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Wireless Personal Area Networks

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Abstract	[Detailed technical information for the IEEE 802.15 voters prior to the TG3a Down Selection Process, currently scheduled for the IEEE802 Plenary in Jul03.]
Purpose	[This white paper uncovers a major performance difference between DS-CDMA systems and the frequency hopped Multiband/OFDM proposal(s). Specifically, due to FCC certification rules, it is necessary to operate frequency hopped systems at a lower power level than a non-frequency hopped system. In order to pass compliance tests, for example, a three-hop system that was supposed to operate to 10m, could now only operate to 5.8m – $1/\sqrt{N}$ as far – assuming $1/R^2$ propagation and N is the number of hops.]
Notice	
Release	

Frequency Hoppers *and* FCC UWB Rules

Certification rules for UWB frequency hoppers are very significant to the IEEE as well as the CE and wireless industry. The FCC rules are violated in the analysis slides put forward by all Multiband-OFDM proposals under consideration by the IEEE802.15.3a committee. Their reported range numbers drop by almost 1/2 in order to be certified by the FCC rules. This is true because frequency hopping (FH) systems are disadvantaged from a performance perspective relative to non-frequency hopped systems based upon the current FCC rules and certification requirements for UWB in the United States. Frequency-hopping is being utilized within the OFDM and “multiband” systems. The DS-CDMA (Direct Sequence Code Division Multiple Access) systems being proposed to the IEEE802.15.3a Task Group do not use frequency hopping. Instead DS-CDMA uses orthogonal codes to occupy the entire bandwidth at all times. This approach maintains a low emission level at all times within the bandwidth of a victim receiver, even if the victim receiver’s bandwidth is relatively wide (e.g. 50 or even 100 MHz).

What is the key issue? The key issue today is not interference, real or imagined but the performance of the various systems under conditions that comply with FCC rules. These rules follow from specific concerns of both the FCC and NTIA about frequency hoppers in the RF environment. Reasonable people might differ on whether the rules are appropriate, nonetheless, the current rules will govern UWB certification for the foreseeable future. The key issue is understanding what the rules are and what they mean, and then taking the appropriate actions given this understanding.

What is frequency hopping? An FH UWB system places a signal on a frequency-band for a short time interval, then moves to a different frequency-band, and continues "hopping" the signal to different frequency-bands, so the signal spans a range of spectrum over a period of time.

Figure 1 shows the basics of how an OFDM or pulsed frequency hopper works. In the case of OFDM, a DAC (digital to analog converter) generates the data-symbol as a baseband signal. The bandwidth of this signal must meet the >500 MHz bandwidth criteria to qualify as a UWB system. This bandwidth is then shifted via the mixer up to the RF frequency that is transmitted out of the antenna. The amount of frequency shift is determined by the local oscillator (LO) signal feeding into the mixer. The drawing shows a simple rotating selector switch that connects to a bank of oscillators so that the transmitted signal is frequency bands that are hopped through a sequence of center frequencies.

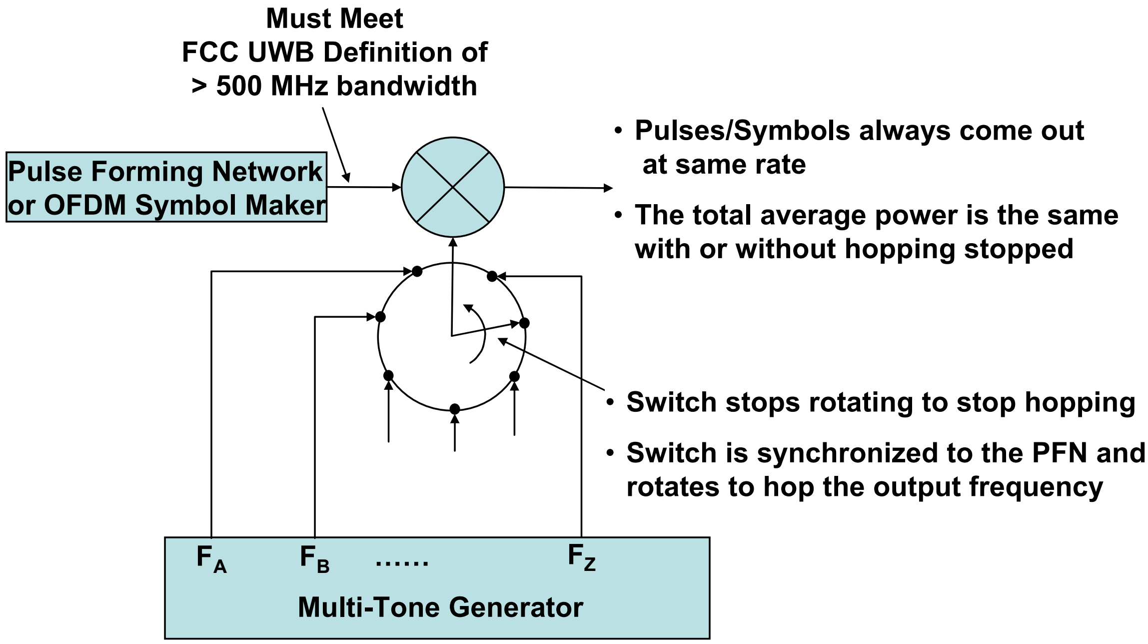

Figure 1. Block diagram of frequency hopping radio

FCC Concerns. At every stage of this proceeding, as far back as the Notice of Proposed of Rulemaking, the FCC has expressed deep reservations about FH, swept frequency, and stepped frequency modulations.

What are the FCC rules. The current FCC rules require FH UWB systems to be tested for compliance with the hopping *turned off* and the signal "parked" or held stationary at one band of frequencies.[1] Once the FH is turned off two conditions must be met:

- The bandwidth of the parked signal must be wide enough to qualify as “ultra-wideband” (500 MHz or more); ***and***
- Emissions levels (average and peak) of the parked signal must fall under FCC maximum limits (-41.25 dBm/MHz in the 3.1 to 10.6 GHz band, etc.).

What does this mean? The emission limit of a compliant hopping system is at least N times lower (where N is the number of frequency hops) than that of the non-hopping system. In other words, with hopping turned on (i.e. normal operation), and assuming both systems have the same total bandwidth, hopping systems can transmit, at most, only 1/N th of the power allowed to a non-hopping system such as DS-CDMA. If the duty cycle of the hops is low, then even more degradation could occur. To understand this we have to look at the basics of how average power is measured according to the above rules.

The top left chart of Figure 2 shows how the power (vertical axis) of the transmitted signal is hopped through the bands as a function of time (horizontal axis). The top right chart shows the same, but with hopping turned off. With hopping off, the bands do not share the power equally,

[1] First R&O at para. 32.

but instead, all the power goes into one band. The pulse rate is constant. The total transmitted power is constant. The only thing different is that the rotating switch (in Figure 1) is stopped so that all symbols come out of the antenna in the same band (In the case illustrated in Figure 1, the switch has stopped on band-B.).

The top row of charts in Figure 2 also shows that if the hopping system were allowed to radiate the same average power as the non-hopping system, the symbol burst in each band would momentarily exceed the -41.25 dB/MHz emission limit. Only by averaging the energy over time (the burst and the dead-time within one frequency band) would the average-power come down to the limit. But when hopping is turned off, as shown in the right chart, the emission limit is exceeded, unless the power in each symbol is reduced.

The middle row of charts in Figure 2 shows frequency on the vertical axis, and time along the horizontal axis, to illustrate how the symbol energy is hopped (left chart), or has hopping stopped (right chart). Again it shows that with hopping turned off, the power is not evenly distributed across the bands, but instead, is concentrated into one band.

In Figure 3, the vertical axis shows power (as in the top row), but the horizontal axis shows frequency. The chart illustrates the application of the current FCC rules as it applies to hopping systems. The left chart shows how the emission limit of the hopping system is N times lower (where N is the number of frequency hops) than that of the non-hopping system. In other words, with hopping turned on (i.e. normal operation), hopping systems can only transmit 1/N th of the power allowed to a non-hopping system such as DS-CDMA. The right chart shows how, when hopping is turned off, the power in each hop is accumulated (all stacked up) in one band. It is this “stacked up” energy level that must meet the FCC emission limit. Assuming equal bandwidth, this means that a non-hopping (e.g. DS-CDMA) UWB system is allowed, for example, three times the power of a three hop OFDM or three hop sub-band-pulse “multiband” system.

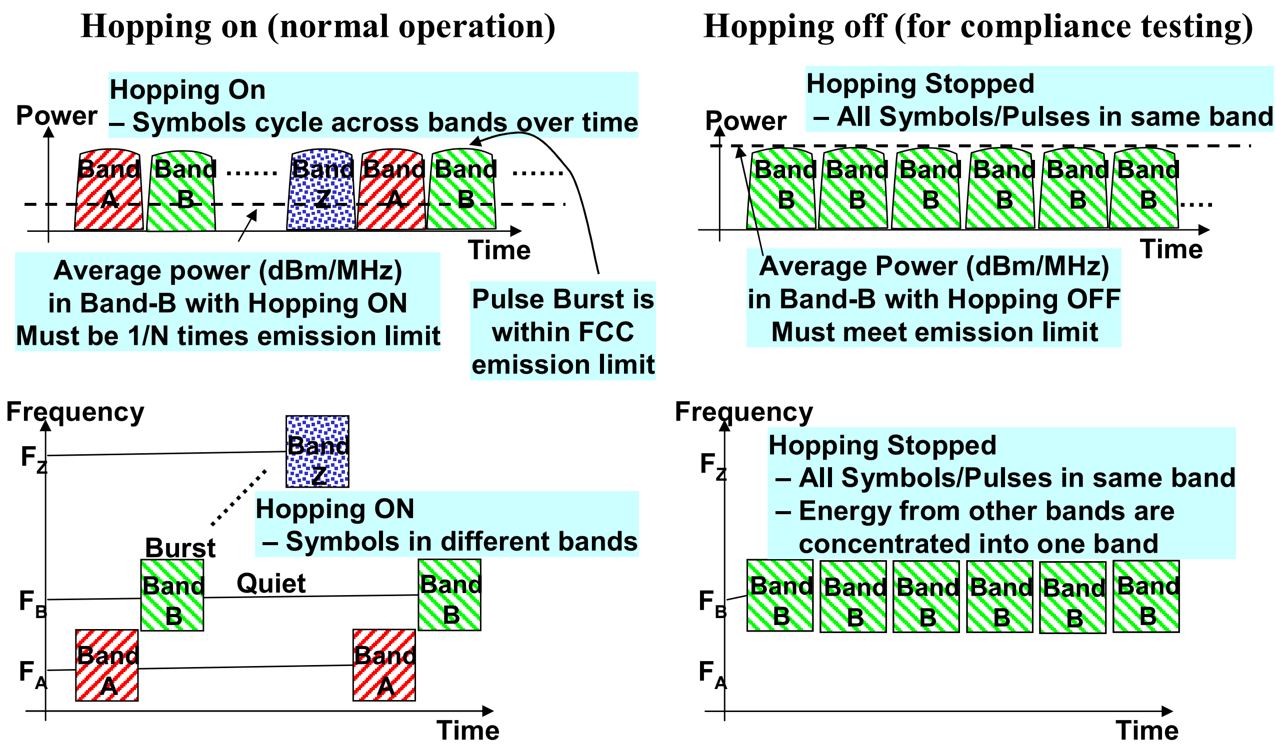

Figure 2. Timing and Power Diagrams with frequency hopping on (left) and off (right)

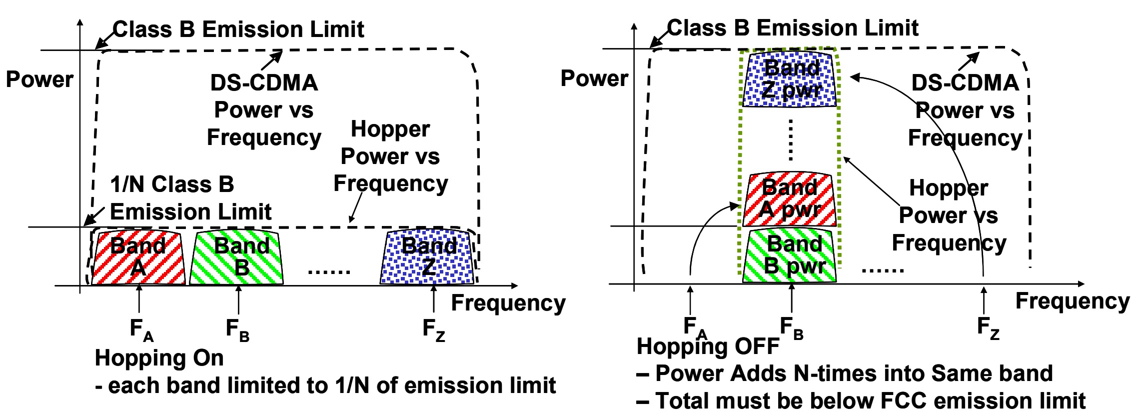

Figure 3. Timing and Power Diagrams with frequency hopping on (left) and off (right)

What does this do to performance? The difference between an FCC certified UWB system that uses frequency hopping vs. one that does not hop has been shown to be a difference in allowed transmit power. A non-hopped system will operate at $\sqrt{N}$ times greater range than a hopped system. For example, assuming N=3 (a three hop system), if a non-hopping system worked at 10m, the hopping system would only work to 5.8m. Similarly, a non-hopping system delivers N times the data-rate if the systems are at the same range. For example, if a non-hopping system delivered 100 Mbps data-rate, then the hopping system would only deliver 33 Mbps. ***As the***

number of hops (i.e. N) gets larger the range performance degrades more. If the duty cycle was lower than that shown, reduction could be even more.

Why did the FCC make this special rule for FH? There are at least three reasons.

1. If an FH system exceeds current FCC emissions limits during the short time it occupies a particular band, the FCC fears it will cause interference into receivers with a fast transient response.[2]
2. None of the interference studies in the UWB docket addressed FH interferers.
3. No measurement procedures have been proposed or established for swept frequency or frequency hopped devices.

The UWB R&O states,

> "The current measurement procedures require that measurements of swept frequency devices be made with the frequency sweep stopped. The sweep is stopped ***because [1] no measurement procedures have been proposed or established for swept frequency devices nor [2] has the interference aspects of swept frequency devices been evaluated*** . . . . Similarly, measurements on a stepped frequency or frequency hopping modulated system are performed with the stepping sequence or frequency hop stopped."[3] *See* 47 C.F.R. §15.31(c).

Similarly, The FCC also stated,

> "We recognize that other types of modulation, such as linear sweep FM, could be employed to produce UWB equipment. However, we do not believe that we have sufficient information to propose limits and measurement procedures for such systems. Until more experience is gained, we believe that our initial rule making proposals should reflect a conservative approach[4]."

Why can't the rules be interpreted such that with hopping turned off, the duty cycle and waveform look the same as when hopping is turned on? In other words, looking at Figure 4, can't "hopping turned off" be system-B instead of system-A?

[2] MO&O & Further NPRM at para. 159.
[3] UWB R&O at para. 32.
[4] *Ultra-Wideband Transmission Systems*, 15 FCC Rcd 12086 at para. 21 (2000) (**Notice of Proposed Rule Making**)

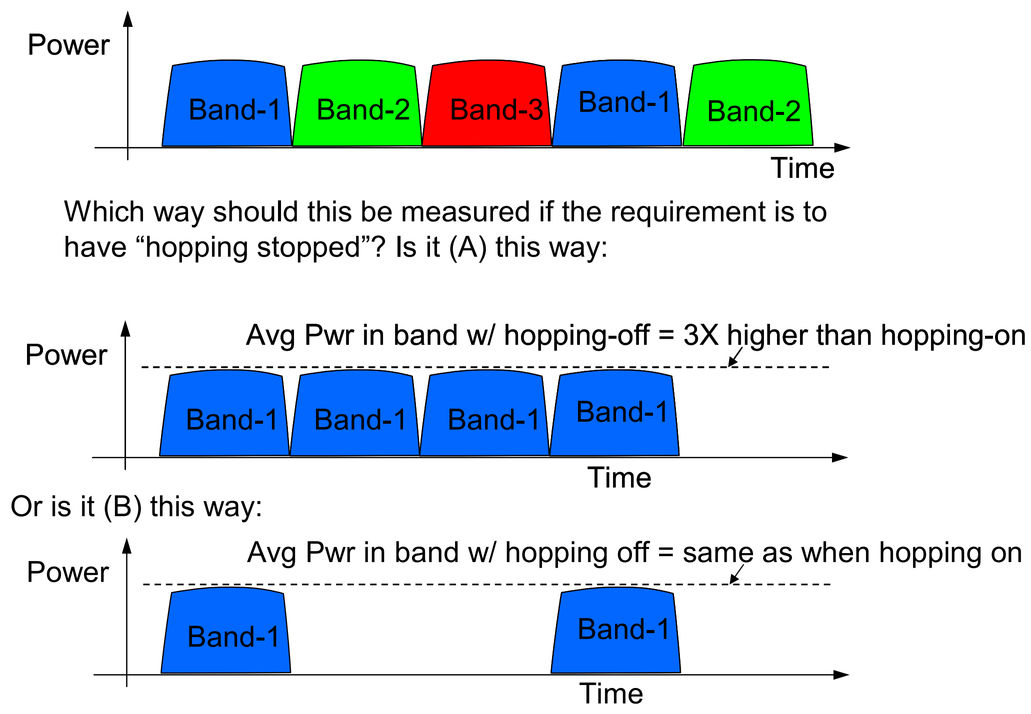

Figure 4. Can't "hopping off" be system-B instead of system-A

Answer: The FCC rules require System-A for several reasons.

1. System-A is the only interpretation that produces rational results. System-B is irrational because it comprises a compliance test that fails guarantee to limit the emissions. The compliance test, with hopping turned off, is blind to what is going on in all the other bands, and is also blind to what could be going on even in the band it is presumably measuring. For example, if a frequency hoping system had bands that overlapped by 50%, then the compliance test as defined in System-A would mis-represent the true emissions by a factor of 2! Unless all of the transmitted energy is accounted for (i.e. all pulses, as in System-A), the test could pass devices that might fail the emission limits in other bands, or even in the band being measured. Examples of FH systems include:

- Random hopping - which could put too much energy in a particular band with a higher duty cycle or a burst that is at high duty cycle.
- Hopping where the hop-bands overlap – which could put too much energy into an overlap region
- Hopping where sidelobe energy of neighboring hops could put too much energy into a band.
- Combinations of the above.

The only way to rationally certify these devices is to define a test (or set of tests) that would account for all factors affecting emissions in all of the bands. But the FCC did not define tests for

FH devices with the hopping turned on. Nor did they do any interference tests with FH systems. Nor did they examine potential FH testing procedures. Given the radical nature of the UWB ruling, which allows radiation into bands otherwise barred to unlicensed operation, the FCC explained that its immediate goals were to adopt rules that were both conservative and timely. The FCC did not make separate rules or measurement procedures to address hoppers with orthogonal pulses, or hoppers with overlapping pulses, or hoppers with sequential/periodic pulses, or hoppers with pseudo-random pulses, or combinations of these. It simply asserted that all frequency hoppers must follow the same rule for compliance testing: measurements "are performed with the stepping sequence or frequency hop stopped." And ***only*** if this test is administered as shown for System-A does the test account for the various factors of FH systems that affect emissions.

System-B simply does not give a rational result. The FCC cannot simply allow a manufacturer to declare that the other bands look the same as the one being measured and leave the others untested. Neither can the FCC allow the manufacturer claim that when hopping is turned off, there is no other energy in the band, and not test for it. To do so would be irrational and not in keeping with the goal of compliance testing, which is to guarantee that emissions are within well defined limits. That only interpretation of this rule that always produces a rational result is the System-A interpretation. It is the only test that includes all the energy transmitted in normal (hopping on) operation, and as a result, is the only test that would guarantee that emissions in any band could never exceed the limit, even if a band temporarily had a 100% duty cycle on the pulses being broadcast, and/or had overlapping spectrum.

2. To avoid potential instantaneous interference, the rules specifically address FH systems differently with the intent of changing the certification measurement result. To simply declare that System-A is appropriate because it does *not* change the result is irrational because it makes the language in the rules superfluous and of no effect, which cannot rationally be the intent of the language.

Wouldn't it be possible to treat hopping OFDM systems as "superpositions" such that each sub-band is an independent UWB system? The FCC says no. First, frequency hopping systems by any other name are still frequency hopping systems. The definition of frequency hopping on page 2 is clear, regardless of semantics. Second, to assert that an FH system can be tested this way is to unilaterally define a new test for FH systems that is not consistent with clear rules on how FH systems are to be tested. Third, it is clear that the only rational answer is NO because such a test would fail to adequately test the FH systems with overlapping bands or the other example FH systems listed above.

But doesn't hopping comply with the rules so long as the peak and average emissions are within FCC limits? The FCC says no. FH proponents argue the emissions in any band *averaged over time* are within FCC limits. (This was illustrated in the top left chart in Figure 2.) FH proponents argue the FH system measured in a given band is quiet in between "over-limit" visits to that band, so that if the emissions are *averaged over time,* they are within FCC limits. *But the FCC has consistently rejected this view*:

- The FCC warns that high instantaneous power is enough to cause interference.[5]
- In testing hybrid FH and direct sequence spread spectrum systems -- a close analogy to FH UWB -- the FCC *requires the FH to be turned off*.[6]
- The FCC specifically *rejects* time-averaged measurements in unlicensed FH devices at 57-64 GHz.[7]

Won't these rules change? (1) Although the FCC has proposed relaxing the bandwidth requirement,[8] its doing so is far from certain, and the change would not take effect before late 2004 or 2005. (2) The FCC refused even to consider relaxing the emissions limit (except for vehicular radar systems at 22-29 GHz), "[b]ecause of . . . interference concerns."[9]

Won't it be relatively "easy" (like HomeRF's changes to the unlicensed 2.4 GHz band – which still took a long time and were hard fought), to get the rules modified for the FH style of multiband-OFDM? --- NO.

Unlike all other rules, the UWB rules allow ***unlicensed*** emissions across all other ***licensed*** spectrum holders from 3.1 to 10.6 GHz. Proceeding 98-153 (the UWB proceeding) was one of the most contentious in the history of the FCC, with over 1000 substantive pleadings filed. Changes to the rules will require an open process following a track of testing FH with various parameter sets, publication of test results and suggested testing procedures, and an NPRM (notice of proposed rule making) from the FCC that addresses the issues raised, comments, and replies. This process took over 3 years from the publication of the 98-153 NOI. Given the contentious history, in addition to the time required by the process, it is not at all clear what the outcome would be.

Conclusion

Frequency hopping in compliance with current FCC rules can only offer degraded range and data-rate performance (the fundamental market requirements for applications of UWB), relative to non-hopping systems. A UWB standard based on frequency hopping technology fails to qualify for FCC certification, unless -- with frequency hopping stopped -- it complies in full with both bandwidth and emissions limits. As a result, a hopper is required to put out less maximum overall energy than a non-hopper covering the same total range of frequencies. The maximum permitted power is reduced in proportion to the number of hops.

The bandwidth requirement, while presently subject to further comment, may remain in place indefinitely -- and at a minimum, will not be addressed further by the Commission for at least 18 months. The FCC's recent FNPRM does not contemplate changing the emissions limit requirement at all.

[5] MO&O & Further NPRM at para. 159.
[6] 47 C.F.R. Sec. 15.247(f).
[7] 47 C.F.R. Sec. 15.255(e)(1).
[8] MO&O & Further NPRM at para. 166.
[9] MO&O & Further NPRM at para. 158.

Frequency Hoppers *and* FCC Rules

(FCC sources)

We preliminarily believe that the definition established by the OSD/DARPA UWB radar review panel is appropriate with some modifications. Specifically, we are proposing to define UWB devices as any device where the fractional bandwidth is greater than 0.25 or occupies 1.5 GHz or more of spectrum. This modified definition will avoid situations where devices operating at several gigahertz and above might unnecessarily use wide bandwidths simply to qualify as an UWB device. We are also proposing to base the definition of an UWB device on the – 10 dB bandwidth rather than the – 20 dB bandwidth. We propose this modification because UWB devices will operate so close to the noise floor that in many cases it will not be possible to measure the – 20 dB bandwidth. For the purpose of this definition, we will define the center frequency of the transmission as the average of the upper and lower –10 dB points, *i.e.*, $(f_H+f_L)/2$, as noted earlier. Finally, we are proposing that the bandwidth be determined using the antenna that is designed to be used with the UWB device. We invite comment on this proposed definition and whether the fractional bandwidth should be changed to account for the narrower bandwidth that would be measured using the –10 dB emission points instead of the –20 dB points. We request comment on whether we should use some other method to determine the emission bandwidth, such as a calculated bandwidth based on pulse width. We also request comment on whether we should define UWB devices as limited to devices that solely use pulsed emissions where the bandwidth is directly related to the narrow pulse width. We recognize that other types of modulation, such as linear sweep FM, could be employed to produce UWB equipment. However, we do not believe that we have sufficient information to propose limits and measurement procedures for such systems. Until more experience is gained, we believe that our initial rule making proposals should reflect a conservative approach. In addition, we request comment on whether extremely high speed data systems that comply with the UWB bandwidth requirements only because of the high data rate employed, as opposed to meeting the definition solely from the narrow pulse width, should be permitted. Finally, we request comment on any alternative definitions that may be appropriate.

Ultra-Wideband Transmission Systems, 15 FCC Rcd 12086 at para. 21 (2000) (**Notice of Proposed Rule Making**) (footnotes omitted)

We agree with Bosch and XSI that transmission systems should not be precluded from the UWB definition simply because the bandwidth of the emission is due to a high speed data rate instead of the width of the pulse or impulse. We also agree with ARRL and Delphi that various modulation types should be permitted as long as the products comply with all of the technical standards that are being adopted in this proceeding. Thus, as long as the transmission system complies with the fractional bandwidth or minimum bandwidth requirements at all times during its transmission, we agree that it should be permitted to operate under the UWB regulations. We recognize that this may preclude certain types of modulations, such as swept frequency (*e.g.*, FMCW), stepped frequency or frequency hopping systems. The current measurement procedures require that measurements of swept frequency devices be made with the frequency sweep stopped. The sweep is stopped because no measurement procedures have been proposed or established for swept frequency devices nor has the interference aspects of swept frequency devices been evaluated based on the different measurement results that would be obtained from measurements taken with the sweep active. Similarly, measurements on a stepped frequency or frequency hopping modulated system are performed with the stepping sequence or frequency hop stopped. With the sweep, step function or hopping stopped, it is unlikely that swept frequency (linear FM or FMCW) or stepped frequency modulated emissions would comply with the fractional bandwidth or minimum bandwidth requirements. It also is unlikely that frequency hopping systems would comply unless an extremely wide bandwidth hopping channel is employed.

Ultra-Wideband Transmission Systems, 17 FCC Rcd 7435 at para. 32 (2002) (**First R&O**) (footnotes omitted).

The UWB regulations permit the operation of vehicular radar systems in the 22-29 GHz band. UWB vehicular radar systems are required to operate at all times with a minimum 500 MHz bandwidth and may employ any modulation technique that results in this minimum bandwidth. In the *R&O*, the Commission specifically precluded the operation of swept frequency systems and frequency hopping systems under the UWB rules unless the transmissions comply with the minimum bandwidth requirement when measured with the sweep or hopping sequence stopped. The Commission indicated that this was necessary as no measurement procedure had been established to permit the emission levels from such devices to be determined while sweeping or hopping. The Commission expressed similar concerns in the *Notice*, and declined to include transmitters employing swept frequency and similar modulation types from consideration as UWB devices.

Ultra-Wideband Transmission Systems, 18 FCC Rcd 3857 at para. 45 (2003) (Memorandum Opinion and Order and Further Notice of Proposed Rule Making) (**MO&O & FNPRM**) (footnotes omitted).

We believe that the requested rule changes from Siemens VDO for its radar application should be proposed so that we might obtain public comment. However, we also are concerned that radar systems using slightly different modulation techniques or radar systems operating in different bands where the victim receiver characteristics are different may have different interference potentials. Because of these interference concerns, we are not proposing to permit the use of frequency hopping systems under the UWB rules for any application other than vehicular radar systems operating in the 22-29 GHz band.

MO&O & FNPRM at para. 158.

Our primary concern is not that the Siemens VDO [frequency hopping] equipment does not comply with the definition of a UWB system. Rather, we are concerned that the Siemens VDO radar system does not comply with the UWB standards using the measurement procedures currently employed for frequency hopping systems. Thus, we are concerned about the possible interference aspects of this type of operation. For example, a UWB vehicular radar system that complies with the existing regulations will place a low level emission on a frequency at any given time. However, the Siemens VDO system momentarily will place a much higher level emission on that frequency. The Siemens VDO system depends on a time averaging of the emission, based on the level of the emission, the number of hops, the occupancy time at any given frequency, and the time period over which the emissions are averaged to demonstrate compliance with the average emission limits. The emission level being measured may not be a true RMS average emission but could be more similar to a time averaged emission. Thus, a victim receiver with a fast transient response may be more susceptible to interference from the Siemens VDO system than from other UWB systems. Siemens indicates that EESS systems operating in the 23.6-24.0 GHz band will not be able to tell the difference between a distributed number of frequency hopping systems operating under the standards requested by Siemens VDO and a similarly distributed number of wideband radars complying with existing vehicular radar standards. However, we are concerned about the potential impact on terrestrial users which may be exposed to relatively few, but nearby, vehicular radars as well as the impact to EESS operations. We request comments on whether the higher instantaneous power delivered by a frequency hopping system would cause harmful interference to these systems.

MO&O & FNPRM at para. 159 (footnotes omitted)

For the purposes of this section, hybrid systems are those that employ a combination of both frequency hopping and digital modulation techniques. The frequency hopping operation of the hybrid system, with the direct sequence or digital modulation operation turned off, shall have an average time of occupancy on any frequency not to exceed 0.4 seconds within a time period in seconds equal to the number of hopping frequencies employed multiplied by 0.4. The digital modulation operation of the hybrid system, with the frequency hopping operation turned off, shall comply with the power density requirements of paragraph (d) of this section.

47 C.F.R. Sec. 15.247(f) (on testing of **hybrid spread spectrum systems**)

Transmitters with an emission bandwidth of less than 100 MHz must limit their peak transmitter output power to the product of 500 mW times their emission bandwidth divided by 100 MHz. For the purposes of this paragraph (e)(1), emission bandwidth is defined as the instantaneous frequency range occupied by a steady state radiated signal with modulation, outside which the radiated power spectral density never exceeds 6 dB below the maximum radiated power spectral density in the band, as measured with a 100 kHz resolution bandwidth spectrum analyzer. The center frequency must be stationary during the measurement interval, even if not stationary during normal operation (e.g. for frequency hopping devices).

47 C.F.R. Sec. 15.255(e)(1) (emissions limits for unlicensed **57-64 GHz transmitters**).