Communications of the IIMA

Volume 6 | Issue 1 | Article 12

2006

Competing Next Generation Wireless Technologies

Warren Adis
Iona College

Competing Next Generation Wireless Technologies

Warren Adis
Hagan School of Business, Iona College, New Rochelle, NY 10801
(845) 352-7132
wadis@iona.edu

ABSTRACT

Wireless computing is facing a choice concerning the next telecommunication standard. Two of the new and competing protocol standards for local area and personal networking are 802.11n and Ultra Wide Band. Each one has its own strengths and weaknesses and both will change wireless networking by dramatically increasing the transmission speed, the QoS and the security of the broadcast. Yet decisions have to be made about which protocol to adopt. The choice rests on a deeper understanding of each protocol, its evolution, compatibility and future direction. This paper analyzes these two competing protocols, discussing their performance and probability for success in the marketplace based on a wide range of criteria.

NEXT GENERATION WIRELESS

The current generation of wireless technologies is approaching the end of its life cycle. It is not surprising since there is a continual demand for higher channel capacity and increased broadcast distances, as well as more enhanced security. Furthermore, each particular wireless application has its own quality of service (QoS) requirements that affect its performance (Shim, 2006). This is particularly true of multimedia programs where jitter and latency can negatively impact the service. Lastly, as more applications use mobile wireless services, there is additional demand for the miniaturization of devices and extended battery time.

Simply stated, the current generation of telecommunications (telecom) protocols is not able to keep up with the requirements of commercial business as well as residential multimedia. Therefore, it is appropriate to evaluate two of the most promising next generation telecom protocols: 802.11n (11n) and ultra wide band (UWB) 802.15a (Welborn, 2005). This paper will focus on determining their strengths and weaknesses, in order to discern which protocols will best meet long term business and performance objectives. This exercise is important because the type of technology chosen by any business will significantly impact its competitive strategy and financial strength. A wrong decision or even no decision can mean lost time and misspent funds, as well as telecom weakness and incompatibilities.

In general, the performance requirements of wireless systems are approaching those of hard wired systems, as users transmit and receive larger files including audio, video, and interactive simulations. Users need the bandwidth and attendant QoS features to handle high definition multimedia (Adis, 2003). At the same time, wireless mobility is dependent on device and battery miniaturization. Without smaller devices having less power requirements, there can be no use of milliwatt power sources. This is particularly important with hand held devices, radio frequency ids (rfids), and remote sensing devices (motes) where overall size and battery life become the driving force of business acceptance (Intel, 2005; Intel, 2004).

In particular this paper will analyze and discuss the two dominant strategies for the extension of wireless LAN. The first is the recently approved 802.11n (11n), which is the extension of the 802.11a/b/g. The other competing approach is ultra wide band (UWB) 802.15a, which many consider a significant extension or replacement of Bluetooth. Deciding between these two platforms must be based on understanding the strengths and weaknesses of the new replacement technologies in providing the best long-term fit.

METHODOLOGY

The two dominant wireless technologies described above are designed with different functionality. The former is used mainly for local area client server networks, while the latter is dominant in the short range transfer of data between equipment. By examining these protocols, one can judge how future upgrades will expand the technical strengths while overcoming any performance weaknesses. In the case of 11n one of the key performance features is trying to maintain compatibility with 11g, while UWB is essentially a new technology with its own issues of compatibility and channel conflicts.

By better understanding these protocols, it will become clearer whether 11n or UWB has the technical characteristics to dominate its functional niche, as well as expand into other service areas and applications. Table 1 spells out the most important technical criteria for judging the performance of these new telecommunication platforms (Kurose, 2005). These functional criteria provide the basis for forecasting the successful penetration and adoption of the next generation of wireless protocols.

Performance Criteria	**Description**
Speed	Channel capacity
Reliability	Fewer re-transmissions
Security	Encryption
Distance	Broadcast range Spatial density
AV streaming	Minimal jitter & latency
Cost	Reduced overhead
Miniaturization	More applicability with less manufacturing expense
Compatibility	Telecom standards
Power consumption	Extended battery life
QoS	Prioritized service

Table 1: Wireless Performance Characteristics.

Each of the competing protocols was initially designed to accomplish a specific task. 11n was developed to work as a superior protocol for the wireless local area network. UWB, in contrast, was initially designed for the shorter range of wireless personal area networks. Consequently there are design tradeoffs with each technology, particularly as developers and users formulate applications outside the initial design range. To understand what the tradeoffs imply, decision makers must weigh performance factors for both the short and long term.

The next sections provide a comprehensive review of 11N and UWB, comparing and contrasting their technical and non-technical parameters.

802.11n

One of the strong contenders for the next generation wireless standard is the 802.11n specification. Its technical specifications for wireless LANs are already written, IEEE approved, and are entering the marketplace. This protocol is a significant upgrade from the current 802.11g standard in terms of performance and QoS. Table 2 provides a comparison between the current generation 11g and the proposed 11n (Wilson, 2004), using the most pertinent specifications. This new 11n standard indicates the fast pace at which mobile technologies are changing, underscoring the rapid timeframe needed for management and technical planning.

Table 2 shows the current Wi-Fi 11g protocol and some of its most important features, including the speed, distance and relative security which make it such a strong performer. By comparison 11n makes significant advances in channel capacity, distance and imperviousness to interference. Its security is strengthened with advanced encryption and its QoS is enhanced by using prioritized streaming of audio and video data (Gast, 2005). It may only be a matter of time before 11n replaces much of the previous protocol as well as much of the wired infrastructure.

Ultra Wide Band (UWB) 802.15.3a

Similar progress has been made in the evolution of ultra low-power radio technology. Currently, this technology is used for the wireless linking of devices in personal networks. Table 3 describes and compares the important characteristics of Bluetooth and Ultra Wide Band (UWB). Again, significant enhancements have been made in terms of speed and security within the new UWB protocol, with relatively minimal increases in power requirements.

It should be noted that UWB technology - as the name implies - uses ultra wide bandwidths across a multi-gigabit spectrum. It accomplishes this task by transmitting pico second pulses of data across a wide range of radio frequencies (Roy, 2004). The pico second pulses incorporated with 256-bit Advanced Encryption Standard (AES) make for a hacker's nightmare in trying to detect and analyze these low power encrypted pico pulses.

Protocols	802.11g Wi-Fi	802.11n
Speed	54 Mb/sec	200 Mb/sec
Distance	100 m	250 m
Bandwidth	2.4 GHz	2.4 & optional 5.6 GHz
Power	1500 mW	>2000 mW
Audio-Video Streaming	No	Yes, QoS Prioritizing
Security	Subset of Advanced Encryption Standard	Advanced Encryption Standard. WPA2.
WiFi Compatibility	N/A	Yes
QoS	No	Yes, 802.11e

Table 2: Wireless Protocols within 802.11.

Protocols	Bluetooth 2.0 802.15.1.	Ultra Wide Band (UWB) 802.15.3a	
Distance	10 m	10 m	2 m
Speed	3Mb/sec	110 Mb/sec	440 Mb/sec
Bandwidth	2.45 GHz	3.1 GHz to 10.6 GHz	
Power	1.0 mW	>100 mW	
Audio-Video Streaming	No	Yes, QoS Prioritizing	
Security	Service-level & device-level security	Pico pulses 256-bit Advanced Encryption Standard (AES)	
Bluetooth Compatibility	N/A	Yes	
QoS	No	Yes	

Table 3: Bluetooth and UWB Performance Characteristics

Initial Comparison

An initial comparison indicates that both next generation protocols have made a significant step forward over the previous standards. It is also clear that the principal advantages of 11n are in terms of transmission distance and compatibility, with improved performance in other categories. Likewise, UWB has multiple advantages over Bluetooth. These include speed, distance, security, and QoS.

In the not too distant future it will be an interesting challenge for designers to adapt these protocols for use in competing design areas. As wireless technology advances, it is likely that 11n will be able to expand into the very high speed and low power arena of UWB. Similarly the logical progression of UWB performance characteristics, particularly as it gains greater distances, may make it a formidable competitor to the 802.11n protocols.
From a business perspective, it is important for IT managers to know which protocol will become dominant in the marketplace before making a choice. This allows standardization of hardware and software, driving down the cost of doing business. Possibilities of technical incompatibilities are also lessened, and therefore management becomes more straightforward.

ANALYSIS OF THE TWO COMPETING PROTOCOLS

802.11 g-n Protocol in Detail

The 802.11g-n transmission methodology (O'Hara, 2005) is Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). It accomplishes this task of carrier sensing by first probing the transmission environment for competing broadcasts, finding a clear channel and applying a jamming signal mechanism to lock in the network for its broadcast. While this method works reliably, it needs to utilize bandwidth resources to accomplish its task, reducing data thruput by approximately 30-40%. In other words, in order to reduce collisions and the need for re-broadcasting, a significant portion of potential performance is sacrificed. Overall the trade-off works, successfully protecting broadcasts in environments where there is competing traffic. Another important protocol enhancement of the 802.11g-n series is the use of orthogonal frequency-division multiplexing (OFDM). This modulation technique is especially effective in reducing noise and interference in the crowded 2.4 GHz bandwidth. In order to maintain compatibility with 11g, the designers have chosen to remain in the busy 2.4 GHz portion of the spectrum and then apply sophisticated and somewhat more expensive modulating techniques to guard against the concomitant multipath interference and noise. Furthermore, the protocol also regulates the channel transmission speeds, in effect slowing down transmission to avoid possible collisions. By intelligently throttling back the broadcast speeds, the protocol is in fact a constraining force limiting potential thruput. Similarly performance is lost in the modulating technique of OFDM, as those frequencies have self imposed limits. These restrictions act to prevent the degradation and loss of frequency synchronization inherent in trying to modulate multiple orthogonal frequencies. The result is that the transmission cannot take full advantage of the raw bandwidth. Yet these tradeoffs are only a step along the performance path, for the real gain for 11n is its use of multiple transmitters and receivers, referred to as MIMO (multiple-input multiple-output). The MIMO performance advantage is that it allows parallel streams of data transmissions, or spatial multiplexing. This is the equivalent of multiplying the speed of 802.11G by a factor of 4, from approximately 54 Mb/sec to more than 200 Mb/sec. In the future as the number of MIMO transmitters and receivers are increased, the expected transfer rate will be greater than 600 Mb/sec. See Figure 1 below.

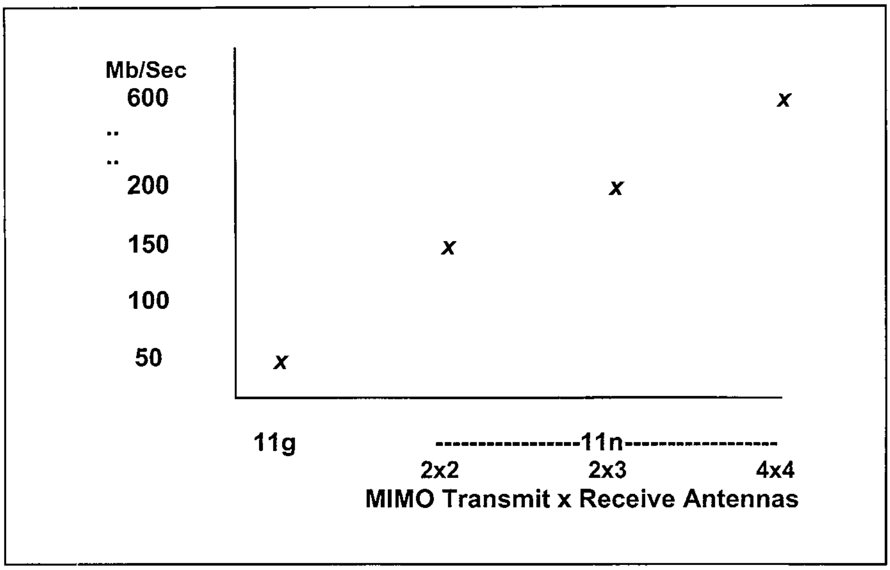

Figure 1: 802.11 g-n Transmission Speed

Increased expenses are associated with OFDM and MIMO, due to the sophisticated radio frequency circuitry, power consumption and size. The RF circuitry is more complex since it has the tasks of providing OFDM and maintaining its sub-carrier orthogonally. The power consumption driving this functionality is also on the high side since it must perform the tasks of reducing the inter-modulation between sub-carriers and the attendant noise level within and between carriers. In addition, designing miniaturized devices is made that much more difficult when factoring in the OFDM circuitry and the multiple transmitters of MIMO.

In discussing the 802.11 protocol series one thing stands out. This is its dominance within the LAN marketplace, which leads to a continual stream of enhancements being designed to increase its performance characteristics. Two especially significant enhancements are 802.11e, which will establish QoS prioritization of traffic, and 802.11i which will use WPA2 as the basis for increased security. The QoS prioritization feature is critical for audio streaming and time sensitive transmissions, which give it precedence over less time sensitive data like email. The increased WPA2 security uses more sophisticated techniques for authentication and key encryption. These enhancements are a strong step towards locking in privacy, confidentiality and integrity.

UWB Protocol in Detail

Ultra wide band (UWB) is also a sophisticated technology which meets much of the telecommunications criteria outlined in Table 1. Its chief performance characteristics are significant improvements in transmission speed and security, while maintaining its small physical envelope and milliwatt power consumption (Kohno, 2004).
UWB protocol transmits data across a very wide radio frequency (RF) spectrum and consequently provides a different model from the narrowband technique found in 802.11n. It is referred to as baseband pulse technology to emphasize the pico-second pulses that it emits simultaneously on an ultra wide range of frequencies. This is similar in nature to an electrical spark filling the RF spectrum with static.

This analogy of a spark has merit for understanding how UWB broadcasts can potentially interfere with other broadcasts within its range. To resolve this issue, the Federal Communications Commission (FCC) adopted the First Report and Order 1 which mandated that UWB broadcasts use exceptionally low power transmission, in the low milliwatt range. More specifically, the FCC only allowed UWB to transmit within the range of 3.1 to 10.6 GHz, with each operating channel having a bandwidth in the range of 500 MHz, and a power range of -41 dBm/MHz. This translates to less than a milliwatt across its broadcast spectrum.

The UWB range of more than 7 GHz is the basis for a very high channel capacity. The reason behind UWB's exceptionally fast communications channel is expressed as Shannon's law, where $C = BW \times \log_2 (1 + S/N)$. This formula states that the channel capacity (C) is directly proportional to the bandwidth (BW) and the log of the signal noise (S/N) ratio. Since UWB uses more than 7 GH, it has a vast channel capacity. In the future as this technology becomes refined, researchers expect that the speed will surpass 2.5 Gb/sec (Green, 2004). In contrast, 11n has approximately 80 MHz of channel capacity in the 2.4 GHz bandwidth, and must rely on multiple transceivers to increase its thruput.

The logic behind the FCC (2004) approval of UWB technology is that it mandates that the transmitters stay within the power restriction guidelines, thereby limiting their ability to interfere with competing broadcasts. The result is that UWB can have large channel capacity, plus the added advantage of having multiple non-interfering UWB devices in close proximity to each other.

In conceptualizing this idea of multiple non-interfering UWB devices in close proximity, it is important to realize that it is the low power of the short range broadcast that limits potential interference with other devices. Furthermore, the low power requirement actually means that multiple devices can be in relatively close proximity and share the same radio frequency spectrum without interference. This means that multiple networks in relatively close range can broadcast on the same frequencies without interfering with each other, which thereby increases the transmission density of the networks. Figure 2 illustrates this concept.

The large bold parentheses (a) in Figure 2 show two separate networks each with a 200 meter transmission range. The networks are separated to minimize competing noise and interference. Alternatively, the smaller parentheses (b) show how the lower power, shorter range of several UWB networks can also be used in the same network space. They too are non-overlapping to minimize competing noise and interference. But in this instance, the short range of the networks is an advantage because 2 larger networks can be replaced by multiple smaller networks. This illustrates how UWB increases the spatial density of the network by the multiple re-use of the same bandwidth. The outcome of this is a significant increase in the number of devices operating in a given location. Some researchers have estimated that UWB networks have a spatial density of approximately 1000 kbs/m^2 (Foerster, 2001). By contrast 11n has a spatial density closer to 5 kbs/m^2. This makes UWB a potentially dominant performer for such tightly packed networks as rfids and motes.

Broadcast Range : a) 802.11n b) UWB

a) 200 m **200 m**

( ) ( )

b) 10 m

( ) ( ) ( ) ( ) ( ) ( ) ( ) ( ) ( ) ( )( )( )...

Figure 2: Spatial Density of Networks with Large and Small Broadcast Range

The technical strengths and weaknesses of UWB represent opposing sides of the same coin. The short transmission distance is compensated by a high spatial density. The low power has the compensating factor of minimal interference and design miniaturization, as researchers take advantage of smaller inexpensive batteries for the milliwatt CMOS transmitters.

Yet there are other intervening and confounding issues. Much of this can be summarized by the fact that UWB has not yet been ratified by the IEEE. There are multiple reasons for this. One of the major concerns is whether UWB transmission will interfere with the very sensitive Global Positioning System (GPS) that is used throughout the world. Since that system is used for commercial and military flights and other mission critical operations, much care must be invested in ensuring that there is no interference from the overlapping bandwidth (Kumar, 2003). GPS has a signal to noise ratio of -164 Db, which does not have much tolerance for any interference.

While there are competing technical designs to address the noise and interference issues, the IEEE committee for the last several years have not been able to finalize the standard. Similarly, much of Europe and Asia have not fully taken up evaluating UWB and are even further behind in trying to adopt the protocol.

Finally, it is important to report that while most of the research has been directed to preventing UWB from interfering with other transmissions, not enough thought has been paid to high power devices interfering with UWB transmissions. UWB devices, unlike 11n devices, do not have front end filters to block outside noise caused by competing transmission in the same bandwidth. The very nature of ultra wide band transmission inherently works against the idea of filtering any transmissions within its ultra wide spectrum. To resolve this problem, UWB developers are working on notch filters that severely attenuate those portions of the spectrum that are known to cause interference. This of course increases the cost and complexity of UWB, while reducing the overall speed.

CONCLUSION

An underlying theme in this paper is the need to understand the progress of technology as it develops, matures and moves through various stages of innovation. In particular, Joseph Martino's work (1993) on technological forecasting is helpful in characterizing the different developmental stages. He also provides a list describing the order in which these stages generally appear, which I have modified as follows:

1. Scientific findings
2. Laboratory feasibility
3. Operating prototype
4. Acceptance by accrediting agencies
5. Commercial introduction
6. Widespread adoption
7. Diffusion to another areas

In this paper I have focused mainly on the middle stages – from development of the operating prototype to acceptance in the marketplace. In protocol development there are several levels of acceptance. First, a critical mass of chip/telecommunication manufacturers and application designers is needed to support the protocol and its implementation. Each one has their own vested interests and visions for the technology. Then, there are accrediting agencies, such as the IEEE and the FCC who review the specification in the broader context of overall use of the radio spectrum and conflict potential with current and future bandwidth usage. Once these groups give their imprimatur, then this hurdle is cleared, and commercial forces can take over.

It is clear that 11n is a protocol which has evolved from the 802.11 series and preserves much of its technical foundations. It is also clear that because of its compatibility with the 11b-g series, it has an easier path from working model to acceptance by the IEEE, manufacturer associations and user groups. Despite the fact that the protocol was only IEEE approved in 2005, it will probably be commercially released over the next two years.
In order to better understand the switchover to 11n it may be worthwhile to review the history of the 802.11 series. During the 2002-2004 timeframe, IT managers had to choose which protocol was best suited to replace the popular 11b protocol. The two replacement choices were 11g which operated in the same bandwidth as 11b and was generally compatible, or the competing 11a protocol. 11a has many of the same technical improvements as 11g, though it traded compatibility with 11b for the ability to operate on the less crowded 5.6 GHz bandwidth. This gave users the opportunity to move away from the congested and noise prone 2.4 GHz to a bandwidth which has the possibility of superior transmissions. However, most IT managers chose not to move to the 5.6 GHz bandwidth and lose their investment in 11b hardware. In order to implement the 11a protocol they would have had to introduce additional non-compatible systems for the new bandwidth. Thus, most chose the safe option, to keep their existing investment and experience with a particular standard rather than experimenting with a new protocol, however potentially superior. Consequently the transition from 11b to 11g moved rapidly from acceptance to wide spread adoption. Tens of millions of 11b/g combination chipsets were shipped in the first two years after approval and ratification of the standard.

Thus it would be reasonable to predict that the adoption of 11n will follow along a similarly rapid path. However, there are some potential problem areas that may cause corporate IT managers to delay the purchase of 11n. Firstly, IT managers recognize that the existing 11g standard is a relatively fast and reliable protocol and therefore not in immediate need of upgrading. This was not the case with the slow and generally immature 11b series, which prompted the immediate shift to 11g. Consequently, managers may wait for 11n's promised improvements in speed, reliability, and decreased costs to become proven before buying in. The second point is that they may well wait for the chipset to mature and include full 11e QoS services and 11i security services. This is more likely to occur with the release of the second generation chipset, rather than in the introductory release of the protocol. The last reason is that managers are well aware that there are a series of parallel events and standardizations playing out in the marketplace. Microsoft's new multimedia operating system and the new variation of Blue Ray/Hi definition DVD standards will significantly impact the fine-tuning of the 11n chipset. So it is likely that after the commercial introduction of 11n, there will be an evaluation period as prices drop and reliability issues are resolved, followed by a more gradual movement to widespread adoption.

In contrast to 802.11n, the UWB protocol is a more revolutionary approach which had its origins in radar technology. As a protocol without an evolutionary track record, it faces much more challenges in being accepted (Templeton, 2005). Currently, manufacturers and application designers are still working on different protocol models and chipset designs, and have not yet come up with an agreement on a standard prototype. The result is that few will fully commit to moving towards what may be a premature introduction and therefore a potential commercial failure in the marketplace. Most are awaiting the protocol's acceptance by the IEEE, and some may even require further acceptance by European and Asian accrediting bodies.

As a revolutionary technology UWB must overcome three specific challenges, or else it will develop only as a niche service. First, it is necessary for UWB supporters to work out their differences and standardize a working prototype to present to various accrediting bodies. Next, it needs to resolve compatibility and interference issues posed by GPS and other protocols operating on the radio spectrum. Lastly, the backers of the protocol have to realize that there is a closing window of opportunity and they need to act quickly. If they can do this in the short time frame of the next two years UWB will still be a contender in the arena of the shorter ranged personal networks. After this time, even this arena may be dominated by 11n. So, despite the fact that UWB constitutes a technology breakthrough with its speed, small size, cost and power requirements, it may only have a limited market share within rfid and mote environments.

To conclude, it is only fair to address the technologist argument that it will pay in the long term to choose the superior technology of UWB, since 11n exists in the over-crowded and eventually self limiting 2.4 GHz bandwidth. 11n's developers realize that this could become a problem and have also incorporated the optional 5.6 GHz bandwidth with the 11n standard. It is likely that this optional feature will become incorporated into the chipset so that a seamless transition to the less crowded channel could take place in the future. Predictably, commercial success will encourage further investment and development in the 11n chipset, adding additional QoS and security features. Similarly, manufacturers would have a strong incentive to incorporate more advanced MIMO transmitters reaching 600+ Mb/s. Therefore, a fair evaluation could conclude that 11n will dominate the LAN market, and as it gains speed, begin to move into the shorter range Bluetooth UWB niche. One might be justified in stating that the niche will narrow for UWB, especially if 11n gains significant market share in the next few years.

REFERENCES

Adis, W. (2003). Quality of Service Middleware. Industrial Management & Data Systems (IMDS), Vol. 103 No. 1

Aiello, G. and Rogerson, G. (2003). Ultra-Wideband Wireless Systems. IEEE Microwave Magazine, 4(2), 36-47

Bluetooth (2006). http://www.bluetooth.org

Coffey, Sean et al. (2005). WWiSE IEEE 802.11n Proposal. IEEE document number 802.11-05-1591r3

Di Benedetto, M. and Giancola, G. (2004). Understanding Ultra Wide Band Radio Fundamentals. Upper Saddle River, NJ: Prentice Hall

FCC (2004). http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-04-98A1.pdf

Finkenzeller, K. (2003). The RFID Handbook, NY: John Wiley & Sons

Foerster J. et al. (2001). Ultra-Wideband Technology for Short- or Medium-Range Wireless Communications, Intel Technology Journal Q2

Gast, M. (2005). 802.11 Wireless Networks: The Definitive Guide. Cambridge, MA: O'Reilly

Green, E and Roy, S. (2004). System Architectures for High-rate Ultra-wideband Communication Systems: A Review of Recent Developments. http://www.intel.com/technology/comms/uwb/download/W241_Paper.pdf

IEEE (2005). 2nd International Workshop Networking with Ultra Wide Band--Workshop on Ultra Wide Band for Sensor Networks. July 4-6, 2005. Rome, Italy: Wiley-IEEE Press

IEEE (2006). http://www.ieee802.org/11

Intel (2004). Broadband Wireless: The New Era in Communications. http://www.intel.com/netcomms/bbw/30202601.pdf

Intel (2005). http://www.intel.com/research/exploratory/motes.htm

Kohno, R. et al. (2004). DS-UWB Physical Layer Submission to 802.15 Task Group 3a. IEEE Document number 802.15-04-0137r4

Kumar, S. and Stokkeland, J. (2003). Evolution of GPS technology and its subsequent use in commercial markets. International Journal of Mobile Communications, Inderscience Vol. 1, Numbers 1-2

Kumar S. (2004). Mobile communications: global trends in the 21st century, International Journal of Mobile Communications. Inderscience, Volume 2, Number 1

Kurose, J. and Ross, K. (2005). Computer Networking. Boston, Addison: Wesley, MA

Martino, J. (1993). Technological Forecasting for Decision Making. New York: McGraw Hill

O'Hara, B. and Petrick, (2005). The IEEE 802.11 Handbook: A Designer's Companion. New York: IEEE Press

Roy, S. et al (2004). Ultrawideband Radio Design: The Promise of High-Speed, Short-Range Wireless Connectivity. Proceedings of the IEEE, VOL. 92, NO. 2

Shamir (2005). http://shamir.eas.asu.edu/~mcn/Ayushman.html

Shim, J., Varshney, U. et al. (2006). Mobile and wireless networks: services, evolution and issues. International Journal of Mobile Communications, Inderscience, Volume 4, Number 4

Templeton, G. and Schmidt, M. (2005). A Critical Time for Ultra-Wide Band. Journal of International Technology and Information Management, Vol. 13, Number 3

Welborn, M. (2005). DS-UWB vs. 802.11n: What's the Best Connectivity Option. http://www.wirelessnetdesignline.com/howto/60406787

Wilson, J. (2002). Ultra-Wideband: a Disruptive RF Technology? http://www.intel.com/technology/comms/uwb/download/Ultra-Wideband_Technology.pdf

Wilson, J. (2004). The Next Generation of Wireless LAN Emerges with 802.11n. http://www.intel.com/technology/magazine/communications/wi08041.pdf