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For information and comment

U-NII BAND CHANNELIZATION
AND THE WINFORUM SRDC

Prepared by the WINForum Sharing Rules Development Committee
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Outline

1.0 Summary and Abstract

The paper is intended to convey the status of the WINForum SRDC committee in establishing a set of rules which promote equitable spectrum sharing and minimization of interference among non interoperable equipment and systems in the 5.2 GHz U-NII band. These rules may specify such parameters as power, channelization, transmission time and access rules. The SRDC expects to coordinate the generation of the rules with the wireless standards committees such as ETSI BRAN and IEEE 802.11.

The SRDC has reached a resolution concerning channelization and recommends that the U-NII band be channelized with fixed center frequencies. This recommendation is described and the technical justification is presented. The frequency assignment is discussed, including the unique U-NII requirements occasioned by the FCC Part 15 restricted band rules which apply at the band edges.

Example intraband channelization specifications are presented and an example frequency assignment plan is presented. The frequency assignment depends on the width of the guard bands necessary to achieve the extreme out-of band suppression required by the FCC restricted band rules. The restricted band rules and clarifications which the SRDC is pursuing are described.

The necessary guard band width depends on practically achievable power amplifier linearity and the potential duty cycle of cost and power sensitive U-NII devices. The effect of amplifier non-linearity is presented and an attachment gives some preliminary measurements. Further work and interaction with the standards committees concerned with interoperability will be needed.

One attachment gives a detailed description of the relative media access capabilities of mixed bandwidth systems and justifies the setting of a minimum frequency spacing. Another attachment presents some intermodulation distortion measurements.

2.0 Objectives of the SRDC

The WINForum Sharing Rules Drafting Committee (SRDC) was established in July, 1996 to represent WINForum in the technical and regulatory matters associated with the acquisition of the U-NII spectrum assignment in the US and in establishing a basic set of spectrum sharing rules for devices utilizing the band. The objective is to develop technical rules for the U-NII band that form a regulatory framework which will permit diverse high signaling rate systems to equitably share spectrum. The rules may utilize power detection techniques, but will not require the exchange of coded information, and consequently do not address the interoperability of unrelated devices. Compliance with the rules will be verifiable by testing. The goal is to allow short and medium range systems using different air interfaces to coexist in an interference-limited environment by specifying constraints on power, bandwidth, transmission time and channel access mechanisms.

The WINForum SRDC continues to work to clarify and improve the FCC regulations concerning the U-NII band and has started the work on the sharing rules development.

The objective is to develop spectrum sharing rules that will permit both controlled quality of service type systems and best effort type systems. It is our understanding that the IEEE 802.11 committee and the ETSI BRAN are planning to develop interoperability standards for these types of systems. The SRDC has previously requested formation of a working relationship with these organizations which is consistent with the SRDC objectives and the SRDC reaffirms that request here.

The SRDC has reached a conclusion concerning U-NII band channelization and recommends that a fixed frequency assignment with a minimal frequency spacing supporting efficient systems with signaling speeds in the range of 20 Mb/s be established. Channelization details are still under study, but an example set of rules are presented here. It is hoped that the sharing rules development can continue with proper interaction with ETSI BRAN and IEEE 802.11, and that the other spectrum sharing issues such as transmission time specifications and access rules can also be interactively established.

This document provides the background for the channelization recommendation and records some of the conclusions reached thus far by the SRDC committee.

3.0 Proposal for Fixed Channelization

WINForum, in its petition for the U-NII spectrum in 1995, requested that frequencies be established in the 5.2 GHz range for all forms of multimedia communications including audio, data, graphics and video interchangeably and with signaling rates of approximately 20 Mb/s. This requirement has two aspects not present in previous unlicensed wireless applications:

1. Higher basic signaling rates and
2. a wider range of application or user signaling rates.

The current U-NII rules support the need for high signaling rates by the definition of U-NII devices in Section 15.403 and by the provision to permit the maximum power spectral density at bandwidths up to 20 MHz in Section 15.407[1].

The U-NII user application signaling speeds cover a range from pure voice at about 32 kb/s to data and graphics which require the full burst signaling capacity of a channel in order to achieve the user response times necessary for the next generation LANs.

Thus, the SRDC considers that the sharing rules should be optimized for signaling rates in the range of 20 to 25 Mb/s. This requires a limit on the minimum spacing between frequency channels.

Appendix A shows that a system utilizing multiple narrow frequency channels has a strong access advantage over those with wider channels when the multiple narrow channels are in the frequency space occupied by the wide band channel. This is the case even when the power spectral density of the narrow channels is the same as that of the wide channels as required by the U-NII rules. Thus, there is an inducement for a system provider to establish a channel width just sufficient to

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[1] The definition of U-NII devices in Section 15.403 is “Intentional radiators operating in the frequency bands 5.15 - 5.35 GHz and 5.725 - 5.825 GHz that provide a wide array of wideband, high data rate, digital, mobile and fixed communications for individuals, businesses and institutions.”

accommodate the particular system's maximum user data rate. Such a system would have a strong access advantage over the system which must establish a wider channel width to accommodate a higher signaling rate application. It would thus be contrary to the U-NII goals to permit very narrow channel spacing within a frequency band intended to support the higher signaling rates of U-NII systems. Thus, there is a strong need for the industry to agree on a minimum channel width or frequency assignment which will permit the high signaling rates and the wide range of application signaling rates that the U-NII systems require.

The industry should then advocate that this specification be incorporated into the regulations.

There is no access advantage if the narrow bandwidth system implements only one channel in the frequency spectrum meant for higher speed systems. Thus, the SRDC has chosen to address the access discrepancy by setting a fixed frequency assignment. However, such a narrow bandwidth system would likely use the spectrum in a very inefficient manner and it may also be necessary to establish some rules for efficient use.

The fixed frequency assignment should not preclude the use of wider channels. The rules should permit channels centered between the basic assignment when signal bandwidths are wider than one channel spacing and less than 2 channel spacings, or in general, when the signal bandwidth occupies an even number of channels. However, the wider channel systems will suffer an access disadvantage when operating in the physical vicinity of channels at the basic spacing and bandwidth. Thus, care will be necessary in the deployment of such systems.

There is also a possibility of using some of the guard band for narrower channels.

The other alternative considered was to establish some complex rules on bandwidth control which would enforce some minimal spacing but allow a wider choice of center frequencies. Fixed frequency assignment has advantages of slightly higher spectrum use efficiency and of simpler rules compared to this alternative.

4.0 The U-NII Out-of-Band Specification; The Restricted Band Rules

Sections 15.205 and 15.209 limit the maximum E field level to an average of 500 µv/m at 3 meters in the restricted bands adjacent to the U-NII frequencies (restricted band frequencies above 1000 MHz). Thus, if the signal envelope is non-varying, the power into an isotropic antenna is limited to

$$\frac{E^2 r^2}{30} = \frac{\left(500x10^{-6}x3\right)^2}{30} = 7.5x10^{-8}Watts\,.$$

This is -41.2 dBm, thus the average is limited to -41.2 dBm. In addition, Section 15.45 (b) limits "emissions as measured using instrumentation with a peak detector function" to no more than the maximum permitted average. Thus, the peak is limited to -21.2 dBm.

There are two main questions concerning the interpretation of the Section 15.45 requirements:

1. The bandwidth to be used for the measurement is not specified and
2. the quantity averaged is not clear; power or voltage.

As is often the case for Part 15 of the rules, the measurement procedures often actually define the requirements and this is the case here. The SRDC is in the process of determining the measurement procedures.

The required measurement bandwidth is expected to be 1 MHz, however the averaging technique is not as certain. Thus, a 1 MHz measurement bandwidth is assumed here and considerations for both voltage (or E-field) averaging and power averaging are given.

The Part 15 restricted band average is the maximum average over a 100 millisecond pulse train and clearly includes the off time during the pulse train. U-NII signals consisting of a sequence of transmission bursts constitute a pulse train. Such pulse trains (sequences of bursts) will normally exceed 100 ms in duration, thus the measurement is taken over the 100 ms in which the measurement value is maximum.

The Power Spectral Density (PSD) of U-NII bursts is defined in the WINForum reconsideration petition as the mean power level out of a 1 MHz bandwidth filter during the U-NII burst. This is taken as the definition of the PSD parameter here and the restricted band specified quantities are translated.

In this paper, the peak is considered to be the peak envelope power or voltage, thus the WINForum parameter proposed as the PSD is lower than the peak by the peak to average power ratio during the burst.

Let

R_{pa} = The peak power to average power ratio during a burst in dB.
P_{a0} = The PSD as defined by WINForum; the mean power out of the measurement filter during a burst in dB quantities.
D = The duty cycle, as a decimal value, during the 100 ms at which the average is highest.

The average power limit at 0 dBi antenna gain per 15.209 is -41.2 dBm and the peak power limit at 0 dBi is -21.2 dBm as stated above. The restricted band specifications can be expressed as constraints on the average level while the burst is on (P_{a0}) as follows.

$P_{a0} \le -21.2 - R_{pa}$ dBm, the peak power constraint,

$P_{a0} \le -41.2 - 10\log D$ dBm as the average constraint assuming power averaging and

$P_{a0} \le -40.2 - 20\log D$ dBm as the average constraint assuming voltage averaging[2,3].

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[2] The fact that the voltage average of the envelope of a wide bandwidth signal measured with a narrow bandwidth filter is about 1 dB lower than the power average is taken into account in this equation.

[3] Part 15.407 (b) also limits the out-of-band PSD, but the restricted band rules are more stringent in almost all cases. WINForum has investigated the intent of the rules; the current interpretation is that the restricted band rules only will apply. The 15.407 (b) rules would require the PSD to be as low as -23 dBm at the U-NII band edge and -33 dBm for frequencies 10 MHz beyond the band edge. The -33 dBm value is less than the restricted band rules for low duty cycle cases and would apply beyond 10 MHz if both sets of rules were required.

		Power Averaging			**Voltage Averaging**	
D (%)	Average Constraint	Peak Constraint	**15.209 PSD Limit**	Average Constraint	Peak Constraint	**15.209 PSD Limit**
1.00%	-21.20	-29.20	**-29.20**	-0.20	-29.20	**-29.20**
2.00%	-24.21	-29.20	**-29.20**	-6.22	-29.20	**-29.20**
3.00%	-25.97	-29.20	**-29.20**	-9.74	-29.20	**-29.20**
4.00%	-27.22	-29.20	**-29.20**	-12.24	-29.20	**-29.20**
5.00%	-28.19	-29.20	**-29.20**	-14.18	-29.20	**-29.20**
6.00%	-28.98	-29.20	**-29.20**	-15.76	-29.20	**-29.20**
7.00%	-29.65	-29.20	**-29.65**	-17.10	-29.20	**-29.20**
8.00%	-30.23	-29.20	**-30.23**	-18.26	-29.20	**-29.20**
10.00%	-31.20	-29.20	**-31.20**	-20.20	-29.20	**-29.20**
12.00%	-31.99	-29.20	**-31.99**	-21.78	-29.20	**-29.20**
14.00%	-32.66	-29.20	**-32.66**	-23.12	-29.20	**-29.20**
16.00%	-33.24	-29.20	**-33.24**	-24.28	-29.20	**-29.20**
18.00%	-33.75	-29.20	**-33.75**	-25.31	-29.20	**-29.20**
20.00%	-34.21	-29.20	**-34.21**	-26.22	-29.20	**-29.20**
25.00%	-35.18	-29.20	**-35.18**	-28.16	-29.20	**-29.20**
30.00%	-35.97	-29.20	**-35.97**	-29.74	-29.20	**-29.74**
35.00%	-36.64	-29.20	**-36.64**	-31.08	-29.20	**-31.08**
40.00%	-37.22	-29.20	**-37.22**	-32.24	-29.20	**-32.24**
45.00%	-37.73	-29.20	**-37.73**	-33.26	-29.20	**-33.26**
50.00%	-38.19	-29.20	**-38.19**	-34.18	-29.20	**-34.18**
55.00%	-38.60	-29.20	**-38.60**	-35.01	-29.20	**-35.01**
60.00%	-38.98	-29.20	**-38.98**	-35.76	-29.20	**-35.76**
65.00%	-39.33	-29.20	**-39.33**	-36.46	-29.20	**-36.46**
70.00%	-39.65	-29.20	**-39.65**	-37.10	-29.20	**-37.10**
100.00%	-41.20	-29.20	**-41.20**	-40.20	-29.20	**-40.20**

Table 4-1: Values of P_{ao} for R_{pa} = 8 dB.

All values are in dBm. The measurement bandwidth is 1 MHz.

The table gives the limit values of the burst power as defined by WINForum (P_{ao}) in the Part 15 restricted bands assuming a 0 dBi antenna. The actual limits are lower by the amount the EIRP of the equipment exceeds the maximum allowed for an isotropic antenna; if the equipment should operate at the maximum allowed EIRP (6 dB above the isotropic limit), the requirements are 6 dB lower than those given. The column labeled "15.209 PSD Limit" gives the minimum of the values computed with each constraint and are thus the requirement.

The peak constraint is in effect up to a duty cycle of about 7% if power averaging is intended and up to about 25% if voltage averaging is intended.

The peak to average ratio while on (R_{pa}) is assumed to be 8 dB for the table.

Table 4-1 shows the Section 15.209 PSD limit when translated from the definition in the rules to the WINForum PSD quantity; that is to the 1 MHz bandwidth mean power during a burst.

The peak constraint determines the limit when the duty cycle is below a critical value. This critical value can be computed by setting the two constraints equal. If this critical value of the duty cycle is D_c, then

$D_c = 10^{\frac{R_{pa}-20}{20}}$ for voltage averaging and

$D_c = 10^{\frac{R_{pa}-20}{10}}$ for power averaging.

Reference 4 reports one spectrum analyzer measurement of R_{pa} of 6.2 dB for a $\pi/4$ DQPSK signal with a 3 dB peak to average ratio and a measurement bandwidth to spectrum width ratio of approximately that which is expected for U-NII applications. The value is expected to range between about 6 and 10 dB. Differing signal types and testing sequences can be expected to produce variable results, but the 8 dB of the table 4-1 is considered to be on the conservative side. Higher values predict lower level requirements.

Table 4-2 shows the value D_c for a range of R_{pa} values.

The critical value of the duty cycle is very dependent on whether the averaging is on a power or voltage basis. Thus, it is critical that this point be clarified. The SRDC is thus in the process of obtaining the clarification.

R_{pa} (dB)	**D_c for voltage averaging (%)**	**D_c for power averaging (%)**	**Restricted band limit level for $D<D_c$**	**Maximum attenuation for lower band with $D<D_c$ (dB)**	**Maximum attenuation for middle band with $D<D_c$ (dB)**
5	17.8	3.2	-26.2	36.2	43.2
6	20.0	4.0	-27.2	37.2	44.2
7	**22.4**	**5.0**	**-28.2**	**38.2**	**45.2**
8	**25.1**	**6.3**	**-29.2**	**39.2**	**46.2**
9	28.2	7.9	-30.2	40.2	47.2
10	31.6	10.0	-31.2	41.2	48.2

Table 4-2. Critical Values of Duty Cycle and Corresponding U-NII Out-of-Band PSD Level

The level column (fourth column) is the level required for an isotropic antenna.

The likely value of $\mathbf{R_{pa}}$ for a wideband U-NII signal is between 6 and 10 dB.

The attenuation columns are the PSD attenuation required if the EIRP is at the maximum value and the duty cycle is below the critical value given in the second column. A level of 30 dB for the intraband attenuation is currently under consideration. Thus, the U-NII band edge attenuation for low duty cycle devices is required to be 8 to 9 dB lower than the intraband value for the lower band and 15 to 16 dB lower for the middle band. About 12 dB more attenuation is required for full duty cycle operation.

Table 4-3 summarizes the required PSD attenuation values for devices which operate with the maximum permitted in-band PSD.

U-NII Band	**100% duty cycle, power averaging**	**100% duty cycle, voltage averaging**	**50% duty cycle, power averaging**	**50% duty cycle, voltage averaging**	**Duty cycle < Dc P_{ao} = 8 dB**
Middle Band, restricted rules	58.2	57.2	55.2	51.2	46.2
Lower Band, restricted rules	51.2	50.2	48.2	44.2	39.2

Table 4-3: U-NII Transmitter Mask Restricted Band Relative Attenuation Requirements

Attenuation Values in dB. The required transmitter PSD attenuation is relative to the maximum in-band with the maximum permitted EIRP. **R_{pa} = 8 dB**

It is expected that most small portable U-NII devices will operate naturally with a low duty cycle. Such devices are normally power and cost sensitive and the power amplifier linearity required for high out-of-band attenuation is critical. If such a device can logically limit the duty cycle it may gain as much as 12 dB over a device such as a base station or LAN access point which can be powered from the AC mains and which are normally less cost sensitive. Thus, the necessary guard band for frequency assignment depends heavily on the expected requirements for small size, cost and power sensitive devices.

5.0 Intermodulation Distortion

An efficient Power Amplifier (PA) has an output signal that is not an exact amplified replica of the input signal. Because of this, the PA introduces unwanted spectral components (intermodulation components) outside the desired frequency band if the transmitted signal in not of constant amplitude. Spectrally efficient modulation techniques have amplitude variations, thus such techniques are needed for the U-NII band. However, the U-NII band in the US also has extreme out-of- band attenuation requirements as shown in section 4. Thus, it is necessary to carefully consider the intermodulation process in setting the carrier frequencies and bandwidths for the U-NII band.

This section reviews some aspects of the intermodulation process.

A bandpass signal can be expressed as

$$S(t) = A(t)\cos v(t) \qquad (5\text{-}1).$$

If this signal is amplified by a non-linear power amplifier, and A is not a constant, then the spectral width of S(t) is increased by the amplification.

The output can be represented as a power series expansion of the input, thus the output will contain terms of the form $A^n(t)\cos^n v(t)$, where n is a positive integer. The angle v(t) has a form $\omega_c t + \phi(t)$ where $\phi(t)$ varies slowly and ω_c is the radian carrier frequency. The cosine term can be expressed as the sum of cosines with angles which are multiples of v(t), thus all but the first order expansion of $\cos^n v(t)$ term is outside the frequency band of S(t) by a factor of at least 2 and the terms of significance relative to frequencies near ω_c are of the form

$$S_m(t) = A^m(t)\cos v(t)\ . \qquad (5\text{-}2)$$

where S_m is the component due to the mth. coefficient in an output envelope-input envelope power series expansion[4].

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[4] The second order distortion in the envelope does not arise from a second order term in the overall I/O power series expansion. In fact, it can be shown that only the odd order terms in the overall I/O characteristic will affect the amplitude waveform of a signal in which the spectrum is constrained to frequencies near the carrier frequency.

A simple AM modulated case will be used to illustrate the production of intermodulation distortion. Consider the case where A(t) is a single spectral line (cosine wave), v(t) = $\omega_c t$ and the output envelope contains a squared term, that is A(t) + $k_2 A^2(t)$.

$$A(t) = \cos\left(\frac{\Delta w}{2} t\right) \text{ and}$$

the output signal with spectral components near ω_c is.

$$S(t) = \left[\frac{k_2}{2} + \cos\left(\frac{\Delta w}{2} t\right) + \left(\frac{k_2}{2}\right)\cos(\Delta w\, t)\right]\cos w_c t$$

This signal spectrum has lines at ω_c, ω_c+/-$\Delta\omega/2$ and ω_c+/-$\Delta\omega$. With

$\omega_1 = \omega_c - \Delta\omega/2$

$\omega_2 = \omega_c + \Delta\omega/2$,

and

$\omega_3 = 2\ \omega_2 - \omega_1 = \omega_2 + (\omega_2 - \omega_1) = \omega_2 + \Delta\omega$.

Or, in terms of frequency

$f_3 = f_2 + (f_2 - f_1)$.

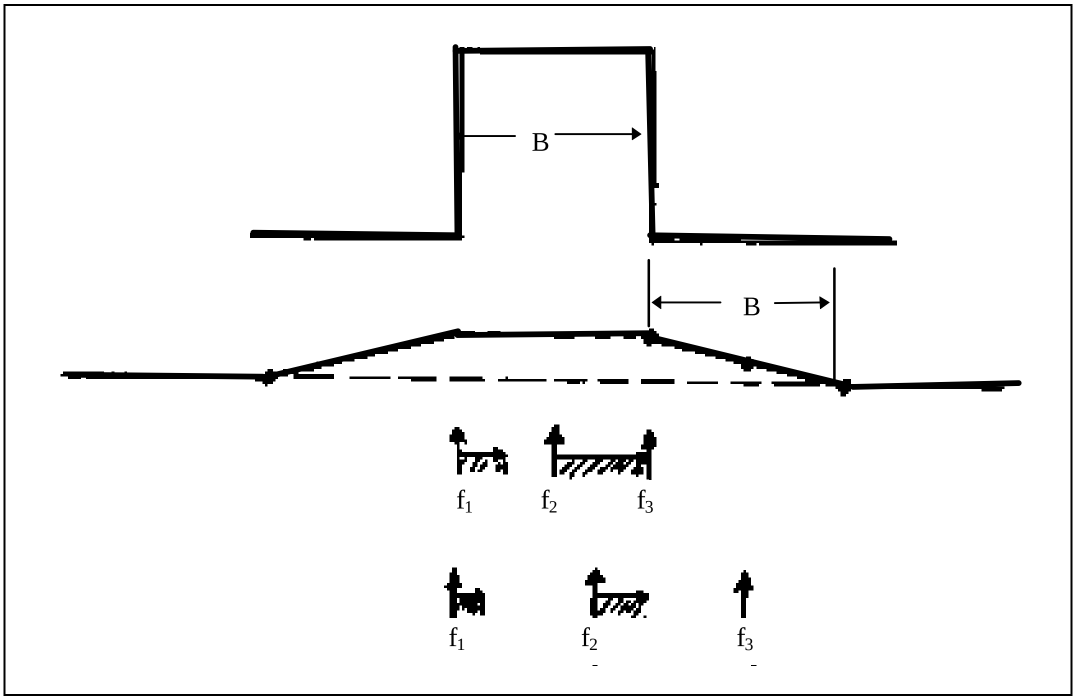

Figure 5-1: Illustration of the Frequency Range of Third Order Intermodulation Distortion

Third order intermodulation distortion exists over a frequency range of three times the frequency difference between the possible generating frequencies. A reasonable upper bandwidth limit is $3B_6$ where B_6 is the 6 dB bandwidth of the emission. The distortion can be expected to be higher near the band edge. The shaded regions illustrate the range of frequencies f_1, f_2 that can contribute to the f_3 power level.

Thus, amplifier non-linearity that affects the amplitude envelope widens the spectral width of the emission. Odd order distortion in the overall amplifier I/O characteristic is necessary to create such variation in the envelope waveform.

The critical frequency spectrum of the equation 5-1signal will be represented as in figure 5-1. This is a non-realizable shape, but it can be used for discussion . It illustrates the spreading of the spectral width of S(t) by the third order term in the output expansion. All odd order terms in the I/O expansion can create spectrum components near the desired band, but the third order term is normally dominant. Third order intermodulation creates unwanted spectral components at frequencies $2f_2 - f_1$ and $2f_1 - f_2$ in which f_1 and f_2 are components within the region +/- B/2 from the carrier frequency. Thus, components are generated by third order distortion at intermodulation frequencies up to +/- 3B/2 around the center frequency of an emission. In most cases, B can be considered the 6 dB bandwidth of the emission. In the same manner, fifth order terms can produce significant unwanted power at frequencies up to +/- 5B/2 and, in general, terms of order 2m+1 creates power at frequencies up to +/- (2m+1)B/2[5].

Third order intermodulation products normally decrease 3 dB for each 1 dB decrease in amplifier input power, Fifth order decrease 5 to 1 etc.

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[5] The amplitude of the f_3 term does not necessarily decrease linearly as shown. An example which illustrates this is shown in appendix B for a QPSK signal. However, the amplitude due to third order distortion is zero at frequencies outside +/- 3B/2.

Figure 5-2 shows the computed spectra of the output of a PA with an Orthogonal Frequency Division Multiplex (OFDM) signal input at a level which saturates the amplifier. The upper trace of the figure shows the signal with distortion and the lower trace shows the signal with linear amplification.

The PSD of the third order components is about 20 dB below the signal PSD in figure 5-2. Also, the fifth order components are detectable at about -50 dB.

More example intermodulation measurements are shown in appendix B.

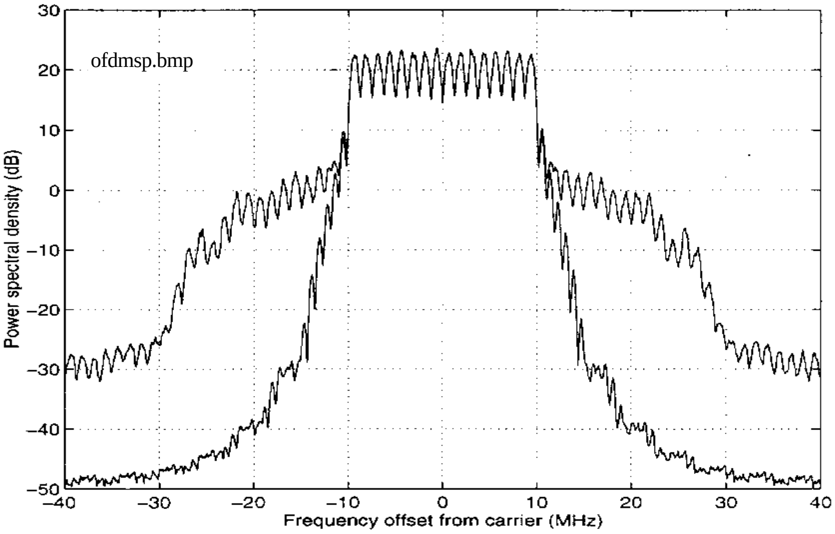


Figure 5-2: Illustration of Spectral Output of a Saturated PA, OFDM Signal With 6.5 dB Peak/Average Ratio
The 1 dB compression point of the amplifier is 2 dB below the saturation level. The input is 1.75 dB above the 1 dB compression point. The spectrum is computed. The figure is from reference 7.

6.0 Frequency Assignment Example

The assignment of frequencies for the U-NII channels is a subject for further work, however this section presents the considerations which must go into making the choice and gives an example frequency assignment.

The frequency assignment will need to be unique to the U-NII band in the US because the frequency bands immediately adjacent to the lower (5.15 to 5.25 GHz) and middle (5.25 - 5.35 GHz) bands are subject to the restricted band rules of CFR 47 Part 15.205 and 15.209. The power spectral density at the band edge relative to the permissible in-band values range from -39 dB to -58 dB depending, among other things, on the device duty cycle (as presented in section 4). This compares to a necessary intraband out-of-channel suppression on the order of 30 dB.

Efficient modulation techniques not only require good spectrum shaping in the linear transmitter components but also create requirements on the linearity of final stage power amplifiers when such severe band edge suppression is necessary. Thus, since U-NII will be used in small, low power, cost sensitive applications, the linearity requirement on the power amplifier is critical. Section 5 and appendix B discusses this more thoroughly.

A provision for guard bands within the U-NII lower and middle allocation is necessary because of the severe band edge requirements. The amount of spectrum to allocate to guard bands depends upon, among other things, the costs of power amplifier linearity, the necessary duty cycle for cost and power sensitive devices and the intraband specifications. Thus, more work on these subjects is necessary before a frequency assignment should be made.

Example Intraband Specification

The following is an example set of parameters which may be specified for the channel specifications within the U-NII lower and middle bands. This example specification is under consideration by the SRDC.

The PSD values specified are with respect to the maximum permissible in-band PSD. B is the frequency spacing and f_c is the channel carrier frequency.

Maximum adjacent channel PSD	-30 dB (outside the range f_c +/- B/2)
Maximum subsequent channel PSD	-50 dB (outside the range f_c +/- 3B/2)

Thus, the maximum absolute adjacent and subsequent channel PSD levels are respectively

Middle Band -19 dBm and -39 dBm per MHz
Lower Band - 26 dBm and -46 dBm per MHz.

With this specification and a receiver filter which achieves 30 dB rejection of the adjacent band power, an overall isolation between adjacent channels of 27 dB can be obtained in all channels of the lower and middle band except for the higher channel of the lower band. The higher channel of the lower band would experience about 22 dB isolation from it's middle band adjacent channel. Thus, a receiver filter with 30 dB suppression of the adjacent channel would only deteriorate the overall adjacent channel rejection by 3 to 4 dB.

Reference 5 shows that it is possible to achieve up to 90% reuse efficiency with 27 dB of interchannel isolation in an unlicensed system with uncoordinated dynamic channel assignment. This is a limit value, but it can be approached closely with systems utilizing access and hold type of procedures such as systems following the UPCS isochronous access rules and those that are likely to be required for controlled quality of service (usually reservation based) systems.

The SRDC is also analyzing studies associated with best effort unlicensed access procedures such as those of the IEEE 802.11 MAC and is expected to achieve like conclusions.

Example Possible Frequency Assignment

The above intraband specifications will be assumed and the necessary guard bands for a particular amplifier and suppression level will be computed.

Assume the following:

1. The necessary suppression at the upper edge of the middle band can be achieved outside the third order range (f_c +/- $3B_6/2$ of section 5).

   Figure B1 (of appendix B) shows a case where approximately 50 dB of PSD suppression is achieved with QPSK at the limit of the third order range. Table 4-3 shows that 50 dB is sufficient for limited duty cycle operation, but that 58 dB may be needed for devices that may operate at full duty cycle, thus the spectrum shaping of figure B1 would be sufficient for operation at limited duty cycle but more suppression would be required in some cases.

2. The same PA is used in the lower band as in the middle band, thus third order intermodulation power is 21 dB lower in the lower band.

3. The power level in the lowest and highest channel is the same as for the inner channels. That is, no reduction is incorporated because of the band edge suppression requirement.

The current U-NII rules permit 7 dB higher power spectral density in the middle band than in the lower band. Thus, the intermodulation power in the lower band with the same power amplifier as used in the middle band would be 21 dB (3 x 7 dB) lower. This corresponds to an intermodulation value of - 14 dB relative to the in-band PSD level since the in-band level is 7 dB lower.

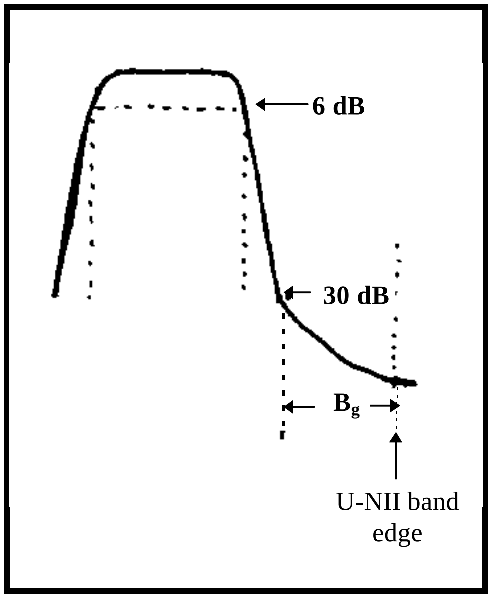
Assumptions 1 and 2 are optimistic. They are based on the limited set of measurements reported in appendix B. Thus, more study is necessary before a frequency assignment can be made.

Let

- B_x = Bandwidth at x dB attenuation (when x is numeric)
- $B_{3i} \cong$ $3B_6$ = Bandwidth limit for third order intermodulation
- B_s = Bandwidth between frequency spacing - frequency difference between assignments
- B_{gu} = The guard band at the middle U-NII band upper edge
- B_{gl} = The guard band at the lower U-NII band lower edge
- B_{gt} = The total guard band = $B_{gu} + B_{gl}$ (upper plus lower)

B_s for U-NII = B_{30} for the example specification under consideration.

See the sketch for the following definition of k_x.



$$B_g = \frac{3k_x B_6 - B_s}{2}$$

k_x = 1 puts all third order distortion products within the U-NII band. The band edge is at $f_c + 3B_6/2$ when k_x =1.

$k_x >= B_s/3B_6$. The minimum value corresponds to a - 30 dB band edge PSD and gives a guard band of zero width.

B_{30}/B_6 for both QPSK and OFDM in the detail graphs of appendix B (figures B3 and B6) ≅ 1.3. For the intraband specification, $B_{30} = B_s$, thus the guard band at each edge is also

$$B_g = \frac{3k_x \frac{B_s}{1.3} - B_s}{2} = \frac{1}{2} B_s \left(2.31k_x - 1\right)$$

Let

- k_{xu} be the value of k_x for the middle band and
- k_{xl} be the value of k_x for the lower band

and set

- k_{xu} = 1 for the upper edge of the middle band and
- k_{xl} = 0 .72 for the lower band.

The k_{xl} value of 0.72 corresponds to a PSD suppression of slightly more than 50 dB in the undistorted transmitter spectrums of figures B3 (QPSK) and B6 (OFDM) when the channel spacing is at the B_{30} point. The measurements of appendix B indicate that the relative distortion level will be in this same range if the PA is operated at a level 7 dB below those of the appendix. Thus, overall out of band suppression of around 47 dB should be possible below the lower band. This is sufficient for limited duty cycle operation at the lower band edge (see table 4-3).

Then,

$B_{gu} = 0.65B_s$
$B_{gl} = 0.33B_s$
$B_g = B_{gu}+B_{gl} = 0.98B_s$.

The restricted band band edge requirement costs 0.98 channels under these assumptions.

If N is the number of channels within the lower and middle U-NII band, then

$B_s = 200/(N+.98)$ or
$N = \mathrm{Int}(200/B_s -.98)$.

For example, the HIPERLAN type 1 signaling speed is 23.5 Mb/s in a channel and approximately 20.4 MHz frequency spacing is needed at 3 bits/symbol or 1.5 b/sec/Hz.

$B_6 \cong 23.5/1.5$ MHz = 15.7 MHz
$B_{30} \cong 1.3B_6$ = 20.4 MHz
$N = \mathrm{Int}(200/20.4 -1) = \mathrm{Int}(8.8) = 8$

Thus, 8 channels are required. However, a slightly lower guard band would permit 9 channels. Thus, it is important to choose the channel spacing carefully.

A safer assumption would be to set guard bands that avoid third order intermodulation distortion at both band edges. In this case, the guard band would be $0.65B_s$ at either band edge for a total guard band of $1.3B_s$. The following is a compilation of the bandwidths and signaling speeds under the two guard band and modulation efficiency assumptions.

	0.98 Channels Guard Band (optimistic)			**1.30 Channels Guard Band** (outside third order intermod range)			
N	B_s (MHz)	1.5 b/s/Hz	1.0 b/s/Hz		B_s (MHz)	1.5 b/s/Hz	1.0 b/s/Hz
5	33.4	38.6	25.7		31.8	36.6	24.4
6	28.7	33.1	22.0		27.4	31.6	21.1
7	25.1	28.9	19.3		24.1	27.8	18.5
8	22.3	25.7	17.1		21.5	24.8	16.5
9	20.0	23.1	15.4		19.4	22.4	14.9
10	18.2	21.0	14.0		17.7	20.4	13.6

Appendix A - Summary of Relative Performance of Mixed Bandwidth Systems

This appendix summarizes the WINForum documentation which quantifies the relative sharing disadvantage of wide bandwidth systems providing high user signaling rates when they must operate in the presence of narrower bandwidth systems which utilize closely spaced frequency channels.

There is an inherent disadvantage to a system employing wide a frequency bandwidth when operating in the presence of a system employing a narrow frequency bandwidth. Thus, there is a need to establish a minimum channel width for U-NII systems in order to achieve the wideband, high data rate objective of the U-NII band called for in Section 15.403. Otherwise, the optimum choice for any system is to establish channel widths that are just sufficient to carry the highest application signaling rate.

References 1, 2 and 3 address this question and this is a summary of those references.

The general problem is covered in reference 1. Consider a system of devices which require a bandwidth B_m in order to perform its function. This could be a U-NII system utilizing 25 MHz of bandwidth. Further, consider one or more other systems of devices in the same coverage area utilizing multiple channels of bandwidth B ($B < B_m$) where B is a part of B_m and no part of B lies outside B_m. Further, assume that each system throughput demand creates a given utilization of the bandwidth which is independent of B. That is, the device density and throughput demand is such that each segment of the spectrum is utilized the same fraction of the time by each system.

The mean power transfer ratio between a transmitter of output power P_t and a receiver of power P_r can be approximately stated as

$$P_t = C P_r r^{\alpha}$$

where C is a constant, r is the distance between devices and α is the propagation exponent which is normally equal to about 4 for the 5.2 GHz band at the indoor distances expected for most U-NII systems.

Reference 1 shows that, in the absence of any procedural rules enforcing coexistence, the power output of the devices would need to be

$$\mathrm{P} \le \mathrm{P_m}\left(\frac{\mathrm{B}}{\mathrm{B_m}}\right)^{\alpha/2} \qquad \text{A1}$$

in order to ensure equal time-spectrum access capability. With $\alpha = 4$, this is a bandwidth squared relationship[6].

CSMA/CA access rules, such as used in IEEE 802.11, have a further problem relative to operation of wide bandwidth systems in the presence of narrow bandwidth systems. These rules require a quiet channel period after a transmission (the IFS gap) in order to permit channel sharing on a burst basis. However, the narrow bandwidth devices within bandwidth B_m do not coordinate the IFS gaps, thus the wide bandwidth systems can suffer a lockout condition in which they sense more than 1 narrow channel and thus are not guaranteed a quiet period of deferral.

However, reference 1 shows that even if rules are incorporated that would prevent this lockout condition, the output power relationship of equation A1 is necessary to ensure equal access capability.

Reference 1 and 2 also consider a general case which is appropriate for both distributed control burst access (HIPERLAN type 1 and IEEE 802.11access) and reserved channel access.

Consider two systems of devices

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[6] The inequality is based on an assumption that the interference area created by a collection of narrow bandwidth devices to a wide bandwidth device is slightly greater than the union of the individual interference areas. If this area were equal, equation A1 would be an equality. Reference 1 gave the equation as an equality and states the assumption.

1. A system of devices of type 1 utilizing n_1 time divided channels of bandwidth B_1
2. a system of devices of type 2 utilizing n_2 time divided channels of bandwidth B_2, $B_2 > B_1$.
3. a detection threshold equal to hB_x where x is 1 or 2 and h is the proportionality constant which sets the threshold at the proper value relative to thermal noise.
4. The systems must obtain capacity in contiguous time or frequency units.

Assertion 4 is appropriate for a frequency divided system, but is not necessarily the case in a time divided system. A time divided (multiplexed) system can obtain signaling rate capability by acquiring non-contiguous time slots. Thus, the restrictive relationships developed next do not apply to a wide bandwidth time multiplexed channel in which the capacity can be obtained in non-contiguous time slots.

The following parameters were defined

K_{xy} = the mean number of devices of type y with power on or contending to turn power on in which the power is detectable above the threshold by a device type x, where xy can take on the values 12, 11, 21, and 22.

N_x = the number of devices of type x (x = 1 or 2) per unit area with power on or contending to turn power on

$S_x = N_xB_x/n_x$ = The spectrum usage demand of system x

e_x = The modulation efficiency of system x in bits/second/Hz and

$\sigma_x = e_xB_x/n_x$ bits/sec is the user signaling rate of channel x.

If K_{xy} exceeds K_{yx} , then devices of type x will sense more devices of type y than will type y devices sense of type x, thus type x devices will suffer an access disadvantage.

The following equations were developed in reference 1 (SRDC/09.11.96.10) for the UPCS power-bandwidth dependence (power proportional to the square root of the bandwidth) and extended in reference 2 (SRDC/01.28.97.11) for the U-NII equal Power Spectral Density (PSD) case.

$$\frac{K_{21}}{K_{12}} = \frac{K_{21}}{K_{22}} \geq \frac{S_1 e_1 \sigma_2}{S_2 e_2 \sigma_1}\left(\frac{B_1}{B_2}\right)^{1/\alpha} \quad \text{when}$$

$$\frac{P_1}{P_2} = \sqrt{\frac{B_1}{B_2}} \quad \text{and}$$

A2

$$\frac{K_{21}}{K_{12}} = \frac{K_{21}}{K_{22}} \geq \frac{S_1 e_1 \sigma_2}{S_2 e_2 \sigma_1}\left(\frac{B_1}{B_2}\right)^{2/\alpha} \quad \text{when}$$

$$\frac{P_1}{P_2} = \frac{B_1}{B_2}. \qquad \text{A3}$$

For equal spectrum utilization and modulation efficiency and with $\alpha = 4$:

$$\frac{K_{21}}{K_{12}} = \frac{K_{21}}{K_{22}} \geq \frac{s_2}{s_1}\left(\frac{B_1}{B_2}\right)^{1/4}$$

when

$$\frac{P_1}{P_2} = \sqrt{\frac{B_1}{B_2}} \text{ and}$$

A5

$$\frac{K_{21}}{K_{12}} = \frac{K_{21}}{K_{22}} \geq \frac{s_2}{s_1}\left(\frac{B_1}{B_2}\right)^{1/2}$$

when

$$\frac{P_1}{P_2} = \frac{B_1}{B_2}. \qquad \text{A6}$$

Equation A6 is appropriate for the equal PSD, U-NII band. Note the strong dependence on the user signaling speed and relatively weak dependence on bandwidth. The high signaling speed system suffers a disadvantage in terms of the incidence of a busy channel condition it will experience that is almost directly proportional to the signaling speed ratio. The wide bandwidth system has an advantage, provided it doesn’t need to supply higher user signaling rates. However, it is the generally recognized objective of the U-NII band to provide a wide range of user signaling rate capability within single systems. Thus, the minimum channel width should accommodate the maximum expected user signaling speed.

Equation A5 is appropriate for the UPCS isochronous rules where the objective is to obtain equal access capability for systems of differing bandwidths but of equal signaling speed (digital voice systems).

These relationships apply only when the user capacity must be obtained in contiguous frequency or time channels. It is not necessary to obtain capacity in contiguous time slots when time multiplexing is employed, thus a wide frequency channel capable of supporting the highest user signaling rates is needed for all systems in order to achieve equal spectrum utilization.

Appendix B - Example Intermodulation Distortion Levels

This section shows some measured transmit spectra for a QPSK signal with 3 dB peak to average ratio and for a 16 tone OFDM signal. The level of intermodulation distortion is determined for each example.

These measurements were made with a spectrum analyzer in the peak-hold mode. The restricted band rules specify the absolute peak and the average power levels. The peak-hold measurement provides an approximation of these quantities. References 4 and 5 give a full discussion of the statistics of potential U-NII band emissions and give notes on measurement. Actual shapes of the spectral plots depend on the measurement bandwidth to spectrum width ratio and to the type of modulation used.

Reference 5 provides some measurements on QPSK signals, but the SRDC has not studied the measurement statistics of OFDM signals. Thus, the measurements presented here should be interpreted carefully.

Estimating the distortion from the emission mask

Here it is assumed that at least two emission masks of a Power Amplifier (PA) output are measured with differing input levels. The method of computing the component of the PSD due to distortion is shown.

Define the following parameters with upper case representing decibel quantities:

X_1 = lower input power level relative to the 1 dB compression point of the PA
X_2 = higher input power level relative to the 1 dB compression point of the PA
Y_1 = PSD level relative to the in-band PSD at the lower input power level at the frequency being evaluated
Y_2 = PSD level relative to the in-band PSD at the higher input power level at the frequency being evaluated
d_1 = relative distortion power at the X_1 power level (watts/watt)
d_2 = relative distortion power at the X_2 power level
s+n = the signal plus noise PSD level relative to the in-band PSD (watts/watt)

Then

$$s+n+d_1 = 10^{\frac{Y_1}{10}}$$

$$s+n+d_2 = 10^{\frac{Y_2}{10}}$$

$$d_2 - d_1 = 10^{\frac{Y_2}{10}} - 10^{\frac{Y1}{10}}$$

$$\frac{d_2}{d_1} = 10^{\frac{2(X_2 - X_1)}{10}}$$

The last expression reflects the 3 dB distortion power per dB of input power dependence of the third order distortion component. The PSD level drops at a 3 to 1 ratio, thus the relative PSD drops at a 2 to 1 decibel ratio.

Combining the last two equations give

$$10\log d_2 = 10\log\left[\frac{10^{\frac{Y_2}{10}} - 10^{\frac{Y_1}{10}}}{1 - 10^{0.2(X_2 - X_1)}}\right] = D_2$$

where D_2 is the relative attenuation of the distortion component relative to the in-band PSD.

A QPSK Measurement

Figures B1 and B2 show the output spectrum measured for a QPSK signal with 3 dB peak to average ratio at two power levels 3 dB separated near the amplifier 1 dB compression point (X_2 =-4 dB and X_1=-7 dB). These graphs were scaled for the above parameters and the distortion level was computed at the center frequency +/- $1.5B_6$, where B_6 is the double sided 6 dB bandwidth as used in section 5.

These figures exhibit near the same PSD attenuation for each input level at frequencies nearer center than about $1.5B_6$ which indicates that there is very little distortion power in this frequency range. But, it can be seen that the PSD attenuation is lower at the higher power level at frequencies of F_c +/- 1.5 B_6 which indicates that there is intermodulation power at this frequency (The diamond markers are at about + $1.5B_6$).

The relative attenuation of the distortion components (D_2) is about -33 dB relative to the in-band PSD.

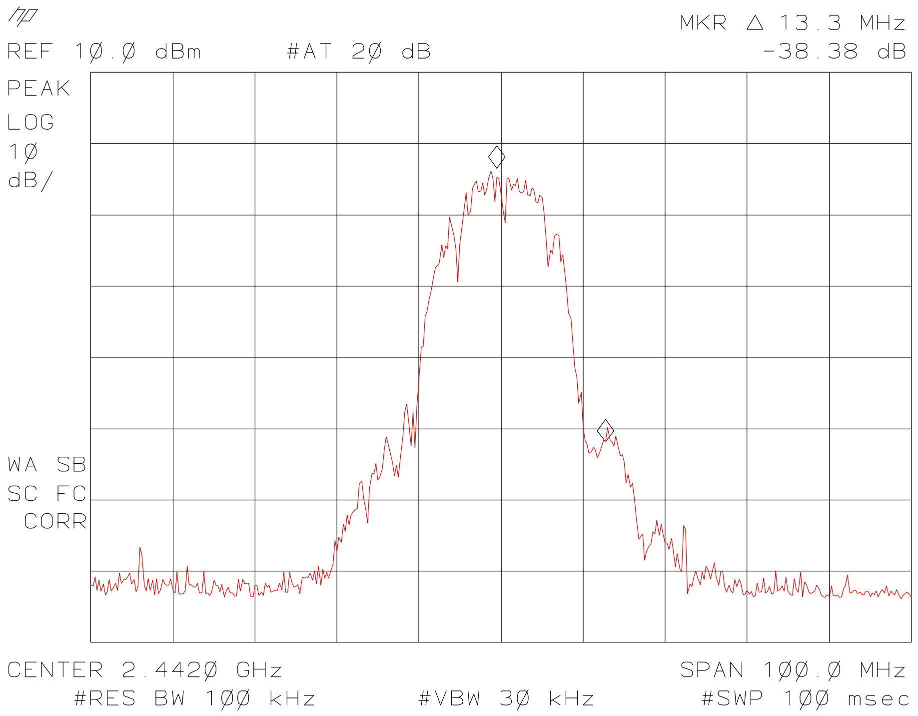

Figure B1. QPSK with 3 dB peak to average ratio, RMS Output Power 7 dB below the 1 dB Compression Point.

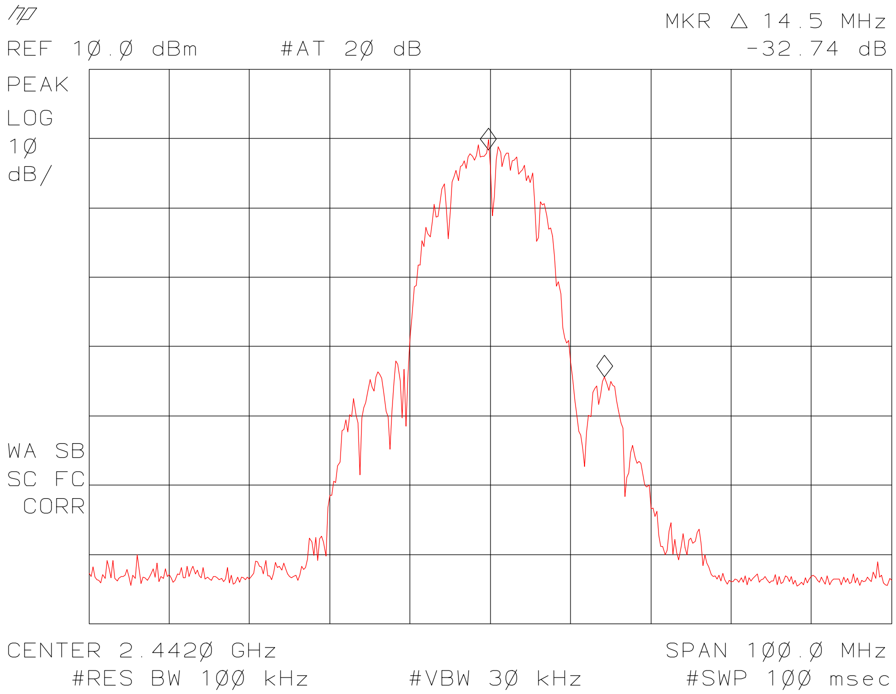

Figure B2. QPSK with 3 dB Peak to Average Ratio, RMS Output Power
4 dB Below the 1 dB compression Point

The following table gives the scaled parameters.

For the QPSK signal of figures B1 and B2

$X_1 = -7$ dB
$X_2 = -4$ dB
B_6 = the 6 dB bandwidth

At $F_3 = F_c$+/-1.5B_6	Y_1 (dB)	Y_2(dB)	d_2 (μW/W)	D_2 (dB)
High side	-38.7	-33.4	430	-33.7
Low side	-37.6	-32.3	554	-32.6

Thus, it can be concluded that the distortion product at 1.5 B_6 (a distortion bandwidth 3 times the 6 dB bandwidth) is approximately 33 dB below the in-band PSD with this amplifier and a QPSK signal with a 3 dB peak/average ratio when the power output is 4 dB below the 1 dB compression point.

However, the measurement accuracy is unknown and further measurements would be needed to establish a reliable value.

Another QPSK case

Figures B3, B4 and B5 show the basic undistorted signal spectrum and output spectrum measurements at two power levels for another QPSK signal with 3 dB peak-to-average ratio. The table below shows the distortion levels computed for this signal.

X_2 = -30 dB (insignificant)

F = F_c +/- 0.92 B_6	D_2 in dB at X_1 = -7.3 dB	D_2 in dB at X_1 = -5.4 dB	Difference (dB)	Distortion change to input change ratio (dB/dB)
Upper Side	-46.4	-42.6	3.8	3.0
Lower Side	-44.3	-39.5	4.8	3.5

Note that the distortion level change is approximately 3 times the input level change with both measured in decibels.

An OFDM Case

Figures B6, B7 and B8 show the basic undistorted signal spectrum and output spectrum measurements at two power levels for a 16 channel OFDM signal. The table below shows the distortion levels computed for this signal.

X_2 = -30 dB (insignificant)

F = F_c +/- 0.80B_6	D_2 in dB at X_1 = -8.6 dB	D_2 in dB at X_1 = -6.8 dB	Difference (dB)	Distortion change to input change ratio (dB/dB)
Upper Side	-41.0	-33.7	7.3	5.1
Lower Side	-36.8	-33.0	3.8	3.1

The distortion level change for the upper side is approximately 5 times the input level change with both measured in decibels. A value of 3 would be expected. This variation is probably within the range that can be expected, given the possible scaling errors and the peak-hold method of measurement.

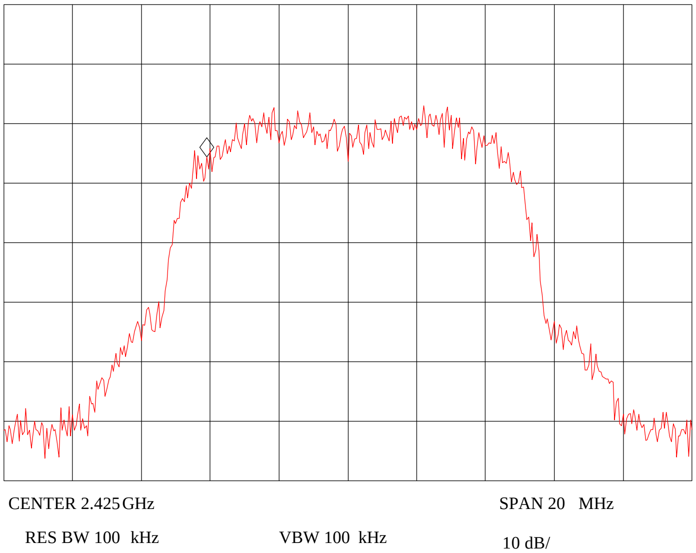

Figure B3. QPSK Signal Input of Power Amplifier
Peak/Average Ratio = 3 dB

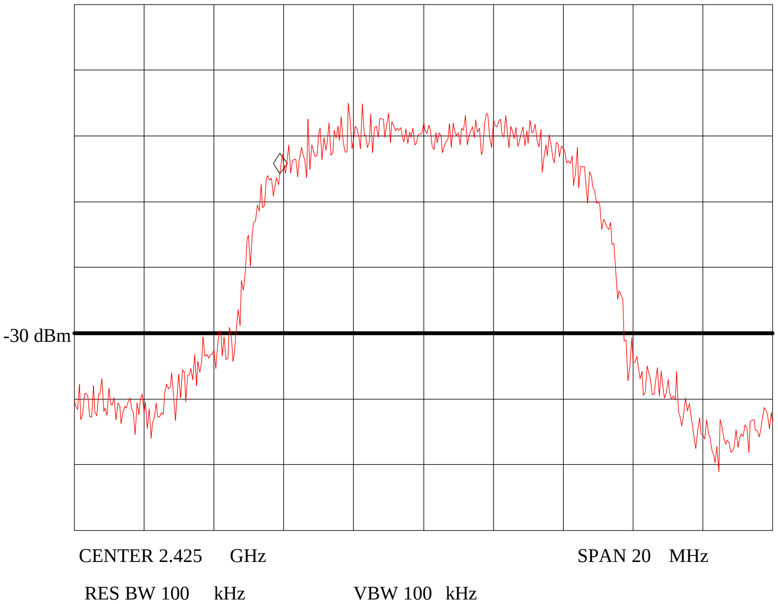

Figure B4. QPSK Power Amplifier Output
RMS output power 7.3 dB below the 1 dB compression point

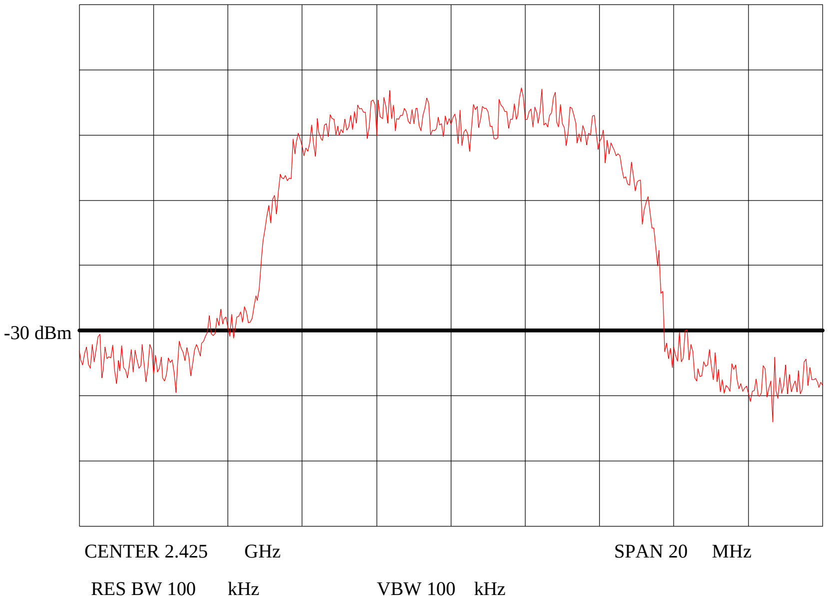

Figure B5. QPSK Power Amplifier Output
RMS output power 5.4 dB below the 1 dB compression point t

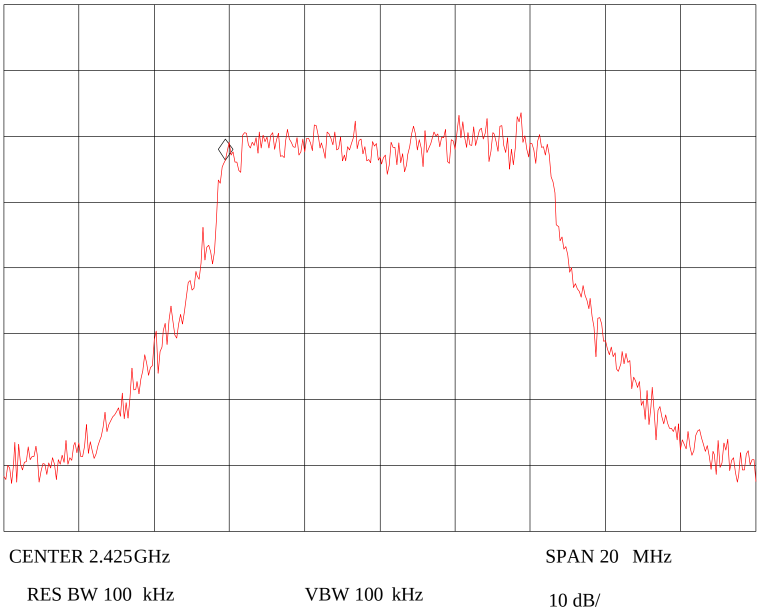

Figure B6. OFDM Power Amplifier Signal Input
16 Channel, Peak/Average = 12 dB

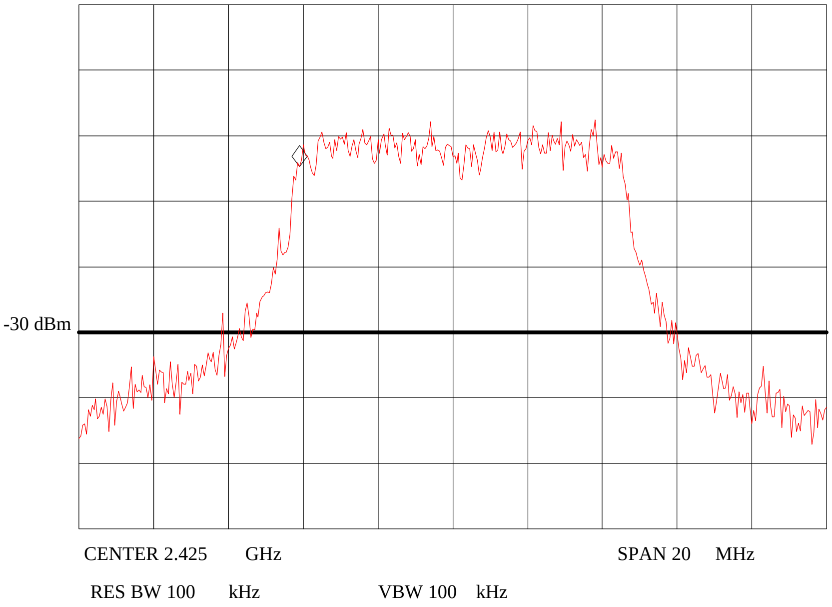

Figure B7. OFDM Power Amplifier Output
RMS Output Power 8.6 dB Below the 1 dB Compression Point

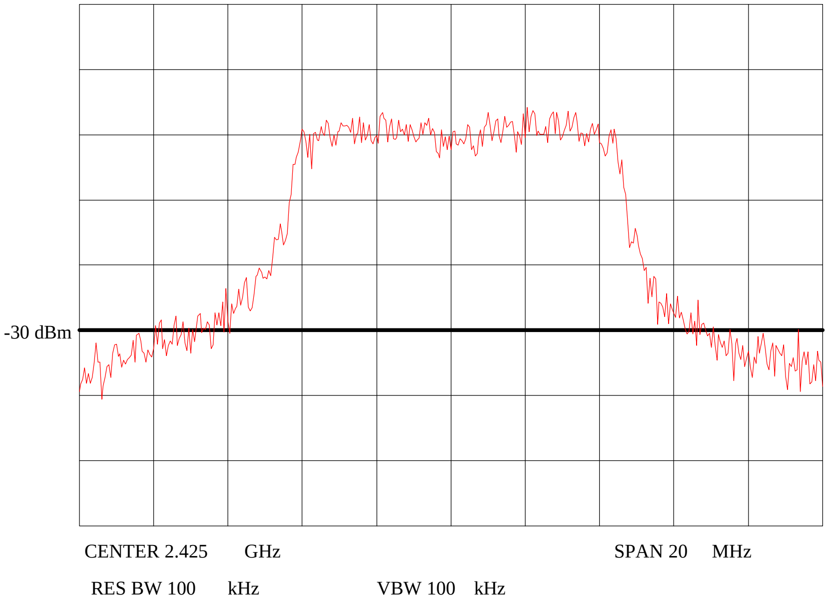

Figure B8. OFDM Power Amplifier Output
RMS Output Power 6.8 dB Below the 1 dB Compression Point

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