



KNUWAVE DESIGN INCORPORATED

80A Nashua Road, Pepperell, MA 01463
www.knuwave.com

Issues and Options for Wireless Local Area Networks in Residential Structures

Den Connors
Principal Consultant
Knuwave Design

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Inadequate Residential Coverage with Wi-Fi

Wireless Local Area Networks based on the 802.11 standard are now widely incorporated into individual residences. Better known as Wi-Fi, the installation and operation of 802.11 wireless technologies by non-technical users has produced mixed results. Knuwave Design has had a great deal of experience in assisting in a large number of what you would expect to be relatively simple installations and this paper describes the issues encountered.

Most of the RF-related problems stem from the inclusion of single wireless access points (WAP) in existing homes and small buildings, where an “obvious” site for the WAP node is found to be inadequate. Unforeseen multi-path effects, simple reflections, unusual absorption and attenuation, and even RF receiver overload¹ have been found to contribute to severely reducing effective data rates and spatial nulls². Knuwave has found that as many as 65% of homes will need additional Wi-Fi support to provide for applications today and in the future, to allow for “seamless mobility” and consistent throughput levels required for ubiquitous applications coverage.

Manufacturers and installers have typically tried the following solutions to address these “inadequate coverage” issues:

- (1) **Use spatial diversity³ (SD) transmission and reception on the WAP – multiple antennas as an example.** Spatial diversity is a key aspect of MIMO technology in 802.11n. This has been an available configuration on most of the off-the-shelf equipment typically found by Knuwave in the New England area. A few of the deep nulls can be improved upon by this technique, but for the majority of larger residences, this technique is inadequate.
- (2) **Use of a high gain antenna, connected to one of the antenna jacks on WAP devices configured with removable antennas.** Typically, one of the antennas is replaced by a directional antenna with 6 dB or 12 dB gain, and some areas of weak reception can be penetrated. This has been found to be a good solution for covering a remote area of the premises, where a single PC is located, but where cabling is difficult to run.
- (3) **Use multiple WAP devices or range extenders⁴ (up to 3).** Again, off-the-shelf equipment allows multiple devices to share the service set identifier (SSID). This technique has been the preferred solution for all of the residential coverage issues encountered to date by Knuwave, since both statically placed desktop PC units and portable notebooks can have complete coverage.
- (4) **One technique NOT employed by Knuwave has been to illegally increase the transmit power of the WAP devices, beyond the limits allowed by FCC part 15 operation.** In the three instances where Knuwave has been called in to

¹ RF receiver overload happens when a strong RF signal overloads the receiver. Overload could be from another signal source, an overwhelming reflected signal or a valid transmitter located too close to the WAP.

² Nulls are locations where reflected RF signals cancel each other out. Also it could be a dead spot caused by the inability of the RF signals to reach a location due to absorption or reflection of the signal.

³ Spatial diversity is separating antennas and transmitters by $\frac{1}{4}$ or more wavelengths to increase the probability of creating a usable path between two remote Wi-Fi devices.

⁴ Range extenders receive signals from the WAP and then rebroadcast the packets. This increases the range of the WAP, at the expense of reduced throughput and increased latency.

repair an RF problem, two of those instances were predicated on complaints by neighboring residences where the signals from the offending neighbor's WAP was stronger than the owner's WAP. Resolution of these issues involved reducing the power of the offending signal to legal limits, and then adding another WAP. In all cases, the increase in power provided no relief for the problem, unless the increase was coupled with moving the PC around, effectively "spatial tuning" the PC location to avoid deep nulls still evident after power gain was employed.

Coverage Solutions Can Create More Problems

The above-mentioned solutions can provide additional coverage, but not every time, and always add complexity to the installation. When a customer installs a WAP, the first physical placement tends to be behind or on top of a piece of furniture. If inadequate coverage is found, relocation of the WAP may be attempted, barring inadequate cable lengths or esthetic issues. As customers find a need to relocate laptops or desktop PC units, they will attempt to improve WAP's as in (1) above, or use of new hardware as in (2) through (4). An impasse is often reached at this time, where professional help is requested, or the system is abandoned. A new set of issues related to the more complex systems are created. Specifically:

- (1) Most often, the cost of the additional components and professional assistance are the first stumbling blocks. Whenever the cost for additional products reaches a figure of roughly 50% above the initial costs of equipment, we find resistance. For the purchase of a system of multiple PC units and WAP devices, adding additional components seems reasonable for some of our clients, but when a customer procures a single WAP to ADD wireless capability to existing systems, any costs greater than that incurred with additional CAT-5 or RF cabling are met with resistance.
- (2) When a more complex solution is put in place, often the actual throughput of actual connections proves to be inadequate for the desired uses. The simpler solutions usually add only several decibels of signal level to the attempted connection, so operation of WAP units near their noise floor occurs, and the user sees typically WAP connection rates as low as 1 Mb/s, and almost always rates not greater than about 20% of the rated capacity of the WAP.
- (3) Aggressive uses of the low-throughput solution also can cause failures in the system. Although Knuwave does not have much experience with applications that require a relatively small amount of bandwidth, such as gaming, we have repaired several installations using WAP connections for remotely "piping" music through households. The typical failure mode, audio connections dropping for several seconds at a rate of at least several times an hour is not atypical, and is completely unacceptable to the users. VoIP dropouts will cause disconnects, as noted below, and any interactive uses like gaming and file transfers will expose any latencies in the system, adding to the level of dissatisfaction.
- (4) The complexity of the solution can be prohibitive for those customers without RF backgrounds. We have found issues with antennas being placed on floors, and behind metal furniture, implying a lack of consumer knowledge of radio fundamentals. Wiring of multiple WAP devices to a router or add-on hub has

involved cable runs through areas not normally “considered” in professional installations, such as cabling being passed through door frames or windows.

One final comment must be made about customers attempting installation of off-the-shelf solutions. As soon as a coverage problem is found by a consumer, virtually all attempts to solve the problem with additional higher-gain antennas, higher power or simple re-location of antennas, simply create more problems. Matching an antenna system solution to a typical residence requires knowledge of RF propagation, spatial interference, and the properties of common household materials - requiring a user to install anything other than a WAP in fringe areas is asking for too much.

Notes on Throughput in Realistic Configurations

It is useful to understand the relationship between the true throughput of a radio channel and the distance between the two radios connected to each other.

The radio connection between the two transmitters and receivers tend to be symmetric, that is, both receivers tend to receive similar signal levels from the transmitters involved, due to antenna reciprocity (they both receive about the same signal level), and due to the power adjusting protocol used by the medium access control (MAC) protocols, which will match transmitter power levels. This would imply that signals should drop off due to the inverse-square-law: when the distance between two WAP units is doubled, the signal should decrease by a factor of four.

However, we typically see instead a “cliff”, where the two radios will see a throughput drop of perhaps 90% (54 Mb/s units with < 5 Mb/s throughput) when distance is increased by as little as 10-20%. This is due to two factors: complex signal transmission (interference) patterns, and MAC and network retransmission/retry protocols. The practical effect of this, especially in trailers and large rooms with any significant metal content (file cabinets, for example), is a very rapid drop in actual throughput. Actual data rates for a 54 MB/s WAP communication with as few as two PC units in an office trailer would range from a connection of 22 Mb/s to 1 Mb/s for one unit, a laptop, based on where the laptop was placed. The actual throughput for 1 Mb/s connection became < 50 kb/s, the same as dial-up!

Although these lower speeds may allow access to the Web and transmission of email, it is expected that these low speeds will be problematic, especially when the required low latencies and adequate throughput (200 Kbps) of live voice connections are factored in.

Extrapolating Design Experience into Wireless VoIP Residential Usage

The solutions chosen for residential operation of PC and notebook devices may prove inadequate when extended to allow “pedestrian mobile” operation of VoIP phones within residences. The issues are created when the user has an expectation that the wireless phone will behave inside and outside the residence in a manner analogous to a cell phone, or to current in-home wireless phone technology now in place and considered current art for consumer wireline connectivity.

None of the coverage solutions above will prove completely adequate for VoIP operation, because the 802.11 protocol, as currently implemented in off-the-shelf devices, do not allow for mobile hand-off from IP node to IP node. The VoIP connection will be lost as the user walks around the house or moves into the yard, as they may

already be accustomed to doing with their current wireless phone. This will restrict solutions to systems with a single WAP (and single IP address).

Further adding antennas of higher gain to a WAP will only allow the user to tailor a solution to extend range to particular areas, without regard to creating interference in residential neighborhoods, and without solving the problem of deep nulls caused by fringe interference patterns common to virtually all of the installations investigated to date by Knuwave.

Knuwave has attempted, without success, to increase effective radiated power in a few single-level residences in rural areas of North East Massachusetts. By employing high-gain antennas⁵ with off-the-shelf WAP devices, a gain of up to 12 dB was available, but did not improve the problem. However, by combining the higher gain with relocation of the PC, the problem was solved. Further investigation was made in several instances with a laptop and an omni-directional vertically polarized antenna. The following was found:

- (1) A typical residence has a complex combination of reflecting and absorbing materials of various sizes. Walls, appliances, windows, mirrors, large furniture all could be shown to be contributing to complex interference patterns.
- (2) The measured interference nulls for a single-antenna off-the-shelf WAP could very easily exceed 30 dB for several inches of orthogonal movement at a distance of less than 10 feet from the WAP.
- (3) Use of spatial diversity at the WAP (two antennas) usually improved the nulls to ~ 20 dB worst case, although the resultant patterns did cause further issues in other directions.
- (4) Research into current and past literature, primarily using the IEEE Transactions on Communications, provided strong mathematical confirmation of the probable existence of deep nulls inside a variety of experimental structures, with similar issues described in external environments at greater distances from the transmitter.

Knuwave has recently added installations in a number of government facilities, including temporary office trailers and structures identical to a private residence, and has found the issues to be virtually identical to those found in residences.

Recommendations for Installation of Residential Wireless Equipment

- (1) For single-room apartments and other small facilities, a single WAP should provide adequate coverage.
- (2) For a more typical residence, with multiple reflection and attenuation components and a resultant complex interference pattern, there are two options: (a) use multiple transceivers with a common IP address, and physical location close to the areas of intended operation and (b) use the new class of solutions based on hybrid technologies. These solutions capture the off-the-air 802.11 signal and place it onto existing phone wiring in the structure and sending it to the room that has the reception problem. Hybrid solutions should be optimal in this case,

⁵ Commercially available high-gain antennas are typically horizontally-polarized, omni directional coaxial collinear antennas with connectors compatible with the more popular WAP devices.

although use of a single WAP with dual (removable) antennas and a single high-gain antenna (replacing one of the supplied antennas) may also work. Since the latter would require aiming, and could still have null areas where voice connections would be lost, hybrid technology would seem the simpler and more reliable of the solutions.

- (3) For the complex residence, very typical of larger houses and older houses as found in New England, particularly if wireless VoIP is used, there two viable options: (a) multiple WAP units for PC operation, and restricting VoIP operation to stationary operation once a connection is made, or (b) using hybrid technology. In the first instance, the user would have to be given instructions NOT to move around once on the phone, and this type of operation may be counter to what is expected of the wireless VoIP capability.
- (4) Based on Knuwave experiences it is strongly advised NOT to offer the users a mix of multiple WAP devices, high-gain antennas and detailed instructions on how to move equipment around to minimize nulls, weak paths and multi-path problems. Return of the equipment should be a likely consequence.
- (5) DO NOT try to solve weak signal issues with higher power. This will overload adjacent PC units and VoIP phones, and will NOT resolve the deep nulls commonly seen by Knuwave in residential installation, and will create a myriad of interference problems in non-rural areas.

About Knuwave

Knuwave Design provides wireless networking engineering, design, development, and implementation consulting services. Knuwave's client base include of enterprises, agencies, and local governments that are interested in incorporating the latest wireless technologies into their mainstream operations. Knuwave has been involved in evaluating appropriate wireless and network technology for many municipal and private communications systems, and has built up a solid, multi-disciplined understanding of providing wireless connectivity and mobility for many types of operating environments.

Knuwave feasibility studies use case analysis, and geo-referenced compatibility and applicability reviews. Knuwave also provides prototype support, and program and project management of pilot projects where appropriate. The company integrates in-house development and other consulting and OEM components into the first phases of a complete product development effort. Knuwave is focused on field deployment of private wireless networks and location-aware wireless communication systems, and has successfully integrated off-the-shelf components into unique proof-of-concept prototypes. The company also provides systems and network administration, especially with new systems.

Knuwave has experience in embedding wireless, location-aware capabilities into portable and field-deployed devices, as well as in-building prototypes and proof-of-concept pilot projects. Knuwave has also provided architectural, design and program services to integrate Wi-Fi, Bluetooth and other wireless devices into products.

Knuwave is a member of the Bluetooth SIG, HP Developer & Solutions Partner Program, and Microsoft Windows Embedded Partner Program, and a supporter of the Code Project.
