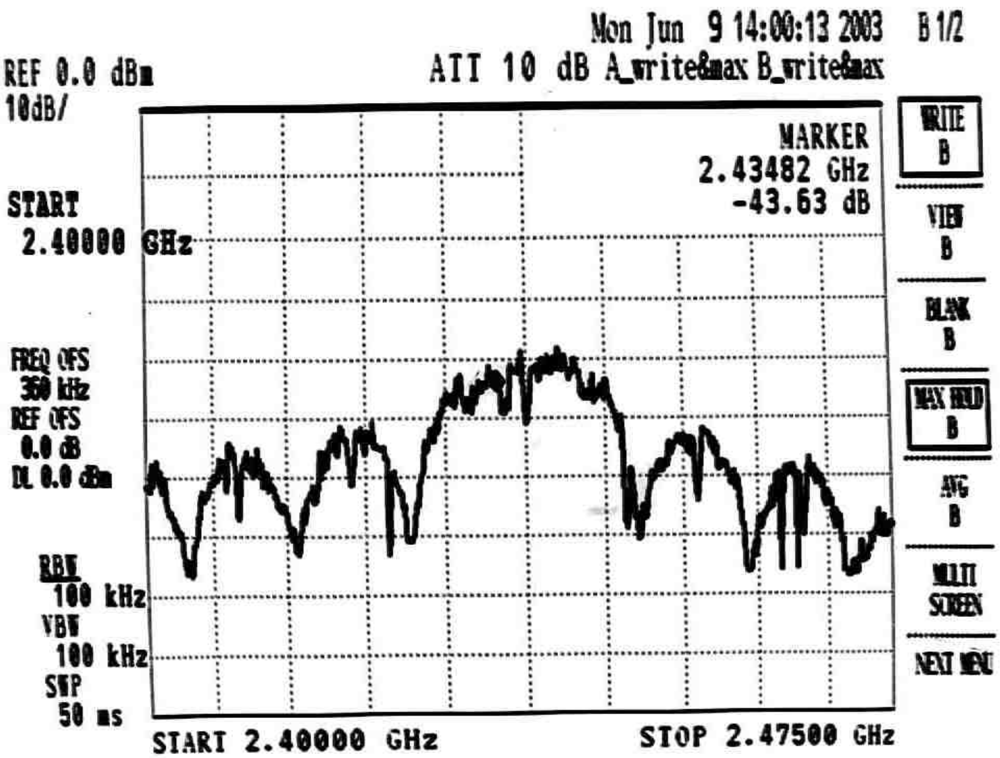

Figure 5: NetGear model WG-602 AP PSD while operating in 802.11g mode.

Operating multiple APs in the ISM band seems to be somewhat problematic, in the sense that one must ensure that the equipment selected conforms to expected spectral performance.

Although only a small inventory of equipment for experimentation was available for the U-NII band (5GHz, 802.11a bands), the equipment on hand seemed to perform largely as expected. The RF outputs of the two 802.11a units that were tested are shown in Figure 6 and Figure 7. Figure 6 shows the spectral output of the Orinoco AP while operating in 802.11a mode on channel 64, and in Figure 7 the LinkSys in the same configuration.

Examining the two figures reveals that the Orinoco has a slightly smoother envelope, and lower sidelobes than the LinkSys. The Orinoco also has slightly higher output power, possibly due to the optimized single-band antennas.

It is also interesting to consider that the flat-topped waveform is the expected shape for the NetGear 802.11g unit seen in Figure 5, since 11g uses the same orthogonal frequency division multiplexing (OFDM) modulation scheme as 11a.

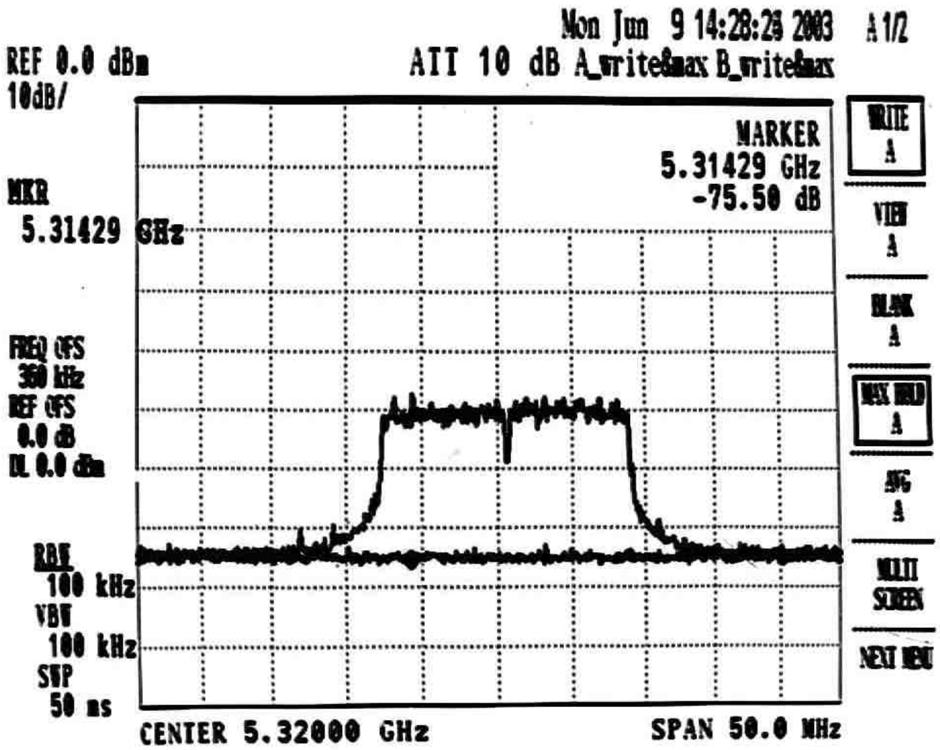

Figure 6: Orinoco model AP-2000 PSD while operating in 802.11a mode.

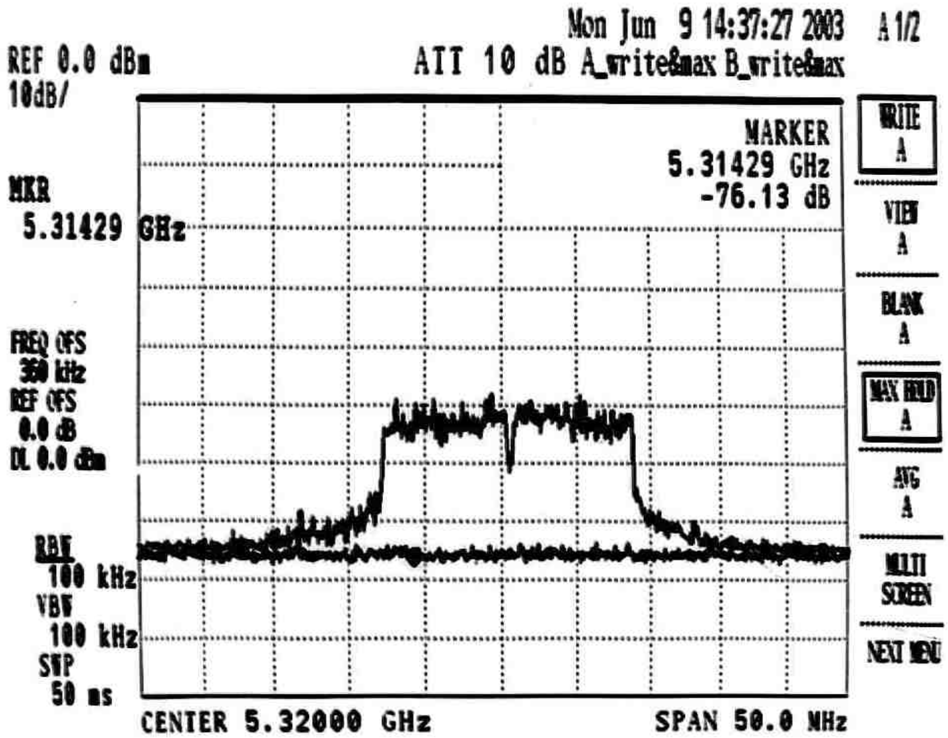

Figure 7: LinkSys model WAP51AB AP PSD while operating in 802.11a mode.

4.4 Aircraft Under Test (B-747, B-767, B-777, A320)

The assessment of performance of wireless networks in aircraft cabins was accomplished by obtaining opportunities to install WLANs within the cabins of several twin-aisle Boeing airplanes, and one single-aisle Airbus airplane. In this section, various sub-sections outline the testing performed and present the results obtained for each aircraft configuration. The experimentation was not uniform between models due to time limitations and other maintenance activities within the cabin. Differences in experimental configuration are noted, but direct comparison between airplane models is generally unadvisable without consideration of variations in configuration.

Configuration changes that made noticeable differences in the measurements include the number of personnel moving about in the cabin, disassembly of the cabin furnishings, and open doors. While having personnel within the cabin increased the losses of the RF propagation somewhat, it also contributed significantly toward ensuring that measurements were not exclusively standing wave measurements. It has been experimentally found that having five or six people moving about within a cabin is statistically similar to having a mechanical mode-stirrer [1]. Cabin disassembly was a factor on two airplanes (the B-767 and B-747). When the seat components were stacked on top of installed seats, the power readings showed that the blockage was noticeable. The door status (open, closed, or slightly ajar) also proved to result in observable differences in power readings during the RF propagation testing. Unfortunately, it was generally difficult to keep the airplane doors closed due to other maintenance teams working on the airplane, and the lack of environmental air handling systems being operational.

Generally the airplanes were totally powered down, with the exception of lights and sweeper outlets, which were used for powering the test equipment. At times, other systems would be powered up for maintenance, testing, or training during experiments. Little or no difference was detected in the measurements during these activities.

At no time during the testing were any other wireless networks detectable with the test equipment. Within the hangars the RF background noise was at or below the level of the test equipment. Outside, approximately two to three dB of additional noise was occasionally detected when many doors were open. With doors closed, the RF noise level was below the level of the equipment.

Depending on the amount of time the airplane was available to the test team, several different types of measurements were conducted. The RF power, network throughput, and upper-layer performance measurements were all first performed on a seat-row basis in the aisle (only one aisle on the twin-aisle airplanes). The choice of aisle used was usually dictated by other maintenance activities within the cabin. If time was left after that data were collected, then other measurements were performed, such as seat-by-seat measurements around monuments, measurements upstairs or down in the cargo hold or electronics bay (e-bay).

All plots presented will be keyed to an airplane LOPA (Layout Of Passenger Accommodations; effectively an airplane floor plan). Careful examination of the LOPA reveals numbers that reference locations within the aircraft and these numbers are referred to as *station numbers.* Station numbers historically are the number of inches rearward of a specified datum point, usually a foot or two in front of the nose of the airplane. The term "historically" is used, since the original station numbers assigned to locations within the fuselage can shift as derivatives of the airplane are produced (the –nnn number after the major model number), meaning that the stations toward the rear of the airplane are no longer exactly the number of inches they might imply. The only airplane under test in this project where the station numbers were inconsistent was the B-767. The point of departure from an inch count is documented in the consolidated data sets contained in the Excel spreadsheets.

4.4.1 Non Airplane-Specific Testing

This test program yielded a unique opportunity to test various facets of wireless network performance and measurement techniques. Capitalizing on this opportunity, several test results are presented below that are not specific to any airplane models or network configurations.

4.4.1.1 RF Power Measurements

Figure 8 compares the 802.11a network power readings obtained via two different test instruments as a function of distance. In Figure 9, the same data is presented for 802.11b networks. These data are of interest to note the difference between the power measurements obtained by the spectrum analyzer, which scans through the channel measuring instantaneous power at each discrete frequency versus the network client card, which uses spread spectrum technology to determine total signal power. This fact might imply that an advanced class of spectrum analyzer, capable of accurate analysis of spread spectrum signals, may be desirable for future 802.11 wireless network testing. Another factor that may account for the disparity of readings, particularly between 5GHz and 2.4GHz readings, were the uncalibrated antennas that were used on the spectrum analyzer.

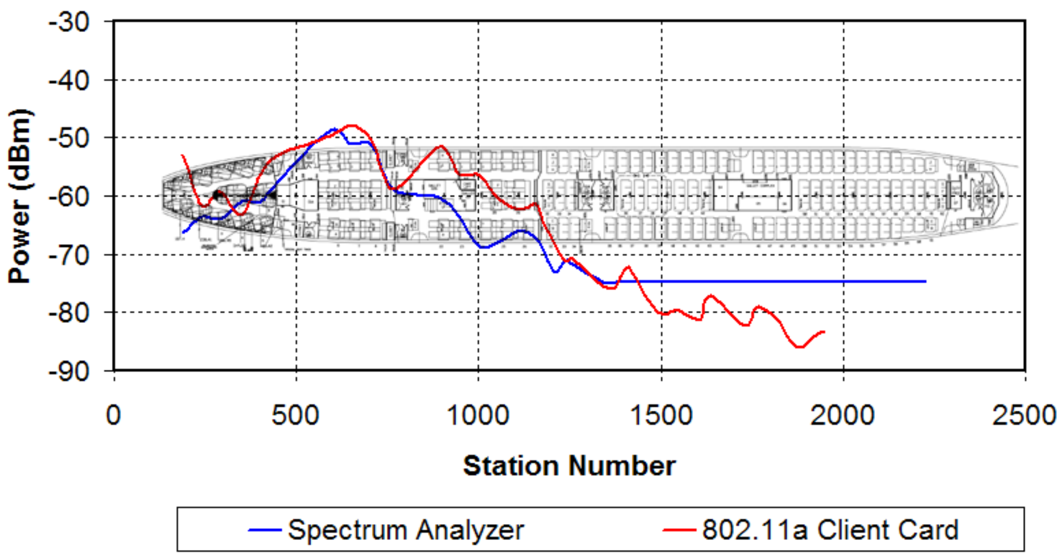

Figure 8: Comparison between 802.11a RF power readings obtained by a spectrum analyzer and the network client card.

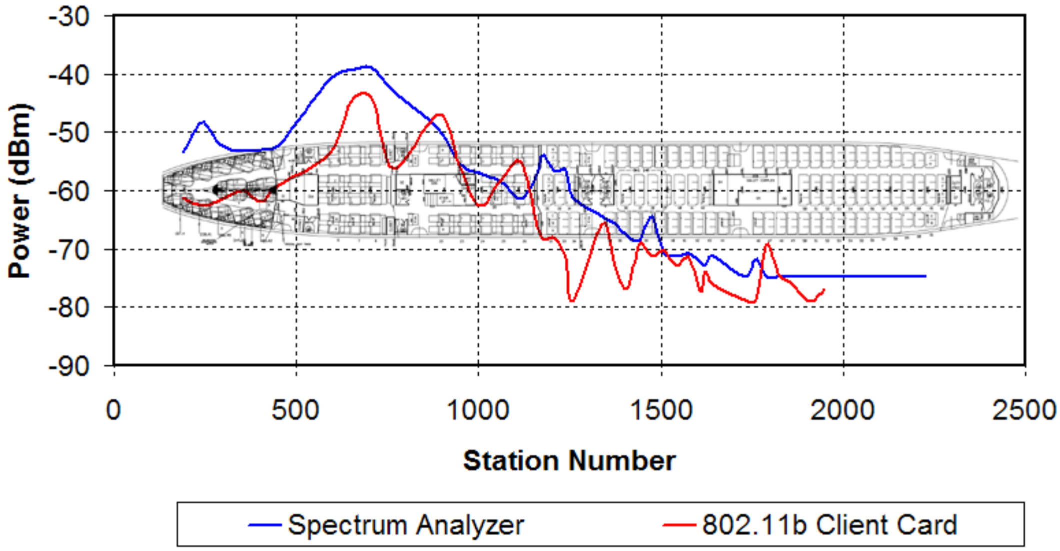

Figure 9: Comparison between 802.11b RF power readings obtained via a spectrum analyzer and the network client card.

4.4.1.2 Comparison between networking technologies

While RF propagation along the length of the fuselage is the primary focus of this work, significant interest in the seat-by-seat network performance is of interest to those outfitting aircraft with wireless networks for passenger use. Using a B-777 as the test bed, the network throughput was measured for each of three different network technologies: 802.11a, 802.11b, and 802.11g. In Figure 10, data is presented depicting the total throughput for each networking technology at each seat location in First and Business Class for a B-777. The APs were mounted upon the bulkhead over the footrests between seats 1E and 1F at the leading edge of First Class. While Figure 10 allows evaluation of the actual data points, it is difficult to visualize the flow of power throughout the cabin.

This shortcoming is overcome in Figure 11, Figure 12, and Figure 13, where the throughput data for each network technology is color-mapped and overlaid on a LOPA. In these figures, red indicates highest throughput measured, and blue indicates the minimum throughput measured. With the exception of the 802.11g network, the typical throughput within the same cabin segment as the AP is near the maximum measured, although severe nulls are found after the monuments. For the 802.11g network, the throughput is moderately uniform within a cabin segment, but significantly below the maximum measurements.

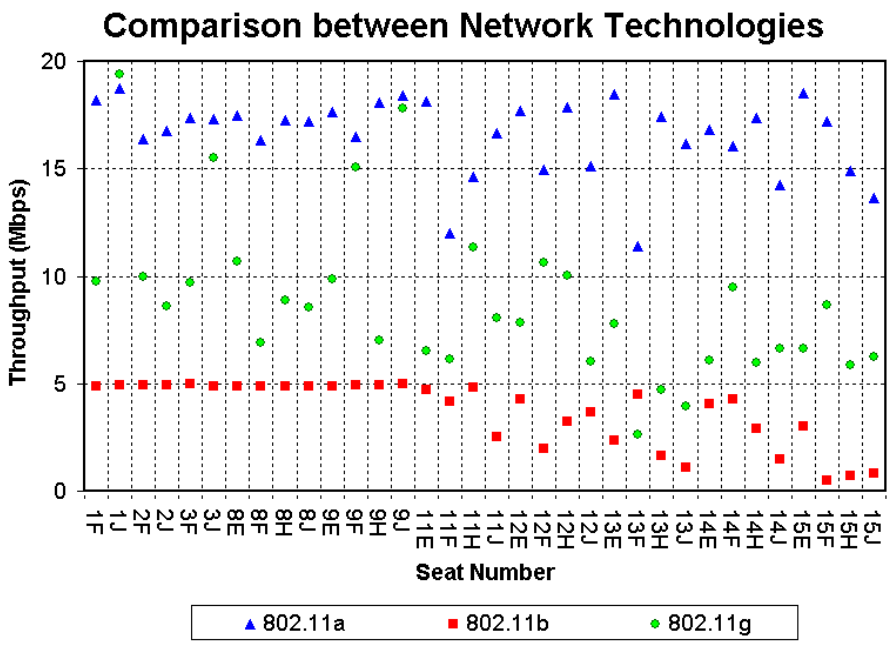

Figure 10: A seat-by-seat mapping of network throughput performance.

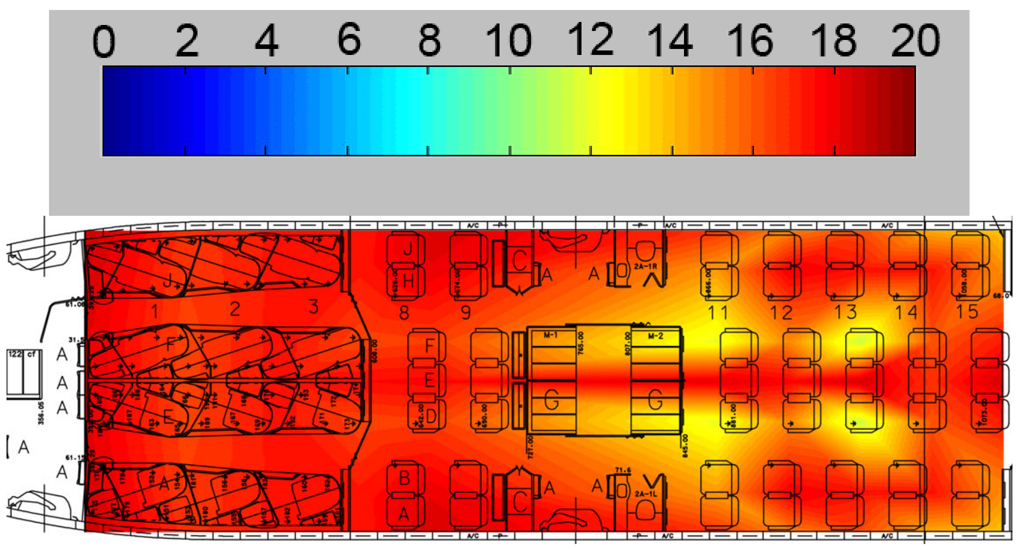

Figure 11: Measured 802.11a wireless network throughput as a color-map in First- and Business-Class cabin of a B-777 airplane. (The colorbar shows relative throughput scale.)

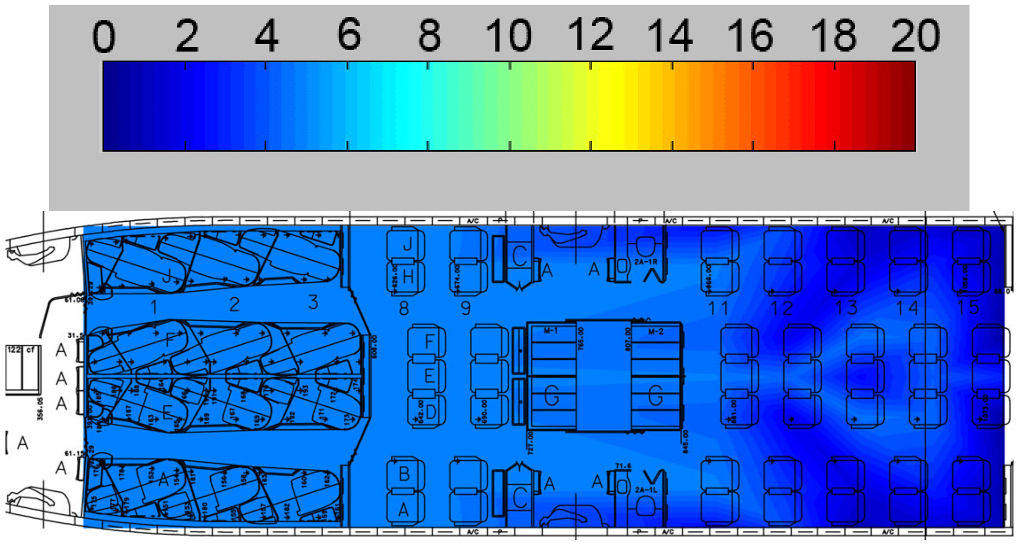

Figure 12: Measured 802.11b wireless network throughput as a color-map in First- and Business-Class cabin of a B-777 airplane. (The colorbar shows relative throughput scale.)

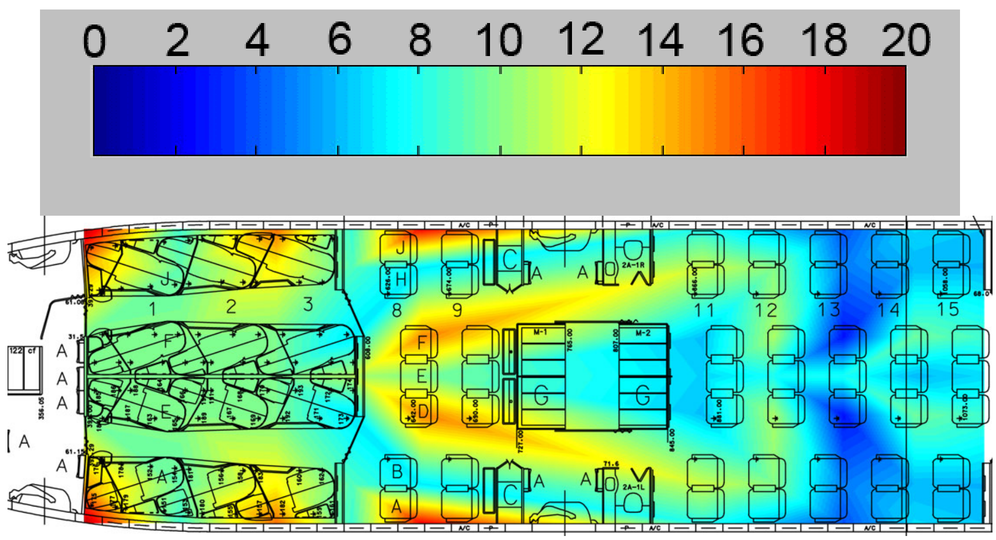

Figure 13: Measured 802.11g wireless network throughput as a color-map in First- and Business-Class cabin of a B-777 airplane. (The colorbar shows relative throughput scale.)

4.4.1.3 Impact of UWB systems upon 802.11 networks

By fortuitous circumstance, the 802.11 performance testing was combined with interference testing that a NASA team was conducting on the impact of ultra wide-band (UWB) devices upon airplane avionics systems. While these tests were possible to conduct, it should be emphasized that the testing was done on an ad-hoc basis with little opportunity for crosschecking and issue follow-up.

The equipment configuration consisted of a UWB device operated at various pulse repetition frequencies (PRFs) and with adjustable power output. The output of the UWB system was via a standard-gain horn, located at seat 14C. The 802.11 networks were configured with the AP located on the back of seat 26C, and the clients located on the tray tables at seat 24C.

The results of UWB device power levels and PRFs upon 802.11 wireless network throughput can be seen in Figure 14. Generally the test results show that, for the equipment configuration used, the UWB device did not interfere with the 802.11 WLAN equipment for any PRF while broadcasting at legal power limits. The WLAN was impacted only when broadcasting at 26dB over the FCC part 209 limits. The UWB system was bandpass filtered such that most of the energy was broadcast between 2-4GHz, thus the 802.11b system was the most affected.

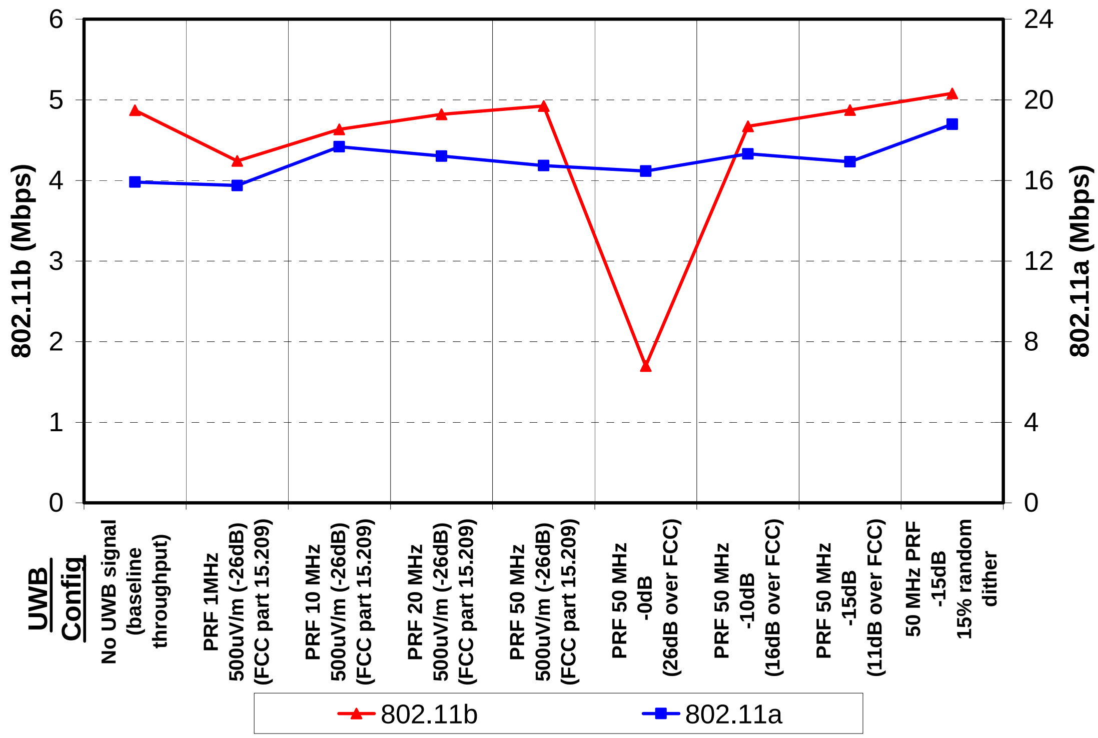

Figure 14: Impact of UWB device power levels and pulse repetition frequency upon 802.11b (blue, triangles) versus 802.11a (red, squares) wireless network throughput.

When considering the data above, one must account for the space loss and absorption of seats, people, and other losses between the UWB antenna and the equipment under test.

Another perspective of the impact of UWB upon 802.11 WLAN operations can be obtained by examining the signal power and noise power seen by the 802.11 client cards. One might expect that points of relatively poor network throughput would correspond to significantly degraded signal-to-noise (SNR) ratio. Referring to Figure 15, however, we see that the noise power seen at the +26dB UWB output is not significantly higher than several other configurations with much less impact to network performance. The SNR at this maximum UWB output is only about 3dB worse than the last data point (-15dB), which doesn't show nearly as much throughput impact.

As noted above, these experiments were very preliminary and loosely controlled tests, designed to obtain a qualitative understanding of UWB interference with wireless LANs and that more rigorous and tightly controlled tests are warranted in the future. While much more rigorous experimentation is undoubtedly desirable to solidly understand UWB impact on wireless networks, this preliminary data suggests that little adverse effects on 802.11 WLANs can be expected except at high power levels or very close proximities.

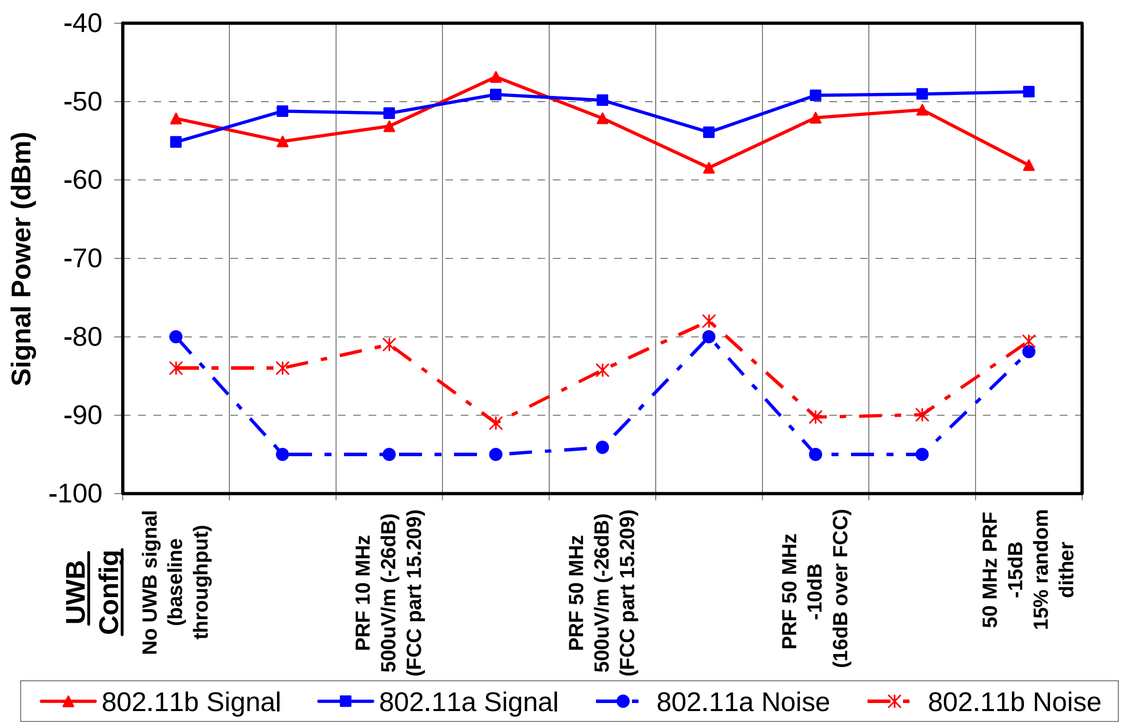

Figure 15: Impact of UWB device power levels and pulse repetition frequency upon 802.11 signal and noise power.

4.4.2 Boeing 747-400

A Boeing 747-400 was available and tested for wireless network performance. A LOPA for the B-747 is shown in Figure 16.

4.4.2.1 Airplane configuration

The airplane was in a hangar, with maintenance being performed on seat 4J in the first-class cabin. The maintenance involved two to three mechanics moving large segments of the seats and footrests around in the first-class section of the airplane. The airplane had doors 1R and 5L open, and door 4L slightly ajar.

4.4.2.2 Tests performed

A "standard suite" of tests was defined that was executed on every airframe that was available. This suite consisted of the following:

1. Testing the RF propagation along the fuselage, using a spectrum analyzer. The spectrum analyzer was calibrated, however an uncalibrated antenna system was employed. Of primary interest were the *relative* levels of RF power, and thus a calibrated antenna configuration was not critical to the success of the mission.
2. Testing the network performance using the Chariot network performance test suite.
3. Testing the physical media and network performance using a wireless network analysis tool supplied by AirMagnet. Unlike the spectrum analyzer or Chariot, AirMagnet has site-mapping functionality, in which the tool associates (or attempts to associate) the client with the AP, and measures signal power, noise, and network performance parameters.

The testing performed on the B-747 consisted of the standard suite of tests.

4.4.2.3 Test equipment configuration

The AP was mounted on the back of seat 6D, at approximately station 610. The Orinoco AP-2000 802.11a/b dual mode AP was used in conjunction with the Orinoco client cards for all throughput tests. Laptop clients were located on seat-back tray tables (similar as for in-flight use) for all testing. For RF power measurements, the receiving antenna was mounted directly on the spectrum analyzer (to avoid cable losses), and the analyzer was moved throughout the cabin on a cart to take measurements.

4.4.2.4 Standard suite test results

The discussion in this section will be reasonably extensive for the B-747, and considerably more abbreviated for other airframes. Much of the same commentary might be made in each airplane, with little gain by repetition.

Figure 17 presents the RF power that propagated along the length of the fuselage as measured by the spectrum analyzer. Unsurprisingly the RF power reaches a peak near the location of the AP, and declines in either direction. It should be noted, however, a local peak in RF power at approximately station 1100, which may be about where the wingbox is located on the B-747. Prior measurements of signal power down in the e-bay and cargo hold below the main deck of B-747's show that the deck floor is essentially electrically transparent at 802.11 frequencies of interest, leading to a suspicion that energy propagating within the cargo hold is somehow being reflected back up into the main cabin again when the cargo bay ends and the wingbox begins.

The average wireless network throughput performance for a B-747 is depicted in Figure 18. These results are contrary to many expectations; specifically that 802.11a networks operating at 5GHz would not have the range equivalent to 802.11b networks operating at 2.4GHz. As can be seen in the plot, the 802.11a network functioned from the nose to tail of the passenger cabin, while the 802.11b network was largely incapable of associating after approximately station 1500. While the average throughput appears to be reasonably robust, examining the variations of throughput is also instructive. The throughput can be very low at certain points, particularly within the fuselage due to the reverberation effects of the metallic structure. While these points of lowered throughput appear problematic, normal WAN TCP/IP network latency and elasticity is frequently equivalent or worse. The variance of 802.11a data rates is shown in Figure 19, and the variance of 802.11b data rates is shown in Figure 20.

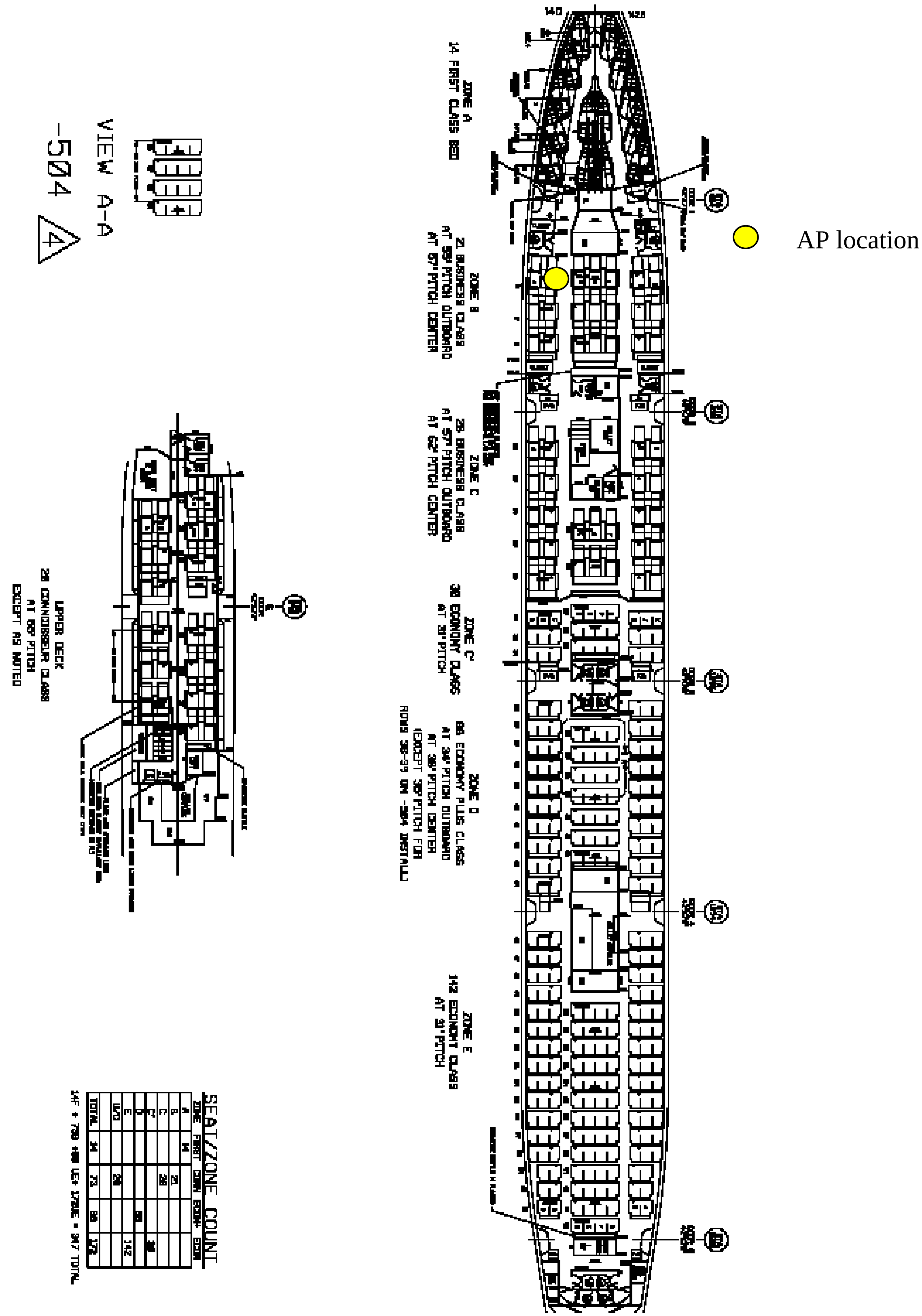

Figure 16: LOPA for B-747 airplane under test.

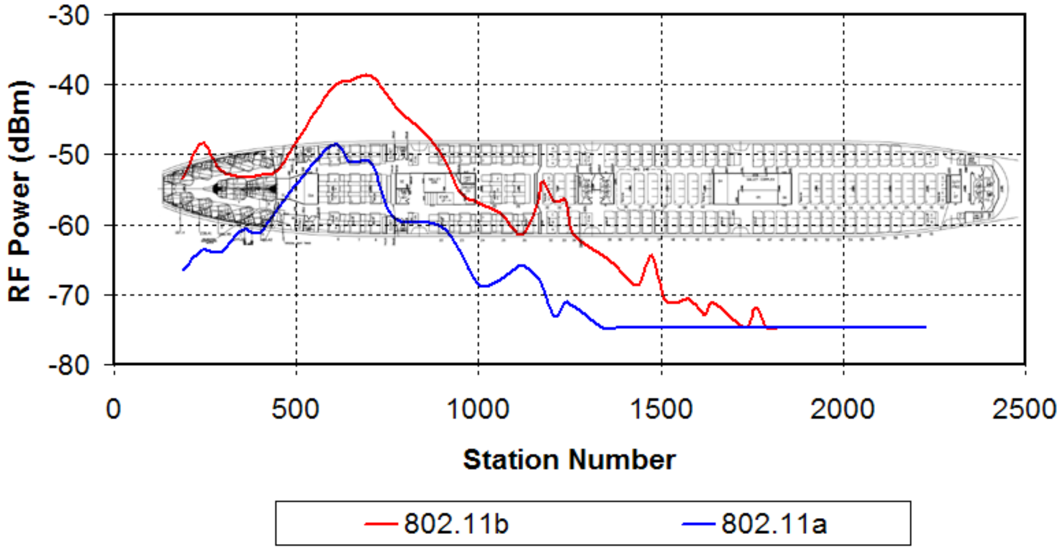

Figure 17: Measured RF power of 802.11a (5GHz) and 802.11b (2.4GHz) wireless networks along a B-747 fuselage (main deck).

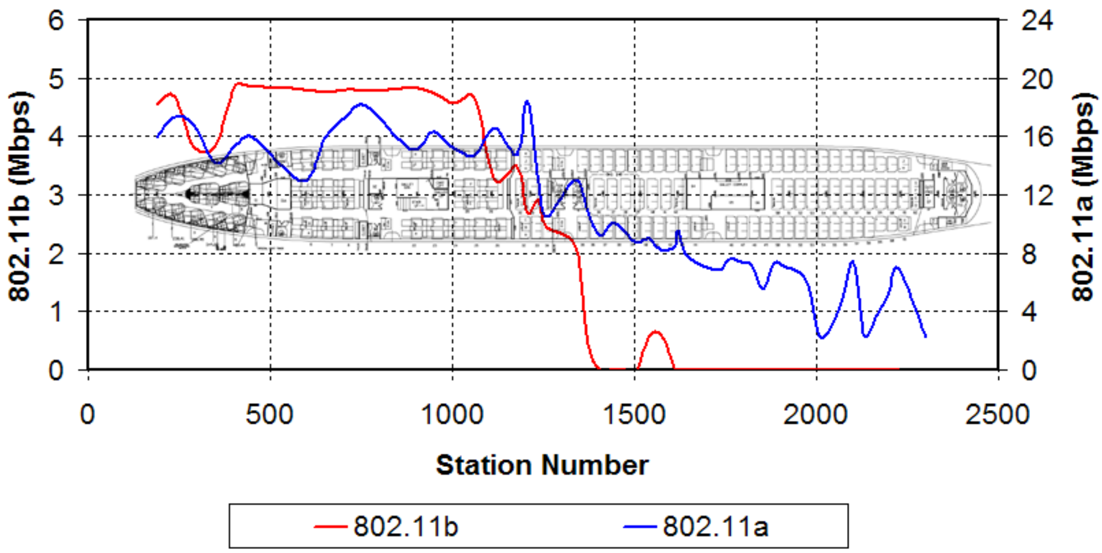

Figure 18: Measured 802.11 wireless network throughput within a B-747 fuselage (main deck).

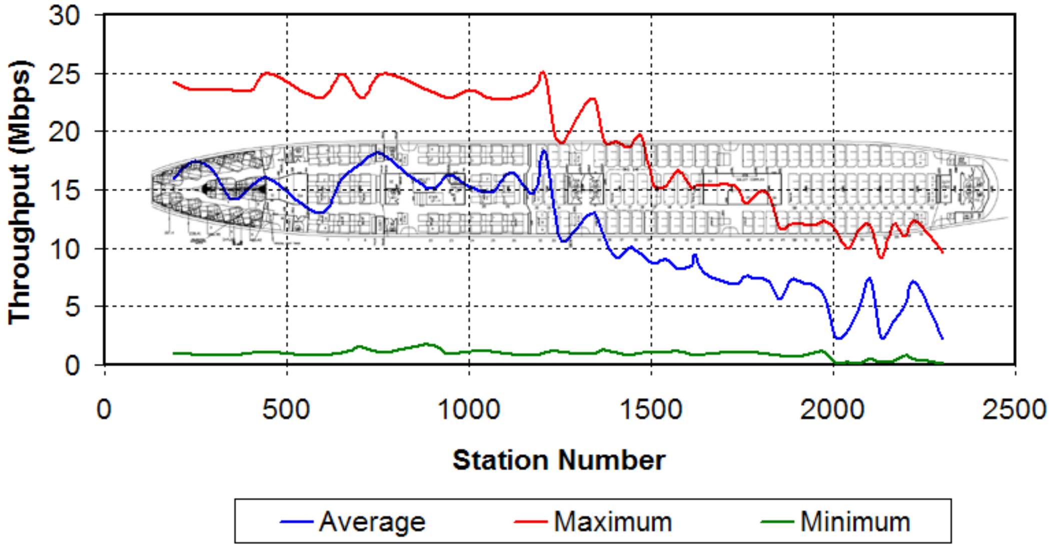

Figure 19: Variance of 802.11a wireless network throughput within a B-747 fuselage (main deck).

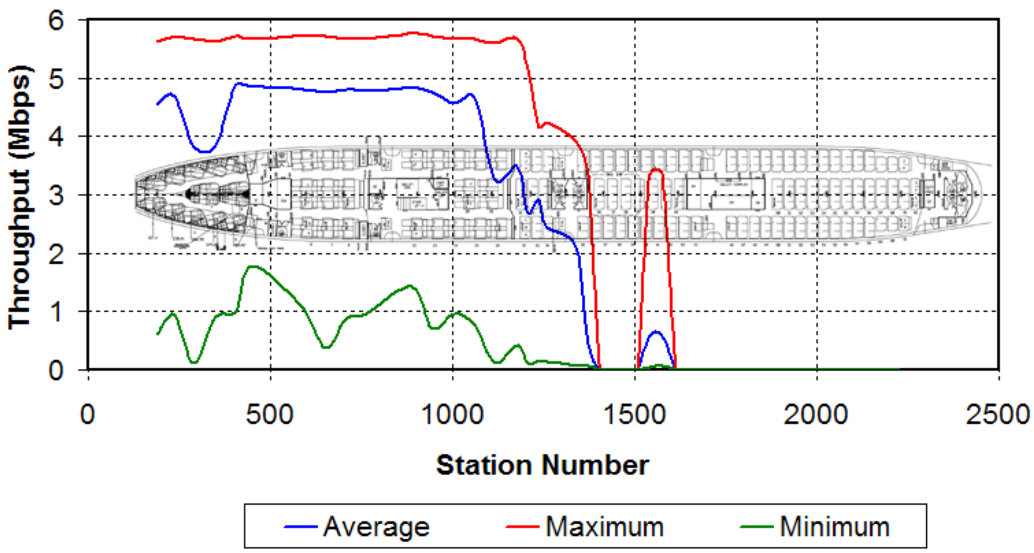

Figure 20: Variance of 802.11b wireless network throughput within a B-747 fuselage (main deck).

In any WLAN installation, a prime objective is to maximize the number of users that have high-speed access to the network; or in WLAN terms, the objective is to ensure that all locations have access to an AP at the highest connect speed. Since the AP and client use a varying set of parameters (some of which are vendor specific), there are few ways to construct a network where the connect speed is guaranteed. Evaluating the connect speed within the cabin of the aircraft, however, should prove enlightening. In Figure 21 and Figure 22 a comparison between the signal power received by the client card, and the associated negotiated connect speed is presented.

Likewise, overall network performance at the upper layers is of some importance when designing wireless networks for reliable, sustainable high-speed performance. Using the site-survey tool capability of the AirMagnet wireless network analyzer, such diagnostics are possible to explore thoroughly. Figure 23 depicts the network performance for 802.11a networks within the main cabin of a B-747, while Figure 24 shows 802.11b network performance. Unsurprisingly, as signal power drops, packet losses and retries increase dramatically. The erratic nature of the loss curves is undoubtedly due to the mode-stir nature of having people moving about within the cabin during the measurements.

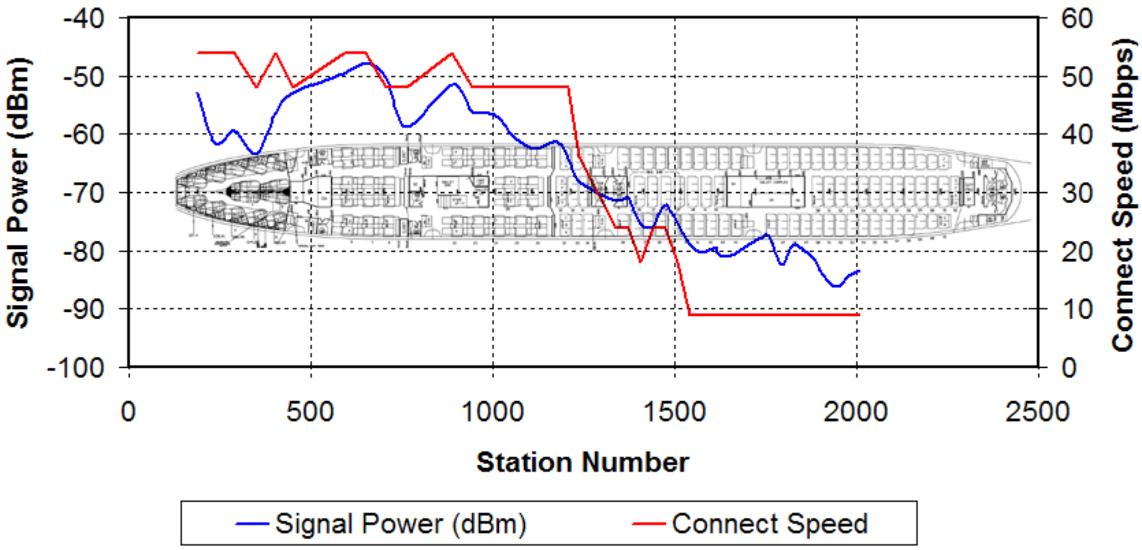

Figure 21: Connect speed vs. signal power for 802.11a wireless networks within a B-747 fuselage (main deck).

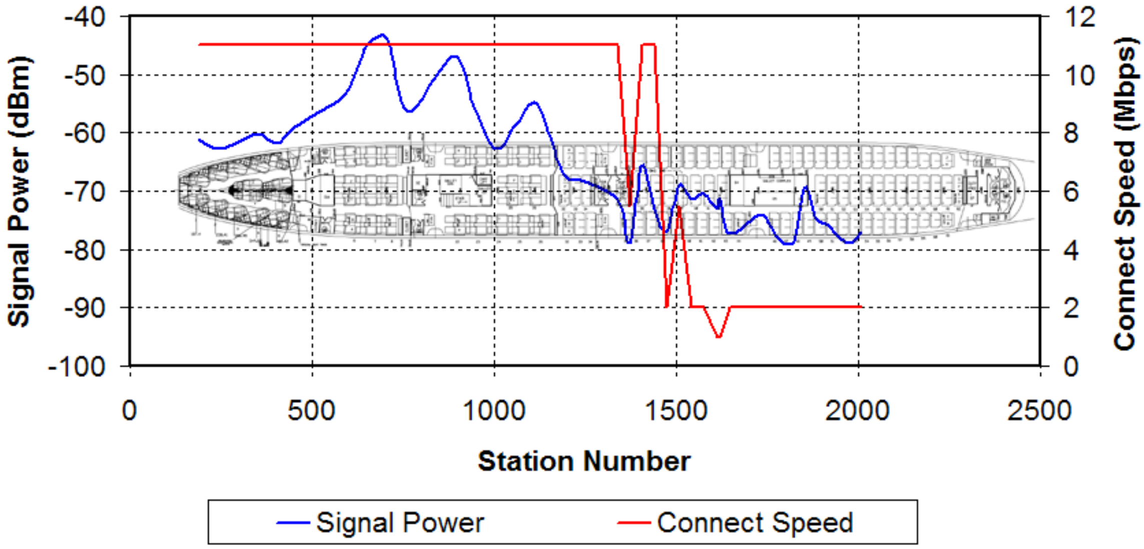

Figure 22: Connect speed vs. signal power for 802.11b wireless networks within a B-747 fuselage (main deck).

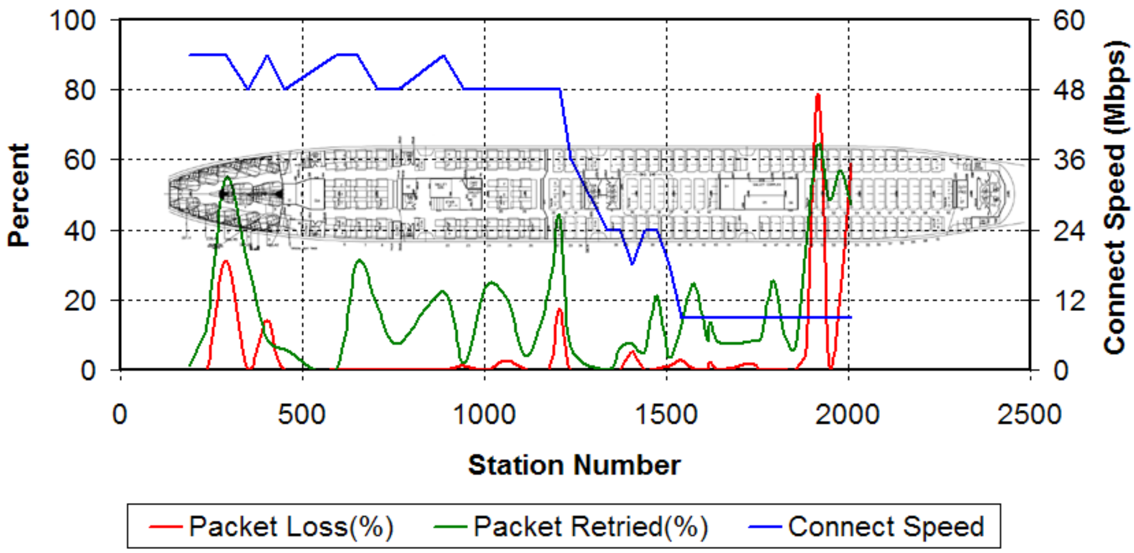

Figure 23: 802.11a wireless network performance at the upper network layers within a B-747 fuselage (main deck).

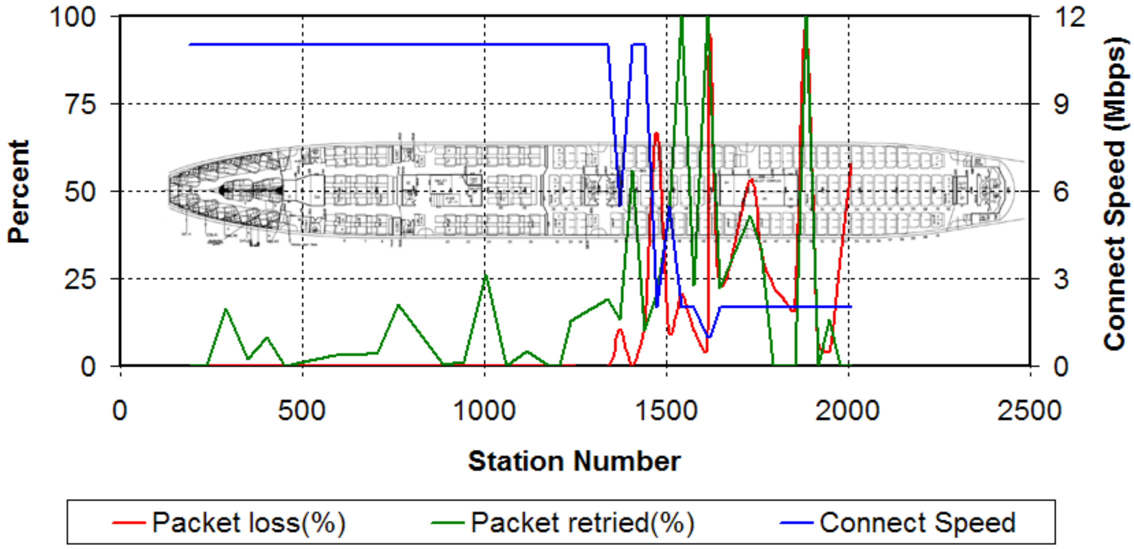

Figure 24: 802.11b wireless network performance at the upper network layers within a B-747 fuselage (main deck).

4.4.3 Boeing 777-200

4.4.3.1 Airplane configuration

This airplane was parked on the ramp in front of maintenance hangars, with no other maintenance underway in the cabin. Sweeper outlets and lighting power was available, but no other systems were operational, including air handlers. Since the airplane was in the sun, all doors were open for ventilation and cooling. The airplane had three classes of passenger accommodations, as shown in Figure 25.

Examination of the cabin interior led to suspicions that the furnishings (stow bins, bulkheads, etc.) were manufactured with carbon-impregnated composite materials. Carbon-based composites are increasingly common in interiors, and generally are considered to be as reflective as metals at the frequencies of interest for wireless networking.

4.4.3.2 Tests performed

Tests performed included the standard suite: RF power propagation, network throughput, and network upper-layer performance. Since more time was available on this airplane, some additional interesting tests were conducted, including:

1. Mounting of an AP in a stow-bin to test whether the carbon composite construction is a major factor, reported in Section 4.4.3.5 below.

2. Measurement of network performance in the e-bay and cargo hold, primarily to help determine if propagation models need to account for cargo hold loading when attempting to determine propagation behavior, reported in Section 4.4.3.6 below.
3. Channel contention testing for 802.11b networks, reported in Section 4.4.3.7 below.
4. Testing 802.11g networks, reported in Section 4.4.1.2 above.
5. A seat-by-seat mapping of network performance in first and business class seating, reported in Section 4.4.1.2 above.

4.4.3.3 Test equipment configuration

The 802.11a/b RF power and network testing was performed with the Orinoco AP and client sets. The 802.11g testing used the NetGear AP and client equipment, and the same-channel testing was performed using the Orinoco and LinkSys APs with Orinoco clients. For the single-AP testing, the APs were mounted on the bulkhead between the footrests of seats 1E and 1F, on the aircraft centerline and at the forward end of the passenger cabin. For the channel contention testing, the first AP was installed as described above, and the second AP was mounted on top of the backrest of seat 43F near the centerline of the aircraft in the extreme aft. During contention testing, client laptops were initially operated in the appropriate cabin segment (same segment as the associated AP). When results became known, they were moved into the galleys beyond the APs in an effort to ensure that the clients were not the cause of the interference problems.

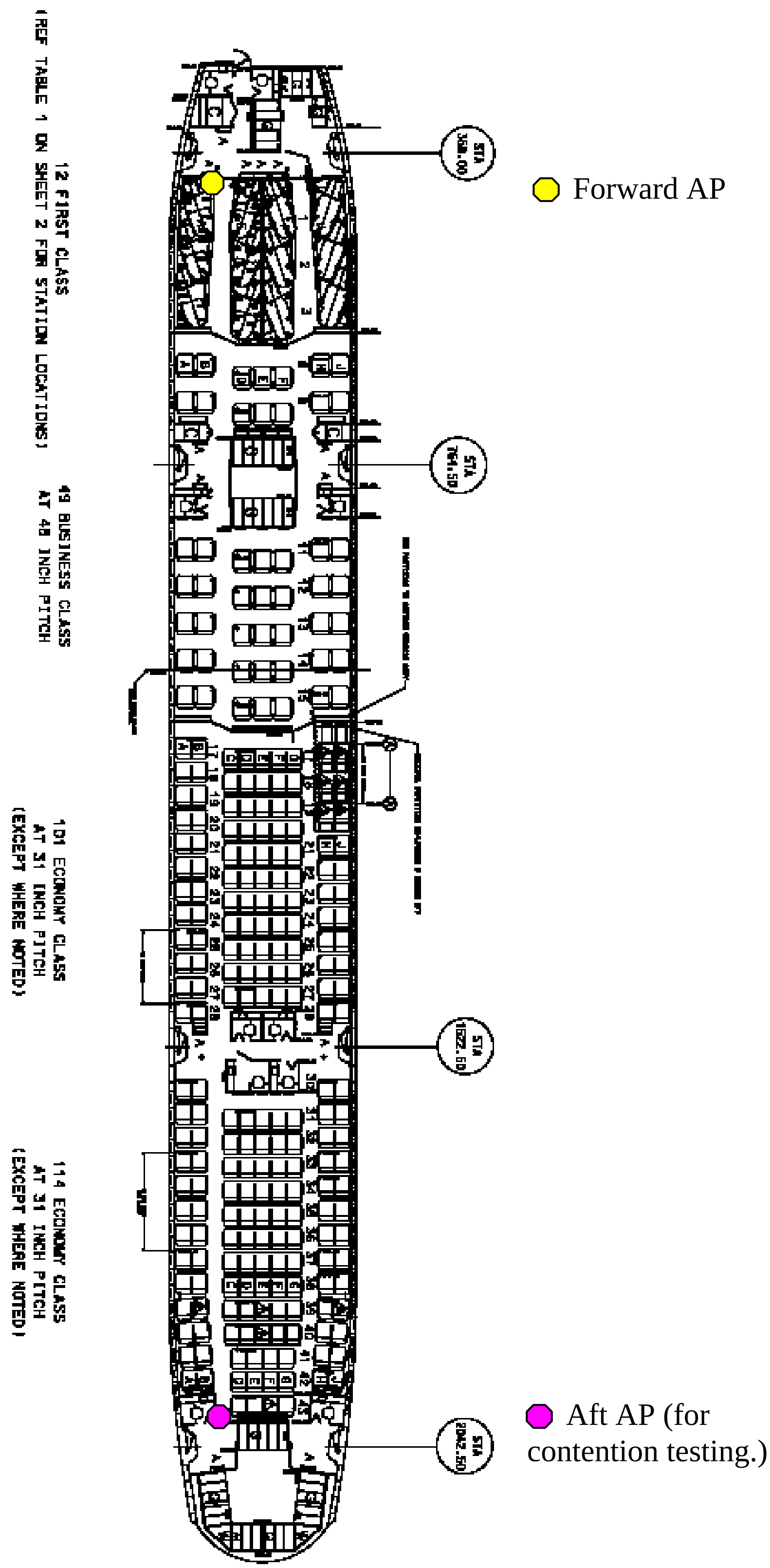

Figure 25: LOPA for the B-777-200, three-class airplane tested.

4.4.3.4 Standard suite test results

The results of the standard test suite are presented below. For guiding commentary, refer to the section on B-747 testing.

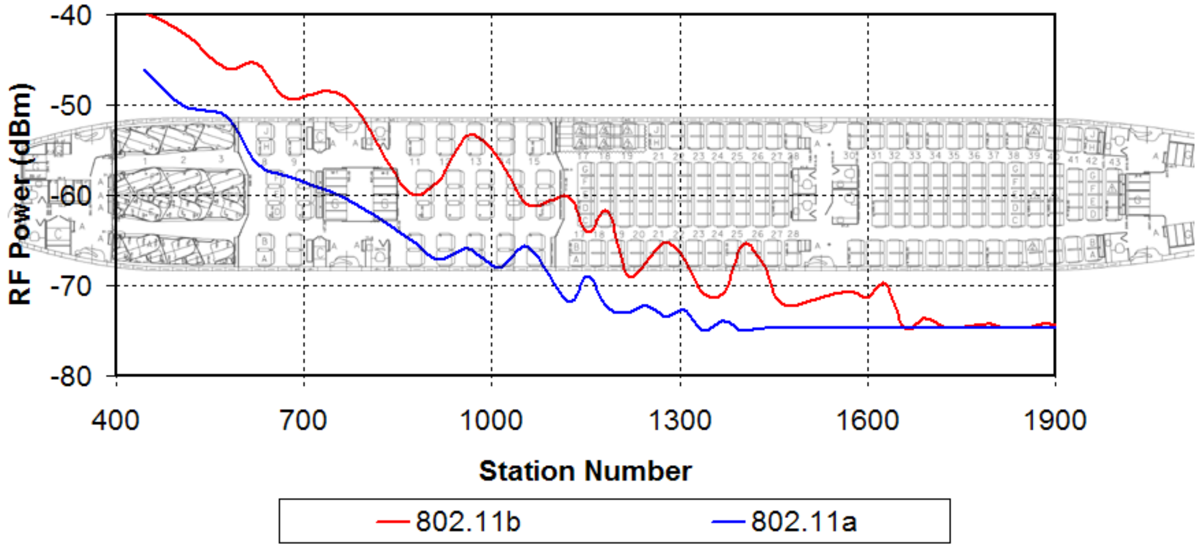

Figure 26: Measured RF power of 802.11a (5GHz) and 802.11b (2.4GHz) wireless networks along a fuselage of a B-777.

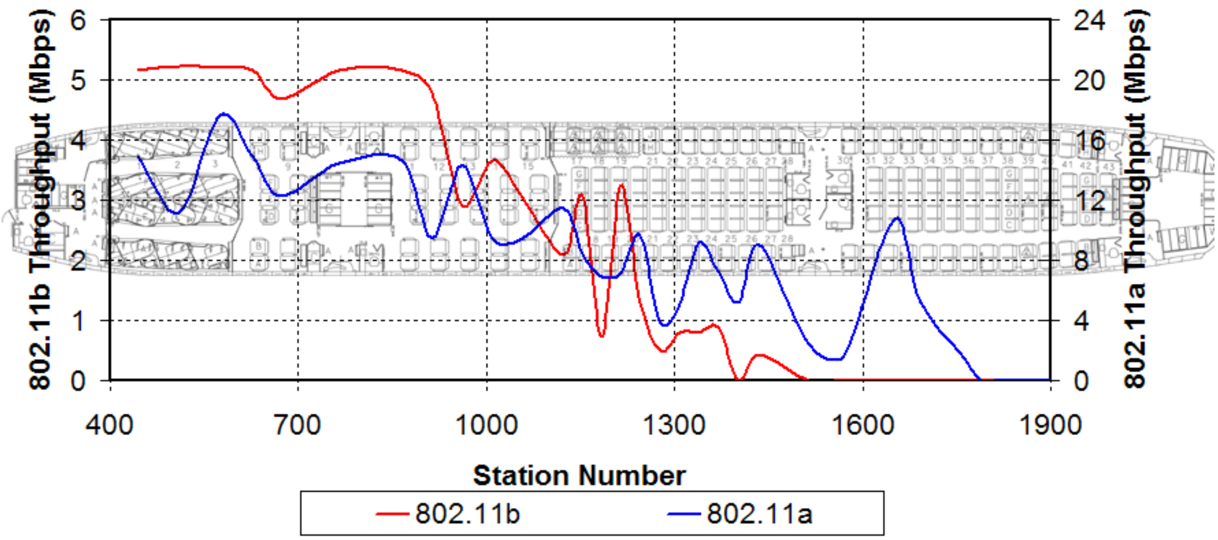

Figure 27: Measured 802.11 wireless network throughput within B-777 fuselage.

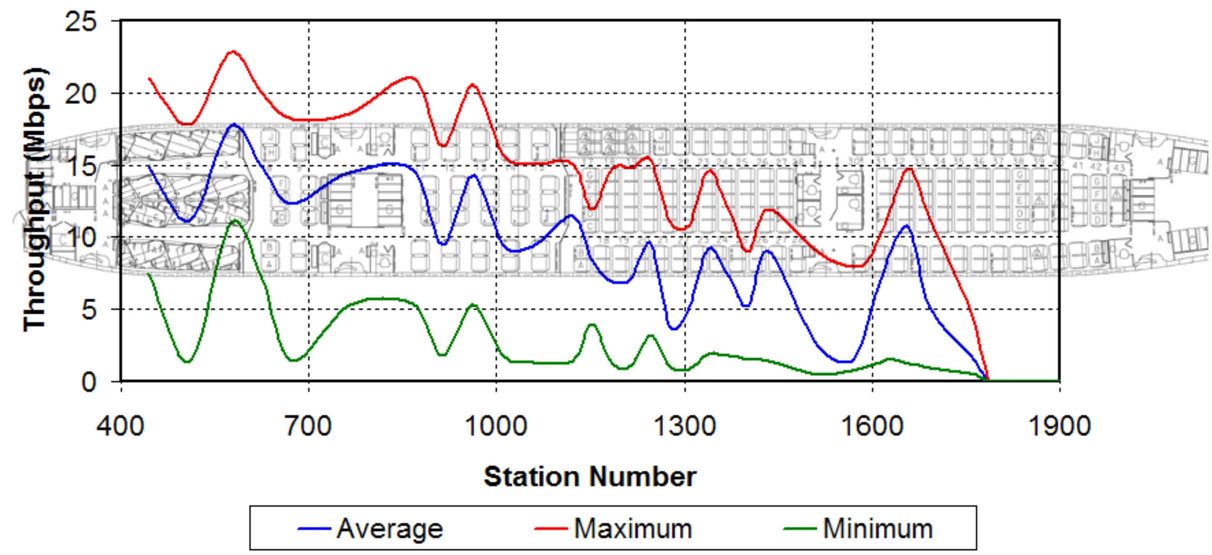

Figure 28: Variance of 802.11a wireless network throughput within a B-777 fuselage.

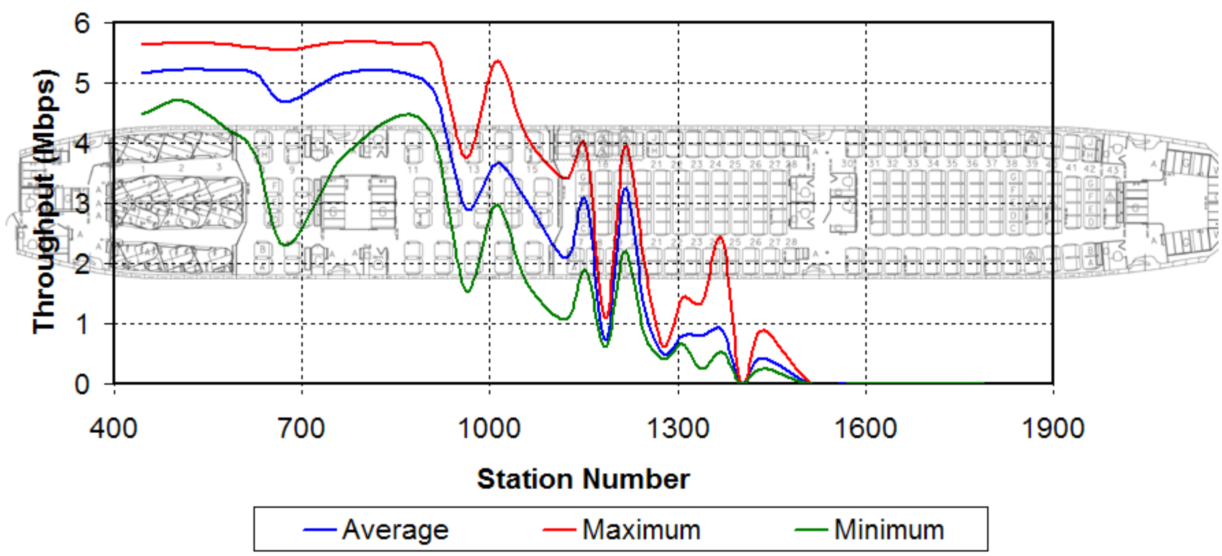

Figure 29: Variance of 802.11b wireless network throughput within a B-777 fuselage.

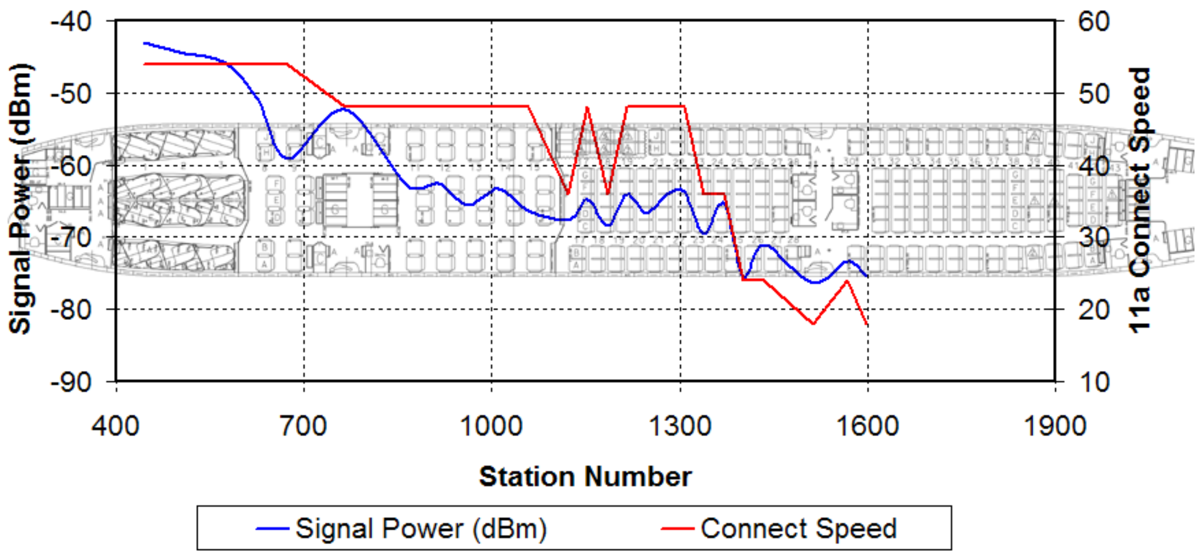

Figure 30: Connect speed vs. signal power for 802.11a wireless networks within a B-777 fuselage.

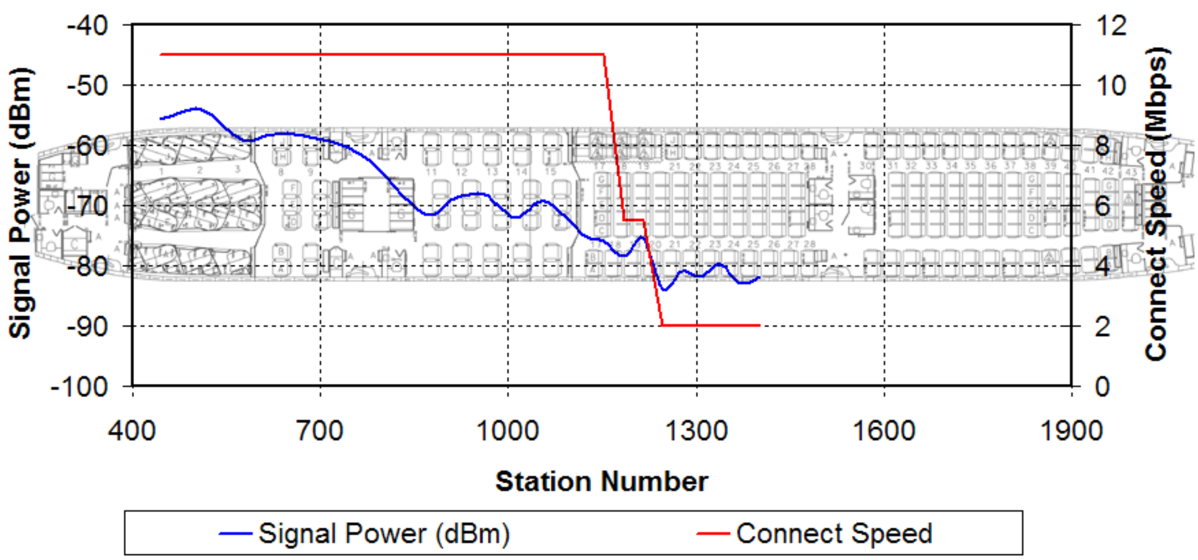

Figure 31: Connect speed vs. signal power for 802.11b wireless networks within a B-777 fuselage.

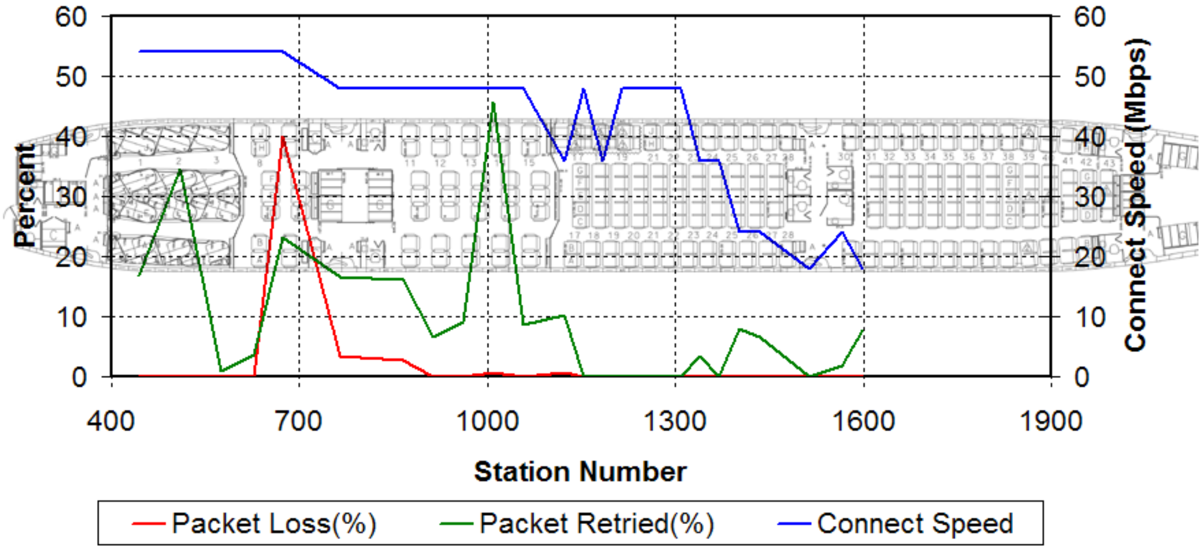

Figure 32: 802.11a wireless network performance at the upper network layers within a B-777 fuselage.

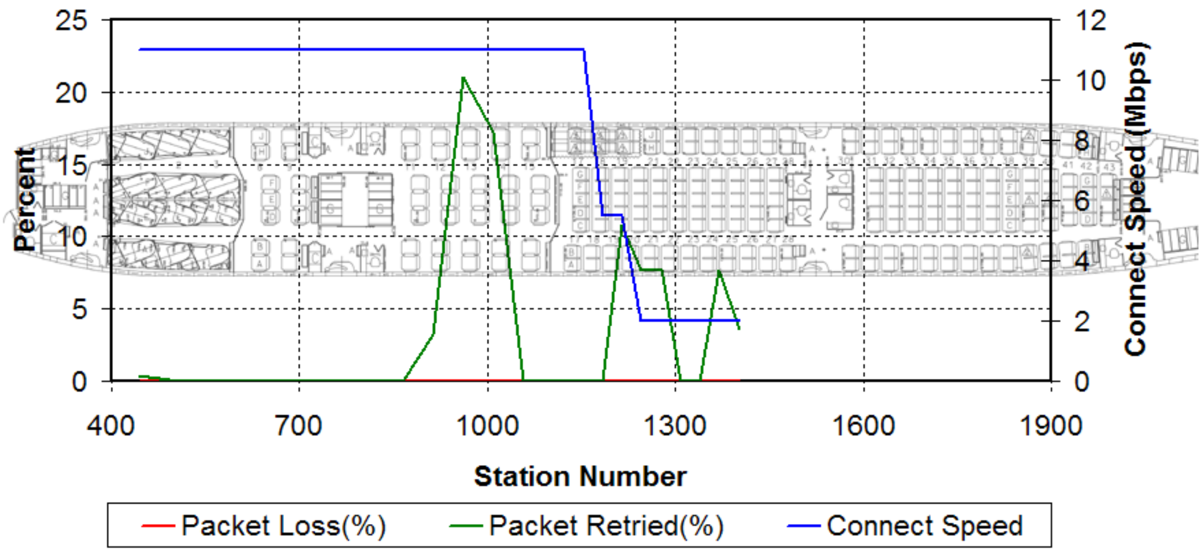

Figure 33: 802.11b wireless network performance at the upper network layers within a B-777 fuselage.

4.4.3.5 Impact of carbon composite cabin interiors

To test the impact of carbon composite upon network performance, signal strength of an AP out in the open, and placed into one of the centerline stow bins was measured. This experiment resulted in the signal strength decreasing by about 10dB, a fairly significant amount. Duplicating the same experiment in a B-747 without the carbon composite bins yielded only about 2dB of loss. Presumably mounting the AP antennas in the crown or above the headliner between the center stow-bins would result in similar losses of signal power for either material.

4.4.3.6 Impact of cargo hold on wireless network functionality

The main deck floor of the B-777 did not appear to be carbon composite. On this airplane, a test of signal strength in the e-bay and forward cargo hold was also conducted. Testing was accomplished using the AirMagnet tool. While testing down in the e-bay and cargo hold, all hatches and doors were closed and latched. The testing showed that very little signal was lost between the passenger cabin and the cargo hold, suggesting that cargo hold loading (lossiness of cargo) could be an important contributor to the overall performance of airborne 802.11 networks.

Another aspect is that the wingbox (attachment point of the wings to the fuselage and main fuel tank) separates the forward and aft cargo holds. One could presume that having a structural interruption in the center of the cargo hold might account for some of the interesting dips and rises that were observed in the signal strength and throughput measurements along the fuselage. Unfortunately, any authoritative information on the exact locations of the wingbox and other structural members was not available during the course of this investigation to guide this analysis.

4.4.3.7 Channel contention with 802.11b networks

Since only three non-overlapping channels exist in the ISM bands used by 802.11b wireless systems, much attention is usually focused upon the layout of network topologies such that channel contention (the problem of multiple APs using the same channel within radio range of each other) is minimized or eliminated. In airborne systems, the potential for network loading to increase to the point where an individual AP is overloaded is present, given the number of passengers common on commercial aircraft today. Thus, it may be highly desirable to install more than three APs within a cabin.

This test was to determine the worst-case contention envelope for an airframe. In this context, "worst-case" means that the cabin was essentially unpopulated, and thus the radio propagation was tending towards the best performance possible inside the airframe. Recall that 2.4GHz is the resonance frequency of liquid water, and thus is readily absorbed by humans, food, and other materials that have a significant water component. Using an AP mounted at the leading edge of the cabin between seats 1E and 1F (as described above) and an AP mounted at the tail of the cabin on the back of seat 43F, two independent 802.11b networks were operated on a common channel.

Surprisingly, the contention was absolute; meaning that the total throughput for a single channel was divided between the two APs. (This is the usual result when attempting to operate two APs on the same channel; the total channel capacity is just divided between the two.) Since neither the spectrum analyzer nor the network clients could detect the forward AP during propagation and throughput tests, it was assumed that the two APs would not be able to contend with each other; and yet they did. This occurred regardless of where the associated clients were located. Placing the clients in the galleys beyond the APs in an attempt to limit the effect of placing a radio in the middle of the cabin yielded the same results.

The dynamic range of 802.11 radios is well known, and leads to obvious problems with channel contention when attempting to re-use frequencies within limited areas. The APs that were used for this project did not have firmware-adjustable radio power settings (and APs with adjustable power radios frequently do not work as advertised), and are presumed to be transmitting at the FCC maximum legal power of 100mW. For specialized applications such as airborne networks it is not unreasonable to assume that the radios can be adjusted to have an output power suitable for use within the cabin, and that the channel contention problem may be solved using lower AP power output. For the client, however, this solution may not be sufficient. Few clients have power adjustment settings; and even fewer passengers would have the knowledge or administrative privileges to do so. Since a passenger might associate with an inappropriate AP, it is difficult to assume that the channel contention problem has an assured solution. Further work is required in this area.

4.4.4 Boeing 767-300

4.4.4.1 Airplane configuration

The Boeing 767 airplane was located within a hangar, with significant maintenance activities being performed during conduction of the testing. Maintenance included removal and replacement of an engine, activity within the flight deck, some type of riveting activity that required personnel both within the cabin and above the fuselage, and installation of drainage systems below the floor. The cabin was somewhat disassembled; the entire right-hand aisle had the ceiling panels removed for the riveting activity, seat rows 21 and 22 (approximately station 1000~1100) were removed from the floor track, and the seats were stacked on top of seat rows 24 and 25 (station 1100~1200). The floor panels at seat rows 21 and 22 (station 1000~1100) were removed for the drainage system installation. Numerous maintenance personnel were present and moving about the cabin during the testing. Door 1R was open.

4.4.4.2 Tests Performed

The standard suite of tests was performed.

4.4.4.3 Test equipment configuration

The Orinoco AP-2000 and Orinoco a/b client cards were used for all throughput and RF power testing. The AP was installed on top of the back of seat 1E (approximately station 440).

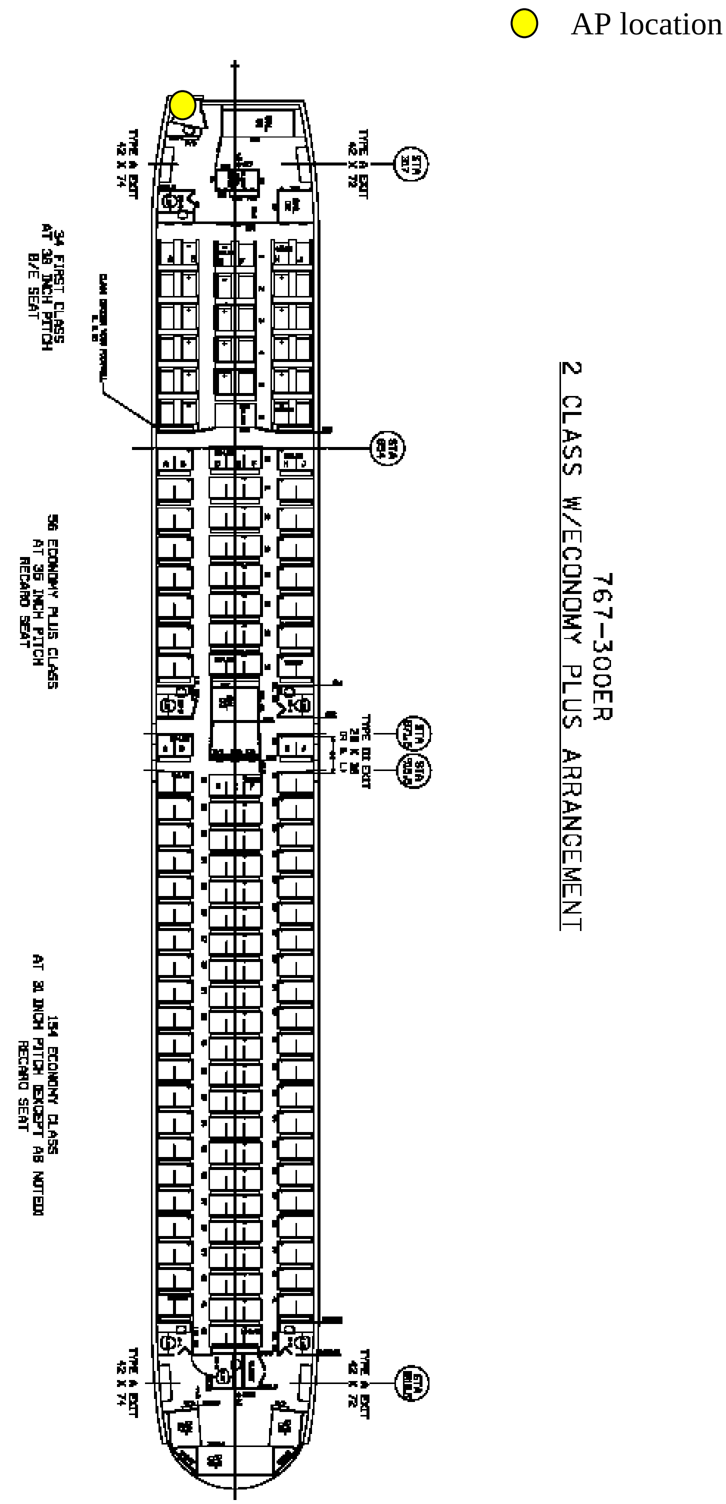

Figure 34: LOPA for B-767-300 airplane under test.

4.4.4.4 Standard suite test results

The results of the standard test suite are presented below. For guiding commentary, refer to the section on B-747 testing.

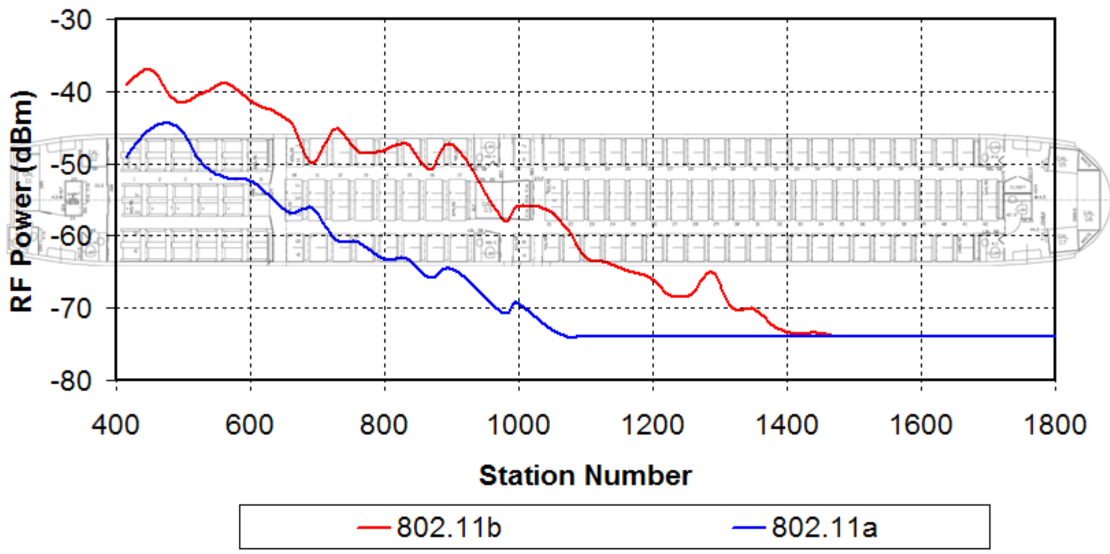

Figure 35: Measured RF power of 802.11a (5GHz) and 802.11b (2.4GHz) wireless networks along a fuselage of a B-767.

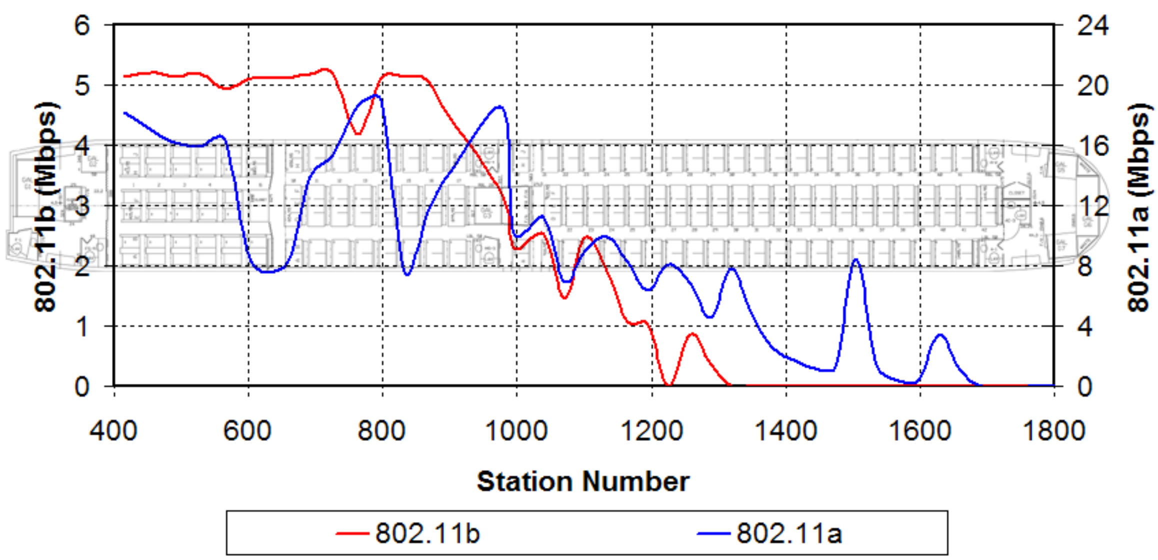

Figure 36: Measured 802.11 wireless network throughput within a B-767 fuselage.

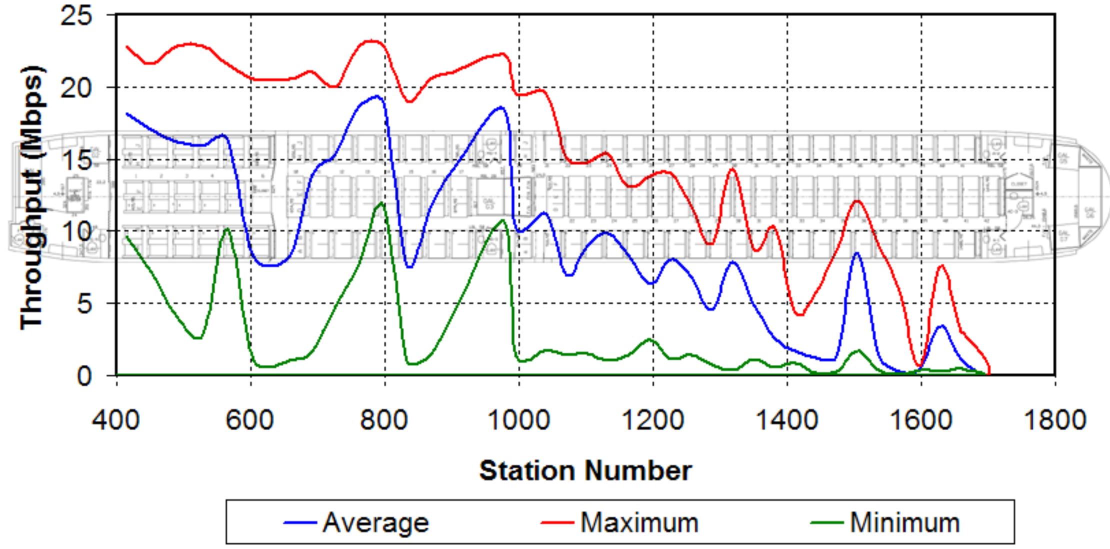

Figure 37: Variance of 802.11a wireless network throughput within a B-767 fuselage.

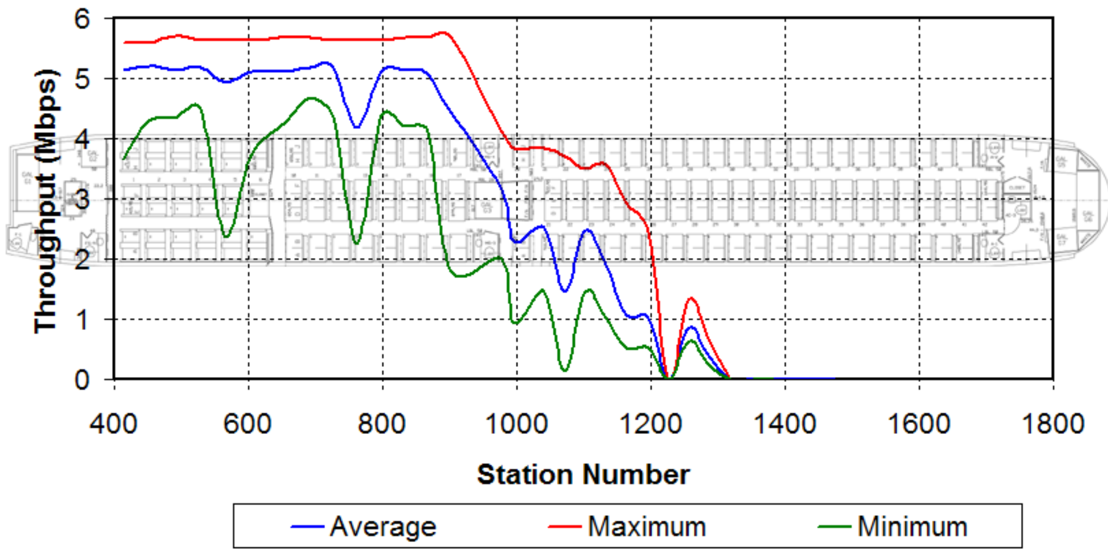

Figure 38: Variance of 802.11b wireless network throughput within a B-767 fuselage.

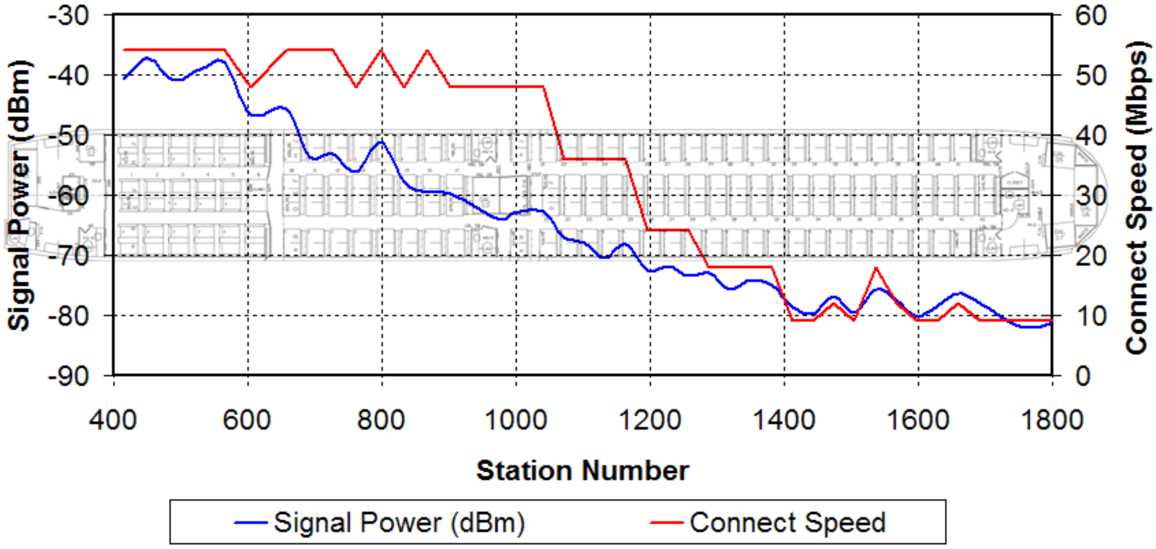

Figure 39: Connect speed vs. signal power for 802.11a wireless networks within a B-767 fuselage.

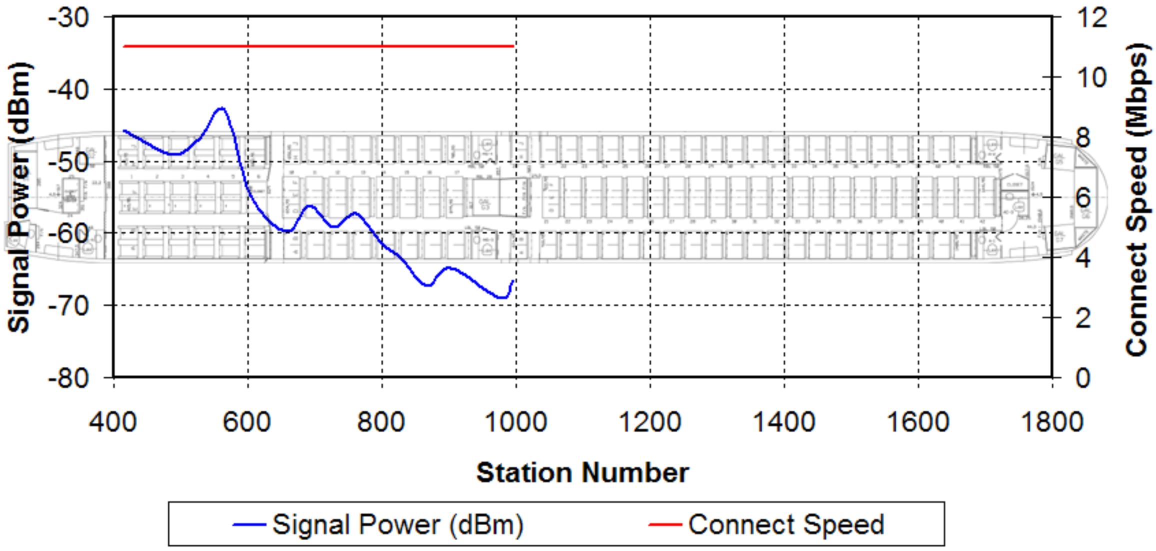

Figure 40: Connect speed vs. signal power for 802.11b wireless networks within a B-767 fuselage.

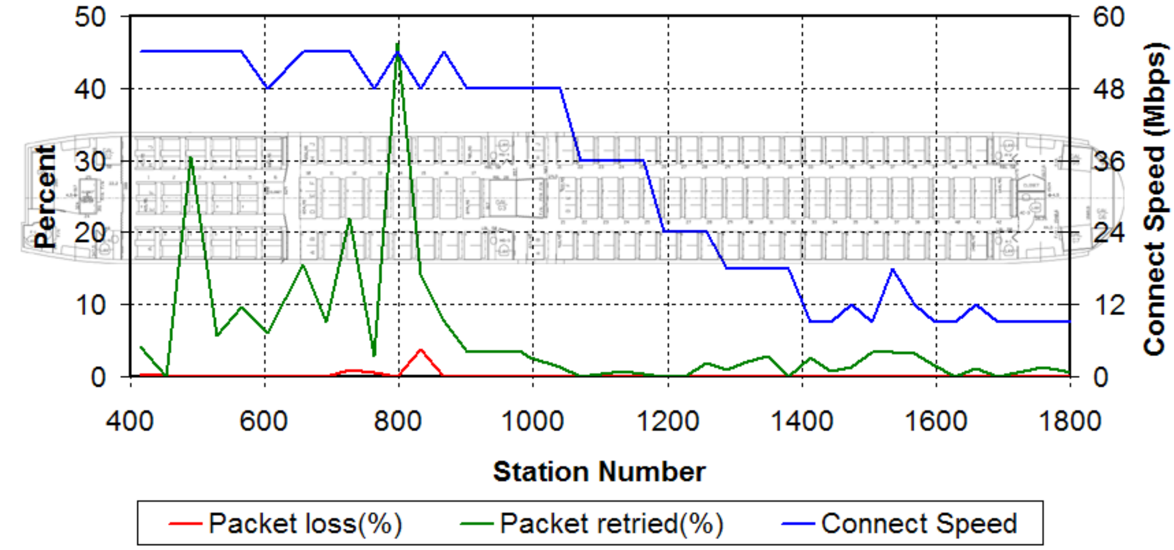

Figure 41: 802.11a wireless network performance at the upper network layers within a B-767 fuselage.

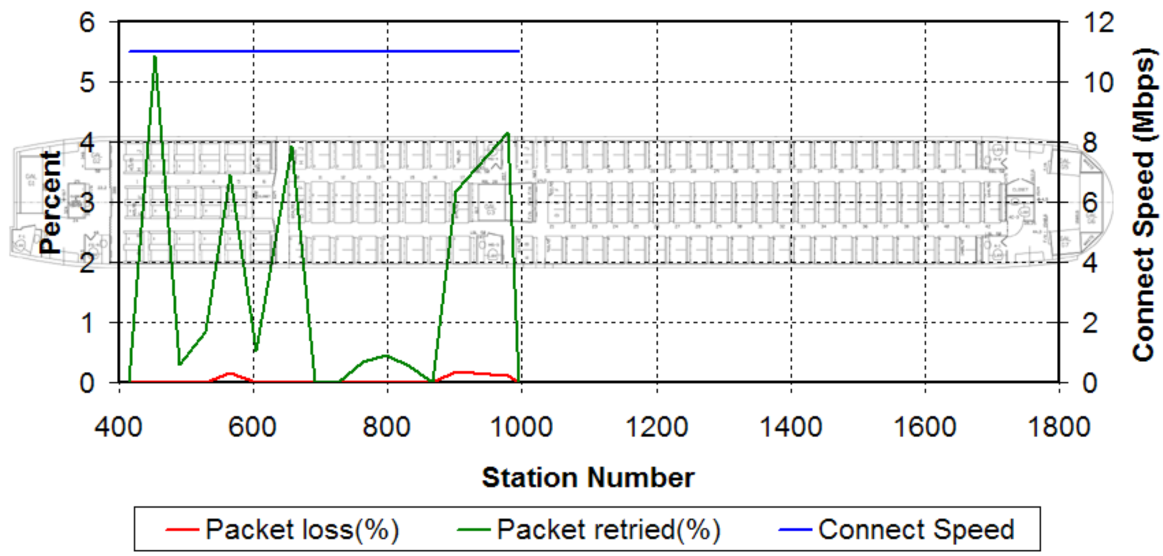

Figure 42: 802.11b wireless network performance at the upper network layers within a B-767 fuselage.

4.4.5 Airbus A320-200

Originally not an airplane considered for testing, an A320 became available for testing by fortuitous circumstance. A NASA team interested in the impact of Ultra Wide-Band (UWB) equipment upon avionics systems was scheduled to be testing the A320 one evening, and some time was available to test the airplane, and explore the impact of UWB upon 802.11 networks as well. Time was, however, extremely limited, and the testing conducted was not as in-depth as desired.

4.4.5.1 Airplane configuration

The A320 was parked in a hangar, with some maintenance being performed on an engine. Doors 1R and 4L were open. The cabin was complete, with only the NASA team (2 people) and the ERAU team (three people) present during the testing.

4.4.5.2 Tests performed

The reason for testing on the airplane was primarily to determine the impact of UWB systems upon 802.11 wireless networks. It was possible, however, to set up the equipment and perform most of the testing in the limited time available, with the exception of the RF power propagation. The UWB equipment was exercised at various pulse repetition frequencies (PRF) and power levels.

4.4.5.3 Test equipment configuration

The Orinoco AP-2000 and Orinoco a/b clients were used for all throughput testing. The AP was mounted on the back of seat 26C. The UWB equipment was located in the forward galley, with the standard-gain horn on a long coax cable.

4.4.5.4 Standard suite test results

The results of the standard test suite are presented below. For guiding commentary, refer to the section on B-747 testing.

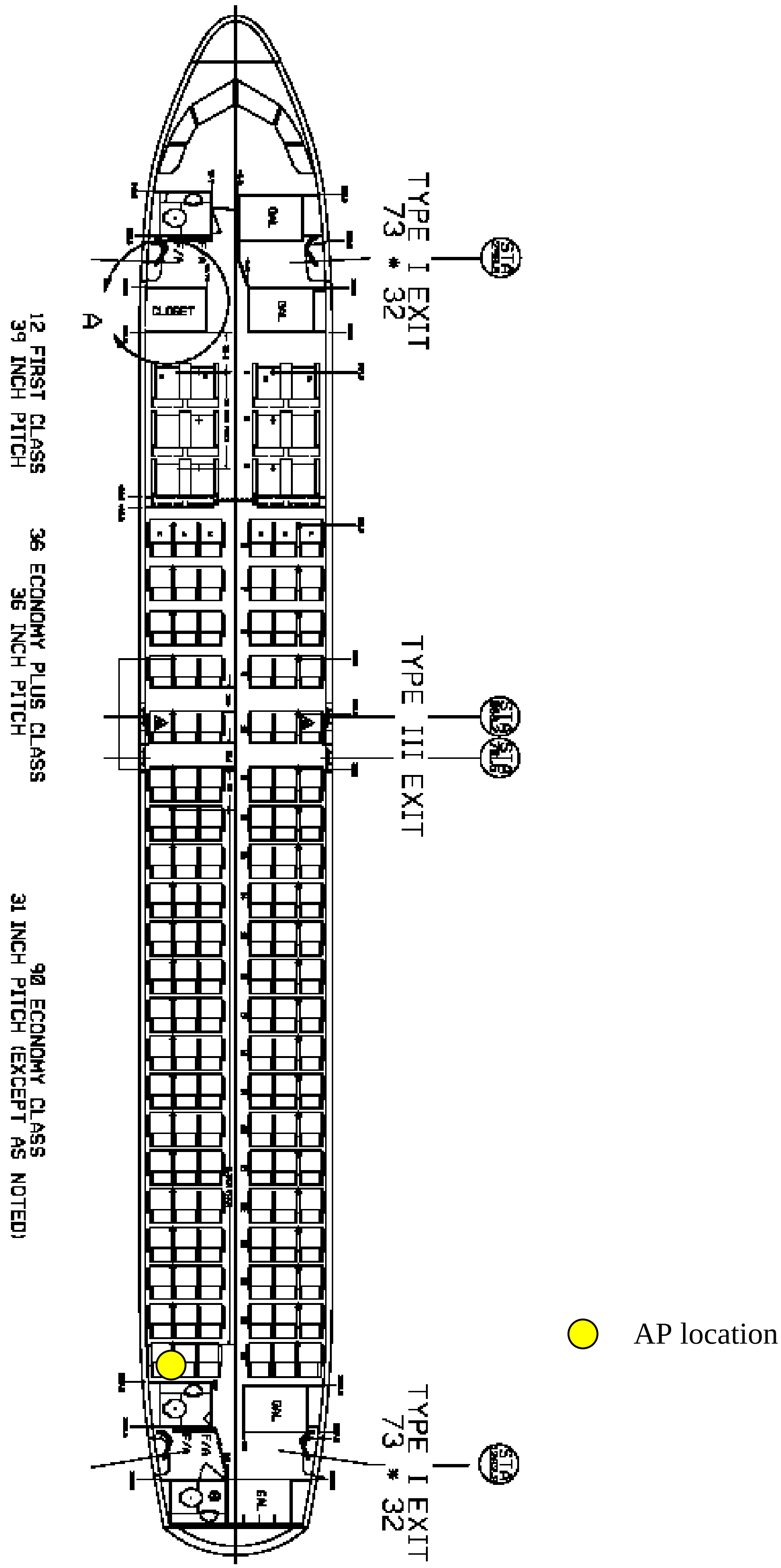

Figure 43: LOPA for the A320-200, two-class airplane tested.

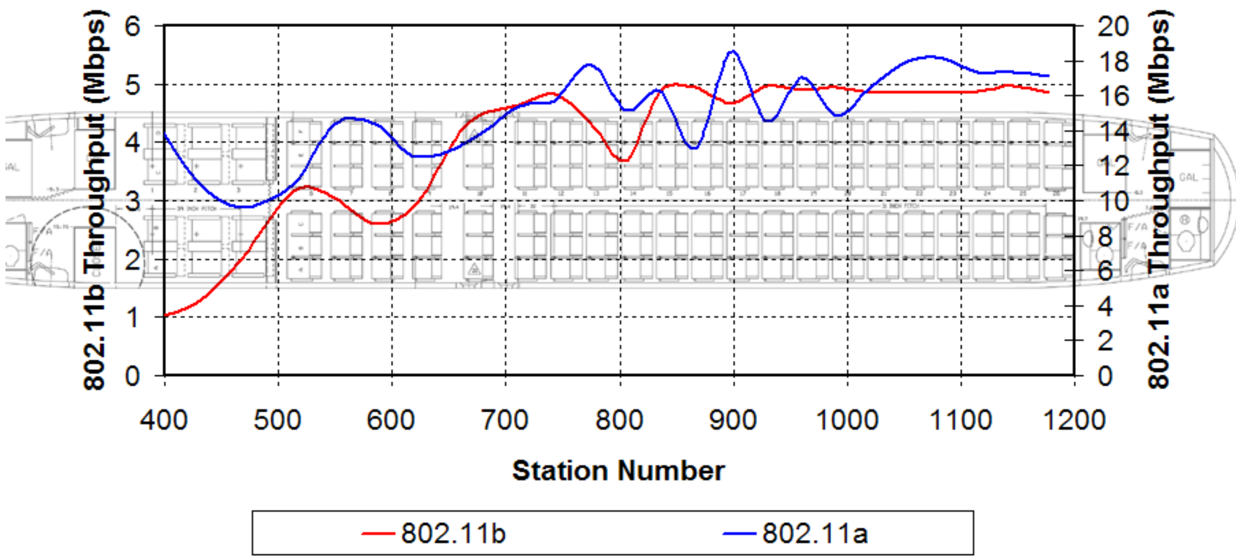

Figure 44: Measured 802.11 wireless network throughput within an A320 fuselage.

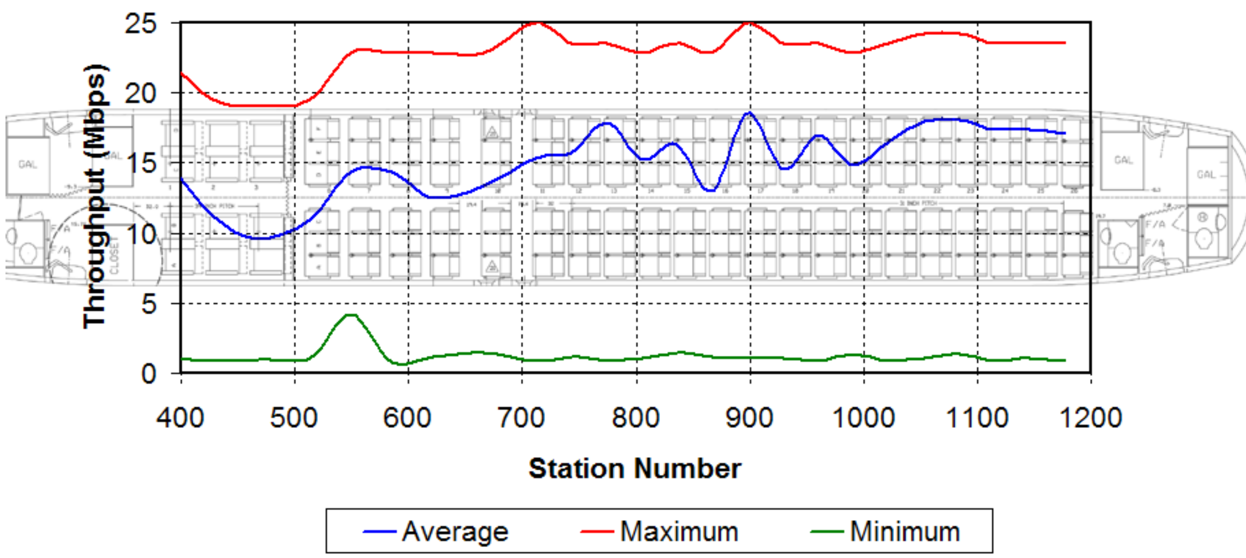

Figure 45: Variance of 802.11a wireless network throughput within an A320 fuselage.

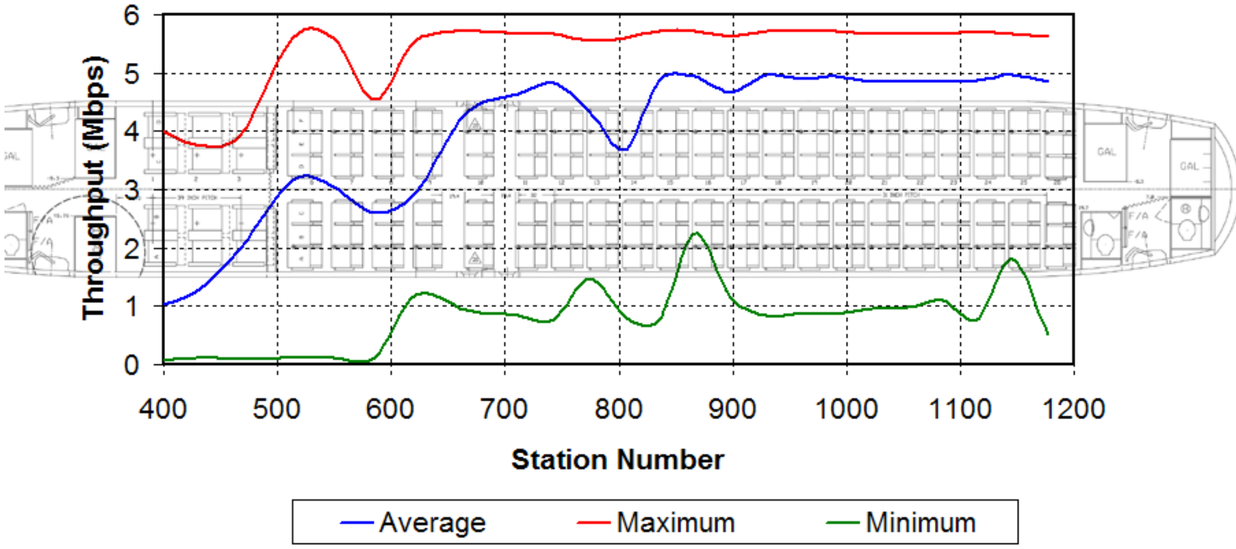

Figure 46: Variance of 802.11b wireless network throughput within an A320 fuselage.

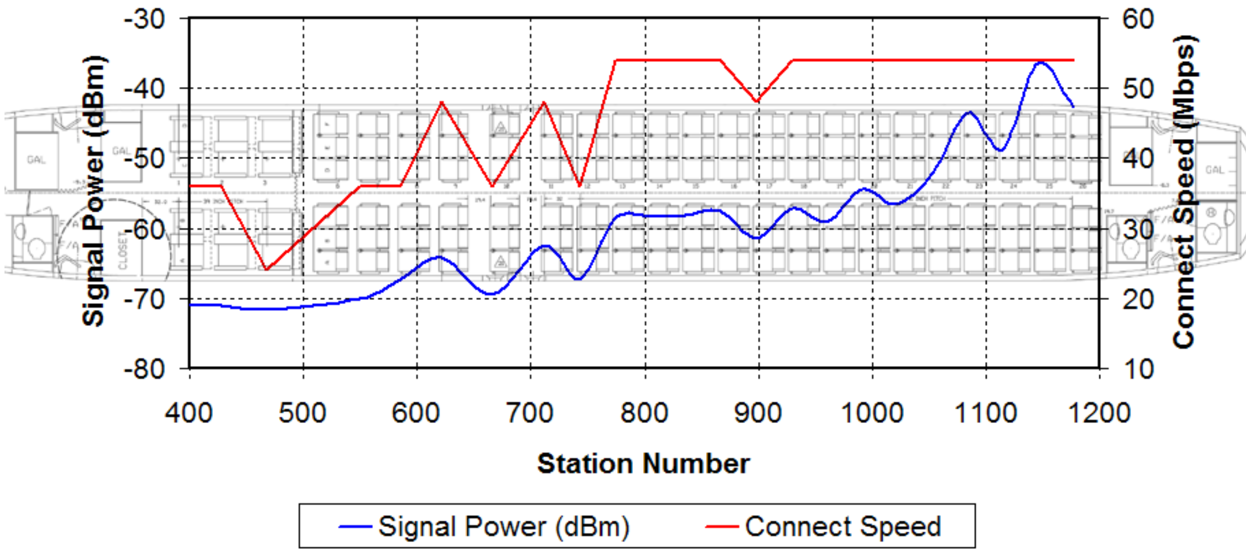

Figure 47: Connect speed vs. signal power for 802.11a wireless networks with an A320 fuselage.

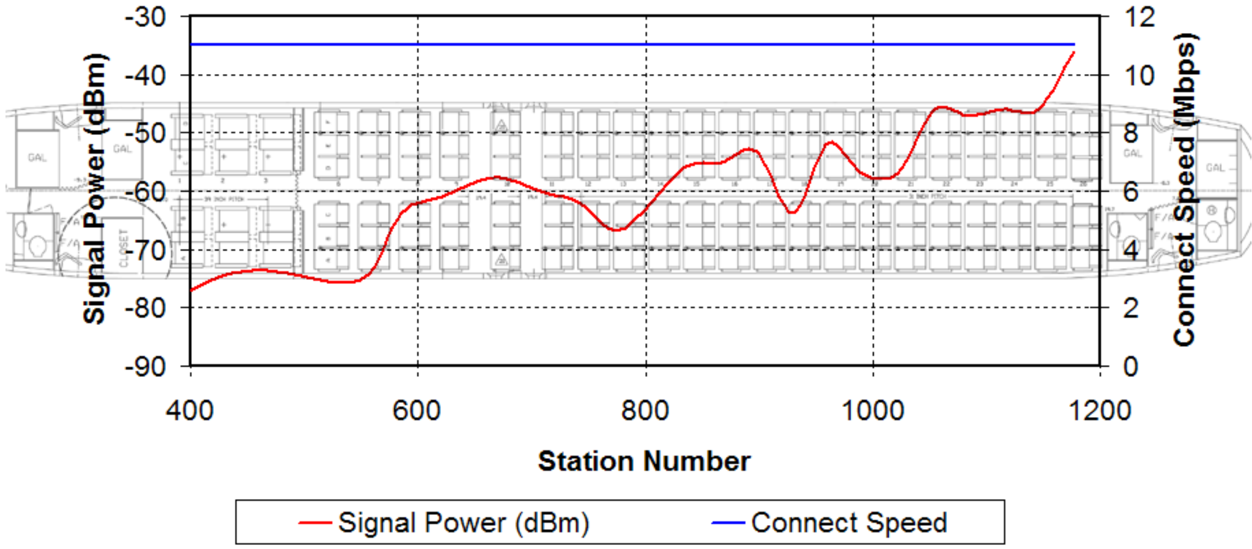

Figure 48: Connect speed vs. signal power for 802.11b wireless networks within an A320 fuselage.

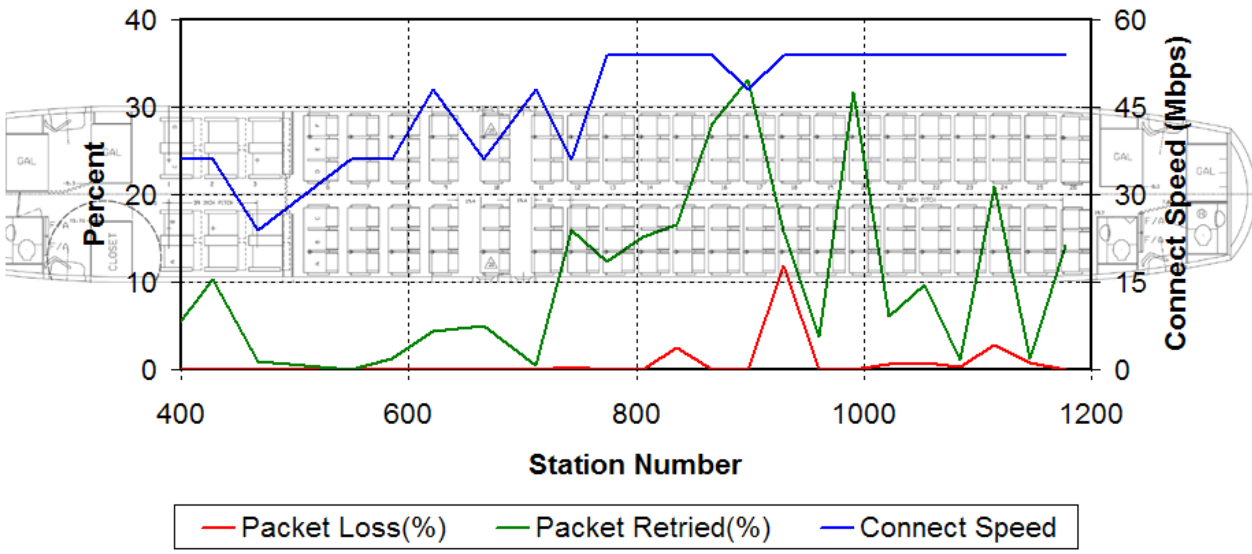

Figure 49: 802.11a wireless network performance at the upper network layers within an A320 fuselage.

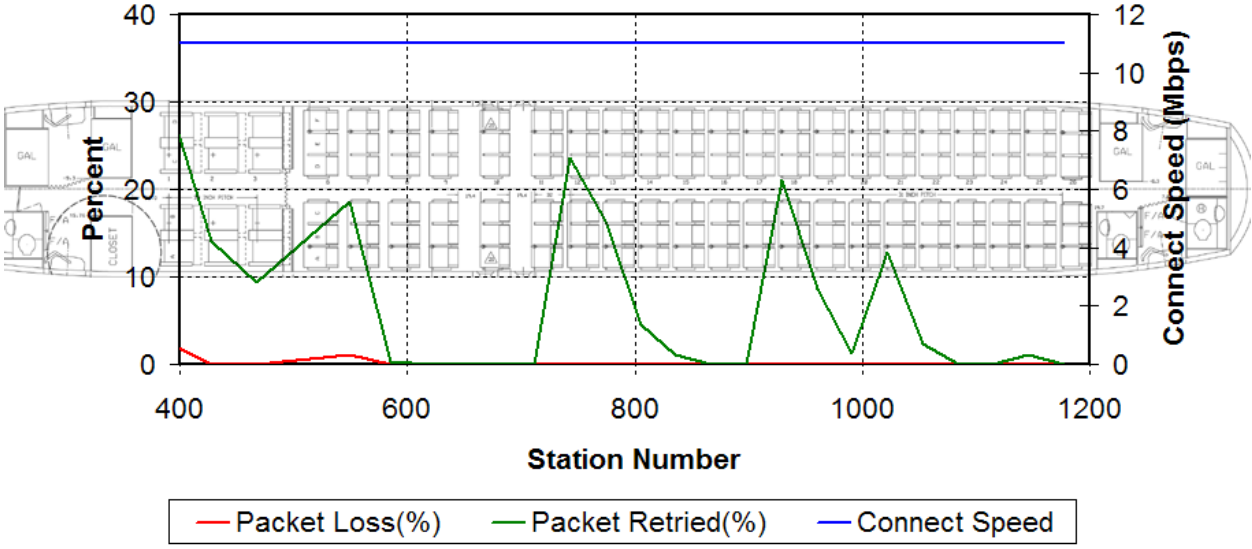

Figure 50: 802.11b wireless network performance at the upper network layers within an A320 fuselage.

5 Conclusions

This research project resulted in some unexpected findings, and confirmed a number of expectations.

5.1 Equipment Selection for Airborne Applications

One author (F.A.W.) has quite a bit of experience with 802.11 WLAN equipment, but has never spent much time assessing the spectral signature of WLAN equipment. After discovering problems with multi-AP throughput testing, a study of the spectral footprint of each radio was conducted. The results of that examination show that not all radios are equivalent. One obvious conclusion is: *if multiple radios are expected to be used, attention must be paid to the quality of the spectral signature of the equipment.* Equipment selected for airborne applications would be of high quality (one would hope), and perhaps this finding is of less value than it appears.

5.2 RF Power Propagation within Aircraft Cabins

Due to the high prevalence of metallic structure in modern aircraft, it is no surprise that the interior of the cabin can be compared to a lossy reverberation chamber. In fact, a 757 airplane has been tested, and found to have a cavity $Q \cong 1000$ at 2.4GHz and $Q \cong 1800$ at 5GHz [4], which is much higher than might have been anticipated. Note that those measurements were performed on an airplane configured for transport, thus had no interior cabin furnishings, which undoubtedly reduced the loss significantly. Nonetheless, one would expect that the propagation of the RF power within the cabin would show less loss than the equivalent free-space loss due to the spherical wavefront. A comparison of the two losses, as in Figure 51, shows that the losses in the cabin are in fact higher than the expected space loss.

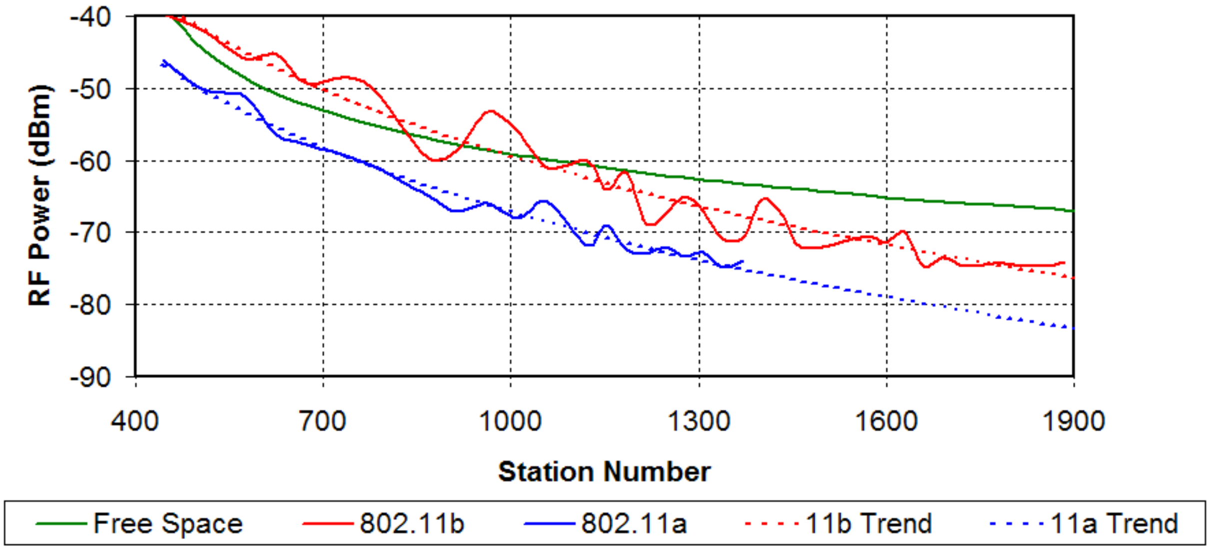

Figure 51: Comparison between free-space loss and measured loss within a B-777 fuselage.

These results indicate that the cabin furnishings do block, shield or absorb a certain amount of the radiated energy.

5.3 Wireless Network Performance in the Cabin

With the assumption that the wireless networks are designed and installed for passenger use, the results of the network performance testing indicate that the WLAN performance would be easily within expectations for passengers within the same cabin segment as the AP. Expecting a single AP to provide adequate performance throughout the cabin is, perhaps, an unrealistic expectation.

Looking at a robust design from the opposite perspective, that of preventing overloading of a single AP by adding more APs to share the load, the results of this testing were a little less encouraging. The channel contention experimentation performed on the 802.11b WLAN system indicated that the two co-channeled APs would still contend for bandwidth, in spite of being installed at opposite ends of the airplane.

It is important to emphasize that all testing performed for this project were upon airplanes with essentially no personnel inside the cabin, relative to standard loads during commercial operation. It is probably safe to assume that crew, passengers, associated luggage, and cargo would significantly alter the propagation profile, and probably significantly increase the loss. In other words, frequency re-use may become feasible when the airplane is full of people, due to the lack of end-to-end propagation.

6 References

[1] Gerald Fuller, Eagles Wings Incorporated, private communication, June 2003.

[2] AirMagnet Laptop Analyzer Version 4.0, http://www.airmagnet.com/products/laptop.htm.

[3] Truong Nguyen, "RF Loading Effects of Aircraft Seats in an Electromagnetic Reverberating Environment", NASA/TM-2000-210626, NASA Langley Research Center, Dec 2000.

[4] Mark Johnson, Michael Hatfield, Mike Slocum, et.al., "*Phase II Demonstration Test of the Electromagnetic Reverberation Characteristics of a Large Transport Aircraft*", Dahlgren Division, NSWC, Sept 1997.

[5] NetIQ Chariot Software, Version 5, http://www.netiq.com/products/chr/default.asp.

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14. ABSTRACT

An examination of IEEE 802.11 wireless network performance within an aircraft fuselage is performed. This examination measured the propagated RF power along the length of the fuselage, and the associated network performance: the link speed, total throughput, and packet losses and errors. A total of four airplanes: one single-aisle and three twin-aisle airplanes were tested with 802.11a, 802.11b, and 802.11g networks.

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