Invited - Ultrawideband – The Next Step in Short-Range Wireless

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(Invited Paper)

Abstract — **Forces of economics and laws of physics have been driving the growth of short-range wireless technologies such as IEEE 802.11b/a, Bluetooth™, and most recently, *ultrawideband*. Developed initially for defense-related communications, ultrawideband offers data rates of 100-500 Mbps at distances of 2-10 meters, using an average radiated power of about 200 microwatts. With its low cost, low power, and small size, ultrawideband looks attractive for inter-connecting portable data-driven devices without wires as well as maximizing wireless *spatial capacity* measured in terms of bits/sec/square-meter.**

I. INTRODUCTION

If wireless were an ideal medium, it could be used to send a lot of data, very far, very fast, for many separate users, all at once. Unfortunately, physical laws make it impossible to perform well on all five of these attributes simultaneously – we must compromise on at least one of them if we wish to do well on the others.

In the early days of wireless, the ability to send data very far was surely the most important attribute. Marconi willingly sacrificed the other four attributes when he sent the first transatlantic radio transmissions in December, 1901. The past 100 years of wireless, however, have shown a clear trend toward improving on the other four attributes at the expense of distance. Radiotelephone installations that once covered an entire city have evolved into clusters of cellular base stations that sometimes cover distances as short as 300 meters.

Next-generation (3G) cellular systems have been designed to bring fast, wireless data connections to users. However, currently planned systems limit data speeds to about 2 megabits per second (and usually much less) because, at the distances they must cover to remain economical, these technologies are constrained by the physical laws and regulations governing loss, noise, power, and available spectrum.

II. ENTER SHORT-RANGE WIRELESS

Over the past several years, driven by data applications, very short-range systems have emerged with maximum ranges of 10 to 100 meters. IEEE 802.11b and 802.11a (also called Wi-Fi™) are today's best-known examples. In these cases, the Internet and wired IP-based local-area networks form the underlying wired infrastructure to cover longer distances. In other cases, to link portable electronic devices to one another, no "network" in the usual sense is required, and wireless technologies with ranges under 10 meters are useful as cable eliminators. Bluetooth™ has been developed separately and specifically for these *personal area connectivity* purposes.

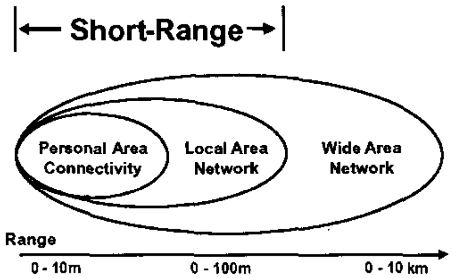

Fig. 1. Two kinds of short-range wireless, separately optimized for *local-area networking* and *personal-area connectivity*.

In general, four trends have been driving the growth of short-range wireless:

1. increasing demand for wireless data capability in portable devices at higher bandwidth and at lower cost and power consumption than that envisioned for 3rd-generation cellular;
2. crowding in radio spectra that regulator authorities segment and license in traditional ways;
3. growth of high-speed wired access to the Internet in enterprises, homes, and public spaces; and
4. shrinking semiconductor cost and power consumption for signal processing.

Of course, short-range technologies cannot offer the geographic coverage that longer-range cellular systems do. But, analogous to electric lighting, they can "illuminate" those areas in enterprises, homes, hotels, convention centers, schools, and other places where the most people gather. And they can be called upon to link clusters of personally owned electronic devices without cables. It is in this latter application, especially over distances of under 10 meters, that we can take full

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advantage of the dividends of short-range wireless – namely, low power, low cost, and high speed, all on unlicensed spectrum that can be re-used many times over, in some cases on a room-by-room basis.

II. ENTER ULTRAWIDEBAND WIRLESS

Barely one year past the FCC Report and Order permitting its commercial use [1], ultrawideband (UWB) is attracting considerable attention. UWB is technically a descendant of the earliest spark-based wireless technologies [2] and until recently has been used primarily in defense-related applications. While mass commercial deployment of UWB may still be three or more years away, its low power and low cost, combined with data rates in excess of 100 Mbps, make it attractive for a number of short-range applications [2,3,4].

As defined by the FCC Report and Order, a UWB signal is one whose –10 dB bandwidth exceeds 20% of its center frequency *or* 500 MHz, whichever is smaller. The FCC rules allow for a power of –41.3 dBm / MHz over the band 3.1 to 10.6 GHz and sharply reduced power elsewhere, as shown in Fig 2.

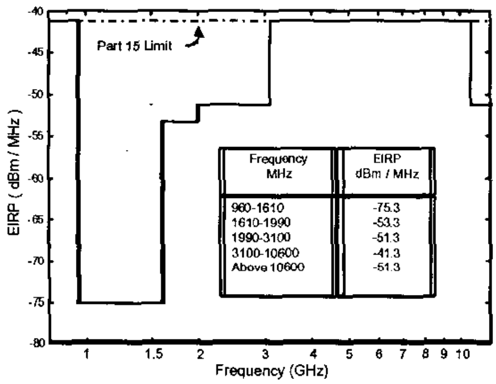

Fig 2. FCC-prescribed mask for ultrawideband signals

There are many ways to use the allotted 7.5 GHz of spectrum. One approach is to use most or all of it directly by transmitting very narrow baseband pulses like those in Fig. 3. Another is to transmit longer pulses consisting of several shaped cycles of an internal "carrier" wave, as in Fig. 4. The broader pulses occupy less spectrum, but by transmitting multiple such pulses with differing center frequencies a broad spectrum may be occupied over time. This approach is sometimes called "multibanding" and is described further in Section VII and References 5 and 6.

The narrow- and broad-pulse alternatives each have their pros & cons. For example, the narrow-pulse approach may lead to simpler transmitter and receiver designs, whereas the broad-pulse / multibanded approach may provide greater flexibility in dealing with interferers and world-wide spectrum regulations by simply dropping bands where & when necessary. Variations on both approaches are under development by different research groups and technology companies [6]. Pulse modulation techniques also vary widely, but a common one is binary phase-shift keying (BPSK) of the pulses, that is, simple polarity reversals to represent logical *ones* and *zeros*.

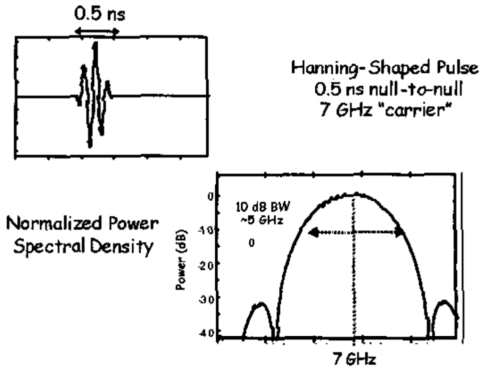

Fig. 3. Example of a narrow ultrawideband pulse occupying ~ 5 GHz of spectrum.

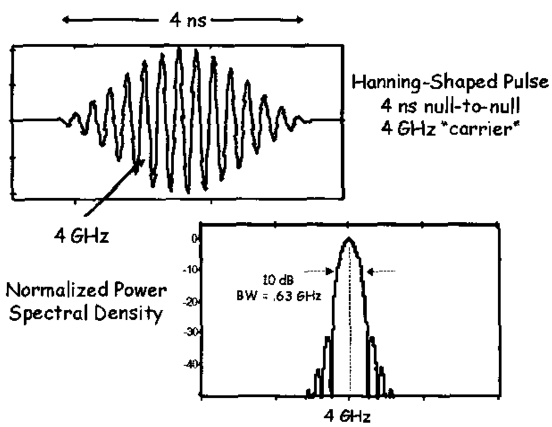

Fig. 4. Example of a broader ultrawideband pulse occupying ~ 0.6 GHz of spectrum.

IV: UPPER BOUNDS ON DATA SPEEDS

The broad bandwidth and limited power of UWB produce interesting capacity-versus-distance comparisons between UWB and more traditional short-range wireless technologies. Using the Hartley-Shannon law (Fig 5), Fig 6 compares the theoretical upper bounds on channel capacity for a 7.5 GHz UWB channel and four different narrowband unlicensed channels at 2.4 and 5 GHz in the ISM and UNII bands.

As shown in Figure 6, UWB has the capacity for very high capacity channels, but at distances above 10 meters, the narrower-band systems have a higher upper bound because of their higher permitted power. Fig 6 illustrates why UWB is not an attractive candidate for covering 10-100 meter ranges when compared to today's 802.11-based wireless systems in the 2.4 GHz and 5 GHz ISM and UNII bands. On the other hand, for shorter distances, especially those below 5 meters, UWB appears to be a very attractive option.

$$C = B \log_2 \left(1 + \frac{S}{N}\right)$$

Fig 5. The Hartley-Shannon Law. C = maximum channel capacity (bits/sec); B = channel bandwidth (Hz); S = signal power (watts); N = noise power (watts).

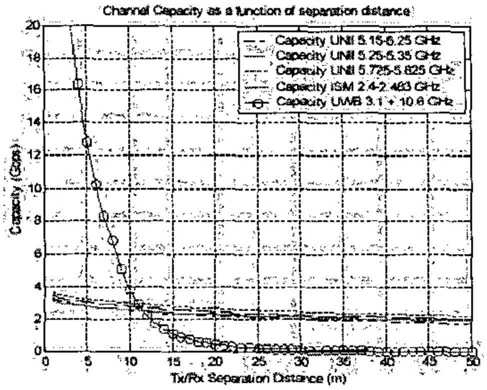

Fig 6. Hartley-Shannon upper bounds on single-user channel capacity for ultrawideband and other unlicensed-band wireless channels. UWB calculations include a 6 dB noise enhancement.

V. Spatial Capacity: An Emerging Figure of Merit

In 1976, the number of mobile radiotelephones that could be supported in New York city was only about 575, a number that seems absurdly small by today's standards. Demand could only be satisfied with the lower power, shorter range, and higher spectral re-use of cellular technologies. Over the next decade, we can expect the same phenomenon to occur for short-range wireless. As more and more users gather in crowded spaces like airports, hotels, convention centers, conference halls, classrooms, sports stadiums, and other venues, the figure of merit for a wireless system will have to take *area* into account as well as peak data speed. A suitable metric is likely to be *spatial capacity* [4]. Measured in bits per second per square-meter, spatial capacity is a measure of *data intensity* in much the same way that lumens per square meter determines the *illumination intensity* of a light fixture.

Figure 7 compares the spatial capacities of today's short-range wireless systems with that of UWB. For each system, the maximum number of nominally non-interfering systems, running at peak speed, are assumed to be offering service within the rated radius of the system. For example, eight 802.11a systems, running at a peak speed of 54 Mbps, covering a circular area with a radius of 50 meters, would have a spatial capacity of $8(54)/[(3.14)50^2]$ = 55 kbps/m². For Bluetooth, the assumption is that ten 1-Mbps systems can operate in a circle of radius 10 meters, and for 802.11b, the assumption is that three 11-Mbps systems operate in a circle of radius 100 meters.

For UWB, conservatively assuming an aggregate speed of 300 Mbps over a 10-meter radius results in a spatial capacity of about 1000 kbps/m². In the near-term, there is little market demand for such high spatial capacities, so today's higher-power, longer-range systems can be expected to dominate wireless LAN access for at least several years to come. In the near-term, UWB's principal application will instead be for high-speed, cable-free data transfers such as MP3 or MPEG file transfers into portable storage and viewing devices. But in the longer term, forces of physics and economics will drive demand for the higher spatial capacities of UWB or other shorter-range, lower-power technologies [2].

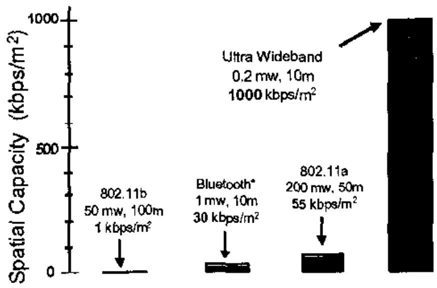

Fig. 7. Comparison of spatial capacities for ultrawideband and other short-range wireless technologies.

VI. A Question of Energy Per Bit

In both the nearer- and longer-term, *total energy per bit* will be another figure of merit for any wireless technology destined for personal, portable electronics. Fully integrated UWB chips do not yet exist, but conservatively, it already appears feasible to build multi-chip, 100-Mbps systems operating over ranges of 5-10 meters that consume 200-300 mw of power. This equates to 2-to-3 nano-joules per bit, which compares favorably with other short-range wireless technologies. As the level of integration and semiconductor processes improve (particularly low-cost CMOS), both power and costs will continue to drop [6].

VII. MULTIPATH AND MULTIACCESS

Recent UWB multipath measurement & modeling efforts [7,8] have produced a set of channel models against which researchers can test their designs. Fig. 8 shows the impulse response from a typical line-of-sight (LOS) modeled channel at a range of 0 to 4 meters. Note that significant echoes occur at delays out to 20-30 ns. In this example, the echoes would not be a serious problem if the UWB pulses could be spaced at least 30 ns apart, but that would limit the pulse rate to only about 30 million pulses per second.

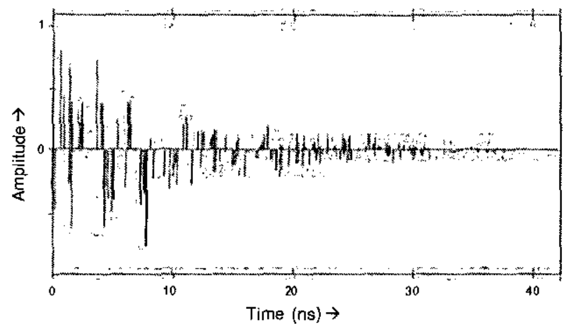

Fig. 8. Impulse response of typical line-of-sight UWB channel as modeled by the IEEE 802.15.3a study group. The response includes a unit impulse at time $t = 0$.

Many methods are available for mitigating multipath including error-correcting codes, rake receivers, and bi-orthogonal coding/modulation schemes [9]. In the case of a multiband design, pulses with differing center frequencies can be transmitted in sequence, as shown in Fig 9a. In this example, the pulses are each 4 ns wide, and there are 12 different center frequencies running from 3.5 to 9.0 GHz in 0.5 GHz steps (Fig 9b). Each frequency is used only once every 48 ns, giving the echoes at that frequency adequate time to "ring down". In this example, using BPSK, the maximum (uncoded) channel data speed would 250 Mbps, and with QPSK, 500 Mbps. Where and when channel conditions permit, the pulses could be overlapped in time, thereby permitting still higher data speeds.

Closely related to multipath issues are those of *multi-access* – the need to allow multiple UWB links to coexist in the same space. This is a topic of intense current research. A wide variety of schemes have been proposed in the IEEE 802.15.3 Task Group 3a [6] involving variations on familiar code-division, time-division, and frequency division multiple-access schemes.

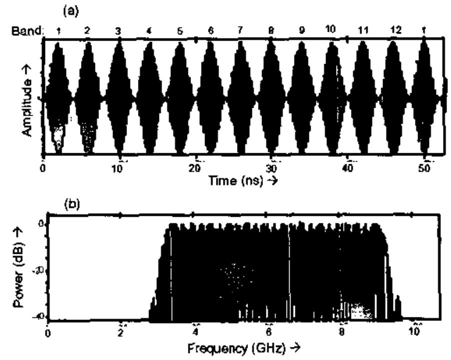

Fig. 9. Example of a possible 12-band "multiband" modulation scheme.

VIII. THE FUTURE OF ULTRAWIDEBAND

UWB promises to deliver low-cost, low-power, wireless connectivity at speeds of 100-500 Mbps over distances of 2-10 meters. These attributes are driving consumer electronics, PC and peripheral, and mobile device manufacturers to consider UWB for new forms of wireless interconnection applications. Commercial interests, standards efforts, and regulatory processes are paving the way for enabled consumer products to appear on store shelves within the next 3-5 years.

REFERENCES

[1] Federal Communications Commission, First Report and Order, ET Docket 98-153, "Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems", adopted Feb 14, 2002.

[2] D. G. Leeper "Wireless Data Blaster," *Scientific American*, vol. 286, No. 5, pp. 46-51, May 2001.

[3] J. Foerster et al., "Ultra-Wideband Technology for Short- or Medium-Range Wireless," *Intel Technology Journal*, Q2, 2001, http://intel.com/technology/itj/q22001/articles/art_4.htm

[4] D. G. Leeper "A Long-Term View of Short-Range Wireless," *IEEE Computer Magazine*, vol. 34, No. 6, pp. 39-44, June 2000.

[5] R. Aiello, "Challenges for Ultra-Wideband (UWB) CMOS Integration," IEEE 2003 IMS/RFIC Symposium, June 8-10, 2003, Philadelphia, PA (this conference).

[6] IEEE 802.15 WPAN High Rate Alternative PHY Task Group 3a (TG3a), see link: *Document Archives* at http://www.ieee802.org/15/pub/TG3a.html. Search PHY layer submissions beginning March, 2003.

[7] J. Foerster, et al, (see Ref 6 above) Document IEEE P802.15-02/368r5-SG3a

[8] S. Ghassemzadeh, V Tarokh, "UWB Propagation Characteristics in Residential Environments," (This conference – see R. Aiello above).

[9] B. Sklar, *Digital Communications*, 2nd Edition, New Jersey: Prentice-Hall, 2001, pp 525-529