IEEE P802.15
Wireless Personal Area Networks

Project	IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)
Title	**DS-CDMA: The Technology Of Choice For UWB**
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Re:	[-03/276.]
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 provides a background on UWB and compares the performance of DS-CDMA based UWB and multiband-OFDM based UWB]
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DS-CDMA: The Technology Of Choice For UWB

Abstract: Both DS-CDMA and OFDM are well understood and proven in other conventional (narrowband) commercial radio technologies (e.g. DS-CDMA in cell phones) (e.g. OFDM in IEEE 802.11a/g). The maturity of these approaches, however, is vastly different in the world of UWB. The entire history of the development of UWB communication systems has centered on pulse based systems that could directly isolate multipath. Already implemented in operating silicon chips, DS-CDMA architectures have proven to be the most mature and scaleable for UWB. Among the proposed approaches before the IEEE 802.15.3a standards committee, the DS-CDMA transmitted waveform (which is the "thing" being standardized) is uniquely capable of serving the broadest spectrum of applications. It can, for example, allow very low-cost low-power transmit-only devices (even at Gbps rates) because it requires no FFT or DAC or DSP. At the same time, receivers can be made with varying degrees of DSP to provide scaleable power/cost versus performance that can, at the high end, grow to outperform all other approaches. DS-CDMA offers the highest aggregate Mbps/m^2 data rates because its CDMA codes are designed from the ground up to support "multi-user" which in this case, means multiple overlapping uncoordinated networks – like two wireless home theater systems in neighboring rooms or apartments.

1. <u>Introduction To UWB</u>

On February 14, 2002 the FCC opened up 7,500 MHz of spectrum (from 3.1 GHz to 10.6 GHz) for use by UWB devices. The basis for the ruling was proof from several properly engineered military systems that proved UWB propagation offered unique capabilities that were not possible with narrowband approaches. For example, a foliage penetration imaging radar produced imagery with 6 inch resolution using a UWB frequency band spanning 40 MHz to 1 GHz.

UWB has the unique property that if an object is large enough to reflect the UWB radio frequency (RF) wave, then the bandwidth of the UWB is wide enough to resolve the object – if the full bandwidth is processed coherently. This property occurs only when the bandwidth to center-frequency ratio is high, preferably one or more. To accomplish this feat, the matched-filtered UWB signal has only a few RF cycles. The fewer the number of cycles, (i.e. shorter the pulse) the more "UWB" it is. Because of this "few-cycles out of the matched filter" property, UWB not only minimizes multipath nulls, but it can out-perform free-space propagation. It can take advantage of multipath reflections to collect more energy than would normally be available at a given distance if free-space propagation was assumed. So UWB works in realistic (i.e harsh) multi-path environments, yet can be implemented in a way that consumes very little power and silicon area.

The key to capturing the full benefits of UWB lies in the engineering. As a new technology, however, there continues to be considerable confusion and misinformation concerning how to best capture the benefits of UWB, and misunderstanding regarding attributes of different approaches. The main outcome of the military R&D was discovering two keys to capturing the full benefit of UWB propagation. The first was simply the importance of the bandwidth being wide in a relative-bandwidth sense. The second key was in architecting the system to coherently process the signal over the whole of the UWB bandwidth. Unlike all other approaches proposed at the IEEE 802.15.3a standards committee, DS-CDMA is the only one that uses coherent processing of its occupied bandwidth, plus, it also uses the widest relative bandwidth. As a result, it is no surprise for those who have been involved in this R&D that DS-

CDMA would be demonstrably technically superior, and simpler to implement since it takes the most advantage of the underlying UWB physics.

In addition to addressing technical differences, engineers must also embrace traditional marketing/application driven issues of cost, power consumption, and time-to-market. Proposals before the IEEE 802.15.3a standards committee largely fall into three categories: (1) single and multi band DS-CDMA (Direct Sequence Spread Spectrum Code Division Multiple Access), (2) multi-band Orthogonal Frequency Division Multiplexing (OFDM), and (3) Pulsed Sub-Band.

In terms of time-to-market, DS-CDMA is clearly 12 to 24 months ahead of other technologies since 2nd generation chips are already here today being integrated into products. The other approaches are in the drawing board phase. XtremeSpectrum, whose founders developed some of the first successful military systems, demonstrated on the day after the regulations took effect in July of 2002 a chipset delivering 100 Mbit/s at 10 meters. The demonstration showed 6 digital video streams going over a single radio link while 802.11a,b and 5.8 GHz cordless phones and microwave ovens were operating between the UWB antennas. The DS-CDMA chip-set was also demonstrated at the consumer electronics show (CES) last January broadcasting two simultaneous HDTV digital streams, again coexisting with multiple other systems. Several exciting new commercial products using the chip-set will be demonstrated at CES this coming January.

The reason for the excitement is that this technology promises to deliver data rates that can scale from where they are today, and do it at low power. So whereas this 100 Mbit/s with high QoS is impressive today, the technology promises to scale to 400 Mbit/s for wireless 1394 and wireless USB, and on to over 1Gbit/s as the technology scales with Moore’s law.

The key scalability factor, however, is across diverse applications—in terms of price, performance, and power. For example, one set of applications requires very low-cost/power and short range like a transmit-only chip that can quickly (and lowest battery drain per delivered bit) download images from a cell phone or low cost digital still or video camera. Another set of applications requires higher performance with more emphasis on performance, like a high end projection TV or machine-control telemetry in a wireless factory, or some military applications. The DS-CDMA waveform offers the widest range of scalability and growth options.

2. What Drives The Design Choices?

There are several ways to design a UWB communication system. The key driver has to do with ***simultaneously*** accomplishing the following objectives:

1. Meets today’s regulatory requirements as well as accommodates different regulatory requirements if regulations differ in different regions of the world. (Only USA has regulations today.)
2. Scales across diverse applications (e.g. as described above).
3. Scales in terms of growing performance (further/faster) as IC process technology improves over time.
4. Supports High-Resolution Ranging – While communications is one axis of applications, there are very significant safety of life applications that require ranging capability. Police, fire, rescue, and the military have ongoing projects to apply the power of UWB to locate injured personnel.
5. Provides High Speed & QoS - Operates at high speed with high QoS that supports streaming video/multi-media applications.

6. Supports Multi-User – Capable of running multiple simultaneous independent overlapping networks where each has the full data rate and QoS.
7. Multi-path immune – Operates well in high multipath environments like offices, homes, factories.
8. RFI/NBI – Operating in the presence of radio frequency interference (RFI) or narrow band interference (NBI).

DS-CDMA uniquely accomplishes all of these simultaneously. In the rest of this article, we will explore why this is true, and hopefully, explode some myths along the way.

3. MEETING CURRENT REGULATORY REQUIREMENTS

What are the key regulatory issues facing UWB in the United States? A UWB standard based on frequency hopping technology, like the 3-hop multiband-OFDM proposal, fails to qualify for FCC certification, unless -- with frequency hopping stopped -- it complies in full with both bandwidth and emissions limits. In order to comply, a 3-band OFDM radio must operate with 1/3 of the energy or 4.7 dB less power than a non-hopping radio. So a calculation that shows 10m of range, would be reduced to 5.8 m of range. All of the submissions to the IEEE 802.15.3a committee have NOT taken this into account, and are therefore non-compliant. In order to compare compliant radios, this performance reduction must be factored in. Document number 03271r0P802-15_TG3a-Frequency-Hoppers-and-FCC-UWB-Rules.pdf is a more complete discussion of this FCC certification issue. This power and performance reduction on compliant multiband-OFDM systems extends the performance lead of the already superior DS-CDMA based solutions.

4. Exploding Some Myths

4.1. Myth: DS-CDMA needs high complexity and multi-finger RAKE to work.

OFDM proponents have attacked DS-CDMA claiming that "building RF and analog [CDMA] circuits as well as high speed analog-to-digital converters (ADCs) to process this extremely wideband signal is a challenging problem and the digital complexity needs to be quite large (at least 16 RAKE fingers) in order to capture sufficient multi-path energy to meet the range requirements of 10 meters for a 110 Mb/s system."

4.1.1. FACT: An advantage of DS-CDMA is that its complexity can scale to an application's need. Very low complexity DS-CDMA systems work.

XtremeSpectrum's operating chip-set (as opposed to power point slide engineering) is proof that low-complexity DS-CDMA systems work. It demonstrates that 100 Mbit/s operation at 10 meters is feasible even with one RAKE finger (a simple single channel receiver). Moreover, this performance is achieved even though these particular chips are sub-optimal "buggy" first silicon. Indeed, given that this is a new technology, it is a testimony to the low complexity that the very first silicon not only runs, but meets the specifications advertised before the chips were laid down. XtremeSpectrum expects its production silicon to be much better. This chip-set, using .18u CMOS from TSMC, uses only 20mm^2 and 19mm^2 of die area for the RF/analog and baseband chips respectively. Claims of high complexity and multi-finger rake requirements are demonstrably unfounded.

In addition to real world operations, the analysis based on the IEEE models shows that a simple 2-finger RAKE DS-CDMA radio performs as well as the far more complex OFDM radio proposed by TI.

4.2. Myth: – Sub-banding is less complex

Sub-band proponents claim that the sub-banding's "advantage is that the information can now be processed over a much smaller bandwidth, thereby reducing the complexity of the design, reducing the power consumption, lowering the cost, and improving spectral flexibility and worldwide compliance …. [OFDM advantages] include using lower-rate ADCs and simplifying the digital complexity."

To address this we separately address the transmitter and receiver.

4.2.1. FACT: The DS-CDMA transmitter is FAR simpler – and opens the way for transmit-only applications that need very high speed over short distances

The DS-CDMA transmitter consists of a simple high chip rate pulse generator and modulator. There are no FFT's, no complex window multiplies, no DAC's, and no multiplicity of frequency generators or fast hopping synthesizers. It is efficient, small, low cost, easy to make with low spurious emissions and FCC compliant, and yet flexible in terms of the variety of codes it can broadcast. It can just as easily send 2-BOK as 32-BOK. It delivers the most payload-bits per consumed-watt of any transmitter by a large margin. Finally, XtremeSpectrum has implemented, tested, and proven a low complexity DS-CDMA UWB solution in working silicon.

The OFDM transmitter proposed by Texas Instruments (TI) is vastly more complex by comparison. It requires an FFT engine capable of a 128 point IFFT every 312.5 ns, plus a pair of 528 Ms/s transmit DAC's, plus filters for the DAC's since they are operating near Nyquist, plus a fast switching frequency hopper to shift the spectrum to the hopped sub-band. TI requires the frequency hopper to shift and be settled to an accurate and low phase-noise state in 9.5 ns.

In addition to all this complexity, the waveform itself has worse properties. The waveform can have a very high peak to average ratio that must be broadcast with very low spurious levels in order to meet the strict FCC compliance tests.

The pulsed sub-band transmitter originally proposed by General Atomics, Intel, *et al*, is also vastly more complex than DS. It is comprised of a mix/shift & filter synthesizer with a bank of simultaneous outputs, all running with low phase-noise and locked together. In addition, it needs a fast high isolation switch to gate the proper frequency through, plus a modulator/gate to generate the 3 ns pulse with BPSK or QPSK modulation.

It is clear that the transmitter complexity comparison very heavily favors DS-CDMA. This low-transmitter-complexity feature of DS-CDMA is important across all applications and metrics because it is smaller, cheaper, simpler, more battery-friendly, and is the easiest to make FCC compliant.

DS-CDMA is the only proposed solution that is simple enough to accommodate applications with a power starved and exceedingly cost-constrained transmit-only node.

4.2.2. FACT – The DS-CDMA Receiver has scaleable-complexity and performance – it can be much less complex, and it can also be more complex allowing it to meet the needs of different intended applications.

DS-CDMA receiver architectures can be designed to use symbol rate sampling, chip-rate sampling, or above-Nyquist rate sampling. Along with the choice of how much DSP is applied, each choice leads to different cost/power/performance envelopes that allow matching to the intended application.

4.2.3. FACT - The DS-CDMA Receiver is Less complex (NOT More) for similar performance

XtremeSpectrum's proven receiver is simply a mixer, a "local oscillator" (LO), an integrate-and-hold, and a low symbol-rate ADC for each of 4 channels (i.e. 2 independent QPSK channels or 2 independent BPSK channels, each with an error term used for tracking.). It is far less complex than either the OFDM or pulsed sub-band receivers, yet has comparable performance to OFDM, and better performance than pulsed sub-bands. The "local oscillator" is actually the same pulse generator as is used in the transmitter. The phase/frequency agile chipping clock is made with a simple fixed-frequency PLL and a pair of mixers forming a vector modulator that is driven by low-rate sine & cosine DACs. This allows fast digitally controlled synchronization and tracking to an accuracy of a few pico-seconds with very simple hardware. The integrate/hold is a simple bank of three round-robin integrate/hold circuits that rotate functions (one integrating, one outputting a voltage to the ADC, and one resetting to zero). So the ADC receives a new constant analog voltage during each symbol. The sign of these ADC values can serve directly as bits. The ADC values can also go into a FEC decoder as "hard" or "soft" bits, and be error-corrected.

In comparison, the OFDM receiver proposed by TI, requires (1) a very fast frequency hopping LO capable of shifting and being settled to a low phase-noise state in 9.5 ns.; (2) a much faster ADC - running at 528 Ms/s; (3) an FFT engine capable of a 128 point FFT every 312.5 ns, (4) a 128-point complex window multiply also running every 312.5 ns, and (5) acquisition and tracking engines running off of the modulated "tracking" tones. All this complexity must be accomplished with low coupling of digital switching noise via the substrate and otherwise. Even if the ADC are 4-bits, this set of hardware is far more complex than an equivalent performance DS-CDMA system.

The XtremeSpectrum chip set proves that DS-CDMA UWB works even in "big old slow" .18u CMOS. Upgrades to 90nm and future CMOS shrinks can only extend the proven performance.

4.2.3.1. But doesn't DS-CDMA also need a complex equalizer?

Yes it needs an equalizer, but NO, the equalizer is not complex. XtremeSpectrum's chip includes and proves the performance of a decision feedback equalizer (DFE) to eliminate multipath induced ISI. While some continue to argue in power-point engineering that the DFE required in DS-CDMA systems is complex, in fact, the real demonstrable DFE in the XtremeSpectrum chip set accounts for only 3% of the die area of the digital chip, and 3% of the power budget. Furthermore, as the number of receiver channels grow (for example, to support higher order modulation like M-BOK), the DFE scales—it stays at 3% power/size. In other words, the facts show that the DFE has such low complexity and is such a small factor on price and power that it can essentially be ignored.

4.2.3.2. FACT – The DS-CDMA ADC is simpler (NOT more complex) for similar performance

The ADC (analog to digital converter) in XtremeSpectrum's chips runs 5X to 10X slower than the one used in the OFDM receiver proposed by TI –57 and 114Ms/s versus 528 Ms/s. It runs 3X to 6X slower than the 300Ms/s ADC in the pulsed sub-band receiver proposed by General Atomics, Intel, *et al*. In other words, the facts show that the ADC is less complex with DS-CDMA for similar performance.

The choice to use a more complex ADC in the DS receiver is entirely driven by the desire for greater performance. The DS-CDMA receiver architecture could adopt chip-rate sampling or even RF sampling and use a different partitioning between analog and digital processing in order to apply more digital signal processing and extend the performance beyond what OFDM could do. The option for DS to use a more complex ADC is not a liability. Rather, this option is the key to scaling the radio to different applications with different appetites for performance-vs-power or performance-vs-cost trades.

4.3. Myth – OFDM captures more multi-path energy than DS-CDMA – giving higher performance.

4.3.1. FACT – DS-CDMA outperforms OFDM with less complexity

The multipath energy capture of DS-CDMA depends on the receiver complexity. It can be higher than that of OFDM. It is true that a simple single channel (1 RAKE term) DS-CDMA radio will capture less energy than a much more complex OFDM radio. But claims that this is the general case are false. The performance of an OFDM radio is limited relative to DS-CDMA because DS-CDMA implementations can capture more energy than OFDM can.

The limitation on OFDM relative to DS-CDMA is caused by OFDM's incoherent processing of the bandwidth. It does not effectively isolate and capture the multipath energy. Instead, OFDM uses incoherent FEC processing to "recover" bits lost in bands that are faded due to multipath. The fact is, this incoherent processing is sub optimal and does *not* result in capturing all the multipath energy. It is true that university research has been attempting to capture more of the multipath energy. They have done this by using a backchannel to the transmitter to tell it the SNR of each tone at the receiver. This allows the transmitter to stuff more bits on the tones with a large SNR, and not use tones with poor SNR. In addition to the backchannel, this approach requires each tone to use a different modulation constellation. So it leads to a significantly more complex radio and complex MAC. In particular, bit stuffing will increase the complexity of the ADCs, the FFTs, and the demodulator/detector.

It is in the final two steps of OFDM's receiver processing that coherent processing is not done. OFDM's processing steps are: (1) treat the channel as a dynamic IIR filter, where the tap weights are fixed over the duration of a single OFDM symbol, but may change between symbols. (2) The OFDM transmitter sends out the bank of tones, each at the desired phase according to the data packet with forward error correction applied. (3) The receiver ignores the first part of the signal (the "cyclic prefix"), which allows the IIR filter impulse response to "nearly" reach a steady-state condition on all the tones. (4) The OFDM receiver digitizes the tones over a precise window-duration where every tone is an exact integer number of cycles over the window. (this constraint is what makes the tones orthogonal) (5) A Fourier transform is done on the window of data to isolate each tone and find the phase of each tone. (6) The phase of each tone is turned into hard or soft bit decisions (according to the BPSK or QPSK constellation). (8) These hard or soft bits are fed into the FEC decoder to produce the output data stream.

The truth is that the complexity of the DS-CDMA receiver is scaleable such that it can grow to outperform the OFDM. Figure 1 illustrates this, even using the TI performance numbers in their slides which have 4.7 dB higher power than the FCC allows, while the DS-CDMA system is a fully compliant one. It compares, using the TI OFDM performance numbers from their IEEE proposal as a reference, (1) a lower complexity analog implementation of DS-CDMA (a 4-BOK 2 rake system), and (2) a DS-CDMA implementation that has similar complexity to the TI-OFDM proposal (i.e. 8-BOK 5 rake). Precisely as the earlier government work discovered, DS-CDMA can outperform OFDM because DS-CDMA coherently processes the signal over the whole of the bandwidth. Additional RAKE terms allow DS-CDMA to outperform OFDM even more.

Averaged Outage Range (m)

	CM1	CM2	CM3	CM4	
TI-OFDM	11.5	10.9	11.6	11.0	← Using OFDM as a reference…
4-BOK, ½ CC, QPSK, 2-RAKE	13.0	12.0	9.9	8.1	← Lower Complexity CDMA Gives Similar Performance
8-BOK 2/3 CC, BPSK, 5-RAKE	18.8	17.6	15.1	12.8	← Similar Complexity CDMA Outperforms OFDM

Figure 1. Performance versus complexity of DS-CDMA relative to OFDM

DS-CDMA is simply flexible enough to: (1) allow the implementation to conform to the needs of the application, and (2) provide about the same performance with simpler hardware, or greater performance with more complex hardware. And in reality, the OFDM ranges should be cut by 1/√3 (almost ½) so that both systems are FCC compliant. Ultimately, the performance/complexity ratio, and the performance scalability of DS-CDMA gives it a tremendous advantage over OFDM.

4.3.2. FACT-2 - DS-CDMA can offer much better performance than OFDM for other reasons – like rejection of multi-user noise from neighboring independent full-rate piconets.

The most important driver for the user experience is the ability of the radio to support independent full-rate high QoS overlapping networks. Again, DS-CDMA has advantages here.

FACT: DS-CDMA inherently allows a higher density of overlapping piconets and thus higher aggregate Mbps/m^2 due to its code isolation

Figure 2 compares the distance ratios provided by two DS-CDMA implementations and compares them with the TI OFDM performance numbers from their IEEE proposal as a reference. The first DS-CDMA implementation is a lower complexity analog implementation using 4-BOK and 2 RAKE fingers. The second DS-CDMA implementation has similar complexity to the TI-OFDM proposal and uses 8-BOK and 5 RAKE fingers. Figure 2 demonstrates that DS-CDMA is better in both cases, and much better (about a factor of 2 better) when the DS-CDMA and OFDM are similar complexity.

But the advantage does not stop here. Even though the baseline performance of DS-CDMA is better, DS-CDMA has room to grow by applying multi user detection (MUD) techniques.

Coexistence Ratios – 1 MUI

	CM1	CM2	CM3	CM4	
TI-OFDM	0.91	0.83	0.94	1.15	← Using OFDM as a reference…
4-BOK, ½ CC, QPSK, 2-RAKE	0.62	0.68	0.82	1.00	← Lower Complexity CDMA Gives Better Performance
8-BOK 2/3 CC, BPSK	0.44	0.47	0.55	0.65	← Similar Complexity CDMA Way Outperforms OFDM

Coexistence Ratios – 3 MUI

	CM1	CM2	CM3	CM4	
TI-OFDM	1.45	1.47	1.46	1.85	← Using OFDM as a reference…
4-BOK, ½ CC, QPSK, 2-RAKE	1.07	1.18	1.42	1.73	← Lower Complexity CDMA Gives Better Performance
8-BOK 2/3 CC, BPSK, 5-RAKE	0.76	0.82	0.95	1.11	← Similar Complexity CDMA Way Outperforms OFDM

Figure 2. Overlapping Piconet Distance Ratios for 1 interferer (top) and 3 interferers (bottom)

FACT: DS-CDMA can take advantage of multi-user-detection (MUD) algorithms that mitigate near-far problems with overlapping networks.

DSP enabled multi-user detection (MUD) algorithms can be applied to DS-CDMA systems. This fact gives DS-CDMA enormous growth possibilities to support much higher aggregate data rates. While some may claim this is "too complex", history has proven that the combination of Moore's law and clever DSP engineers can win these battles. For example, the same was said of Reed-Solomon decoders at the dawn of CD's. The fact is, the theoretical framework for using MUD algorithms to mitigate the near-far problem has already been laid. With DS-CDMA, the performance gain is available on the horizon for the applications that will require it.

FACT: OFDM cannot use MUD techniques. This fact simply recognizes that an interfering tone from a neighboring OFDM network has no ear-mark that can tell the receiver where the tone came from—there is no identifying code. Each tone is independently faded and independently (orthogonally) received. Overlapping tones just result in a vector summation of arbitrary phase which results in errors. So with OFDM, what you get today is all you can get tomorrow—it has no path to grow its future performance.

4.4. Myth –OFDM has better spectral efficiency.

4.4.1. FACT: The performance of the DS-CDMA is superior to OFDM at equal transmit power, so the "efficiency" is better with DS-CDMA.

The claims by OFDM proponents are unfounded. The peak-to-average power spectral densities (PSD) are essentially the same:

- 2.2 dB (with 2-BOK BPSK) to 1.3 dB (with 16-BOK) for the 24-chip ternary codes published by XtremeSpectrum
- 1.3 dB for the TI OFDM waveforms

Furthermore, what matters is the performance. As shown in section 4.3, CDMA can use less power to provide greater performance. Therefore, CDMA is more spectrally efficient.

4.5. Myth – OFDM can easily (i.e. software programmable) place deep notches in its transmit spectrum to protect sensitive services or comply with new regulations in other countries that are different from those in the United States.

4.5.1. FACT – OFDM provides shallow (9dB) notches and has few tones to spare

The orthogonal nature of OFDM is due to the FFT analysis window being just the right length so that each frequency is an integer number of cycles. The tones are NOT orthogonal to a general receiver. All the tones are gated on and off (so that they remain stable with flat fixed amplitude over time) to fill up the channel with the "cyclic prefix" and remain fixed over the receiver collection period. Even assuming smooth raised cosine weighting over a 9.5 ns window from one OFDM symbol to the next, a bank of 10 tones must be turned off just to get a 20 dB reduction in energy. With only one tone disabled, there is only a 9 dB notch relative to the average PSD. These two cases are shown in Figures 3 and 4 respectively. Figure 5 shows the spectrum of a single gated tone. The relatively smooth (2.3 dB of ripple) overall spectrum (as opposed to sharp peaks at the tone frequencies), is due to the summation of all the sidelobes of all the tones. Similarly, the shallow notch depth is caused by the sum of all the sidelobes from all the other tones filling in the "notched" frequency. Figure 6 shows the notch depth versus the number of tones disabled. The TI multiband OFDM proposal provides partitioning of the 128 tones into 100 data tones, 22 pilot tones and 6 null tones. 6 null tones is not enough.

So while OFDM proponents claim notching ability, in fact, there are not enough spare tones available to generate significant notches, much less, several of them.

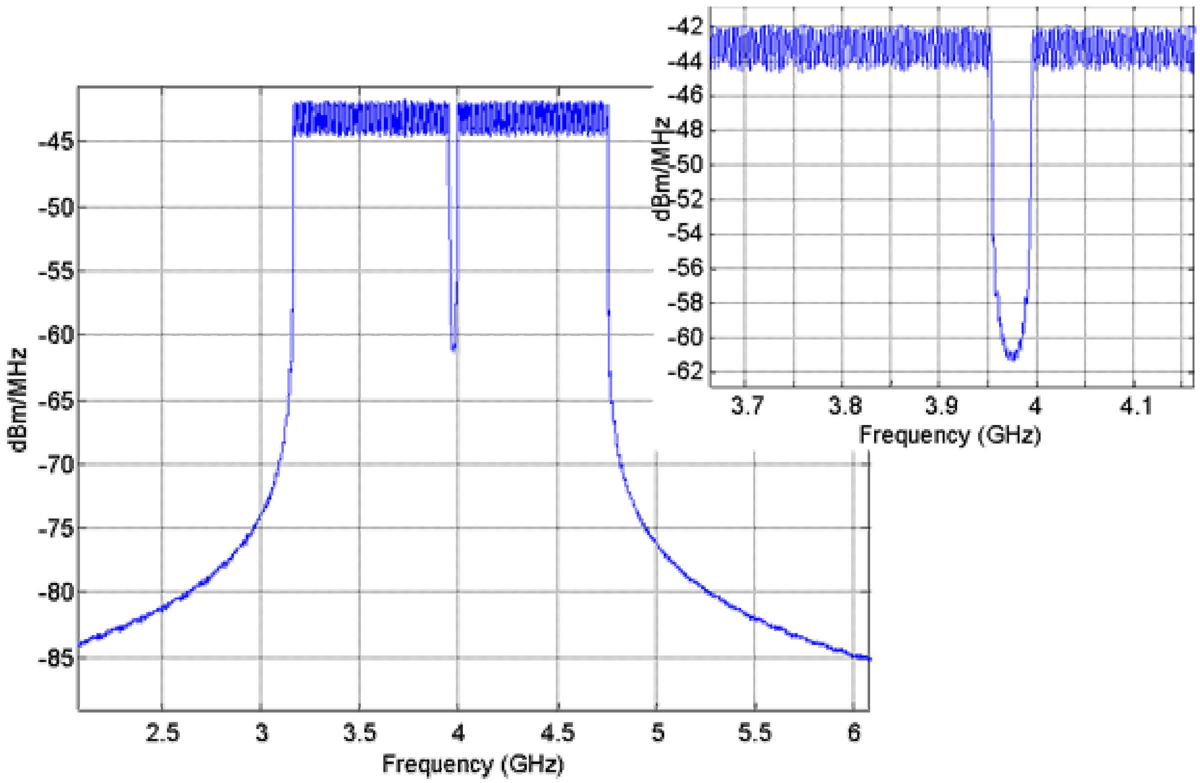

Figure 3. 10 tone notch using 1 MHz RBW spectrum analyzer with RMS detector

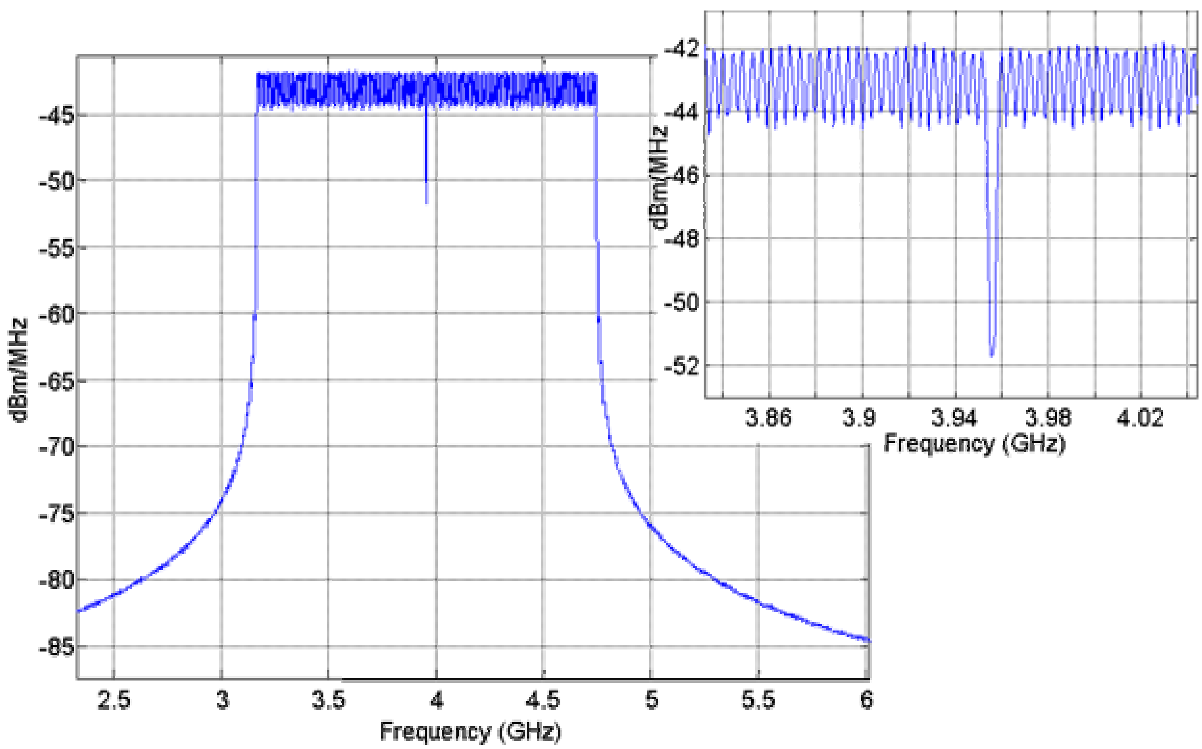

Figure 4. 1 tone notch using 1 MHz RBW spectrum analyzer with RMS detector

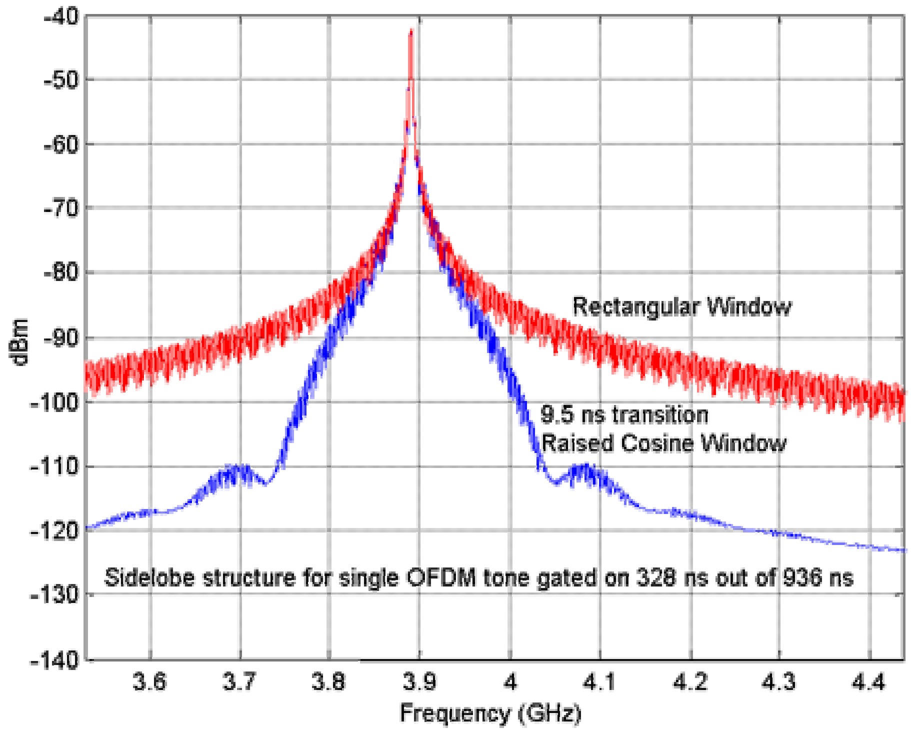

Figure 5. Gated Tone Spectrum

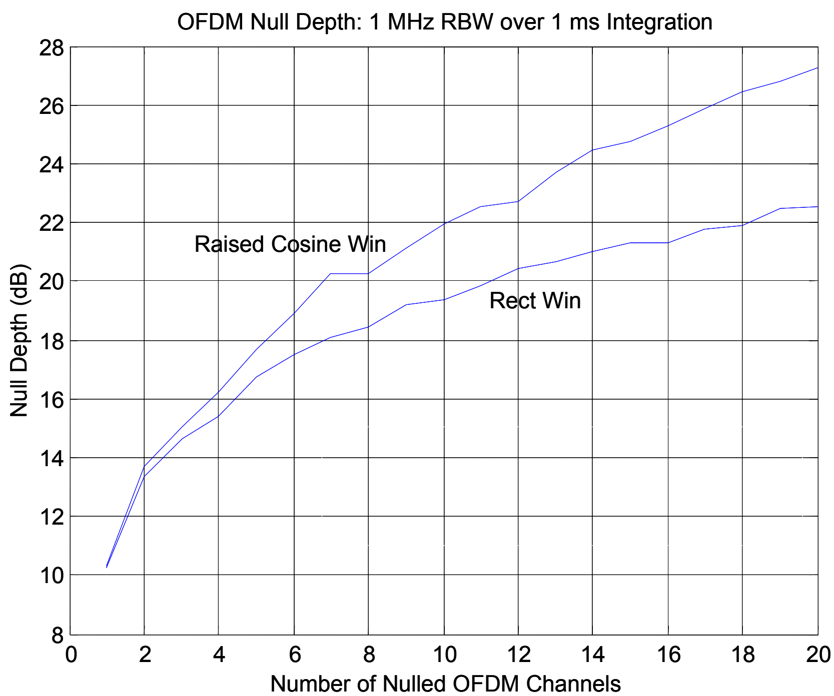

Figure 6. Null Depth versus consecutive tones turned off

4.6. Myth: OFDM is lower power

4.6.1. FACT: Power tracks complexity – an DS-CDMA has lower complexity

It is misleading to compare power budgets based on future process technology. It is not reasonable, for example, to compare first-silicon DS-CDMA chip sets built in .18u aluminum CMOS and operating today, with another radio designed 2 years later built on 3-generation-later copper 90nm CMOS technology. To remove process-technology from the equation, one typically assumes that the same technology is available to alternative solutions and uses complexity as a gauge for the power consumption. As shown in section 4.2, DS-CDMA can be significantly less complex, yet has better or equal performance. ***Given the same process technology, DS-CDMA will provide greater performance for equal power, or will require less power to deliver equal performance.***

5. Conclusion

In this paper, OFDM and DS-CDMA approaches have been compared as they apply to UWB. The facts show that across many metrics, DS-CDMA consistently outperforms OFDM for UWB. It allows neighboring piconets to operate closer together. As a result, DS-CDMA offers the highest aggregate Mbps/m^2 data rates because its CDMA codes are designed from the ground up to support "multi-user" which in this case, means multiple overlapping uncoordinated networks – like two wireless home theater systems in neighboring rooms or apartments. Its range/complexity ratio is higher. So it goes further (or faster) with similar complexity, or performs equivalently to OFDM with less complexity.

DS-CDMA is uniquely capable of serving a very broad spectrum of applications due to its mapping to scaleable implementations. The DS-CDMA transmitter is significantly simpler. DS-CDMA can, for example, allow very low-cost low-power transmit-only devices (even at Gbps rates) because it requires no FFT or DAC or DSP. At the same time, receivers can be made with varying degrees of DSP to provide scaleable power/cost versus performance that can, at the high end, grow to outperform OFDM by even wider margins. Furthermore, it complies with the FCC rules while operating with an average power of nearly the maximum allowed (-41.3 dBm/MHz). By contrast, all of the multiband-OFDM analyses presented at the IEEE 802.15.3a standards meeting must be operated at 4.7 dB lower average power in order to be certified. This 4.7 dB was ***not*** factored into any of the analysis papers and slides submitted in the 802.15.3a process.

Most significantly, the DS-CDMA approach is the only one that is beyond power-point engineering. It has not only been demonstrated over several years, but has been implemented in silicon, proving it can transition from lab to commercial applications.