IEEE P802.11
Wireless LANs

Analysis of the Interaction of Wide Bandwidth and Narrow Bandwidth Systems in the U-NII Band Using the P 802.11 MAC

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1.0 Abstract and Summary

An analysis of the interaction of systems of different bandwidths in the same physical region using best effort type media access procedures such as those of IEEE 802.11 is presented. The media access disadvantage of the high bandwidth, high signaling rate systems compared to lower bandwidth systems is shown in a quantitative comparison. This disadvantage is shown to be excessive. It is concluded that some method of controlling the use of low bandwidth systems in the U-NII band is needed if the U-NII band is to provide the high signaling rate systems that are needed.

It is proposed that a bandwidth value be set in the 20 MHz range by industry consensus and some restrictions be imposed on systems which use a narrower bandwidth in order to equalize the media access capability for systems of the consensus bandwidth. Some possible rules are presented with quantitative information on their effectiveness.

2.0 Introduction

The 5.2 GHz Unlicensed National Information Infrastructure (U-NII) band is intended for high signaling rate wireless applications in the range of 20 Mb/s. However, there is an access disadvantage when systems of wide bandwidth and high signaling rates occupy the same spectrum as multiple narrower bandwidth systems. Thus, there is a need to control the frequency assignments of systems with lower signaling rate (and thus bandwidth) requirements. The access discrepancy is particularly true for best effort type medium access procedures (systems such as IEEE 802.11 and HIPERLAN type 1).

This intent of this paper is to describe the relative media access capability for systems of different bandwidth quantitatively. This should assist in establishing the necessary sharing rules to promote the high speed systems that the U-NII band is intended to foster.

Best effort type access procedures suffer from two effects when wide bandwidth systems compete with narrow bandwidth systems for media access.

1. A wide bandwidth receiver tends to sense more narrow bandwidth transmitters when each system has the same spectrum use.
2. The wide bandwidth devices experience a deferral lockout condition. The inter frame gaps, or deference intervals, of the multiple frequency, narrow bandwidth systems in the frequency band of the wide bandwidth devices do not occur simultaneously. This prevents the wide bandwidth receiver from sensing the quiet period necessary for effective medium access.

Any wide bandwidth system in which the full signaling rate of the channel is used during transmission periods experiences condition 1. Condition 2 applies to procedures such as IEEE 802.11 and HIPERLAN type 1 which require a quiet channel condition prior to medium access.

Reservation type systems which use some method of coordination of multiple low signaling rate devices in a high speed channel (such as time division multiplexing) do not necessarily suffer these disadvantages. However, in these type systems the devices with higher user signaling rates (net signaling rates per device while sending) suffer a like disadvantage. References 1 and 2 describe the mixed bandwidth problem for both type systems and provide some quantitative comparisons for the general case of mixed bandwidth systems of both best effort type and for time division or reservation type systems. This paper concentrates on the best effort type systems. It covers the conclusions of the references in more detail and extends some of the analysis for best effort systems.

3.0 Description of the Problem

A narrow bandwidth access advantage in best effort systems utilizing the full signaling rate per device occurs independently of the actual back-off procedures primarily because, with equal spectrum use, on average there are more narrow bandwidth transmitters with power on at any given time. This is only partially offset by the normally higher threshold levels of wide bandwidth receivers.

Figure 3-1 illustrates the relative number of interfering sources of each type when two systems of mixed bandwidth exist in the same area. The figure shows the typical number of devices transmitting when the narrow bandwidth system occupies 4 channels in the same band as the wide bandwidth system and where each system has the same spectrum usage[1]. In the conditions of this figure, the number of devices transmitting in a particular area is proportional to the reciprocal of the emission bandwidth if the spectrum use is the same. Thus, in the case illustrated, an average of four narrow bandwidth devices transmit for each wideband device that does so.

For simplicity, first assume that all devices in the region are near enough that any transmitter in their channel creates a received level in excess of the threshold. The wide bandwidth receiver is subjected to all narrow bandwidth transmitters. On the other hand, the narrow bandwidth receivers only sense transmitters in their particular narrow channel, thus they experience only an average of one fourth as many narrow bandwidth interference sources as do the wide bandwidth receivers[2]. This gives the narrow bandwidth receivers the access advantage.

This advantage is partially offset in large deployment areas by the fact that the interference region of a wide bandwidth receiver to a narrow bandwidth transmitter is typically smaller than that of a narrow bandwidth receiver. Consider that the region shown in figure 3-1 is part of an infinite plane of mixed bandwidth devices. Here, the 4 to 1 disadvantage of the wide bandwidth devices is partially offset if the receiver power threshold at which the negative effect occurs is higher in the wide bandwidth device. If each system uses the same power spectral density (as permitted in the U-NII band), then this threshold will likely be proportional to the receiver bandwidth and will thus be higher in the wide bandwidth device.

Figure 3-2 illustrates the relative regions of interference for the various interfering transmitter - receiver cases. The illustration shows the smaller interference area of the higher threshold, wide bandwidth receiver for narrow band transmittters compared to that of the narrow bandwidth receiver. The mean number of devices that a receiver senses is proportional to the interference area times the mean number of devices transmitting in its band. Thus, the smaller interference area reduces the number of interferers sensed by the wide bandwidth receivers in the large area deployment[3].

The offset is not complete in normal conditions. This is studied quantitatively in the detail of this report.

[1] Here spectrum usage means the bandwidth - transmission time product.

[2] For simplicity, it is assumed that the narrow bandwidth receivers are completely isolated form adjacent channel signals.

[3] It is shown later that the smaller interference area completely offsets the larger number of transmitters in free space propagation conditions.

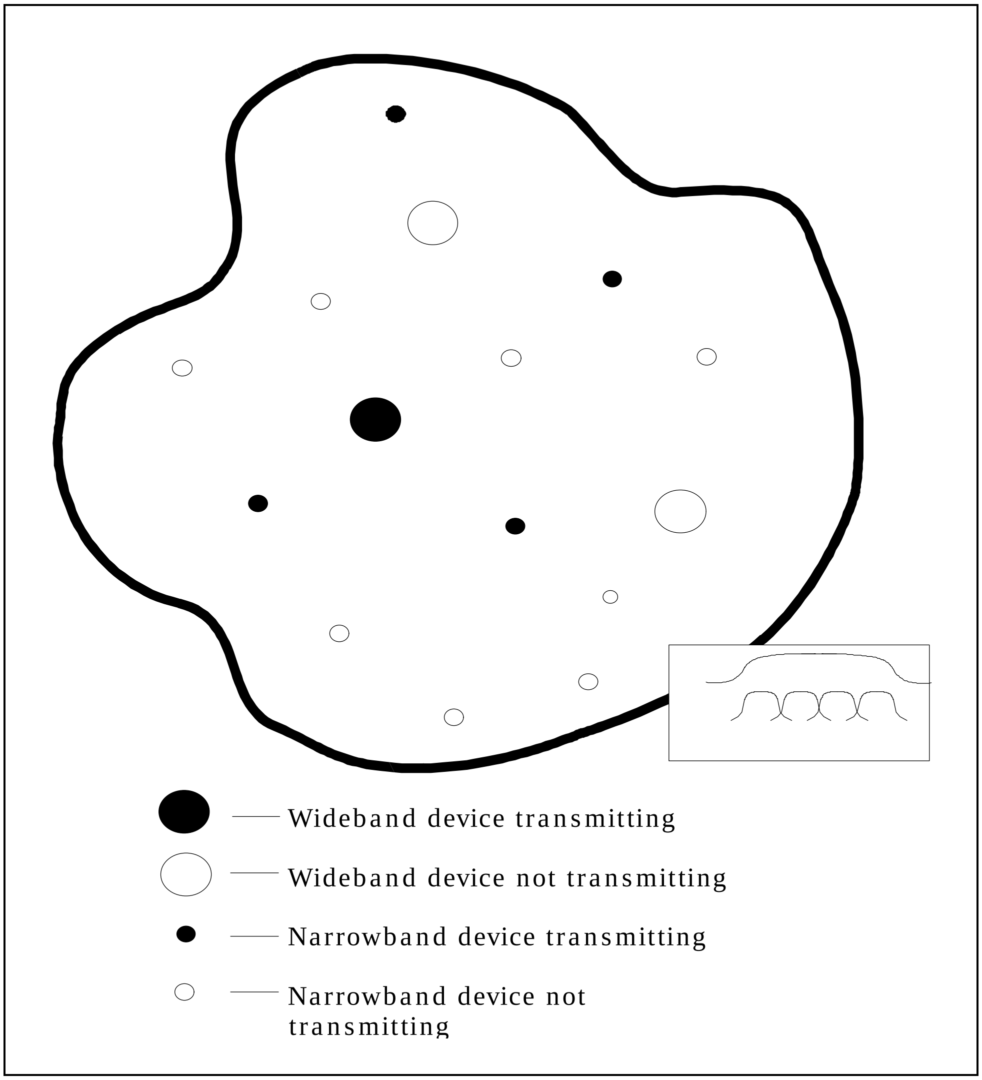

Figure 3-1. Illustration of the Density of Transmitting Devices versus Bandwidth

If two systems of U-NII devices have the same throughput and timing latency, the density of transmitting devices is proportional to the reciprocal of the bandwidth when all channels are utilized in a spectrum region. This illustrates the typical case where a narrow bandwidth system of devices with 4 channels each of bandwidth ¼ that of a wideband system of devices shares the same spectrum and physical location. In a given region, an average of 4 narrow bandwidth devices are transmitting at a randomly chosen time for each wideband device that is transmitting.

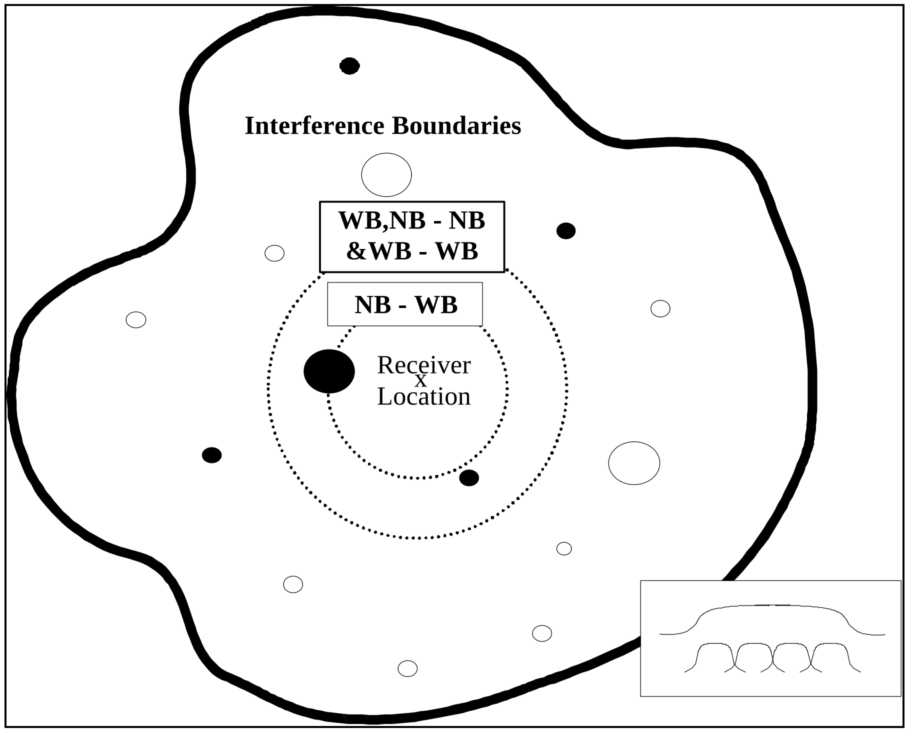

Figure 3-2. Illustration of the Median Interference Boundaries for Wide Bandwidth and Narrow Bandwidth Systems

This illustrates the median interference range for a receiver in the vicinity of a region of transmitters. Receivers of two bandwidths are considered. The wide bandwidth is four times the narrow bandwidth in the illustration. The receiver has a received power threshold above which interference is intolerable. This threshold level for in-band signals is assumed to have the same ratio to thermal noise power for each bandwidth.

The inner broken line circle represent the case where a narrow bandwidth transmitter interferes with the wide bandwidth receiver. The interference range is lower for this case because of the higher threshold level in the wide bandwidth receiver. The outer broken line circle represents the other cases. The wide bandwidth transmitter is assumed to have the same power spectral density as the narrow bandwidth transmitter in the outer circle case.

4.0 Propagation Assumptions

For the purpose of this analysis the propagation conditions are adequately defined by the propagation exponent α. That is, with P_t/P_r the median transmit to receive power ratio and r the distance

$$\frac{P_t}{P_r} \propto r^{\alpha} . \qquad 4\text{-}1$$

In a relatively homogeneous area, the probability density of the attenuation (log of the power ratio) is nearly symmetrical about the mean, thus the mean attenuation is approximately equal to the median and the distance r at which a given value of attenuation occurs can be considered the median range for that attenuation. Thus, the mean attenuation can be expressed as

$$Mean\ Attenuation = A = A_1 + 10\alpha \log r \qquad r_1 < r < r_2$$

where A_1 is the attenuation at distance r_1.

A value of α of about 4 is typical for inside propagation for distances (r_1) in excess of about 5 to 10 meters and up to the normal distance where firm barriers such as walls occur (r_2). This is the normal range for U-NII deployment.

5.0 Parameter Conventions and General Relationships

Parameter Conventions:

- C — A constant of proportionality. It is reused in various developments.
- α — The propagation exponent. As defined above, the median transmit to receive power ratio is proportional to r^{α} for the propagation assumption used.
- h — The ratio of a device receiver threshold to signals in its band to thermal noise power. Normally, the same value of h is used for wideband and narrowband devices when a comparison is made.
- xy — When used as subscripts they take on the values 1 and 2. 1 refers to a narrowband device parameter and 2 refers to a wideband device parameter.
- P_x — The transmit power of device x (x = 1 or 2).
- T_{xy} — The received power level at device x received from a device y at which device x either senses power (for LBT) or experiences destructive interference. A threshold level.
- B_x — The bandwidth of device x (x = 1 or 2).
- N_{xy} — The mean number of devices of type y for which the power level at a device type x exceeds T_{xy} when a single device of type y is active at a time.
- A_{xy} — The mean interference area created by a device of type y for a device of type x.
- β — The ratio of N_{21}/N_{11} when the threshold of each type of device stands in the same ratio to thermal noise and is thus proportional to bandwidth.
- W — The number of narrow bandwidth channels sharing spectrum with the wide bandwidth channel.
- R — The packing density of the narrow bandwidth channels, $R = WB_1/B_2$.

Normally R =1 and thus $W = B_2/B_1$. This is the condition if idealized rectangular band shapes are assumed and the narrow bandwidth system utilizes the complete spectrum available.

General Relationships:

If r is the median range at which transmissions from a device type y exceeds the threshold of a device type x then from 4-1,

$$r^{a} \propto \frac{P_y}{T_{xy}}$$

$$r \propto \left(\frac{P_y}{T_{xy}}\right)^{\frac{1}{a}} . \qquad \text{5-1}$$

The area over which a device type y affects reception at device type x is proportional to r^2 providing the region of deployment extends to a radius r from the receiver, thus if this area is A_{xy}

$$A_{xy} = C_2\left(\frac{P_y}{T_{xy}}\right)^{\frac{2}{a}} \qquad \text{5-2}$$

providing the devices are deployed over an area that is much greater than A_{xy}.

As shown in figure 3-1, when the two systems that are deployed evenly in a large area have the same spectrum usage (approximately the same system information throughput), the relative number of narrow bandwidth devices transmitting in a particular area compared to the number of wide bandwidth devices transmitting in the same area is proportional to the number of narrow bandwidth channels within the wide bandwidth. With x = 1 or 2

$$N_{xy} = C\left(\frac{P_y}{T_{xy}}\right)^{\frac{2}{a}} \qquad xy \neq 21 \qquad \text{5-3}$$

$$N_{21} \geq WC\left(\frac{P_1}{T_{21}}\right)^{\frac{2}{a}}. \qquad \text{5-4}$$

Equation 5-4 is an inequality because the mean interference area created by multiple transmitting devices is slightly larger than the union of the areas of each device. Equality requires that the mean number of transmitting devices be the same in all cases. N_{21} is slightly higher than the right side of 5-4 because N_{21} is usually larger than the other cases of N_{xy}. This will be indicated where necessary with a >= or <= sign in the expression.

The ratio of the number of narrow bandwidth devices sensed by a wide bandwidth device to the number of wide bandwidth devices sensed by a narrow bandwidth device is

$$\frac{N_{21}}{N_{12}} \geq W\left(\frac{T_{12}}{T_{21}}\right)^{2/a}\left(\frac{P_1}{P_2}\right)^{2/a} = R\frac{B_2}{B_1}\left(\frac{T_{12}}{T_{21}}\right)^{2/a}\left(\frac{P_1}{P_2}\right)^{2/a} \qquad \text{5-5}$$

in large areas of deployment.

The ratio of the number of narrow bandwidth devices sensed by a wide bandwidth device to the number of narrow bandwidth devices sensed by a narrow bandwidth device is

$$\frac{N_{21}}{N_{11}} = b \geq W\left(\frac{T_{11}}{T_{21}}\right)^{2/a} \qquad \text{5-6}$$

If the receiver threshold of a narrow bandwidth device (type 1) is hB_1 for signals in its band, it is hB_2 for transmissions from a wide bandwidth (type 2) device of transmission bandwidth B_2 because the narrow bandwidth device does not receive all of the power from the wide bandwidth device. Otherwise, the threshold for either signal type is the same. For the 4 cases when the threshold for in-band signals is hB,

$$T_{11} = hB_1 \qquad \text{5-7}$$

$$T_{12} = hB_2 \qquad \text{5-8}$$

$$T_{21} = hB_2 \text{ and} \qquad \text{5-9}$$

$$T_{22} = hB_2. \qquad \text{5-10}$$

Thus

$$\beta = \frac{N_{21}}{N_{11}} \geq W\left(\frac{T_{11}}{T_{21}}\right)^{2/\alpha} = R\frac{B_2}{B_1}\left(\frac{B_1}{B_2}\right)^{2/\alpha} \text{ or}$$

$$\beta = R\left(\frac{B_2}{B_1}\right)^{\frac{\alpha-2}{\alpha}} \qquad 5\text{-}11$$

The other extreme is the case in which the deployment area is small enough that all receivers sense all others at a level above the threshold. In this case, the ratio of N_{21}/N_{12} and N_{21}/N_{11} is independent of the thresholds and is

$$\frac{N_{21}}{N_{12}} = \frac{N_{21}}{N_{11}} = R\frac{B_2}{B_1} = W = \beta \qquad 5\text{-}12$$

if the deployment area is small. Note that this is equivalent to the case in which α approaches ∞.

6.0 Relationship Between the Number of Interferers Sensed and Bandwidth

<u>Necessary Power Level Ratio to Equalize the Number of Interferers:</u>

For the time being, ignore the fact that the narrow bandwidth devices tend to lock out the wide bandwidth devices because of the non-simultaneous inter frame gaps. In effect, assume that this problem is solved in some way, possibly by requiring coordination of the narrow bandwidth devices. In this case, if $N_{21} = N_{12}$ the systems would have equal access probability.

The power spectral densities are not equal in the general case since it is desired to vary the relative power levels. However, the median, and thus the mean, received power can be considered proportional to the receiver bandwidth. If one system must reduce power to achieve equality, it is assumed that it also reduces the maximum range proportionately. Thus, each system has the same signal amplitude distribution relative to thermal noise and equations 5-7 through 5-10 define the respective error producing thresholds.

The following applies either to an LBT system in which the threshold is set at a consistent value proportional to thermal noise power or to a non-LBT system. If, in the non-LBT case, each type receiver has the same C/I requirement for successful reception, then if the interference power in either receiver exceeds the received level minus the C/I requirement, the reception is unsuccessful. Then, if the distribution of the received level of the desired signal is the same in either case, the distribution of the interference level at which errors are produced is the same for each receiver.

It is desired to determine the transmit power ratio which will make the mean number of interferers the same in each case.

Equal access probability occurs if $N_{21} = N_{12}$, thus the ratio can be set equal to 1 in equation 5-5. Since equations 5-8 and 5-9 apply, the ratio of thresholds in 5-5 is 1, thus

$$\left(\frac{P_2}{P_1}\right)^{2/\alpha} \geq W$$ for equal numbers of transmitters sensed in each case, or

$$\frac{P_1}{P_2} \leq \left(\frac{B_1}{RB_2}\right)^{\alpha/2} = W^{-\alpha/2} \qquad 6\text{-}1$$

for equal access capability.

The narrow bandwidth system can use an R value of 1 and possibly higher. Thus, equal access capability requires that the power ratio be less than the bandwidth ratio raised to the $\alpha/2$ power.

A typical value of α is about 4 at 5.3 GHz in relatively open areas such as typical offices, thus an approximate power squared relationship is necessary in this case to provide equal access in the U-NII band even in the absence of the deference lockout condition.

In deployment areas characterized by smaller regions separated by absorbing walls or other barriers, values of α of 7.5 are typical. If the deployment area is small, or if α is high due to the presence of walls or other absorbing barriers, the relative interference range tends to equalize, thus in such coverage regions, an even lower power ratio would be needed to equalize access capability.

The free space value of α is 2, thus a power ratio equal to the bandwidth ratio (equal power spectral density) is sufficient in free space conditions and large areas.

<u>The Relative Number of Interferers with Equal Power Spectral Density:</u>

The U-NII band permits a power level proportional to bandwidth for bandwidths of 20 MHz and lower by putting limits on the power spectral density. Thus, the ratio N_{21}/N_{12} for equal power spectral density (β) is of interest. This is given directly by equation 5-5 for the general case of different threshold factors and large deployment areas. For the case where threshold is = hB then $P_1/P_2 = B_1/B_2$ for equal power spectral density, and from 5-5,

$$\frac{N_{21}}{N_{12}} \geq \frac{RB_2}{B_1}\left(\frac{B_1}{B_2}\right)^{2/\alpha} = R\left(\frac{B_2}{B_1}\right)^{\frac{\alpha-2}{\alpha}} \text{ or}$$

$$\frac{N_{21}}{N_{12}} = \beta \qquad \text{6-2}$$

For equal power spectral density.

For small areas in which all receivers are in range of all transmitters, equation 5-12 holds and

$$\frac{N_{21}}{N_{12}} = \beta = R\left(\frac{B_2}{B_1}\right)$$

which is equivalent to the case where $\alpha = \infty$.

With α =4 and R = 1, β is the square root of the bandwidth ratio. In small isolated areas in which all receivers are in range of all others, with R =1, β is equal to the bandwidth ratio.

7.0 The Effect of the Lockout Condition or Non-Simultaneous Inter Frame Spacing Intervals.

The objective of this section is to quantitatively investigate the deference lockout effect of section 2, namely the fact that the inter frame gaps, or deference intervals, of the multiple frequency, narrow bandwidth systems which occupy the same frequency band as the wide bandwidth system do not necessarily occur simultaneously, thus failing to guarantee the wide bandwidth receiver an inter frame quiet period.

Consider two receivers, one a narrow bandwidth receiver (type 1) and the other a wide bandwidth receiver (type 2) placed in a region of common deployment of type 1 transmitters. The relative performance will be analyzed by comparing the fraction of the time each receiver will sense an idle channel for various levels of transmitter activity.

Let

m = a random variable equal to the number of transmitters in range of the type 1 (narrow bandwidth) receiver,

M = the Mean of m over the possible locations of the receiver. The mean number of transmitters in range of the type 1 (narrow bandwidth) receiver,

u = the mean utilization (duty cycle) of each transmitter

n = a random variable equal to the number of transmitters in range of the type 2 (wide bandwidth) receiver,

N = the mean of n over the possible locations of the receiver and

P_o(q,Q) = The Poisson probability distribution of q in which the mean value is Q.

$$P_o(q,Q) = \frac{Q^q \mathrm{e}^{-Q}}{q!}.$$

From 5-11

N = βM.

The Poisson distribution is appropriate to describe the number of outcomes of a binary event (success or failure for instance) when the number of trials is very high and the probability of success for each trial is equal and very low. This is the case for purely random placement of transmitters in a large region in which the interference range of the receiver is relatively low. In this case the probability of success is equal to the ratio of the interference area to the total area, thus the distribution of m and n is approximately Poisson.

Then, the probability density of m and n are approximately

$$p(m,M) = \frac{M^m \mathrm{e}^{-M}}{m!}$$

$$p(n,\mathrm{b}M) = \frac{\mathrm{b}M^n \mathrm{e}^{-\mathrm{b}M}}{n!}.$$

Let

$P_{2,1}$ = the probability that a type 2 receiver senses a free channel in the presence of the type 1 system of transmitters of mean fractional channel utilization u and

N_{11} = the mean number of transmitting type 1 devices sensed by a type 1 receiver.

It will be assumed that the access procedures for type 1 devices are ideal in the sense that there are no type 1 collisions. Thus, the maximum value of N_{11} is 1. Further, N_{11} is the relative utilization of the complete type 1 system compared to the maximum achievable utilization.

Note: N_{11} is actually the mean number of devices either transmitting or waiting to transmit in the development that follows. In the cases where a device is waiting because another type 1 device is transmitting, the subsequent transmission will nevertheless occur. Thus, the type 1 device in question will experience N_{11} as the fraction of time its channel is busy.

If u is the same for all transmitters[4], then P_{21} can be found by first considering the conditional probability that at least one transmitter has power on, given that there are n transmitters within range of the wideband receiver. The sum of this conditional probability over all possible values of n is $P_{2,1}$. Thus

$$P_{2,1} = \Pr\{type\,2\,receiver\ senses\ a\ free\,channel\}$$ and

$$P_{2,1} = \sum_{n=0}^{\infty} P_o\left(n, \mathrm{b}\,M\right)\left[1-u\left(N_{11}\right)\right]^n . \qquad \text{7-1}$$

The available relative utilization of a set of wide bandwidth devices within range of each other when the type 1 system is present is slightly higher than $P_{2,1}$. This is shown in Appendix C. Thus, $P_{2,1}$ is a good indicator of the performance level achievable by a system of wide bandwidth devices in the vicinity of a system of narrow bandwidth devices.

In order to compute $P_{2,1}$, it is necessary to express u in terms N_{11}, which is the actual mean fraction of time that the low bandwidth channel is used by low bandwidth devices. This can be done as follows.

If m type 1 transmitter devices are within range of the type 1 receiver, then the probability that at least one is transmitting is

Pr(at least one of m are transmitting) = $1-(1-u)^m$.

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4 Normally u is not constant over all transmitters. When it isn't, the $(1-u)^n$ term becomes $\prod_{k=0}^{n}\left(1-u_k\right)$, where u_k is the utilization for each individual transmitter. These terms are approximately equal when k is in the range of 20 or more and uk < 1, which is normally the case. For example with n taking on the values 0.0125, 0.025 and 0.0375 with equal incidence (mean of 0.025), with n = 18 and u of the $(1-u)^n$ term equal to the mean value (0.025), the $(1-u)^n$ expression exceeds the product expression by 0.1%. Thus, equation 6-1 is appropriate for the usual cases if the mean value of u is used.

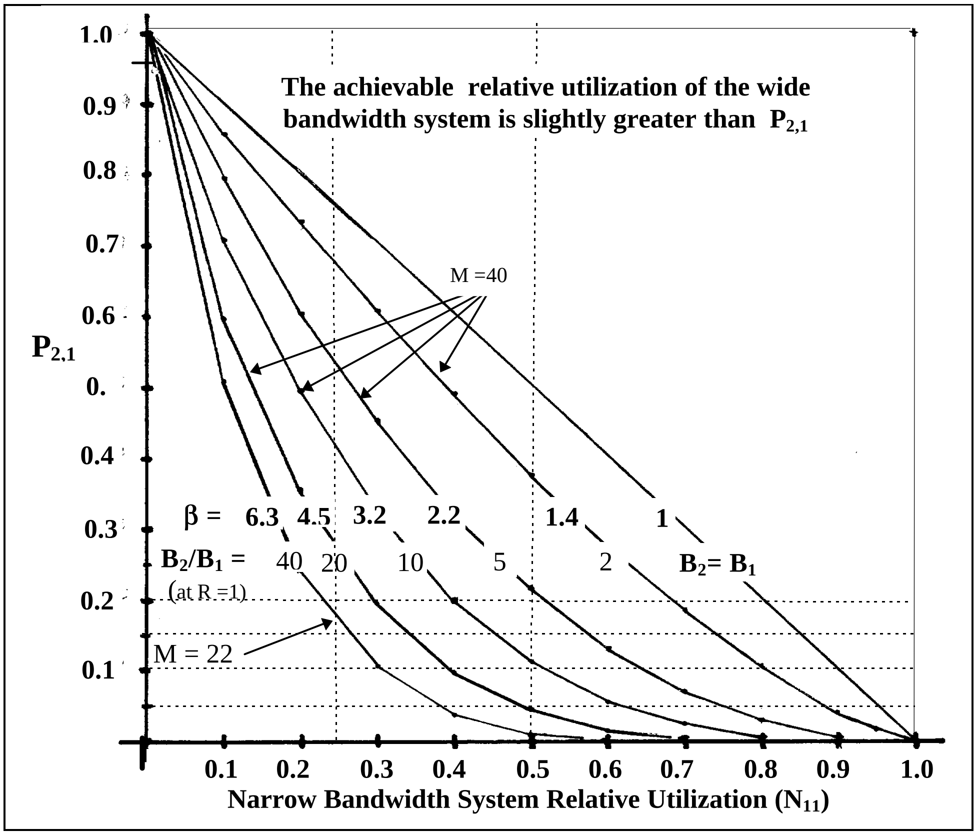


Figure 7-1: The Upper Limit of the Relative Utilization of a Wide Bandwidth System in the Presence of a Narrow Bandwidth System

N_{11} is the mean probability that a narrow bandwidth receiver senses a busy channel due to a narrow band transmission. It is also the ratio of the mean channel utilization of the group of devices of bandwidth $B_1 <= B_2$ that are within range of each other to the achievable utilization. Thus, $N_{11} < 1$.

The ordinate ($P_{2,1}$) is the mean probability that a single receiver of bandwidth B_2 will sense an open channel when all of the other devices are of bandwidth B_1. The achievable utilization of a wide bandwidth system is slightly higher than $P_{2,1}$ (see appendix C). R is the relative packing density of the narrow bandwidth channels. See the text for the definition of β and a further definition of R.

The carrier sense threshold is proportional to bandwidth.

If it is again assumed that the access procedures operate ideally, no more than one narrow bandwidth device will be transmitting. Other transmitters may have work queued and will eventually transmit, but only one will transmit at any given time. In fact, the media access procedures will tend to insure that the complete offered load of each narrow bandwidth device is eventually transmitted.

The overall mean value of the number of devices either transmitting (or waiting to transmit) is the sum over all m of the probability that m are within range times the probability that at least one of the m are transmitting. That is,

$$N_{11}(u) = \sum_{m=0}^{\infty} P_o(m, M)\left[1 - \left[1 - u\left(N_{11}\right)\right]^m\right].$$

Since $\sum_{m=0}^{\infty} P_o(m, M) = 1$, this can also be expressed as

$$N_{11} = 1 - \sum_{m=0}^{\infty} P_o(m, M)\left[1 - u\left(N_{11}\right)\right]^m . \qquad 7\text{-}2$$

<u>Evaluation of Equation 7-1:</u>

Evaluation of equation 7-1 requires that u(N_{11}) be determined. This requires indirect evaluation using the inverse equation (equation 7-2). However, there is an approximation that is sufficiently accurate in the cases considered here.

If it is assumed that there are always exactly M transmitters in range of the type 1 device, then the following would be the case.

$$N_{11} \approx 1 - (1 - u)^M \text{ and}$$

$$u\left(N_{11}\right) \approx 1 - \left(1 - N_{11}\right)^{1/M} \qquad 7\text{-}3$$

Figure 7-1 was computed from the approximation and spot checked for accuracy. It was found to be accurate within the resolution of the figure. Also, comparison of computations from equations 7-3 and 7-2 are shown in appendix A. This further verifies the accuracy within the figure 7-1 resolution.

In the conditions of significance concerning performance evaluation, the mean number of devices in range of other type devices is very large. For example, the typical duty cycle of LAN devices is under 1 % and performance problems are seldom experienced at utilization levels below about 50%. In this condition M would be about 50%/1% = 50. At values of M in this range, equations 7-1 and 7-2,3 are relatively independent of M. Appendix B shows some calculated values for various values of M and demonstrates the sensitivity.

<u>Discussion of Figure 7-1:</u>

Figure 7-1 shows the probability of a single randomly placed wide bandwidth device (type 2) sensing an idle channel in the presence of a system of type 1 devices. Appendix C shows that this is slightly less than the fractional utilization achievable by a system of wide bandwidth devices in the presence of a type 1 system with relative demand of N_{11}.

The narrow bandwidth devices (type 1) always experience the $\beta = 1$ curve. A wide bandwidth device (type 2) would need to operate with $P_{2,1}$ slightly higher than the $\beta = 1$ curve to have equal access capability. This is because even with $\beta = 1$, the wide bandwidth device will experience some cases in which it senses more than 1 type 1 device transmitting on different channels and thus doesn't sense all type 1 inter frame gaps.

Figure 7-1 shows that there is a strong potential for narrow bandwidth systems to effectively prevent wide bandwidth systems from operating. As an example, consider the $\beta = 6.3$ curve. In small deployment areas this corresponds to a bandwidth ratio of 6.3. Here, the wide bandwidth system is virtually prevented from operation ($P_{2,1} = 0.02$) if the narrow bandwidth system has a demand of 50% of that achievable.

The U-NII band offers an opportunity to achieve signaling rates in the order of 20 Mb/s which require bandwidths on the order of 20 MHz. It is necessary that a minimum protected bandwidth in this range be chosen and sharing rules be put in place to assure such systems can have equitable access to the U-NII spectrum.

8.0 Possible Solutions

This section will assess the type of rules that may be incorporated to assure equitable wide bandwidth operation.

Assuming that there is a minimum bandwidth B which is to be protected, potential rules approaches are:

1. Prohibit systems with bandwidths less than B.
2. Control the number of narrow channels which can be implemented within a channel width B.
3. Restrict the power level of systems with bandwidths less than B more severely than just the current Power Spectral Density (PSD) requirement.
4. Restrict narrow bandwidth systems to a limited region of the U-NII band.

Rule 1 would be the most restrictive. It should be used only if a less restrictive rule can not be found.

It may be that the actual proliferation of low bandwidth systems will never become high enough to create a problem. If this is the case, then something along the lines of 2 or a combination of 2 and 3 would be the best approach.

Number 4 (segregating the band) would effectively give up a portion of the U-NII band for wide bandwidth systems and should be avoided if possible.

Some combination of numbers 2 and 3 is conceivable.

2. Limit the number of narrow bandwidth channels per channel width B:

The number of narrow channels per wide channel is W from section 5. To assure equitable wide bandwidth access the value of N_{21}/N_{12} from equation 5-5 could be set to some value k, with k <1.

If the threshold to thermal noise ratio is maintained then $T_{12} = T_{21}$ in 5-5 and

$$\frac{N_{21}}{N_{12}} \geq W\left(\frac{P_1}{P_2}\right)^{2/a}.$$

If this is to be less than k then the limit on W must be:

$$W \leq k\left(\frac{B_2}{B_1}\right)^{\frac{2}{a}}.$$

In this case equation 5-5 is treated as an equality.

In the case of isolated small groups, the equivalent value of α is unlimited. Thus, in the extreme, W must be less than k, but in this case k can equal 1. However, in the extremely small groups which this represents, the throughput is not likely to be restricted, so a rule this extreme may not be needed.

The large area case with $\alpha = 4$ will not likely occur predominantly. The size of typical buildings will limit deployment areas and throughput limitations will nevertheless be experienced. The third column of the following table (bolded) is a potential candidate for guidance in setting the rules.

B_2/B_1	W_{max} /k @ α =4	**W_{max} /k @ α = 7.5**	W_{max} @ $\alpha = \infty$
2	1.41	**1.20**	1
4	2.00	**1.34**	1
10	3.16	**1.45**	1
20	4.47	**1.54**	1

Either of the last 2 columns would cause spectrum inefficiency when narrow bandwidth systems share spectrum with wide bandwidth systems and one of the cardinal rules should be to promote spectrum efficiency. This would suggest that some control of the bandwidth and signaling speeds at values within say a factor of 4 of that of the bandwidth B could be incorporated.

For example a value of W less than about 1.3 and a signaling speed lower limit of about B/4 would likely suffice. This approximately corresponds to $B_2/B_1 = 4$ and $\alpha = 7.5$ in the table.

3. Limit the power level of narrow bandwidth systems:

As before, to assure equitable wide bandwidth access, the value of N_{21}/N_{12} from equation 5-5 could be set to some value k, with k < 1. A power ratio rule could then be imposed.

If the threshold to thermal noise ratio is the same, the threshold level ratio in 5-5 equals 1. Then the power ratio from equation 5-5 should be

$$\frac{P_1}{P_2} \leq \left(\frac{W}{k}\right)^{\frac{-a}{2}}.$$

The following table results. As before, the last column represents the small area case and the third column is a good compromise.

W/k	P_1/P_2 @ α = 4 (dB)	**P_1/P_2 @ α = 7.5 (dB)**	P_1/P_2 @ $\alpha = \infty$ (dB)
1	0	**0**	0
2	-6	**-11.3**	- ∞
3	-9.5	**-17.9**	- ∞
4	-12	**-22.6**	- ∞
5	-14	**-26.2**	- ∞

The third column would likely be the necessary rule as it represents a case somewhere between the extremes. For example, two channels might be permitted to share a wide bandwidth channel providing the power is reduced by 12 dB etc. this could be combined with a rule from the last subsection covering lower values of W. For example full power could be permitted for W < 1.3 and a power level reduction could then be imposed for W>1.3.

In U-NII applications there is not likely to be enough C/N margin to permit wide bandwidth systems to take advantage of a lowered receiver threshold in narrow bandwidth systems. Thus, this alternative can likely be dismissed.

Appendix A: Comparison of an Approximation for $u(N_{11})$

$$N_{11} = 1 - \sum_{m=0}^{\infty} P_o(m, M)\left[1 - u\left(N_{11}\right)\right]^m \qquad 7\text{-}2$$

$$u\left(N_{11}\right) \approx 1 - \left(1 - N_{11}\right)^{1/M} \qquad 7\text{-}3$$

	M = 40			M = 20		
N_{11}	**u from 7-2**	**u from 7-3**	**% error**	**u from 7-2**	**u from 7-3**	**% error**
0.10	0.002640	0.002631	-0.38	0.00527	0.00525	-0.4
0.20	0.005580	0.005563	-0.31	0.0112	0.01109	-0.8
0.70	0.03010	0.029651	-1.5	0.0602	0.05842	-3.0
0.90	0.057565	0.055939	-2.90	0.1152	0.10875	-5.9

Appendix B: Dependency of $P_{2,1}$ Computations on the Variable M

The following table gives some computations of the value of $P_{2,1}$ with various values of M, the mean number of type 1 devices within carrier detection range of another type 1 device. It was necessary to limit the value of M for computational efficiency.

When the value of $P_{2,1}$ is significant, it is relatively independent of M over the range of parameters shown.

B_2/B_1	**N_{11}**	**$P_{2,1}$ at M = 15**	**% variation**	**$P_{2,1}$ at M = 30 (reference)**	**$P_{2,1}$ at M = 45**	**% variation**
5	0.1	0.7908	+0.05	0.7904	0.7903	-.01
	0.5	0.2199	+1.8	0.2161	0.2148	-0.6
	0.9	0.0085	+21	0.0070	0.0066	-6
10	0.1	0.7175	+0.06	0.7171	0.7169	-.03
	0.5	0.1174	+2.5	0.1145	0.1136	-.8
	0.9	0.0012	+33	0.0009	0.0008	-13
20	0.1	0.6253	0.08	0.6248		
	0.5	0.0483	+3.4	0.0467		
	0.9	0.0001	-	0.0000		

Appendix C: Relationship of Wide Bandwidth System Throughput to $P_{2,1}$

Consider the activity of two systems of disparate bandwidths in the same vicinity, a type 2 high bandwidth system and a type 1 low bandwidth system. A typical condition would be

$N_{11} = 0.5$
R = 1 and
β=3.2

At R=1and $\alpha = 4$, $B_2/B_1 = 10$. At R=1 and $\alpha = \infty$ (small area deployment), $B_2/B_1= 3.2$.

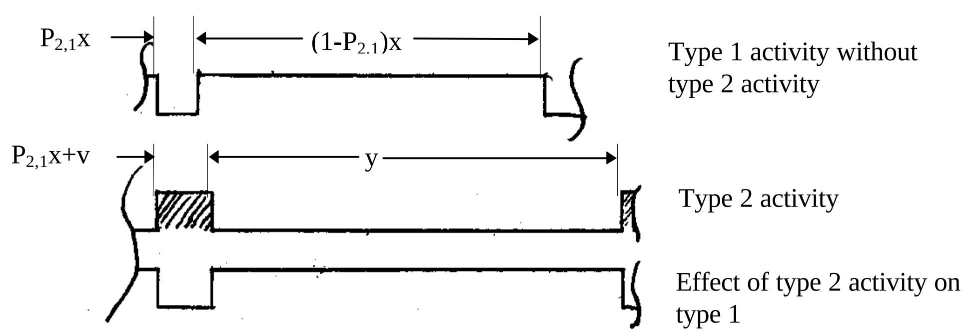
The probability of the type 2 receiver experiencing blockage is about 0.89 from the graph in figure 7-1. Or, the probability of sensing a free channel ($P_{2,1}$) is about 0.11. In this situation, the type 1 system is handling the full demand, thus the mean type 1 demand is also about 50% of the total that can be handled.

The single wide bandwidth (type 2) device has only 11% of the channel capacity available. In this situation, the type 2 device will obtain access when the idle channel condition occurs. The condition may occur because only one type 1 device is transmitting a group of packets and provides an IFS. However, more than one type 1 device on separate narrow channels will be transmitting about 60% of the time, thus, the type 2 device will usually have to wait until the type one devices finish before it sees an IFS. Thus, most of the type 2 idle time will occur when none of the type 1 devices in range have packets queued.

Note: In the stated condition, the mean number of type 1 devices in range of the type 2 device that are transmitting will be 1.8 (3.2*.5/.89). The mean number is directly proportional to β, thus with larger β, the likelihood of observing a quiet period due to an IFS gap is much less.

If there is more than 1 type 2 device and the composite type 2 demand of devices within range of each other is greater than 11%, then a type 2 device will eventually access, and the type 2 system will then utilize the channel until another type 1 device wins contention. At this time, the type 1 devices will begin to empty their built up traffic plus any new traffic that arrives during the type 1 access time. The type 1 devices will usually hold the wide channel until nearly all traffic is sent because of the lockout condition.

The figure below shows a typical type 1 transmission cycle as sensed by a type 2 receiver and illustrates the interaction when a type 2 system is present. The upper illustration shows the average type 1 off-on transmission cycle time (x) as perceived by a type 2 receiver when there is no type 2 traffic. A typical type 2 receiver would perceive the type 1 traffic to be inactive $100P_{2,1}$% of a mean cycle time.



The lower illustration shows the average cycle time when a type 2 system is introduced with a demand which exceeds the capacity available. In this case, when the type 1 traffic becomes inactive, the type 2 system obtains access and uses the capacity for all of the time it would perceive the type 1 traffic to be inactive plus a carry over time of v seconds which represents the average time the type 2 system continues to maintain access after the type 1 system begins to compete.

The type 2 system will achieve more than $100P_{2,1}$% utilization when $v > 0$.

In the upper illustration, without type 2 interaction, the type 1 on time starts with no traffic build up for the devices in range of the type 2 receiver. This traffic plus that which arrives during the on time is transmitted at a mean rate of $N_{11}/(1-P_{2,1})$ until the level again reaches zero. In the lower illustration with v>0, there is a build up of traffic when the type 1 on time begins. Since the type 1 system has excess capacity, this results in a rate greater than before, thus the increase in y is less than the proportional increase in the type 2 on time, resulting in a net increase in type 2 throughput.

However, the increase in type 2 throughput is not in proportion to the increased on time. For this to be the case, y would have to be unchanged with increasing v. The build p at the start insures that y will increase somewhat with increasing v.

Thus, the following

$$P_{2,1} < \text{Type 2 relative utilization} < P_{2,1}\left(\frac{P_{2,1}x+v}{P_{2,1}x}\right) = P_{2,1} + \frac{v}{x} \qquad \text{C3}$$

The value of the expression in parenthesis is the ratio of the type 2 mean on time to the mean duration of the type 1 off time when there is no type 2 interaction. It is the utilization that would exist if y were $(1-P_{2,1})x$.

The value of v is small because of the unfairness of the access procedures. If the probability of access for the type 2 devices was equal to that for type 1 devices, then v would achieve a value that would split the capacity in proportion to relative demand. It can be expected that v will be a fraction of a packet time for the wide bandwidth devices, thus the relative utilization of the wide bandwidth devices will not greatly exceed $P_{2,1}$.

References

1. WINForum NPRM Reply Appendix, The Need for Channelization and Procedural Rules for SUPERNet, SRDC Document Number SRDC/09.11.96.10

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