The Future of Personal Area Networks in a Ubiquitous Computing World

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ABSTRACT

In the future world of ubiquitous computing, wireless devices will be everywhere. Personal area networks (PANs), networks that facilitate communications between devices within a short range, will be used to send and receive data and commands that fulfill an individual's needs.

This research determines the future prospects of PANs by examining success criteria, application areas and barriers/challenges. An initial set of issues in each of these three areas is identified from the literature. The Delphi Method is used to determine what experts believe what are the most important success criteria, application areas and barriers/challenges.

Critical success factors that will determine the future of personal area networks include reliability of connections, interoperability, and usability. Key application areas include monitoring, healthcare, and smart things. Important barriers and challenges facing the deployment of PAN are security, interference and coexistence, and regulation and standards.

ACKNOWLEDGEMENTS

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I would also like to thank all the experts who participated in the Delphi surveys of this study for their support and professional expertise. I really appreciate all the time and effort they have contributed for this research.

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CHAPTER 1: INTRODUCTION AND BACKGROUND

Introduction

Well into the first decade of the 21st century, a new paradigm of computing is emerging. The new trend of the computing world is moving towards becoming mobilized and embedded. This is reflected in three paradigm shifts in how the relationship between humans and computers has been perceived.

The first wave of computing was the centralized mainframe computers. A mainframe computer is a large computer system which has a central processing unit (CPU) with large memory and storage capacity. From the 1950's to the mid-1980's, these large, expensive, and difficult-to-use computers were operated by highly skilled operators. End users accessed mainframes through appropriately-named dumb terminals which included a keyboard and a cathode-ray computer screen.

The second wave of computing is personal computers and the Internet. The second wave began when Steve Wozniak and Steve Jobs invented the Apple I computer in 1976. Soon first-wave computer companies such as Digital and IBM started to develop their own desktop computers to join the trend. In the mid-1990's, everything changed when the Internet appeared into businesses and even people's everyday life. Email and the Web became the killer applications of this second wave.

Ubiquitous computing is the emerging third wave in the computing world. This continuing trend, in which computers are becoming smaller, faster, and cheaper, means that computing is becoming ubiquitous. Ubiquitous computing moves information technology services out of the desktop interface into a true-life environment (Mattern, 2004). The father of ubiquitous computing, Mark Weiser (1991) described ubiquitous computing as: "A new way of thinking about computers, one that takes into account the human world and allows the computers themselves to vanish into the background."

In other words, computers are finding their way into everyday objects. Figure 1 shows the trends in the computing world from Weiser's 1996 study.

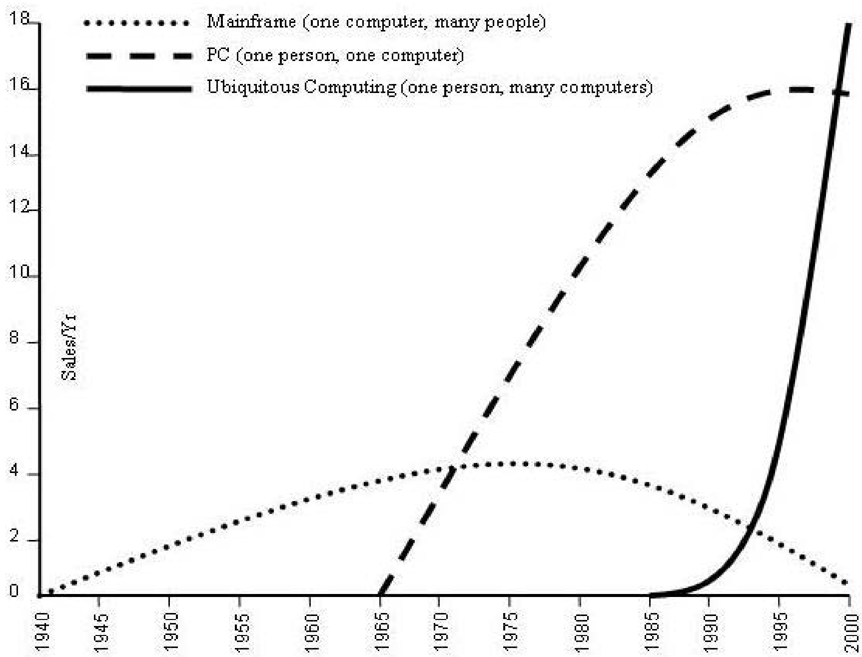

Figure 1: Major Trends in Computing (Weiser, 1996)

Ubiquitous computing (ubicomp) was introduced by Mark Weiser in 1988. In this vision, computer devices in the ubiquitous computing model tend to become invisible in everyday life. This requires ubiquitous computing to be mobilized and embedded into true-life environment. In fact, only in such an environment, people will use computing devices without even being aware of them.

At the moment, everyone seems to have one or more mobile phones. Mattern (2004) claims that mobile phones are forerunners in the ubiquitous computing field. Mobile phones will become true computers equipped with a whole range of functionality and will continue to develop into control centers for a multitude of other personal auxiliary services.

In the near future, more and more ubicomp devices will become part of the natural environment. However, wireless networking, a critical component for interconnecting the mobile components of a ubiquitous system, is still in its infancy, and yet there are no widely adopted universal wireless standards even though it was invented nearly 20 years ago (Want & Pering, 2005). For example, it is impossible for Bluetooth mobile phones to send or receive data from infrared-enabled cell phones.

In addition to mobility, the second critical aspect of ubiquitous computing is embeddedness. Embedded computers are assigned specific tasks, and often include task-oriented hardware which is normally not found in personal computers. Embedded computers could be evident in smart houses, smart clothes, etc. Because embedded systems allow computers to perform specific tasks, the size and cost of these computers could be dramatically reduced. Moreover, embedded computers require device-to-device networking. How these devices are able to communicate with each other should be a vital concern for designers.

Therefore, it is important to study the future of wireless networking so that it will be able to contribute to achieving a true ubiquitous computing world. This study focuses on one critical aspect of wireless technology – the personal area network.

A personal area network (PAN) is an ad hoc network, established and maintained solely by the self-organizing actions of the participating devices (Popovski, Yomo, & Aprili, 2004). A PAN allows interactions among the devices carried by an individual and provides the user with links to other nearby devices.

For the purpose of this study, a personal area network is considered to be a wireless network. Occasionally the terminology wireless personal area network or WPAN appears in the literature. In this study, PAN and WPAN are equivalent terms.

Purpose of the Study

The importance of this study lies in the assumption that in the not too distant future, ubiquitous computing will be part of everyday life. As described above, this ubiquitous computing future will depend on device-to-device communication, or personal area networks, to allow the environment to respond to individual needs. Defining the role of personal area networks in this ubiquitous computing world is the primary focus of this study.

In addition, adopting a new technology can be expensive and time-consuming for organizations and individuals. To avoid the possibility of implementing and/or maintaining PANs incorrectly, a prediction of the future criteria for PAN success and/or future barriers and challenges of PAN is important. Primary beneficiaries of this study will be researchers and professionals who are planning PAN implementations, to help them make correct decisions. Similarly, organizations that have or will have a PAN in the workplace will benefit by being able to understand and benefit from understanding the future trends associated with this wireless technology.

The primary research question of this study is what are the future prospects for personal area networks in a ubiquitous computing world? The sub-research questions are:

1. What are the key criteria or combination of criteria that will determine the future success of PAN technologies?
   The future success of PAN technology will depend on various factors. Such criteria could be transmission speed, cooperative exchange, power management, and others.

2. What application areas will be the most important for PAN implementations?
   The concern of this sub-research question is to identify potential PAN application areas and their influence on the implementation of PANs. Application areas might include body area networks, cable replacement, monitoring, and others.

3. What barriers and challenges will be associated with PAN implementations?
   Obstacles for implementing PAN should be clarified in order to design solutions that will enable PAN technologies to succeed. These barriers/challenges might be security, privacy, interference, and others.

This study will conduct a review of previous research studies on PAN in order to identify how the literature addresses the research questions. Then the Delphi Method will be used to obtain a consensus from a panel of PAN experts to systematically answer the research questions.

Background

In order to develop communication standards for a wireless personal area network, PAN was first introduced in March 1999 by a working group formed by the IEEE 802 Network Standards Committee. PAN standards (e.g. Bluetooth) were developed for portable and mobile devices, which were defined as network devices, unobtrusive computing devices, software, and peripherals that can be worn by individuals to enhance the ability to perform productive work as well as provide entertainment (Braley, Gifford, & Heile, 2000).

PANs are likely to become commonplace in the near future because a number of mobile smart devices such as PDAs and sophisticated mobile phones are already available and the trend is set to continue with more devices becoming wirelessly connectable and communicable (Sze-Toh & Yow, 2002).

There are several technologies which are utilized for PAN currently. These technologies include infrared, Bluetooth, ZigBee, and Ultra-wideband (UWB) (see Table 1). These are active device-to-device wireless technologies with power supplies at both sender and receiver.

Table 1: Comparisons of Personal Area Network Technologies

Technologies	Range (meters)	Speed	Power consumption	Maximum nodes
infrared	0.2 – 1	2.4 Kbit/s – 16 Mbit/s	Low	1
Bluetooth	~10	720 Kbit/s – 3 Mbits	Medium	8
ZigBee	~30	250 Kbits/s	Low	255
UWB	~20	110 Mbit/s – 480 Mbit/s	Medium	255

Currently, there is an abundance of mobile phones and PDAs with Bluetooth capability in the consumer market, but Bluetooth has some limitations. So now other PAN technologies are emerging, but this raises questions of conflicting standards. In the future, PANs should coexist and be interoperable for each wireless technology. For example, a recent study (Leong, Ong, Tan, & Gan, 2006) has proposed a NFC-Bluetooth bridge system which allows near field communication (NFC)-enabled customer services to be adopted in Bluetooth.

A PAN can be achieved by technologies such as Bluetooth or infrared. Bluetooth is a radio standard and communication protocol primarily designed for low power consumption with a short range based on low-cost transceiver microchips in each device. Infrared is a communication technology which enables devices to engage in useful interactions with each other without having to mediate their communications through some common control point (Williams, 2000).

PAN technologies vary according to their power consumption, speed capability, cost, and frequency. From a marketing point-of-view, devices with communication capabilities should not be more expensive, more complex to use, or provide significantly shorter operation time than these available now (Strommer, Kaartinen, Parkka, Ylisaukko-oja, & Korhonen, 2006).

Passive PAN Technologies

PAN technologies with a passive component are not included in this study. This includes tag-to-reader or card-to-reader technologies. The following discussion aims to explain two typical examples of passive PAN technologies, radio frequency identification and near field communication.

Radio Frequency Identification

Radio frequency identification (RFID) technology is a wireless automatic identification and data capture (AIDC) technology that allows radio signals to identify a product, animal or person (Song & Mitchell, 2008). RFID tags create a physical link for objects to be numbered, identified, cataloged, and tracked (Liu & Wang, 2005). These tags can be attached to products and scanned a few meters away via RFID readers for applications such as inventory control and supply chain management (Sheng, Tan, Li, & Mao, 2008). In general, RFID tags are embedded or attached into objects which need to be identified or tracked.

As RFID can be used in many areas, RFID tags vary significantly in their capabilities, from dumb tags which merely transmit a particular bit-string when scanned by a reader, to smart tags which have their own power supply, processing units, and memory (Kodialam & Nandagopal, 2006). Normally, there are two types of RFID tags including active tags which have a power supply and passive tags which do not. In passive tags, the power needed to transmit their IDs to the interrogating reader is supplied by the reader itself through radio frequency (Vaidya & Das, 2008). Passive tags are the most common because of very low costs.

As with many other technologies in the wireless field, security is also one of the biggest concerns for RFID technology. For example, an industry espionage may eavesdrop on wireless RFID communications to collect inventory information or tag spoofing or cloning may cause significant loss to supply chain partners (Y. Li & Ding, 2007). Furthermore, privacy is another important concern for RFID. Unprotected communications between tags and readers over a wireless channel can disclose information about the tags and their positions (Song & Mitchell, 2008).

Near Field Communication

Near field communication (NFC) was jointly developed by Philips and Sony in late 2002 to facilitate secure, very short-range communication between electronic devices (Ortiz, 2006). NFC is a very short range (maximum 20cm), wireless interconnection technology, evolved from a combination of earlier RFID contactless identification and interconnection technologies (Strommer et al., 2006). To engage the wireless NFC interface and configure them to link up in a peer-to-peer network, the wireless devices are required to be located closely together or touching (Leong et al., 2006).

NFC works at the 13.56 MHz spectrum and can be used for communication between two active devices or between an active and a passive device (Dominikus & Aigner, 2007). A NFC device with an internal power supply, such as a smart card reader, is considered to be an active device while the other device with no power supply, such as a smart card, is considered to be a passive device (Ortiz, 2006). The use of magnetic coupling, which transfers energy and data from one device to the other, is a principal difference between NFC and radio frequency-based technologies such as Bluetooth and Wi-Fi. Inductive coupling ensures a passive device will absorb energy from an active device when close enough, and communication and data exchange will occur once the passive device is powered up (Ortiz, 2006).

There are several advantages of NFC listed in a recent study (Krishnamurthy, Chakraborty, Jindal, & Mittal, 2006). First, NFC does not require line-of-sight. Second, the data transfer occurs securely because the data are captured in close proximity. Third, NFC does not pose difficulty in selecting the correct device from a multitude of devices in the range for data capture and actuation. Fourth, unlike other long-range communication technologies, NFC takes less time to capture data. Fifth, NFC not only allows communication between self-powered devices (active mode), but also between active and passive devices.

Other Wireless Network Technologies

The previous discussion focuses on the commonly known PAN technologies, both active and passive. Passive tag-to-reader and card-to-reader PAN technologies are not included in this study and a more detailed examination of the four active device-to-device technologies (Table 1) will be offered in chapter 2. However, to comprehend PAN fully, it is essential to outline what distinguishes PAN from other wireless technologies such as WLAN, WMAN, and WWAN, as shown in Figure 2.

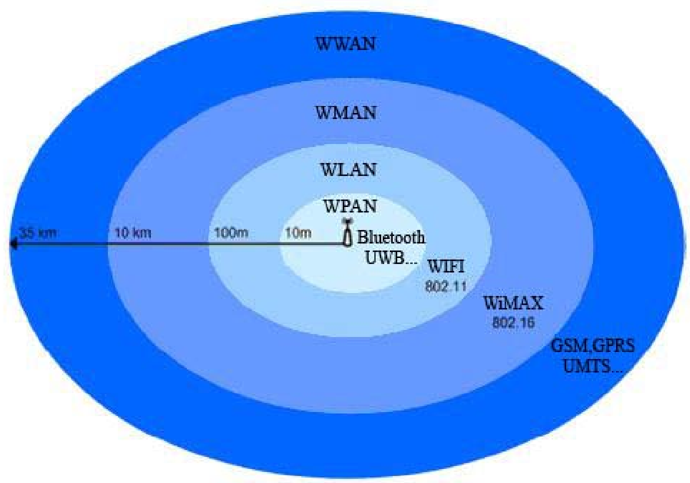

Figure 2: Wireless Networks Division (Šimek, Míča, Kacálek, & Burget, 2007)

Wireless Local Area Network

The goal of a wireless local area network (WLAN) is equivalent to a wired local network with high throughput, reliable data delivery, and continuous network connections (Morrow, 2004). WLAN is a generic term to refer to different technologies providing local area networking via a radio link (Boukerche, 2005). WLAN technologies emphasize higher peak speed and longer range at the expense of cost and power consumption (Prasad, 2006). WLAN standards can achieve up to 54Mbps transmission speed and 20m to 40m range for indoor areas and 100m to 200m in open space (Prasad, 2006). Typical examples of WLAN technologies include IEEE 802.11, HiperLAN, and digital enhanced cordless telecommunications (DECT) (Boukerche, 2005). The most common WLAN specifications are IEEE802.11a, IEEE802.11b, and IEEE802.11g, each providing varying access bandwidth and coverage level (Morrow, 2004).

Wireless Metropolitan Area Network

Wireless metropolitan area network (WMAN), i.e. IEEE802.16, is a standard for air interface for fixed broadband wireless access systems (Boukerche, 2005). WMAN supports integrated services such as constant bit rate voice, variable bit rate video, high speed FTP, and low speed World Wide Web data (H. Wang, Agrawal, & Zeng, 2007). WMAN provides a platform to support broadband multimedia services for a large number of end users with different quality of service (QoS) (Wang, Agrawal, & Zeng, 2007). Several characteristics of WMAN are high data rate support, the intrinsic QoS capabilities and the much wider area of coverage up to 10 km that enables ubiquitous connectivity (Ali-Yahiya, Sethom, & Pujolle, 2007). WiMAX, as a representative of WMAN technology, provides data rates of up to 75Mbps per cell, which has a size from 2 to 10km (Boukerche, 2005).

Wireless Wide Area Network

The defining characteristic of wireless wide area networks (WWAN) is the use of a shared channel with long and variable round-trip times, typically on the order of 500ms, coupled with a relatively low and variable bandwidth (usually in the tens of Kb/s) (Snoeren, 1999). Some other characteristics of WWAN are very high and variable delays, significant non-congestion rated losses, asymmetric uplink and downlink channels, and occasional blackouts (Sinha, Nandagopal, Venkitaraman, Sivakumar, & Bharghavan, 2002).

Many well-known WWAN standards exist including the global system for mobile communication (GSM), code division multiple access (CDMA), general packet radio service (GPRS), enhanced data rates for GSM evolution (EDGE), universal mobile telecommunication system (UMTS), and mobile broadband wireless access (MBWA). GSM and GPRS are currently available in the second generation (2G) networks worldwide and EDGE and UMTS are for 3G networks. MBWA or IEEE 802.20 is for the future 4G systems which promote digital mobile multimedia services with data rates of up to 20Mbps or more (Boukerche, 2005).

Outline of the Study

This chapter began by describing the current and future computing world which is the primary focus of this study. The second section of this chapter explained the purpose of this study as well as the primary research question and three sub-research questions. This chapter also provided some background for the study, including a definition of PAN, a brief comparison of key PAN technologies and overview of all wireless network technologies.

Chapter 2 reviews the relevant literature, beginning with a general introduction to PAN, and then focuses on three areas including criteria, application areas, and barriers/challenges that will determine the future success of PANs.

Chapter 3 explains the research methodology (Delphi Method) used to answer the research questions. The data collection procedures (i.e. rounds one through three, the panelists) will be outlined as well as how the data will be analyzed by the researcher. The methodology and analysis are justified in the context of the study.

Chapter 4 contains the results of the three rounds and feedback gained from the panelists. The results gained from the Delphi process of this study will be presented in an objective manner. In addition, the importance of all issues included in this study will be listed in rank order.

Chapter 5 is divided into three sections: success criteria, application areas, and barriers/challenges. The results from the Delphi surveys will be analyzed and discussed using relevant literature as well as panelists’ comments.

Chapter 6 concludes this thesis by offering an extended summary of the research as well as limitations of the study and suggestions for future research.

CHAPTER 2: LITERATURE REVIEW

Introduction

The purpose of this chapter is to provide a detailed review of personal area network technologies from the current literature. The first section focuses on the four major PAN technologies in this study: Bluetooth, Ultra-wideband (UWB), infrared, and ZigBee. The second section provides a discussion related to PAN issues in terms of the research questions stated in the previous chapter. These PAN issues include success criteria, application areas, and barriers/challenges. The chapter concludes with a statement of this study's contribution to the literature.

Personal Area Network Studies

Most studies define PAN according to its short-range characteristic. For example, PAN typically covers a few meters around a user's location and provides the capacity to communicate and synchronize a wireless device to other computing devices (Boukerche, 2005; Zhang & Chen, 2004). Key characteristics of PANs are low-power consumption, frequent make-and-break connections, varied data rates, varied network topologies, and low production costs (Boukerche, 2005; Morrow, 2004; Prasad, 2006).

Originally, PANs were mostly intended for simple cable replacement duties (Molisch, 2005; Prasad, 2006). For example, a PAN can provide wireless links between computers and peripheral devices (e.g., printer, mouse) and between a cellular phone and hands-free headset. The emerging and future view of PAN development is to allow seamless connectivity to meet user needs in a ubiquitous computing world.

"The user-centric PAN concept leads to certain technical choices that can serve the users' purpose" (Prasad, 2006, p. 260). This is evident in claims that usage models of PAN technologies were originally conceived into categories including Internet bridge, data access point, automatic synchronization, and file transfer (Morrow, 2004).

Based on its data transmission capability, PANs can be sorted into three system variants, namely low data rate (LDR), medium data rate (MDR), and high data rate (HDR) PAN systems (Prasad, 2006).

PAN Technologies

There are several personal area network technologies in the current computing world. PAN technologies with a passive component, either tag-to-reader (e.g., RFID) or card-to-reader (e.g., near field communication) are not considered here. Instead the following discussion will focus on four technologies which are frequently employed in active device-to-device PAN applications. These technologies include Bluetooth, infrared, ZigBee and UWB.

Bluetooth

Bluetooth, also known as IEEE 802.15.1, was originally envisioned by Ericsson in 1994 as cable-replacement technology to connect cell phones and laptop computers. Bluetooth is a standard for short range, low power, low cost wireless communication that uses radio technology (McDermott-Wells, 2004). The Bluetooth specification has been further developed by the Bluetooth Special Interest Group and Bluetooth is now being applied in new areas such as sensor networks, streaming applications, and multiplayer gaming (Boukerche, 2005).

The Bluetooth specification defines how Bluetooth devices will group themselves for the purposes of communication (McDermott-Wells, 2004). The Bluetooth specification includes two parts: the core and the profiles. The core specifies the architectural details of the Bluetooth system, its hardware components and protocols, and its interoperability with different legacy communication protocols (Prasad, 2006). The core portion consists of a radio frequency transceiver, baseband and protocol stack that includes both link layer, and application layer protocols (Boukerche, 2005). Figure 3 on the following page shows the Bluetooth protocol stack.

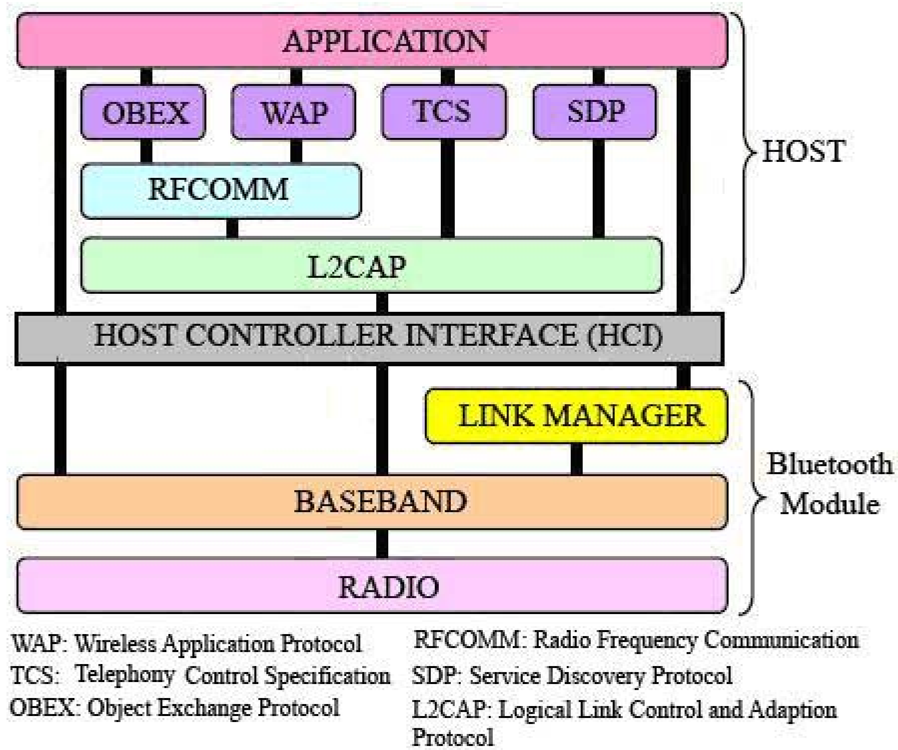

Figure 3: Bluetooth Protocol Stack (Conti & Moretti, 2005)

In a Bluetooth PAN, up to eight devices can be connected to form a piconet (Boukerche, 2005; Prasad, 2006; Zheng & Feng, 2002). One device is designated as the master, which is responsible for controlling the traffic on the data channel, while the other devices are the slaves. Any device could be a master or a slave in a piconet. It is not necessary for some devices such as headsets to be masters, which can only increase the cost and complexity (Zheng & Feng, 2002). Two or more piconets can be connected through a gateway or bridge to form a scatternet as shown in Figure 4. Bluetooth is regarded as a critical candidate for PANs because several piconets can form a scatternet and several scatternets can be linked together for ubiquitous network coverage. The common node of two piconets is called the bridge node (H. Li & Singhal, 2005). A bridge node can be either a master or a slave device.

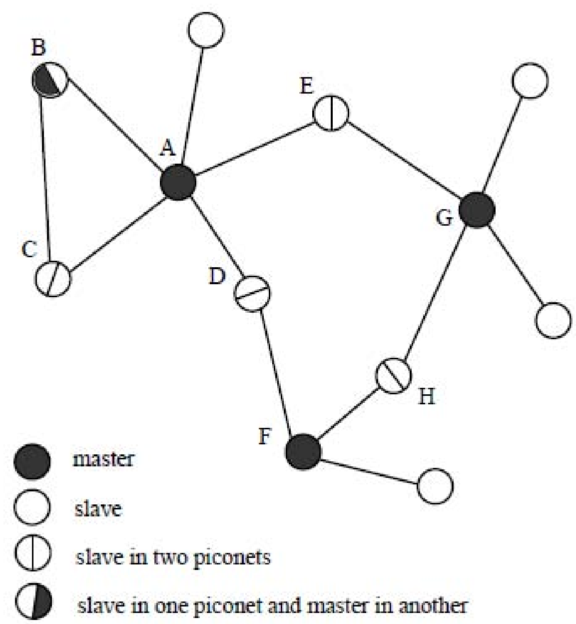

Figure 4: Bluetooth Scatternet (Rácz, Miklós, Kubinszky, & Valkó, 2001)

Bluetooth technology transmits data in the unlicensed 2.4 GHz ISM band, at a speed of up to 3 Mbps (Rashid & Yusoff, 2006). Bluetooth technology uses the frequency hop spread spectrum (FHSS) signaling technique which changes its signal 1,600 times per second to reduce collisions (Boukerche, 2005; H. Li & Singhal, 2005). The transmission range can be up to 100 meters depending on varied Bluetooth classes.

Infrared

The Infrared Data Association (IrDA) was formed in June 1993 and has worked steadily to establish specifications for a low-cost, interoperable, and easy-to-use wireless communications technology known as infrared (Williams, 2000). As one of the oldest wireless technologies, infrared is often used in point-to-point communications between devices such as PDAs, digital cameras, mobile phones, laptops, and printers (Wei, Sato, Fujii, & Nemoto, 1998). The 2001 infrared specification defines data rates of up to 115.2 Kbps, 576 Kbps, 1.152 Mbps, 4 Mbps, and 16 Mbps (Boukerche, 2005).

The infrared protocol stack consists of a set of protocol layers designed to facilitate short range indoor infrared communication links for applications (Boucouvalas & Huang, 2006).

The required standard infrared layers are physical layer, infrared link access protocol (IrLAP), infrared link management protocol (IrLMP), tiny transport protocol (TinyTP), and object exchange protocol (OBEX) (Boucouvalas & Huang, 2006). Figure 5 shows the infrared protocol architecture.

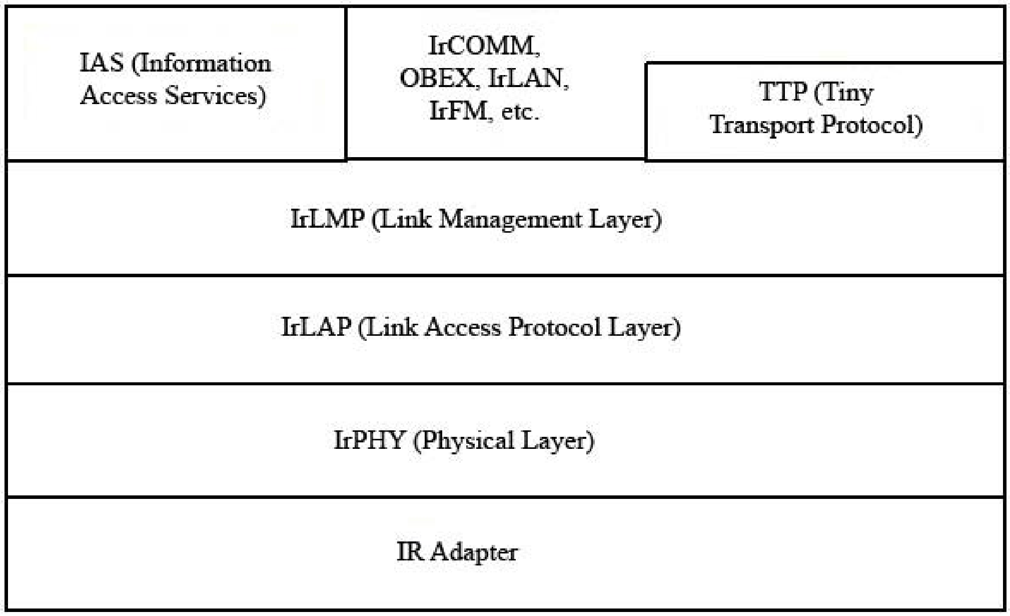

Figure 5: Infrared Protocol Stack (Jimenez & Nunez-Arzuaga, 2004)

Infrared device discovery uses a polling scheme to collect responses from all devices in line-of-sight within a one meter range (Woodings, Joos, Clifton, & Knutson, 2002). The device performing discovery is called the primary device and the devices that respond are called secondary devices. Infrared uses the non-visible infrared light spectrum and, therefore, cannot pass through obstacles that block light such as walls or other objects (Boukerche, 2005).

ZigBee

In December 2004, the ZigBee Alliance released its first specification based on the physical and medium access control layer of the IEEE 802.15.4 protocol. The Alliance released ZigBee for low cost and low power wireless networking of residential and industrial environments (Ran, Sun, & Zou, 2006). Several studies (Kohvakka, Kuorilehto, Hännikäinen, & Hämäläinen, 2006; Shuaib, Boulmalf, Sallabi, & Lakas, 2006) show that ZigBee is best suited for low rate sensors and devices used to control applications that do not require a high data rate but must have long battery life, low user interventions, and mobile topology. Such applications could be home security, lighting controls, wireless smoke detectors, and automatic meter reading.

ZigBee supports both star and peer-to-peer topology. The device types supported by the IEEE 802.15.4 (ZigBee) specification are full function device (FFD) and reduced function device (RFD) (Kim, Kim, Park, Yoo, & Lopez, 2007). A FFD is able to communicate with other FFDs and RFDs. A RFD must be an end device because it can only communicate with a FFD. Therefore, a RFD requires relatively small resources including memory size (Kim et al., 2007). In addition, a FFD can be the PAN coordinator, router and end device. Figure 6 shows FFDs and RFDs in a star and peer-to-peer topology.

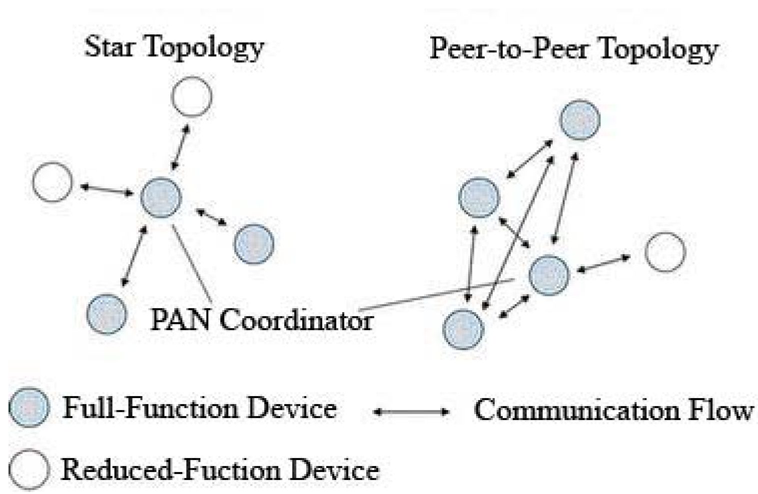

Figure 6: FFD and RFD in a Star and Peer-to-Peer Topology (Shuaib et al., 2006)

The ZigBee specification establishes the framework for the network and application layers (Kim et al., 2007). The PHY (physical) layer defines 16 channels at a maximum rate of 250 Kbps in the ISM 2.4-2.4835 GHz band, 10 channels at 40 Kbps in the ISM 902-928 MHz band, and one channel at 20 Kbps in the 868.0 -868.6 MHz band (Kim et al., 2007; Liang et al., 2006). Figure 7 shows the ZigBee protocol stack.

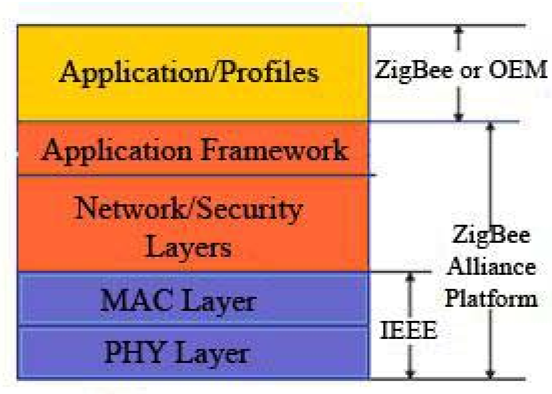

Figure 7: ZigBee Protocol Stack (Kim et al., 2007)

Ultra-wideband

Ultra-wideband (UWB) is a promising technology that supports high rate data communication for future wireless personal area networks (Lu, Wang, Wu, & Fang, 2006). The UWB technology transmits an extremely short duration pulse of radio frequency in the order of 10^{-12} to 10^{-9} sec (Boukerche, 2005). The characteristics of UWB are low cost, low complexity, low power consumption, and high data transmission rate.

The discrete transmission pulses of UWB allows numerous advantages including high rate data communication (up to 110 Mbps at 10m and 480Mbps at shorter distances) and extremely high accuracy for location-based systems (Kalghatgi, 2007). Boukerche (2005) pointed out that because the very short time period of UWB pulses, it exhibits some unique physical properties such as multipath cancellation which occurs when a strong wave arrives partially or totally out of phase with the direct path signal, causing a reduced amplitude response in the receiver. Another advantage of UWB is its relatively flat power spectral density (PSD) over a wide bandwidth for more efficient use of the RF spectrum (Morrow, 2004). Unlike other technologies which force users into a narrow bandwidth, UWB users are able to coexist over several GHz. Granelli and Zhang (2005) have listed the additional advantages of UWB:

- enhanced capability to penetrate through obstacles,

- high precision ranging (at the centimeter level), and
- support development of small-sized and processing-powered devices.

These advantages make UWB an ideal candidate for wireless home network applications such as security, see-through-the-wall, search-and-rescue, and supervision of children, (Saeed, Khatun, Mohd, & Khazani, 2006). In addition, another notable application that uses the UWB platform might be a wireless universal serial bus (WUSB) since the technology itself offers outstanding usability and convenience for users.

Issues That Will Determine the Future of Personal Area Networks

This second part of the literature review focuses on the relevant issues which will influence the future success of PAN technologies. This section is organized according to the research questions of this study, specifically PAN success criteria, PAN application areas, and PAN barriers/challenges to implementation.

PAN Success Criteria

The future of personal area networks might well be determined by several criteria. This section discusses criteria found in the literature that are likely to influence the future success of PANs.

Transmission Speed

The transmission speed of the wireless network technology could be the key success factor for wireless personal networks. The availability and immediacy of future network access will be magnified by high-speed wireless connectivity (Orman, 1999).

As discussed in the previous section, PAN technologies have different transmission speeds. A high speed PAN such as UWB is suitable for multimedia applications which require high speed combined with a high quality of service (QoS) (Shinde & Borse, 2005). In contrast, a low speed PAN, such as Bluetooth, is suitable for applications with relaxed needs for data speed and low QoS (Shinde & Borse, 2005).

Assigned speed versus maximum speed.

The success of emerging future applications (e.g., multimedia) will depend on high data transmission speed (Orman, 1999). However, not all current and future applications require maximum speed levels. Instead transmission rate should be assigned according to the nature of the applications. Assigned throughput should be application dependent and assigning the same throughput to all applications is not efficient (Touati, Altman, & Galtier, 2002).

Power Management

As wireless networking is being used in an increasing number of applications, efficient battery power utilization is rapidly becoming an important issue (Calinescu, Kapoor, & Sarwat, 2004). The main drawback of wireless technology is the limited battery life associated with wireless-enabled devices, especially when used in content (e.g. multimedia) delivery over the network (Cornea, Nicolau, & Dutt, 2006).

Consumption types.

The power consumption of PAN devices can be divided into three main components: processing, storage, and communication (Want & Pering, 2005). Discussion in the literature on how to improve power consumption mainly focuses on these three areas. Consumption for processing can be highly varied, depending on the processing requirements. For example, monitor-and-wait applications operate with a very low power supply while intensive applications such as a neural net require a much higher power supply (Want & Pering, 2005). Communication consumes power by sending or receiving signals during data transfer. Storage power consumption refers to local data storage such as physical disks or flash, which can consume considerable power in a ubiquitous system (Want & Pering, 2005).

Sleep/wakeup scheduling.

One method to effectively reduce power consumption is sleep/wakeup schedules. However, the sleep/wakeup approach has the shortcoming of high delay since during the sleep phases nodes cannot communicate (Anastasi, Conti, Francesco, & Passarella, 2006). This study also proposed a power management protocol in which schedules are automatically adapted based on the network congestion and on the application traffic demand, so that networks can operate efficiently and completely in dynamic conditions (Anastasi et al., 2006).

Speed gap.

From the human and user interface side, Zhong and Jha (2005) analyzed human factors and user interfaces that have a significant role in determining and improving energy efficiency. They found the bottleneck in system energy efficiency is an increasingly large speed gap between users and computers in their interactions. In other words, energy is consumed as power-hungry interfacing components are kept waiting for a slow user.

Wireless power transfer.

An interesting proposal for solving the power management issue is wireless power transfer (e.g., magnetic or inductive coupling). Magnetic or inductive coupling of radio frequencies (RF) for wireless power and data transfer is a widely acknowledged solution for low power devices (Fotopoulou & Flynn, 2007). The interest in utilization of RF or microwave power for providing power to devices has increased because of the need for low-power components for portable wireless applications (Heikkinen, Salonen, & Kivikoski, 2000).

Frequency

Because wireless communication is so dependent on wireless frequency, wireless frequency usage efficiency is one of the most important success criteria in evaluation of PAN technologies. Since all users of the unlicensed band can equally affect the quality and the usefulness of this spectrum, the major downside of the unlicensed band is that frequencies must be shared and potential interference tolerated (Golmie, 2006).

Currently, most PAN devices are limited to a single frequency. In the future, using multiple radio frequencies in a collaborative manner could dramatically improve system performance and functionality over the traditional single radio wireless systems that are popular today (Bahl, Adya, Padhye, & Walman, 2004).

Range

Because signal strength decays with distance, due to channel propagation properties, radio transmission covers only a certain radius for a given transmission power, channel and signal type (Golmie, 2006). To ensure covering large areas with wireless high speed access, dense deployment of network infrastructure is needed (Hiertz et al., 2006).

One study (Miluzzo, Lane, & Campbell, 2006) observed that static wireless networks coverage is limited by the physical placement of devices. Larger coverage can be obtained if the humans, vehicles, or other movable objects, are in motion to effectively extend the coverage.

In addition, larger wireless coverage might also be achieved via many wireless devices located together (e.g., scatternet via Bluetooth) which can extend range to considerable distances. For example, in a static sensor network, the overall range can be extended by positioning more sensors in wider areas.

Cooperative Exchange

Currently, there are many PAN technologies with varied capabilities in the consumer market. Since many PAN wireless technologies are operating in the unlicensed 2.4 GHz ISM frequency band, it is critical for them to coexist as well as cooperate with each other and access each other's resources (Agrawal & Zeng, 2005). According to the forms of outsourcing, cooperative exchange can be divided into external or internal cooperation. Different PAN technologies that exchange information with each other is referred as to external cooperation while internal cooperation refers to communication between the same PAN technologies.

Wireless cooperation refers to PAN devices that establish a connection to transmit data through one or two types of wireless PAN technologies. A study (Woodings et al., 2002) proposed a technique that integrates existing infrared technology with Bluetooth technology to improve the ad hoc connection establishment time of Bluetooth devices. The proposed technique uses an infrared connection to reduce Bluetooth device discovery time and improve the exchange of information between Bluetooth devices (Woodings et al., 2002).

BlueStar.

In order to obtain data, sometimes PANs might require outsourcing through other forms of wireless technologies. Agrawal and Zeng (2005) explained a cooperative example called BlueStar. In the BlueStar architecture, selected Bluetooth devices are also members of a WLAN, empowering short-range devices to access the global Internet infrastructure through the use of WLAN-based high-powered transmitters (Agrawal & Zeng, 2005).

Widespread deployment

With the steady rise in wireless technologies and wireless applications, widespread deployment should be considered as another significant criterion in determining the success of PAN technologies. As the cost of production of single nodes reduces to less than one dollar this paves the way for large scale deployments (Tynan, Marsh, O'Kane, & O'Hare, 2005).

To ensure widespread deployment of a particular wireless technology, several technological challenges have to be overcome, including authentication, security, radio frequency range, network performance, network management, and support for context-aware services (Balachandran, Voelker, & Bahl, 2005). From the commercial aspect, emerging wireless technologies' deployments are still at their infancy because routing protocols are rather complex for practical applications found in enterprise, office or home domains (Koulamas, Orphanos, Lucas, & Colin, 2004).

Application Areas

This section discusses six application areas related to the future success of PANs. These application areas include body area network, cooperative exchange, cable replacement, data access, monitoring, and remote control.

Body Area Network

Body area networks (BAN) applications are environments in which mobile networked computing devices travel with a person and can be integrated with the human user (Gupta, Lee, Purakayastha, & Srimani, 2001). The trend is that BAN devices will likely be able to use multiple physical links, for example, a mix of wired, RF, and infrared links in the near future (Prasad & Ruggieri, 2003).

Healthcare usage scenario.

BANs appear to be a particularly appealing solution to provide information about the health status of patients with chronic diseases such as diabetes or asthma (Domenicali & Di Benedetto, 2007). A BAN can provide continuous health monitoring and real-time feedback to the user and medical personnel (Braem, Latre, Moerman, Blondia, & Demeester, 2006). The physiological parameters of the patient can be transmitted to medical services via a public network to be further analyzed (Goulianos & Stavrou, 2007). Furthermore, the measurements can be recorded over a long period of time which improves the usefulness of the measured data (Braem et al., 2006).

In order to establish a wireless network for a patient, a number of wireless sensors should be located on the human body or in close proximity, such as on everyday clothing (Domenicali & Di Benedetto, 2007). Since mobilized health-care applications are on-body communication networks, the human body can be used as a communication channel between wireless wearable devices (Domenicali & Di Benedetto, 2007).

Several issues that influence or inhibit BAN system design are (Jovanov, 2005):

- sensor resource constraints,
- intermittent availability of uplink connectivity,
- reliability of transmission,
- security,
- interoperability of different platforms, and
- user’s compliance of sensor weight and size.

Currently, the idea candidate for BANs is UWB because of its characteristics of low-power operation and extremely low radiated power (Klemm & Troester, 2006).

Cable Replacement

Despite rapid advances in wireless technology capabilities over the past few decades, the original purpose of PAN technology, short-range cable replacement, remains an important application area. In the past, information transfer between devices such as PCs, laptops, printers, and PDAs has been cumbersome, mainly relying on cables (Haartsen, 2000). Today, data communication no longer needs to depend on cables; short-range wireless technologies can replace cables.

Currently, the principal wireless technology used for cable replacement is Bluetooth because of its advantages such as low cost, low power requirement, small size, and widespread deployment in devices. However, new applications have posed new challenges for cable replacement. For example, digital audio/video (AV) cables require multi-Gbps rates at a bit error rate (BER) of 10^{-9} from the source to the display (MacMullan & Patel, 2007). In order to cater to these high data rate requirements, wireless technologies such as UWB offer a simple and inexpensive installation with secured connectivity and high transmission rate (MacMullan & Patel, 2007).

In the cable replacement scenario, nodes can discover each other using the inquiry procedure, which has been designed to satisfy the requirements of cable replacement applications so that all nodes in close proximity will be discovered in a fixed amount of time (Ronai & Kail, 2003). However, the inquiry procedure is not well suited for nodes in a Bluetooth ad hoc network because of three weaknesses (Ronai & Kail, 2003):

- Inquiry takes a long time and therefore requires too much overhead.
- It is inefficient to transmit data simultaneously.
- The assumption of asymmetric roles is not suitable to ad hoc networks of peer nodes.

Although the concept of cable replacement might create a vision of ubiquitous point-to-point communication, the fact is that wireless devices can communicate with several other devices that are within range (Shepherd, 2001). For example, in a Bluetooth scatternet, a device can be either a master or a slave but not both, and, at most, a Bluetooth device is able to communicate with seven other devices.

Data Access.

At the beginning of this century, the barriers to wireless data communication included low speed, high-power consumption, and high cost per transmitted bit (Yates & Mandayam, 2000). Today, using wireless technologies to transmit data is no longer an issue. However, because there are so many variables, such as dependability, capabilities, pricing, popularity, and so on (Sreenan & Agrawal, 1999), the priority for now is for efficient and effective wireless data services.

In general, the common wireless network components that enable wireless data access include (Engerman & Kearney, 1998):

- mobile data terminals,
- radio frequency modems,
- radio base stations,
- radio network infrastructure (e.g., routers, switches),
- collectors/concentrators combining multiple base stations into a service area, and
- server applications and corporate databases.

In addition, unlike other wireless networks such as a WLAN, PANs do not require interaction with a wired infrastructure. Instead a PAN looks inwardly at interaction with device-to-device data communication (Prasad, 2004).

Monitoring

Monitoring systems and environments using PAN technologies require information communication between mobilized objects within a short-range. The most critical design challenge for PAN-based monitoring systems is the limited power supply. For example, improving energy efficiency extends the overall system lifetime in wireless sensor networks (Q. Wang, Xu, Takahara, & Hassanein, 2006). Furthermore, when high-density sensors send highly redundant report messages simultaneously, scheduling a subset of nodes for monitoring service could improve power efficiency (Boukerche, 2005).

In addition to the use of PAN technologies in healthcare monitoring scenarios (i.e., body area networks), there are many other application areas in which these technologies can be used for monitoring. Monitoring systems can be categorized into areas of functionality (Chou & Park, 2005):

- Event detection vs. data acquisition vs. data aggregation: such as in light detectors, seismographs and a vehicle's line-of-bearing computation.
- Passive vs. active sensing: passive sensors observe the readily available signals while active sensors emit signals directed at the subject and measure reflections.
- Data logging vs. real-time monitoring: data logging refers to devices which do not require transmission immediately, such as habitat monitoring, compared to real-time monitoring systems which require real time reporting (e.g., health monitoring).

Convenience

Convenience is a strong driving force in consumer markets (Leen & Heffernan, 2001). Today, remote control applications on devices such as mobile phones and PDAs must obey communication standards to understand each other and to allow uniform access to peer devices (Feldbusch, Paar, Odendahl, & Ivanov, 2003). This leads to the concept of a conventional remote control. A typical example of PAN technologies being used for remote control is a television set. Because of emerging PAN technologies such as Bluetooth, remote control devices no longer require a line-of-sight.

Smart Things

In the ubiquitous computing world of the future, ubiquitous computation service will be the main driving force, and the corresponding essential element would be smart things with embedded computers (Ma et al., 2005). Smart things are commonly understood as wireless, ad hoc networked, mobile, autonomous, special purpose computing appliances (Ferscha & Keller, 2003). Such smart things could be in a smart environment, smart car, a smart home or any other set of objects as long as they are capable of communicating and responding with some intelligence.

The vital advantage of smart applications is the invisibility of computational technology. Smart applications are capable of populating the real world with hidden and invisible services, thus building up an invisible world of services associated with real world objects (Ferscha & Keller, 2003). The main challenge of ubiquitous computing is to deploy such unobtrusive smart environments that provide reasonable advantages for those who use it, without violating the social and legal rules of our society and life (Römer & Domnitcheva, 2002).

The computing world will evolve towards a smart world mainly characterized by ubiquitous intelligence and filled with smart things which encompass three categories: smart object, smart space, and smart system (Ma et al., 2005). The future of smart applications is to coordinate smart objects and integrate these isolated smart spaces together into a higher level of environments known as smart hyperspace or hyper-environments (Ma et al., 2005).

Barriers and Challenges to Implementation

The following section focuses on barriers/challenges associated with PAN implementation. These problems can be categorized into five broad aspects: security, interference and coexistence, privacy, trade-off of QoS and power efficiency and operating environment.

Security

Five wireless network security facets are authentication, authorization, integrity, confidentiality and availability (Zhang & Chen, 2004):

- authentication: ability for two parties to validate each other’s identity;

- authorization: ability for a party to determine whether a user should be allowed to access a network;
- integrity: ability to protect information from unauthorized changes;
- confidentiality: ability to ensure only authorized users can access private information; and
- availability: ability to avoid malicious users from blocking legitimate access to a network or an network service.

Other, less critical, security concerns not explained here include:

- Freshness ensures the message is recent and valid in the context of the applications (Lee, Zheng, & Anshel, 2006).
- Fairness ensures network resources are used in a fair and efficient way (Lee et al., 2006).
- Non-repudiation refers to ability to supply undeniable evidence to prove the message transmission and network access was performed by a user (Zhang & Chen, 2004).

Authentication.

Because connectivity in a PAN is intermittent and ubiquitous, the traditional approaches for networks to authenticate users are unworkable. Specifically, wired networks rely on online connectivity to an authentication or revocation server (Stajano & Anderson, 2002). Therefore, a major concern for PAN authentication is how to secure transient association via an ubiquitous security approach.

Authorization.

Discriminating between authorized and unauthorized usage usually involves a three-step process: identification, authentication, and authorization (Stajano & Anderson, 2002). Unauthorized usage might cause the network to be vulnerable to hackers, viruses, and intruders (Agrawal & Zeng, 2005). Software such as firewall products or anti-virus products can provide protection against these threats. On the other hand, revocation of certificates becomes necessary if malicious users have corrupted devices to gain access to PANs (Hiertz et al., 2006).

Integrity.

PAN system integrity can be compromised from both internal and external sources. First, because of malicious attacks or due to benign failures such as transmission collisions and radio propagation impairment, a message may be corrupted in transit (Lee et al., 2006). Second, malicious attacks originated from outside of PAN systems are considered as external sources (e.g., tampering or deliberating). To provide high-grade tamper resistance is expensive and difficult (Anderson & Kuhn, 1996), in part because tamper detection relies on tamper evidence which assumes tampering attacks leave a visible trace (Stajano & Anderson, 2002).

Confidentiality.

A barrier to achieving confidentiality on PANs is the computational power of PAN devices which is much less than in wired network devices. Intensive tasks, such as public-key cryptography, cannot be performed easily (Stajano & Anderson, 2002). However, new emerging technologies seemed to overcome this problem. For example, ZigBee supports access control lists, packet freshness timers, and 128-bit advanced encryption standard (AES) (Kohvakka et al., 2006).

More importantly, protecting the information which is stored in PAN devices is as important as protecting the information in the wireless traffic (Stajano & Anderson, 2002). However, wireless devices are usually not protected by encrypted storage and not password protected at all.

Availability.

The classic attack on a wireless system's availability is to jam the communication channel (Stajano & Anderson, 2002). Interestingly, Stajano and Anderson suggest that the methods for dealing with system jamming lie outside systems design. Instead the solution is to move the jammer out of range. Consequently, the traffic jammed system will no longer provide services or information to authentic users causing denial of service (DoS). DoS involves preventing a service from being provided to users which causes significant disruptions to the services (Zhang & Chen, 2004).

Interference and Coexistence

Most PAN technologies operate in the same 2.4 GHz ISM frequency band as WLANs. The major downside to the use of this unlicensed band is that frequencies must be shared and potential interference tolerated (Golmie, 2006). For instance, Bluetooth devices experience a perceptible drop in throughput due to interference when multiple piconets operate in the vicinity, as well as in the presence of a network using the IEEE 802.11 (Wi-Fi) protocol (Agrawal & Zeng, 2005). Hence, there needs to be coexistence mechanisms.

The coexistence of wireless communication systems operating in the same environment has become a popular topic in recent years as more systems are choosing to use the unlicensed bands and forfeiting the need to purchase spectrum (Golmie, 2006). The IEEE 802.19 technical advisory group is responsible for developing and maintaining policies defining the responsibilities of IEEE 802 standards regarding coexistence (Prasad & Ruggieri, 2003).

Signal strength is an important factor that influences the interference between PAN and WLAN devices depending on distances between nodes in a specific scenario (Prasad, 2006). Moreover, the long packet size of 802.11b (1,500 bytes) makes it more likely for a single Bluetooth packet (362 bytes) to collide with it (Prasad, 2006). However, when both technologies are operating at the same time but separated by more than 3 meters, they do not interfere with each other to any great degree (Golmie, 2006).

One seemingly simple solution to the interference problem is to simply increase the transmit power so that the receiver at the other end has a better chance of extracting the desired information (Morrow, 2004; Prasad & Ruggieri, 2003). However, power control is not an acceptable approach because of increased interference to other devices, decreased battery life, and higher component cost (Morrow, 2004).

Some interference-reduction techniques to improve the performance of co-located PAN and WLAN technologies are (Prasad & Ruggieri, 2003):

- adaptive frequency hopping,
- dual-mode radio switching,
- driver level switching and MAC level switching,
- transmit power control, and
- adaptive fragmentation.

The source interference can appear in different ways, with characteristics that can be modeled in both time and frequency (Morrow, 2004). The time domain refers to interference that can be continuous or intermittent while frequency domain can be narrowband or broadband.

Different networks can either work as individual entities or with each other when addressing coexistence, formally known as noncollaborative approach and collaborative approach, respectively (Morrow, 2004). The noncollaborative approach assumes that the interfering systems have no means of communicating among them to negotiate access to the medium while the collaborative approach to improving coexistence is through collaborative methods, which generally apply to co-located nodes (Morrow, 2004).

There are several general techniques can be used to improve coexistence between wireless networks (Morrow, 2004):

- clear channel assessment technique,
- modulation method,
- link-quality indication,

- reduced duty cycle,
- lower transmit power,
- channel alignment,
- reserved times for neighbor network operation,
- antenna isolation,
- packet structure, and
- retransmission algorithm.

Privacy

Privacy is currently of pressing interest, especially in the context of wireless networks, which are simultaneously the best medium to provide privacy as well as the most threatening medium to user privacy. As the medium to provide privacy, PANs technologies do not require physical infrastructure or connection end-point. They are also a threat because PAN technologies have the potential of disclosing not only the identity of the user, but also their physical location (Karygiannis, Kiayias, & Tsiounis, 2005). A key issue in the future of PANs will be new interpretations of privacy in a constantly monitored world (Orman, 1999).

Hidden privacy or anonymity could cause wireless networks to become potential places to commit a crime. One suggestion is that wireless networks should encompass a controlled privacy solution which provides privacy to individuals, but maintain the ability to revoke that privacy when required (Karygiannis et al., 2005).

Location privacy.

Location privacy is a major focus area in privacy. By eavesdropping on transmitted packets, an attacker can track the place and time of the communication between the mobile devices (Singelée & Preneel, 2006). Interestingly, it does not even require the attacker to be physically close to the communicating devices, instead the eavesdropper uses a device with a stronger antenna (or a tracking device) (Singelée & Preneel, 2006). The solution to this problem is to apply low-cost cryptographic primitives to generate a temporary random identifier that can be used to communicate privately (Singelée & Preneel, 2006).

Social norms.

From a social aspect, ubiquitous sensor technology might allow ill-intentioned individuals to deploy secret surveillance networks for spying on unaware victims (Perrig, Stankovic, & Wagner, 2004). Moreover, technology alone is unlikely to solve the privacy problem; rather, a mix of societal norms, new laws, and technological responses are necessary (Perrig et al., 2004).

Tradeoff Between Quality of Service and Power Efficiency

The quality of service (QoS) of the PANs is a critical issue, especially for wireless multimedia applications which require a high data transmission rate as well. On the other hand, power consumption has emerged as one of the most critical challenges to designing complex systems (Benini, 2003). However, because of quickly increasing requirements in QoS and slowly improving battery capacity (Park, Raghunathan, & Srivastava, 2003), the tradeoff between QoS and power efficiency is critical in system design.

To ensure a guaranteed QoS for a particular PAN, a sufficient power supply is essential. A lack of speed and coverage might reduce QoS. Most PAN devices are battery-powered, therefore more efficient power consumption connotes increasing the system’s lifetime which maintaining sufficient QoS.

From the power consumption aspect, varied PAN devices consume power differently. Therefore, energy should be allocated accordingly to ensure better QoS. For example, transmit mode consumes the highest power while doze mode consumes very little energy (Qiao, Choi, & Shin, 2007). From the system design point-of-view, designers should always consider the power requirements in terms of the system’s intention to maintain the QoS.

Operating Environment

Another major concern associated with wireless networks is the operational environment. The operational environment is quite heterogeneous so that during the course of its movements a mobile node may encounter base stations that provide different services, protocols, and interfaces (Boulis, Lettieri, & Srivastava, 1998). More importantly, wireless networks should be designed to accommodate energy efficiency, dynamic self-organization, and mobility in a dynamic operational environment (Chung & Kim, 2006).

From the nature environmental aspect, one recent study (Johnson & Margalho, 2007) claimed that data transmission over a wireless link in an Amazonian climate will adversely affect the network performance causing data loss. The network capacity should be also considered for PAN implementation in nature environments. Chen and Chen (2006) stated that within the same network capacity, the more the population, the less the shared bandwidth, and the worse the QoS will be.

Contribution to the Literature

Most studies about personal area networks focus on technologies (e.g., Agrawal & Zeng, 2005; Gupta et al., 2001; Haartsen, 2000; McDermott-Wells, 2004; Rashid & Yusoff, 2006). Many other studies focus on application implementation (e.g., Anastasi et al., 2006; Dominikus & Aigner, 2007; Leen & Heffernan, 2001; MacMullan & Patel, 2007). Only a few studies (e.g., Granelli & Zhang, 2005; Prasad & Ruggieri, 2003) discuss the future prospects for PAN. Granelli and Zhang (2005) introduce the concept of cognitive UWB radio and its future challenges. Prasad and Ruggieri (2003) focused their work focus on the future technology trends in various wireless communications.

Several studies in the literature have explored the future of various telecommunication technologies (e.g., Prasad & Ruggieri, 2003; Press, 1997; Siekkinen et al., 2007; Williams, 2000). A number of Delphi studies have been used to predict technological futures. Some studies do not have a telecommunications focus – for example the future of mobile commerce (Xu & Gutierrez, 2006), technological futures in Korea (Son, Park, Oh, & Yu, 2006), and the future of mobile technology (Lehmann, Kuhn, & Lehner, 2004). A few other studies have explored the future of telecommunication technologies, including the future of the wireless application protocol (Viehland & Hughes, 2002) and the future of radio frequency identification (Viehland & Wong, 2007). However, no other research has applied the Delphi Method to study the future of personal area networks in a ubiquitous computing world, as is done in this study.

Summary

In this chapter, related literature of PANs has been studied in terms of five main PAN technologies including Bluetooth, infrared, UWB, and ZigBee. Furthermore, discussions were carried out according to issues laid to three sections: success criteria, application areas, and barriers/challenges. These issues will be used as the content of the questionnaire in the research design chapter.

CHAPTER 3: RESEARCH DESIGN

This chapter discusses the research method and data collection procedures of this study. The Delphi Method is selected as the research method because it is considered to be the best candidate to answer the research questions posed in chapter 1. Furthermore, the implementation of the Delphi methodology for this study will be discussed in detail.

Introduction to the Delphi Method

The Delphi Method originated in a series of studies that the Rand Corporation conducted for Project Delphi in the early 1950's for the defense community (Linstone & Turoff, 1975). At that time, the Delphi method was defined as a method for structuring a group communication process allowing individuals as a whole to deal with complex problems (Linstone & Turoff, 1975). A more recent and comprehensive definition of the Delphi Method is "systematic solicitation and collation of judgments on a particular topic through a set of carefully designed sequential questionnaires interspersed with summarized information and feedback of opinions derived from earlier responses" (Adams, 2001, p. 27).

Researchers employ the Delphi Method primarily in cases where judgmental information is indispensable, and typically use a series of questionnaires interspersed with controlled opinion feedback (Rowe, Wright, & Bolger, 1991). The questionnaires of a Delphi Method study are designed to elicit and develop individual responses to the problems posed and to enable the experts to refine their views as the group's work progresses in accordance with the assigned task (Adler & Ziglio, 1996).

The Delphi Method uses anonymous interaction among members of a panel. Results are then returned to the panel so that adjustments can be made. It is organized to encourage members to modify earlier positions and judgments as they exchange information and learn from each other (Sahakian, 1997).

In addition to a significant usage in the forecasting procedure area, the Delphi Method has been employed in other application areas such as (Linstone & Turoff, 1975):

- Gathering current and historical data unknown or unavailable,
- Examining the significance of historical events,

- Evaluating budget allocations,
- Exploring urban and regional planning options,
- Creating the structure of a model,
- Delineating the pros and cons associated with potential policy options,
- Developing relationships in complex economic or social phenomena,
- Distinguishing and clarifying real and perceived human motivations, and
- Exposing priorities of personal values, social goals.

In general, the first questionnaire poses the issues in broad terms and invites answers and comments. Then the responses of the first questionnaire are used to generate the second questionnaire. The second questionnaire includes the results of the first questionnaire and provides respondents an opportunity to re-evaluate their original answer in the light of comprehensive feedback on the responses of the whole group (Adler & Ziglio, 1996). This interactive process can be repeated as long as needed depending on the circumstances.

The selection of the panelists for the Delphi Method must follow a procedure governed by explicit criteria which depend on the aims and context with the Delphi process carried out. Most importantly, the expert panelists should be knowledgeable about the issues under investigation. “Another criterion is the capacity and willingness of the selected experts to contribute to the exploration of a particular problem” (Adler & Ziglio, 1996, p. 14). Other criteria such as dedication of sufficient time, skill in written communication, and ability to express priorities can also be significant (Adler & Ziglio, 1996).

On the subject of expert group size, with a homogeneous group of experts, good results can be obtained even with small panels of 10-15 individuals (Adler & Ziglio, 1996), but most studies use a panel of 15-35 individuals (Gordon, 1994). Depending on the situation, when various reference groups are involved, the size of the panel might be considerably larger (Goldschmidt, 1975). Additionally, there is an improvement in the quality of the group outcome with increasing group size (Delbecq, 1968).

The group judgments, which are achieved through the methodological procedures associated with the Delphi Method, are generally more reliable than individual judgment (Brown & Helmer, 1964). The reliability of Delphi Method depends on whether the results gained are better than, for example, traditional face-to-face interactive group. The Delphi Method has distinct advantages over traditional interactive group processes because it involves a systematic process of querying and aggregating experts' judgments (Adler & Ziglio, 1996). Furthermore, the Delphi Method minimizes the problems related to reliability because of the natural characteristic of iteration.

Delphi Method for this Study

This section describes why the Delphi Method was chosen as the research method in this study. The Delphi Method is the most suitable method because it is designed for use in forecasting situations in which statistical methods are impractical or impossible because of a lack of appropriate historical information, and where some form of human judgmental input is needed (Rowe et al., 1991). Meanwhile, PANs embrace many wireless technologies which are rapidly and continuously updated. Therefore, experts' opinions on this subject are vital to gain a consensus opinion of the future.

Linstone and Turoff (1975) listed four properties to determine whether or not the Delphi Method is the desirable choice. The properties and their suitability for this study are listed as the follows:

- The problem does not have appropriate analytical techniques but would benefit from subjective judgments on a collective basis. This study is about the future prospects of fast developing technologies. Predicting the future development of these technologies relies on subjective expert opinion.
- The experts may not have any history of adequate communication and may represent diverse backgrounds with various levels of experience or expertise. Lack of adequate communication between panelists ensures these experts will hold their own opinions. Various levels of experiences or expertise guarantee the diversity of the responses to reach a consensus. Together these two improve the validity of this study.
- Time and cost make frequent group meetings infeasible. As most PAN experts are located geographically remote from each other, frequent group meetings are

impossible. Communications through e-mail message facilitates the Delphi process to save time and cost of group meetings, which would be impractical in this study.

- The different views of the participants must be preserved to ensure a set of valid results. Different opinions from panelists will be shared to ensure the diversity of the results for this study and so to achieve valid results.

Because an important characteristic of the Delphi Method is iteration, the results gained from this study are likely to be reliable. Also, since the Internet applications facilitate the communication process dramatically, the Delphi Method would be the best choice for experts with diverse backgrounds and expertise to communicate.

As mentioned before, group judgment is more reliable than individual judgment, the results gained from the Delphi Method will be much more reliable than results from other methods for forecasting technology future. Moreover, as PAN is a relatively new set of technologies, there are no widely recognized universal standards to predict the future trends. Thus, a consensus of opinion of a group of experts is appropriate.

Delphi Method Implementation in this Study

This study uses the Delphi Method as the research methodology. The Delphi Method process is described as a structured process for collecting and distilling knowledge from a group of experts by means of a series of questionnaires interspersed with controlled opinion feedback (Adler & Ziglio, 1996). This process, as applied to this study, is described in this section.

The first step in the Delphi Method process is to convene a panel of experts. The goal was to select a panel composed of heterogeneous experts who have the knowledge of the topic being investigated (Rowe et al., 1991). In the first step of the panel selection process, 151 individuals with some expertise in PAN technologies were identified from research and industry publications, PAN-related Web sites (e.g., Bluetooth Special Interest Group, ZigBee Alliance), and LinkedIn, a professional networking Web site. Unfortunately, only seven individuals responded with a commitment to participate in the panel.

In the second step of the panel selection process, an invitation was sent to over 100 members of the contacts database of the Centre for Mobile Computing at Massey

University. Twenty individuals responded positively to this request. Not all of these could be considered to be PAN experts, but all were interested in mobile computing technologies and a supplemental reading was prepared to provide background on PAN technologies for their use. Accordingly, at the commencement of round one, 27 individuals were on the panel.

Nineteen of the 27 panelists responded to round one and 18 panelists participated in rounds two and three. Brief biographical information about these individuals is included in Appendix A, but in summary:

- Seven panelists were employed by ICT vendors, four panelists were academics, and three panelists were government employees.
- Fifteen panelists were from New Zealand and one each were from Brazil, Denmark, and the United States

Although it was desirable to have a panel with greater international representation, individuals from the PAN industry in other parts of the world were reluctant to participate for various reasons.

The Delphi Method process in this study consisted of three rounds as briefly described in Table 2 and detailed in the following paragraphs.

Table 2: The Delphi Method Process

Round Number	Purpose	Circulation Date	Due Date	Total Sent	Total Replies
1	Identify new issues and delete inappropriate issues	11 March	25 March	27	19
2	Rate and comment on accepted issues	6 April	20 April	19	18
3	Re-rate on accepted issues to achieve a consensus	1 May	15 May	18	18

The principal purpose of round one is to determine if the identified PAN issues from the literature are appropriate to answer the research questions. To commence round one, the following materials were sent to the initial 27 members of the Delphi panel on 11 March 2008:

- Research Study Information Sheet: a concise description of the research study, including provisions regarding ethical approval of the research;
- Delphi Method Information Sheet: an explanation of the research methodology used in this study;
- Background Reading: a description of each of the issues listed in the round one questionnaire, as derived from the literature review;
- Round One Questionnaire (see Appendix B): issues from three PAN aspects – success criteria, application areas, and barriers/challenges – as listed in the background reading with space for responses (i.e., retain? delete? comments? missing issues?) from the panelists; and
- Supplemental Reading: additional background reading for panelists who may not be familiar with all of the PAN technologies discussed in this study, mostly derived from the literature review.

Nineteen of the 27 panelists returned the questionnaire by the due date with a small extension.

The Delphi coordinators consolidated the results from all panelists (described in the following chapter) and prepared new materials for the next round. In round two, the 19 panelists who responded in round one were sent a Round One Report that provided anonymous but detailed responses from all panelists on all issues plus an analysis and description of all new issues nominated by the panelists (see next chapter). Panelists were also sent a Round Two Questionnaire (see Appendix C) that asked them to rate each issue on a five-point Likert scale as follows:

Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Panelists were also asked to retain or delete the nominated issues from other panelists for further inclusion in round three. Eighteen of the 19 panelists responded by the due date, with a short extension of time.

The purpose of round three was to attempt to achieve a consensus opinion from the panelists. Responses and comments from round two were provided in a Round Two Report. A Round Three Questionnaire (see Appendix D) was sent to all panelists. The questionnaire specifically asked the panelists to review their individual rating for each issue, especially in light of the ratings and comments from other panelists. Each panelist was then asked to re-rate each issue on the same five-point Likert scale, keeping the rating the same or modifying it. All eighteen panelists returned the round three questionnaire by the due date.

This chapter has described both the research methodology used in this study as well as its implementation. The results are quantitative and qualitative data from 18 panelists as to what they view are the most important success criteria, application areas, and barriers/challenges that will determine the future of personal area networks. These results are fully described in the next chapter.

CHAPTER 4: RESULTS

Introduction

This chapter presents the results from all three rounds of the Delphi study in an objective manner. All questionnaires and summarized results are included in the appendices.

Round One Results

The round one questionnaire (see Appendix B) was circulated during March 2008 to 27 panelists. Nineteen responses were received and are included in this report. Appendix E contains a summarized record of the panel's responses to the first round, including three tables that show how each panelist voted (retain, delete, no clear decision). The following sections summarize the results from the round one questionnaire.

Success Criteria Results

The focus of this section is the key criteria that will influence the future success of personal area networks. Table 3 summarizes the panelists' decisions for each success criteria identified from the literature. Most experts indicated clear decisions of retain or delete. In a few instances, the responses were unclear or no response was made. These instances are indicated by no decision.

As shown in the top section of Table 3, seven criteria were accepted by the panel to go forward into the second round. In these cases, at least 11 of the 19 panelists voted to accept these criteria as critical to the future success of personal area networks. Four criteria did not get sufficient support to be included (bottom section of Table 3).

Table 3: Success Criteria Results in Round One

Success Criteria	Retain	Delete	No Decision
Frequency switching	19	-0-	-0-
Power management	18	-0-	1
Widespread deployment	17	-0-	2
Transmission speed	16	2	1
Cooperative exchange	14	3	2
Range	13	5	1
Consumption type	11	5	3
BlueStar	10	6	3

Wireless power transfer	10	7	2
Sleep/wakeup scheduling	8	9	2
Speed gap	6	13	-0-

As part of the round one questionnaire, panelists were asked to suggest success criteria that were not found in the literature review. Generous comments from the panelists suggested 18 additional success criteria. After careful consideration and some research, four criteria – usability, functionality, reliability of connection, and cost – were accepted for inclusion in round two. Another criterion, cooperative exchange, was modified to be interoperability. Table 4 lists all criteria nominated by the panelists with an explanation.

Table 4: Results of Nominated Success Criteria in Round One

Success Criteria Accepted for Inclusion in Round Two	
Usability	The single most widely nominated success criterion was usability. For example, panelists suggested "must be very easy to use with simple user interface and non-technical actions"; "ease of use"; "good human interfaces to control the technology are now seen as vital"; "simple, user friendly identify management and access control will be critical"; and "how seamlessly can I integrate this technology into my personal life". The aim of usability is to guide users through efficient, effective, and satisfying process to accomplish their goals in using a product. Usability involves many aspects of a product such as ease of use, user satisfaction, connectivity, user interface, etc. It is an important factor that ensures the future success of PAN technologies in many ways. Usability is included in round two.
Functionality	Several panelists suggested functionality, or aspects of functionality, as a success criterion (e.g., "if a technology offers unique utility / functionality that is widely desired, then it will succeed"; "the technology is not as important as the functions that the devices will perform"). Functionality includes convergence, as in "the success of PAN systems may also be linked to the convergence of functions in a cell phone". Generally, functionality is the degree to which a PAN technology is able to meet the needs of the user, and this is included in round two.
Reliability of	Two panelists explicitly suggested reliability of the device-to-device connection, described by one panelist as "being able to connect and

connection	stay connected”. This was accepted for inclusion because increasingly PAN technologies are demanding highly reliable connections, especially multimedia connections that consist of high data capacity and fast speed. Connection errors are most likely to occur in multiple-path connections and network capacity is another factor which influences on the connectivity (e.g., interference or congestion). Reliability of connection is a new critical success factor in round two.
Cost	Three panelists raised the issue of the cost of PAN technologies as a success factor (e.g., “overall low cost”, “cost”; “price (how much is one chip of PAN?”). This does not appear in the literature principally because the PAN technologies are seen as being inherently inexpensive. Interestingly, cost was also raised as a challenge in Section 3 (affordability “is a key for success of PAN” and “any solution is going to be determined by its return on investment”). After some debate about how to handle this, the Delphi coordinators felt it was appropriate to include “cost” here and invite panelists to retain it or delete in round two, and especially to comment on it. Cost is, with hesitation, included in round two.
Success Criteria Modified for Inclusion in Round Two	
Interoperability	The literature review identified cooperative exchange as a critical success factor and this was widely accepted by the panel. However, several panelists nominated interoperability (the ability for diverse systems to work together) as an additional success criterion. For example, “the ability to access PAN, LAN, and WAN systems as needed” and “multi-network and open-network interoperability… via various multi-protocol devices that will be owned and controlled by the user, or which they can access via public shared open access networks. A specific example was offered by this same panelist: “register on-line with Google advertising for roller blades on sale at a specific price threshold, then stand-by for a proximity advertisement matching you to your desired purchase”. Accordingly, the success criterion “cooperative exchange” (PAN-to-PAN) has been revised to “interoperability” to also include PAN-to-LAN and PAN-to-WAN connectively.
Success Criteria Not Accepted for Inclusion in Round Two	
Privacy	Privacy is the ability to ensure that activities of individuals or a group of people are hidden or kept away from public viewing. In this study, privacy is explicitly considered as a barrier/challenge in Section 3.

	Therefore, it is not included in round two as a success criterion.
Interference	As with privacy, interference is listed as a barrier/challenge and so is not included as a success criterion in round two.
Security and firewall	Again, security is explicitly listed as a barrier/challenge, and so it is not included as a success criterion in round two.
Access control	Access control refers to approaches that restrict access to PAN resources from unauthorized users. This issue can be considered a security issue, as listed in Section 3. Therefore, it is not included as a success criterion in round two.
Speed of handshake	In technical terms, a handshake refers to a transmission prior to actual data communication to ensure that two devices agree the procedure and protocol for the communication process. There are many approaches to speed up handshakes such as simple handshake procedure and short handshake packet. In this study, this issue is considered as one aspect of the interoperability issue; therefore it is not included in round two.
Public perception or appreciation or understanding	Public perception refers to how well users understand the PAN technology which they are using. This could include aspects of usability and interoperability, which are included elsewhere. Accordingly, this is not included in round two.
Vendor support	Vendor support refers to service provided by vendors for a product's installation, maintenance, configuration, etc. One expert suggested "most technologies succeed when they have wide ranging vendor support." However, the primary focus of this study is PAN technologies themselves, so it is not included in round two.
Size	To meet the needs of ubiquitous and embedded requirements of PANs, it is necessary consider "how much can we downsize PAN chips?" However, by their nature, embedded PAN chips/devices are considered to be small. Size is also considered a key part of a new barrier/challenge (wearability). Therefore, this issue is not included in round two.
Wearability	This suggestion was accepted, but as part of a new barrier/challenge that will be discussed as a barrier/challenge.

Application Area Results

This study identifies key application areas that will have an important impact on the future of personal area networks, especially in a world of ubiquitous computing. The panel accepted all six application areas found in the literature (see Table 5). Full results of this section can be found in Appendix E.

Table 5: Application Area Results in Round One

Application Areas	Retain	Delete	No Decision
Smart things	16	-0-	3
Monitoring	16	2	1
Cable replacement	16	3	-0-
Body area network	15	2	2
Healthcare usage	14	3	2
Convenience	13	4	2

As with the success criteria, the panelists were quite generous in their suggestions for additional application areas that should be included in the study – thirteen application areas were nominated. After serious consideration, it was determined that four application areas – universal identification, proximity sensors, eco-PAN, and agriculture – merit entry into round two (see Table 6).

For the most part, the application areas nominated but not accepted (see Table 6) were included already and/or principally involved tag-to-device applications which are excluded from this study. Specifically, while tag-to-device technologies such as radio frequency identification (RFID) and near field communication (NFC) are sometimes characterized as personal area networks, a tag is not a network device and so, in this study, these are excluded. This was explained in the optional, supplemental reading, but probably this should have been more prominently drawn to the panelists' attention.

Table 6: Results of Nominated Application Areas in Round One

Application Areas Accepted for Inclusion in Round Two	
Universal identification	Universal identification, or universal ID, is similar to having a passport in a PAN device. According to one panelist, it "will be a very important application whereby identifying a person positively will help multiple

	applications such as payments, cards, driver licensing, cross border travel, etc." Given the increasing concern about identify theft, PAN technologies may provide increased security and privacy for a variety of business and consumer applications. Accordingly, this application area is included in round two.
Proximity sensors	One panelist suggested "a tag for singles that you load with the profile/attributes you are looking for in a partner. As you walk around your tag wirelessly compares profiles with other single's tags and alerts you when you are close to a match." Although tag is used here, the context clearly indicates a device which contains a sensor and sends/receives data communications without physical contact with other devices. Another panelist suggested "people meeting each other in a train, without talking or getting up. Alerting when friends are near". These are social interaction examples, but the panel should consider this application area broadly – for example in location-based advertising and security monitoring. Proximity sensors is included in round two.
Eco-PAN	One expert suggested PAN technologies could be applied to "eco-conscious applications which help monitor, reduce, and eliminate waste – even down to being able to remote monitor electricity use at home and switch off 'rogue appliances'". While this might be considered an aspect of smart things, the suggestion has considerable merit and the panelists have been given an opportunity to consider it in round two.
Agriculture	Two panelists suggested agriculture as an area in which there are numerous PAN applications. For example "each field could have a network allowing for wireless monitoring and control of irrigation levels, fertilizer usage etc. Livestock could carry devices that record details such as inoculations and even monitor movements and the health of the animal". This suggestion includes device-to-device applications and also sensor networks. There could be some overlap with body area networks ("animal area networks") and also some tag-to-device applications. Nevertheless, agriculture has been included for the panel's consideration in round two.
Application Areas Not Accepted for Inclusion in Round Two	
Ad hoc network between PANs and servers	An ad hoc network refers to temporary network connections in which data communications are performed through wireless devices. A typical example of an ad hoc network between PANs and other networks is BlueStar, which allow PAN devices to access the Internet through the use of WLAN-based transmitters. It was decided that ad hoc networks between a PAN and a server was not an application area; rather it is part of interoperability, as listed above. This is not included in round two.

Rescue missions	One panelist nominated rescue missions, but without an explanation. It isn't clear at all how short range technologies can assist in long-range rescue missions. And, if PAN technologies are used to monitor health conditions for rescues, then that is included in the healthcare usage application area. According, rescue mission is not included in round two.
Research studies	Frequently, PAN technologies are utilized in various research studies, especially for healthcare monitoring, traffic control, livestock observation, etc. In most cases, these can be included in other application areas and so research studies is not included in round two.
Product tracking	Product tracking applications (e.g., inventory control, supply chain management, theft prevention) are popular applications for tag-to-device applications. However, the focus of this study is on device-to-device applications and so product tracking is not included
RFID and NFC paradigms	One panelist suggested an article which involved Bluetooth connection to an external RFID reader to read RFID tags. This is mostly a tag-to-device application (excluded from the study) and is somewhat related to interoperability (covered elsewhere). Accordingly, this is not included in round two.
Security monitoring	Security monitoring was suggested without explanation. After careful consideration, it was decided that universal identification, proximity sensors and especially the monitoring application areas could include most aspects of security monitoring. So, it was decided not to include security monitoring in round two.
Shopping tag	This application "loads your shopping list in a tag. When you go to a shop the tag connects to the shop's network and downloads the locations of all the items you are seeking". Although tag is used, this is clearly a device. This is considered a smart thing application and is not included in round two.
Smart handbag	Similarly, smart handbag was suggested by another panelist. Similarly, this is considered to fall within the smart things application and, similarly, it is not included in round two.
Sports medicine	Sports medicine was mentioned without explanation, but generally sports medicine refers to prevention and treatment of injuries caused by participating in physical sport activities. This application can be considered part of both body area network and healthcare application areas, and so it is not included in round two.

Barriers and Challenges Results

The barriers/challenges discussed in this section cover problems associated with PAN implementation in the future. Five of the six barriers/challenges were clearly accepted by the panel for inclusion in round two (see Table 7). Location privacy is the only issue that did not receive strong support, and even then some panelists who supported its retention had reservations about its inclusion and its overlap with security and privacy. Accordingly, location privacy is not included in round two. More detailed results for Table 7 are included in Appendix E.

Table 7: Barriers/Challenges Results in Round One

Barriers/Challenges	Retain	Delete	No Decision
Security	19	-0-	-0-
Interference and coexistence	18	-0-	1
Tradeoff of QoS and power	17	1	1
Environment	15	3	1
Privacy	14	4	1
Location privacy	11	5	3

Collectively, panelists nominated at least 12 barriers/challenges. Six of these – regulation and standards, self-organization, data management, environment issues, human interface, and embeddedness and wearability – were accepted for inclusion in round two (see Table 8). Some barriers are quite broadly defined, as described below. The barriers/challenges not accepted for inclusion are shown in Table 8, with an explanation. Finally, because environment issues was accepted as a barrier/challenge, the previously identified environment barrier is now renamed operating environment.

Table 8: Results of Nominated Barriers/Challenges in Round One

Barriers/Challenges Accepted for Inclusion in Round Two	
Regulation and standards	The most frequently nominated barrier/challenge was regulation and the closely related area of standards. For example, panelists commented: “the regulation to utilize a frequency band should be designed so that the above coexistence is easy and beneficial for everybody”; “regulatory issues: international roaming and varying rules for radio emitters in different jurisdictions”; “multiple protocols/technologies – no universal

	standard will cause huge problems and slow down the deployment"; and "regulatory authority (who controls what)". A related issue also included in here is "spectrum availability (how much can we provide PAN with available frequency? If there is not enough spectrum for PAN, there will be congestion, and it will be difficult to widely spread". Clearly the issue of standards (to enable interoperable PAN communications) and regulation (who will set and enforce the standards) is a key challenge facing PAN implementation, and so it is included in round two.
Self-organization	Self-organization in PAN technologies reflects issues such as self-configuration and self-customization. Self-organization ensures that PANs can perform in a changing environment, especially with applications that utilize discovery and monitoring. The challenge is made more difficult with the enormous complexity of the various technologies. This barrier/challenge is included in round two.
Data management	This barrier/challenge focuses on how the data resource is organized and used in the context of PAN technologies. The data collected from PAN implementations will have to be integrated so it can be used for generating useful information. As PANs multiply and grow, there will be an increasing quantity of data to collect, process, and store. Data management is included in round two.
Environmental issues	Two panelists listed "environmental issues" and "environment-friendly PAN device" with an explanation that "there will be billions of PAN devices in the future, so it is important to design PAN devices in an environmental-friendly way, allowing us to recycle many parts of the device, or disposable without harming the environment". This is a valid point, especially in an increasingly eco-friendly world. Accordingly, it is included in round two.
Human interface	"Poor intuitive use is a technology barrier at the moment" was one comment from a panelist and another listed "people's abilities, skill levels". On the one hand, this can be a concern if users need to set, control, read or operate these devices, principally because of their small size. However, if these devices are mostly hidden and embedded, then human interaction with them should be minimal. However, to be inclusive, human interface with PAN devices and technologies is included in round two.
Embeddedness and wearability	In a ubiquitous computing world, PAN devices will have to be embedded in clothes (body area networks), appliances (smart things) and even wristwatches, eyeglasses, etc. How can this be done without interfering with the operation of the "thing" or the user? Smaller, but related issues include heat management (will heat generated from these

	devices be detrimental?) and robustness (can these embedded devices withstand shock and moisture?). This fairly broad and inclusive barrier/challenge has been included in round two.
Barriers/Challenges Not Accepted for Inclusion in Round Two	
Data security	One panelist suggested “the ability to erase or destroy all stored data remotely by the owners, should be devices be lost or stolen” will be necessary, and a challenge. This is closely related to security and data management, and so data security is not included in round two.
Cost and return on investment	Two panelists mentioned “cost” as well as “affordability” and “return on investment”. Three panelists also listed cost as a benefit, as noted earlier, this was interpreted to mean that the cost of individual PAN devices is very low at this time, but of course in a large deployment and with associated infrastructure costs (e.g., a sensor network), cost could be a barrier, especially for ROI. In the end, it was decided that cost is a better candidate as a benefit than a barrier, and so it is excluded from round two here.
Heat management	The human body might suffer from heat generated by implanted or wearable PAN devices – “keeping things below 98.7 (body temperature) will be a very important human factors challenge for these wearable network devices”. On the other hand, this should not be a primary concern since PAN devices are powered with very low power supply that is unlikely to generate a high temperature. It was decided that this barrier/challenge could be included in embeddedness and wearability. Heat management by itself is not included in round two.
Impacts to culture and ethics	This barrier/challenge was offered without explanation. Without any clear idea as to what is implied here and with no support from the literature, this potential barrier/challenge was not included in round two.
Mass deployment	A panelist pointed out “deploying them to masses will have its own headaches, but unless it is available as ubiquitous network everywhere, it would be futile.” It was decided this very broad statement could be included in other barriers and challenges such as environment issues and interference and coexistence. Mass deployment is not included in round two.
Moisture proofing	PAN devices might fail due to moisture “due to sweat, humidity and occasionally falling into the river”. Another panelist suggested “robustness – what if it goes through the wash?” This seems to be a very specific circumstance and fixed by waterproofing. However it is also mentioned in embeddedness and wearability (e.g., smart clothes will

	have to be washable). Moisture proofing itself is not included in round two.

Round Two Results

The purposes of round two were (a) to determine how important the issues identified in the relevant literature and nominated by panelists are to the future of PAN and (b) whether the nominated issues by the panel in round one were appropriate to include in the study. The round two materials were circulated to 19 panelists on 6 April 2008. The materials included all results from round one including all panelists' comments and decision tables (see Appendix E) as well as a round two questionnaire (see Appendix C). Eighteen responses were received in time to be included in round two results. This section summarizes the panels' responses, with the detailed responses reported in Appendix F.

In round two, panelists were asked to review the panelists' comments for each of the issues. Panelists' comments provide important insight and judgment to the issues, to supplement the factual material provided in the background reading.

All ratings from the panel have been combined to calculate a mean for each issue, in order to rate how important each issue is. A non-response from a panelist was not included in the calculation and all means have been rounded to two decimals.

Success Criteria Results

In this section, the results of success criteria for round two will be presented. First the fate of the four nominated success criteria are discussed, then the rating results.

Nominated Success Criteria

Panelists' decisions on the nominated criteria in round two are summarized in Table 9. Three of the four nominated issues received strong support for inclusion in the study. One criterion (cost) was not accepted and so it is dropped from further consideration.

Table 9: Nominated Success Criteria Results in Round Two

Success Criteria	Retain	Delete	No Decision
Usability	17	1	-0-

Reliability of connection	16	1	1
Functionality	15	2	1
Cost	8	9	1

Rating of Success Criteria

The four new (nominated) success criteria were rated with the existing eleven issues on a Likert scale of 1 (very important) to 5 (not important at all). Panelists were also asked to provide comments to justify their responses.

The results (mean) are shown in Table 10, with all criteria ranked from "most important" to "least important". Complete individual panelist ratings are included in Appendix F. As can be seen in Table 10, range and power consumption type received means that are higher than the threshold rating of 2.50. Therefore, they are not considered in round three.

Table 10: Success Criteria Rating in Round Two

Success Criteria	Mean
Interoperability	1.53
Reliability of connection	1.65
Usability	1.67
Power management	1.72
Transmission speed	1.78
Frequency switching	1.94
Widespread deployment	1.94
Functionality	2.13
Range	2.53
Power consumption type	2.61

Application Area Results

In this section, the results of application area for round two will be presented. First the fate of the four nominated application areas are discussed, then the rating results.

Nominated Application Areas

Panelists' decisions on the nominated areas in round two are summarized in Table 11. As can be seen in Tables 11 and 12, universal ID was only nominated application area which received less than three negative votes and exceeded the threshold mean of 2.50. Accordingly, universal ID clearly goes through to round three.

Agriculture and proximity sensor received four no votes and their means were above the threshold rating of 2.50. However, based on the comments provided by the panelists, it is reasonable to believe that most panelists agree that these two application areas should be considered in the next round. On the other hand, eco-PAN received five negative votes and it has been given a noticeably higher mean than all others. Based on the mean and comments from the panel, eco-PAN is not included in round three.

Table 11: Nominated Application Area Results in Round Two

Application Area	Retain	Delete	No Decision
Universal ID	15	2	1
Agriculture	12	4	2
Eco-PAN	12	5	1
Proximity Sensors	11	4	3

Rating of Application Areas

The four new (nominated) application areas were rated with the existing six issues on a Likert scale of 1 (very important) to 5 (not important at all). Panelists were also asked to provide comments to justify their responses.

The results (mean) are shown in Table 12, with all application areas ranked from "most important" to "least important". Complete results that show individual panelist ratings are included in Appendix F.

Table 12: Application Areas Means in Round Two

Application Area	Mean
Healthcare	1.78
Monitoring	1.83
Smart things	1.83
Cable replacement	1.94
Body area network	2.28
Convenience	2.33

Application Area	Mean
Universal ID	2.33
Agriculture	2.56
Proximity sensors	2.67
Eco-PAN	3.11

Barriers and Challenges Results

In this section, the results of barriers/challenges for round two will be presented. First the fate of the six nominated barriers/challenges are discussed, then the rating results.

Nominated Barriers/Challenges

Three (regulation and standards, embeddedness and wearability, and self-organization) out of the six nominated barriers/challenges were included in round three for receiving more than 14 positive votes and reasonably low means (see Tables 13 and 14).

Two (data management and environment issues) out of six nominated barriers/challenges were given seven delete votes and the same mean of 2.89, therefore they did not go through to round three. Similarly, the mean for human interface (2.47) was slightly less than the threshold mean of 2.50, it received six negative votes and so it was excluded from round three.

Table 13: Nominated Barriers/Challenges Results in Round Two

Barrier/Challenge	Retain	Delete	No Decision
Regulation and standards	16	1	1
Embeddedness and wearability	15	2	1
Self-organization	14	3	1
Human interface	11	6	1
Data management	10	7	1
Environmental issues	10	7	1

Rating of Barriers/Challenges

The six new (nominated) barriers/challenges were rated with the existing five issues on a Likert scale of 1 (very important) to 5 (not important at all). Panelists were also asked to provide comments to justify their responses.

The results (mean) are shown in Table 14, with all barriers/challenges ranked from "most important" to "least important". Complete results individual panelists are included in Appendix F.

Table 14: Barriers/Challenges Means in Round Two

Barrier/Challenge	Mean
Security	1.33
Interference and coexistence	1.47
Regulation and standards	1.67
Privacy	1.94
Trade-off of QoS and power efficiency	1.94
Operating environment	2.00
Embeddedness and wearability	2.06
Self-organization	2.11
Human interface	2.47
Data management	2.89
Environmental issues	2.89

Round Three Results

The aim of round three was to achieve a consensus of the panel's views on the issues presented in previous rounds. In this study, consensus is defined as a degree of acceptance by all panelists on all identified issues. Achieving consensus does not imply conformance. Panelists were still required to use their independent judgment in making decisions in this round, but to do so in light of the ratings and comments provided from other panelists in round two.

Round three materials were circulated on 1 May 2008 to the 18 panelists who responded in round two. These materials included results from round two including all panelists' comments, ratings (see Appendix F), and the round three questionnaire (see Appendix D). All ratings from the panel have been combined to obtain a new mean in round three for each issue, in order to rate how important each issue is. As in round two, all unclear ratings were discarded and all means have been rounded to two decimals. Individual ratings for each issue are included in Appendix G.

Success Criteria Results

In this section, the results of the success criteria for round three will be presented. A new ranking list in terms of the mean value is included in Table 15. Reliability of connection has replaced interoperability to become the most important success criterion with a mean of 1.33. Frequency switching has received a mean of 2.12 and is considered to be the least important success criterion.

The results in round three changed slightly from the results obtained in round two (compare Tables 10 and 15). Frequency switching and transmission speed were the only two issues which received a higher mean (i.e., less important) compared with their mean in round two. But the ranked order changed for several of the criteria. The top four most important success criteria remain the same as they were in round two, but the order changed slightly.

Table 15: Success Criteria Results in Round Three

Success Criterion	Mean
Reliability of connection	1.33
Interoperability	1.44
Usability	1.44
Power management	1.61
Widespread deployment	1.88
Functionality	2.00
Transmission speed	2.00
Frequency switching	2.12

Application Area Results

As with success criteria, application area results also changed slightly compared to the results in round two (compare Tables 12 and 16). The mean for monitoring has decreased to 1.67 to make it the most important application area. Universal ID and proximity sensors have means of 2.47 to become the two least important application areas.

Table 16: Application Area Results in Round Three

Application Area	Mean
Monitoring	1.67
Healthcare	1.78
Smart things	1.83
Cable replacement	1.94

Body area network	2.11
Convenience	2.12
Agriculture	2.44
Proximity sensors	2.47
Universal ID	2.47

Barriers and Challenges Results

A total number of eight barriers/challenges were included in round three. The means for these issues are shown in Table 17. Security remained as the most important barrier/challenge with the same mean of 1.33 in rounds two (Table 14) and three (Table 17). Self-organization rose several positions in the rank order, but all other rankings in the table remained the same.

Table 17: Barrier/Challenge Results in Round Three

Barrier/Challenge	Mean
Security	1.33
Interference and coexistence	1.44
Regulation and standards	1.83
Self-organization	1.89
Privacy	2.00
Trade-off of QoS and power efficiency	2.17
Operating environment	2.17
Embeddedness and wearability	2.28

The changes in results from round two to round three were larger than anticipated (e.g. monitoring rise to first in application areas, self-organization rise several positions in barriers/challenges). The Delphi coordinators discussed whether to conduct a fourth round to verify these results (i.e. to confirm a consensus) but decided not to because (a) panelists had been told to expect only three rounds, (b) a deadline for completion of the research was looming, and (c) there is no reason to expect the round three results are not an accurate portrayal of the panelists' views. Accordingly, the research moved to the next stage, an analysis of these results as discussed in the next chapter.

CHAPTER 5: DISCUSSION

Introduction

In this chapter, the results from the three Delphi rounds will be analyzed, interpreted, and discussed according to relevant literature as well as panelists' comments. This chapter is divided into three sections: success criteria, application areas, and barriers/challenges. Each section contains the related issues which have made it through all three rounds. In addition, all issues are discussed in the order of their ranking from the final round.

Success Criteria

This section identifies what are the most important success criteria that will determine the future of personal area networks (PAN). After the three Delphi surveys, eight success criteria have passed through (see Table 18) and are discussed below. In general, most criteria received lower means in round three compared with their means in round two.

Table 18: Summarized Results of Success Criteria

Success Criteria	Source	Round 1 or 2		Round 2		Round 3	
		Retain	Delete	Mean	Rank	Mean	Rank
Reliability of connection	panel	16	1	1.65	2	1.33	1
Interoperability	literature	14	3	1.53	1	1.44	2
Usability	panel	17	1	1.67	3	1.44	2
Power management	literature	18	-0-	1.72	4	1.61	4
Widespread deployment	literature	17	-0-	1.94	6	1.88	5
Functionality	panel	15	2	2.13	8	2.00	6
Transmission speed	literature	16	2	1.78	5	2.00	6
Frequency switching	literature	19	-0-	1.94	6	2.12	8

Reliability of Connection

Reliability of connection was nominated by one of the experts in round one. Although the expert did not provide any explanation for this issue, it was accepted in round two and agreed to be the most important criterion in round three with the lowest (most important) mean of 1.33. The reason why this issue was not found in the related literature might be that the academic literature tends to focus on possible solutions for existing barriers/challenges rather than to focus on what the existing barriers are.

After being identified as a criterion, its importance was recommended by several panelists. For example, one panelist commented that a reliable connection between wireless devices ensures “customers satisfaction and acceptance” (expert 5) of these technologies as well as quality of service (QoS). Several experts commented that an unreliable connection will cause “frustration” to users and hereby reduce the level of its acceptance by users (experts 6, 10, 18).

Interoperability

This issue was originally selected from the literature as cooperative exchange and revised to interoperability after comments in round one. Cooperative exchange refers to communications between various PAN technologies while interoperability extends the description from PAN-to-PAN to other wireless technologies such as WLAN or WWAN. As the main focus of this study is PAN technologies, the original point-of-view was to study issues related to PAN only. However, in the real world, many other wireless technologies also exist and PAN must receive or send data and commands with these other networks. For this reason, PAN technologies or devices should not be limited to be interoperable with other PAN but also be interoperable with other types of wireless networks.

Although this issue’s mean decreased from 1.53 in round two to 1.44 in round three, its position dropped from the most important criterion in round two to the second position in round three. Several panelists (experts 10, 11, 14) commented that the main reason interoperability is a very important criterion is that a PAN technology should not be limited to communicate or function with its own type, especially nowadays when new technologies are emerging frequently. In the future ubiquitous computing world, interoperability will be vital for PAN technologies to share data and command among PANs, WLANs, WMANs, and WWANs.

Usability

Usability was nominated by a few panelists in round one. In the literature, many studies have been conducted on the issue of system usability. For example, researchers have investigated usability evaluation (e.g. Ali-Yahiya et al., 2007), usability testing (e.g. Au, Baker, Warren, & Dobbie, 2008) and usability analysis (e.g. Qiu, Chui, & Helander, 2006). In hindsight, the reason that usability was not identified in the literature review is that academic studies tend to focus on technical solutions or improvements. Once identified in round one, usability received 17 out of 18 votes for inclusion in round two.

Usability was ranked third in round two with a mean of 1.67 and ranked second equal with interoperability in round three with a mean of 1.44. Because usability covers a wide range of issues for a product or services, there is little doubt that it will become one of the most important success criteria for PAN to succeed in the future. One reason that this issue was not rated even higher might be that users should not even be aware of the usability or even existence of products or services in a ubiquitous computing world in which many PAN devices will be embedded in the environment. Also usability is a given condition for any new technology (expert 19).

Power Management

Power-related issues are frequently discussed in the relevant literature. This will always be a problematic issue because almost all wireless devices are supported by batteries with limited life. The panel agreed with a vote of 18 to zero in round one to retain this as a criterion. According to the panel's comments, battery life is an important aspect of power management, but not the only one. For example, new power resources such as Li-ion, NiMH, and NanoSafe are also solutions for better power management in PAN technologies (expert 8).

Although the problem of limited battery life is irresistible, battery-related issues will reduce as hardware capacity and power management techniques increase (expert 19) and PAN devices will still perform at an acceptable level as long as they have sufficient power supply. Furthermore, PAN technologies are designed for low cost and low power consumption in general. Therefore, battery life is generally longer for PAN devices than other high capability wireless devices. All of these reasons may reduce the importance of this criterion.

Widespread Deployment

One panelist (expert 18) defined PAN success as "general acceptance and wide deployment". The literature described wide deployment as requiring lower cost and needs to overcome many technical challenges. This view was supported by related comments from several panelists (experts 2, 10, 16).

Widespread deployment moved from sixth (out of ten) in round two to fifth (out of eight) in round three. Not only did its rating mean improve, but also the means for two other criteria dropped in round three. Panelists' comments such as "a killer app" (expert 9), "a future PAN is only viable if there is widespread deployment" (expert 6), had a positive impact on its ranking in round three.

Functionality

Functionality in various forms was nominated by several panelists in round one. Having unique functions which are widely desired or a convergence of functions (e.g. in cell phones), will contribute to PAN success in the future ubiquitous computing world.

This criterion was ranked sixth equal with a mean of 2.00 (important) in round three. Generally, many panelists (experts 3, 6, 9, 10, 12) believe that functionality helps ensure PAN systems will meet user expectations and that unique or converged functionality of PAN systems will guarantee success. However, uncertainties exist. For example, new communication platforms evolve along a long path from kluged prototypes to engineer-friendly and consumer-friendly systems (expert 14) and "functionality will always be a subjective issue" (expert 19).

Transmission Speed

Transmission speed is defined as one of the key success factors for wireless technologies in the literature. It directly impacts QoS, usability, power consumption, and many other aspects of PAN technology. In round one, transmission speed received 16 retain votes. Several panelists (experts 3, 9, 16) pointed out that as technologies develop, speed will be a key factor to meet users' expectation of fast and reliable transmission. In contrast, one expert stated that speed is not too important as long as it exceeds a threshold for effective use (expert 2). This seemed to influence other panelists as transmission speed's relative importance dropped in round three. For example, ratings for 3 (neutral) of the 18 panelists changed from one vote in round two to four votes in round three.

More panelists (experts 6, 8, 10, 11, 18,) mentioned that transmission speed should be designated according to users and applications' requirements as these vary. Similar statements, that speed should be application dependent, can be found in the literature (e.g. Touati et al., 2002).

Frequency Switching

In round one, frequency switching received the strongest support for inclusion by receiving all 19 votes to retain. As found in the literature, the capability to share an unlicensed frequency band or utilize multiple frequencies is vital for the future success of PAN technologies. The results and panelists' comments proved that most of the panelists agreed with this statement. For example, "2.4 GHz is very 'busy' in many areas, PAN must be able to work" (expert 6). "As well as the ability to negotiate the use of multiple frequencies, devices should be able to negotiate the use of various signal strengths" (expert 11).

At the conclusion of this study, frequency switching was ranked eight out of eight but still with an important rating of 2.12. As with transmission speed, a few panelists (experts 2, 7) believe frequency switching is dependent on applications and might be useful but other criteria are more important. One expert (expert 7) rated it neutral as a success criterion because it was considered to be a barrier/challenge, related to interference, rather than an ability to adopt multiple frequencies or tolerate interference and coexistence.

Application Areas

In this section, the nine application areas which made it through three Delphi surveys in this study will be discussed along with the results from these surveys. Three out of four nominated application areas in round two have remained in the final round and are discussed in this section. The other six application areas were identified from the literature (see Table 19).

Table 19: Summarized Results of Application Areas

Application Areas	Source	Round 1 or 2		Round 2		Round 3	
		Retain	Delete	Mean	Rank	Mean	Rank
Monitoring	literature	16	2	1.83	2	1.67	1
Healthcare	literature	14	3	1.78	1	1.78	2
Smart things	literature	16	-0-	1.83	2	1.83	3
Cable replacement	literature	16	3	1.94	4	1.94	4
Body area network	literature	15	2	2.28	5	2.11	5
Convenience	literature	13	4	2.33	6	2.12	6
Agriculture	panel	12	4	2.56	8	2.44	7
Proximity sensors	panel	11	4	2.67	9	2.47	8
Universal ID	panel	15	2	2.33	6	2.47	8

Monitoring

Monitoring was initially chosen from the relevant literature because a vast number of studies have been done on sensor monitoring, health monitoring, security monitoring, and other forms of monitoring. Monitoring was included in this study to confirm if the expert panel also felt monitoring will be an important application area for PAN technologies.

Monitoring was ranked as the most important application area in round three with the lowest mean of 1.67. Monitoring is considered so because it possesses a lot of opportunity in the marketplace. Such opportunities could be for security, healthcare, production, supply chain management, and others. Even so, a few panelists qualified their ratings with comments such as “over-specified” (expert 17) and other technologies such as longer range wireless networks might perform better (expert 11).

Healthcare

PAN applications which are used specifically for healthcare was selected separately from body area network because PAN technologies offer significant advantages in this area. These advantages could be real-time feedback, continuous health monitoring, and small size devices which can be attached or embedded within the human body. Healthcare did not receive full support for inclusion mostly because this application is very specific and perhaps it should be expanded to a broader scope.

Although the mean rating for healthcare remained the same in rounds two and three, its ranking dropped from first place in round two to second place in round three. This probably reflects the increased importance panelists gave to monitoring (from 14 votes of very important or important in round two to 16 votes in round three), rather than decreased importance to healthcare.

Smart Things

Smart things was primarily chosen from the literature because it has an important role to constitute the ubiquitous computing world in the future in which computational devices are everywhere and users might not even be aware of the existence of these smart devices. In round one, all 16 experts who a provided clear decision on this issue agreed smart things should be retained as an important application area. However, one obstacle of this application area was that users' unawareness and nescience to these devices might result in perceived less importance with regard to smart applications (experts 9, 15).

The mean of smart things (1.83) remained the same in both rounds but its ranking dropped from the second equal in round two to third position in round three. This suggests that experts' opinion in round two on this issue has not been affected much by others in round three (e.g. only three experts changed their ratings). One of the panelists commented that in order to for PAN technologies to be successful, more substantial functions are required to avoid smart things becoming fads (expert 9).

Cable Replacement

Cable replacement was identified in the literature review because it is one of the original purposes of wireless technologies and it still is the basis for many applications now. Over the last decade, wireless technologies, including PAN technologies, have taken an important part in everyday life and many applications have used PAN technologies to replace cables (e.g. Bluetooth headset). However, there is a question of just is how important cable replacement is as one of the application areas of PAN technologies in the future. Comments from the round one survey showed that many panelists (experts 3, 6, 8, 12, 16) deem it will be an important application for PANs, but problems will also exist in some aspects such as access control and application development (experts 11, 13).

Although experts' ratings were slightly different in rounds two and three, the rating of 1.94 in both rounds reflect the majority opinion of the panel is that it will be important in the future. One outstanding difference is from expert 19 who voted 5 (not important at all) in both rounds, commenting that there will always be a need for cable as a back haul requirement and wireless and cable transmissions will coexist peacefully.

Body Area Network

One prominent example in the literature of how PAN technologies will be frequently used in the future ubiquitous computing world is body area network (BAN), in which smart devices will be attached to or embedded in the human body. In round one, one panelist (expert 9) mentioned in the comments that BAN is currently considered a leading edge technology and many studies (e.g. Domenicali & Di Benedetto, 2007; Jovanov, 2005) in the literature describe the utilization of body area networks, especially in the medical field.

Panelists' ratings changed only slightly between round two and round three. Panelists who rated BAN low commented on it as "an uncomfortable idea" (expert 14), "may go too far" (expert 3), and "acceptance is low" (expert 12). One reason for these negative comments might be there are still not many widely adopted BAN applications at moment.

Convenience

The basis for this application area is that PAN technologies have an important role to make life more convenient for people in everyday life, and many studies in the literature have been done to facilitate or utilize these technologies into practice (e.g. Feldbusch et al., 2003; Shan, Liu, Prosser, & Brown, 2005). The main reason convenience received four delete votes was that convenience might not be the key driving force to PAN development even if its purpose is to make life easier for users (experts 6, 7, 9, 16). The significant driving force would still be market requirements (expert 19) and user's demands.

In round three, the mean of convenience was 2.12 and it ranked sixth. Seven out of 18 responses were 3 (neutral) for this issue. Experts' ratings of this application area may not be very high because convenience is not perceived to be a significant driving force for PAN development. Secondly, many other alternatives also exist to accomplish tasks and might even perform better than PAN technologies (expert 2).

Agriculture

Agriculture was nominated by two panelists because of significant potential of PAN technologies in the agricultural sciences. In the literature, not many studies have specifically focused on how to apply PAN technologies in agriculture. Therefore, this application area was not identified in the literature review and not included in the round one questionnaire. In round two, 12 out of 18 panelists voted to retain this application area in this study.

In round three, agriculture received a mean of 2.44 and ranked seventh. A number of panelists were from New Zealand. If PAN technologies will significantly benefit agriculture, New Zealand will benefit due to its large agricultural economy. This could explain why agriculture was nominated and retained through all rounds. The relatively high average ratings in both rounds reflect that agriculture might be a specific example of how PANs can be applied into practice and it is not a general application area (experts 14, 19).

Proximity Sensors

Two panelists suggested concepts similar to proximity sensors in round one. According to the comments provided by the panelists, the concept of proximity sensors implies that two PAN devices are able to interact with each other when they are within their communication range. Therefore, it is a very broad notion and can be included in many PAN applications. One of the four experts who voted delete for this issue in round two mentioned that proximity sensors is similar to other areas such as monitoring (expert 5).

Proximity sensors was ranked eighth equal in round three with a mean of 2.47. This relatively high mean can be attributed to the seven neutral votes from the panelists.

Universal ID

Universal ID was nominated in round one and included in this study because of its importance in assisting other applications such as payments and driving licensing (expert 16). At the moment, there are no widely adopted PAN technologies used for universal identification. That is the key reason why universal ID was not identified in the literature.

In round two, universal ID was ranked sixth with a mean of 2.33. Notably, two panelists (experts 10, 12) rated this 5 (not important at all) in round 2. This rating and related comments from these panelist may have influenced other panelists to change their rating, moving universal ID down to eighth equal in round three. Comments suggest that it is difficult to adopt and popularize universal ID as security and privacy are critical concerns in this application, and many PAN devices do not have powerful authentication systems (experts 10, 12, 19).

Barriers and Challenges

The purpose of this section is to discuss barriers/challenges that the panel agrees are critical to PAN technologies in the future. A total of eight barriers/challenges will be discussed by their ranked order (see Table 20).

Table 20: Summarized Results of Barriers/Challenges

Barriers/Challenges	Source	Round 1 or 2		Round 2		Round 3	
		Retain	Delete	Mean	Rank	Mean	Rank
Security	literature	19	-0-	1.33	1	1.33	1
Interference and coexistence	literature	18	-0-	1.47	2	1.44	2
Regulation and standards	panel	16	1	1.67	3	1.83	3
Self-organization	panel	14	3	2.11	8	1.89	4
Privacy	literature	14	4	1.94	4	2.00	5
Trade-off of QoS and power efficiency	literature	17	1	1.94	4	2.17	6
Operating environment	literature	15	3	2.00	6	2.17	6
Embeddedness and wearability	panel	15	2	2.06	7	2.28	8

Security

Security is a significant concern as it influences many aspects of many applications in all wired and wireless technologies. In the PAN literature, many studies have focused on how to prevent or protect PANs from malicious users or system corruptions (e.g. Boukerche, 2005; Karygiannis et al., 2005; Perrig et al., 2004). By obtaining an unanimous decision to retain in round one, security was the top barrier/challenge to go into round two. This result was a preliminary indication that it is commonly accepted by many experts that security is a major concern, especially for emerging and immature technologies which might create new opportunities for malicious attacks.

In rounds two and three, security ranked as the top barrier/challenge with a mean of 1.33 in both rounds. These results verify the findings of the literature review that security is considered to be perhaps the most important barrier/challenge that will determine the future success of PAN technologies. Some panelists also mentioned that the security level should correspond with the requirements of the various applications. For example, healthcare might need a higher degree of security (expert 15) while other applications might have lower security requirements.

Interference and Coexistence

As the unlicensed 2.4GHz frequency band is shared by many wireless technologies, there are many studies focusing on how to solve problems associated with interference and coexistence (e.g. Golmie, 2006; Morrow, 2004; Qiao et al., 2007). Many panelists considered this issue to be a critical challenge as it received no delete votes in round one. An inability to deal with interference and coexist with other wireless technologies will result in unreliable service and loss of functionality and information for PAN technologies.

Interference and coexistence was ranked as second in both rounds with a mean of 1.44 in round three. In the future ubiquitous computing world, wireless technologies will be used everywhere. Therefore, interference and coexistence will be a critical challenge to any wireless technologies including PANs. In addition, several panelists (experts 5, 7, 14) commented that this is a technical issue as well as a regulatory issue. New regulatory mechanisms for interference and coexistence will be needed to avoid these problems.

Regulation and Standards

Regulation and standards was nominated by several panelists in round one. Having widely adopted regulation and standards would ensure PAN technologies and other types of wireless technologies perform effectively and efficiently.

The average rating for this issue was 1.88 in round three, with the same ranking (third) in both rounds. Panelists (experts 2, 8, 12) who provided explanations for their ratings generally agreed it will be an important barrier/challenge to the future success of PAN technologies. On the other hand, two experts made some negative comments about regulation and standards such as it will “slow the roll out of the technology” and there is a need to “minimize regulation” (experts 3, 6). One possible explanation for these comments is concern that too many regulation and standards might limit the development of PAN technologies.

Self-organization

This issue was nominated in round one by one panelist. Although the expert who suggested this issue did not provide any explanation for it, the discussion was carried out based on the superficial meaning of the words “self-organization”. Self-organization can be considered as one of the capabilities which PAN technologies use to complete tasks.

Self-organization was ranked as seventh in round two (mean=2.11) and increased dramatically to the fourth position (mean=1.89) in round three. One possible explanation for the relatively high means might be that self-organization is considered as a feature of PANs, not necessarily a barrier or challenge. The challenge is actually how to achieve this capability for PAN technologies in the complexity of the various technologies. Self-organization is also a significant function in proving usability and functionality for PAN systems. A lack of self-organizing requires manual intervention, which will reduce acceptance (expert 16).

Privacy

This issue was identified from the relevant literature for consideration in round one. Privacy was included because wireless networks could pose a threat to user privacy if users’ identities and related information are not protected. In round one, privacy received four delete votes mostly because it was considered to be related to security (experts 8, 9, 16).

In round three, privacy was rated 2.00 (important) and ranked fifth. In addition to the comments mentioned above that privacy issue is a part of security, some (experts 14, 16) comments stated that the privacy issue itself is not the source of privacy crimes, but the users are the source.

Trade-off of QoS and Power Efficiency

There are many power management related studies for the various wireless technologies, and so the trade-off between quality of service (QoS) and power efficiency is a potential determinant in the future deployment of PAN technologies. Panelists tended to agree, with only one delete vote in a total 18 responses. Failure to control the balance between QoS and power to PANs might become a barrier to technology adoption (expert 10).

This issue was ranked sixth with a mean of 2.17 in round three. Although the trade-off commonly exists in battery-powered PAN systems, PANs still need to perform effectively as long as there is sufficient power supply. More importantly, other aspects such as speed and functionality will be more important than this trade-off (expert 3). Perhaps because of these comments, this issue received a relatively high mean and lower ranking in round three.

Operating Environment

As PAN devices will be utilized everywhere in the future ubiquitous computing world, PANs should accommodate various types of operating environments. For this reason, the issue of operating environment was identified in the literature for consideration in this study. In round one, several panelists (experts 4, 9, 12) claimed that this issue will be increasingly important as more and more new PAN technologies are invented and put into practice. One expert who voted to delete explained that operating environment will not be an issue because it will eventually be overcome as the infrastructure and standards progress (expert 19).

Operating environment ranked sixth equal with a mean of 2.17 in round three. There are two main reasons for this rating. First, some experts believed that there are many possible solutions to overcome this challenge. Such solutions could be additional bandwidth (expert 14), well established infrastructure and standards (expert 19), and excellent engineering (expert 2). Second, a few experts considered it somewhat similar to interference and coexistence mentioned previously (experts 4, 6).

Embeddedness and Wearability

As one of the characteristics of ubiquitous computing, embeddedness and wearability was nominated as a barrier/challenge because of the difficulty of incorporation PAN devices within other objects. Although it is commonly agreed that PANs utilize low power consumption and are small size devices, there remain concerns about how well PAN devices can be attached or embedded within other objects.

In the end, embeddedness and wearability was ranked in eighth (last) position with the highest mean of 2.28 in round three. These results imply that although it is accepted as a barrier/challenge to the future implementation of PANs, this issue is less important than all others included in this study. One reason for this result might be that it will not be important initially in the development and acceptance of PAN technologies as the level of adoption and deployment is still low (expert 9). Moreover, there are still many obstacles associated with embeddedness and wearability, such as heat management and robustness.

Summary

In summary, this chapter mainly focused on an informed discussion of the results obtained from the Delphi process of this study. A total of 25 issues are discussed in this chapter, categorized into three sections. The following chapter will summarize the highlights of the results as well as list the limitations of this study and suggest future directions for research.

CHAPTER 6: CONCLUSION

This chapter presents a conclusion of this study in which the Delphi Method was utilized to predict the future prospects of personal area networks in a ubiquitous computing world. The results of this study will be summarized, limitations of this study will be discussed and suggestions for future research studies will be offered.

Summary

The purpose of this research is to analyze and predict the future prospects of personal area networks. As PANs will be everywhere in the ubiquitous computing world of the future, it is important to understand the future success criteria, application areas, and barriers/challenges of PAN technologies to evade incorrect implementation and maintenance for PANs. Primary beneficiaries of this study will be researchers and professionals, to help them make correct decisions. Organizations that are involved in PANs will also benefit from understanding the future trends associated with PAN technologies.

PAN prospects have been examined in three areas:

- Success criteria: the future success of PAN technologies will depend on various criteria which ensure the general acceptance and widespread adoption of PAN technologies.

- Application areas: this aspect represents PAN technologies are utilized in various areas to facilitate individuals or organizations' performance.

- Barriers/Challenges: this area refers to the problems and obstacles associated with implementation of PANs in the future.

The Delphi Method is the research methodology utilized to collect data in this study. The Delphi Method is a method for structuring a group communication process to acquire the most reliable and consolidated consensus of opinion from a group of geographically dispersed experts. In this study, the Delphi Method used three rounds of questionnaires spread over eight weeks. Initially, 27 experts accepted the invitation to participate in this study and 19 responses were received in time to be included in the results for round one.

These panelists were recruited from research and industry publications, PAN-related Web sites, the LinkedIn professional networking Web site and the contact database of the Centre for Mobile Computing at Massey University (see Appendix A for a list of panelists).

The first purpose of round one was to review and comment on the 23 issues identified from the review of the literature (see Table 21). At the end of the first round, 16 issues were retained by the Delphi panel (see top portion of Table 21) and seven issues were not accepted by the Delphi panel (see bottom portion of Table 21).

Table 21: PAN Issues Identified from the Literature Review

	Success Criteria	Application Areas	Barriers/Challenges
Accepted by the panel	• interoperability • power management • transmission speed • frequency switching • widespread deployment	• healthcare • monitoring • smart things • cable replacement • body area network • convenience	• security • interference and coexistence • privacy • trade-off of QoS and power efficiency • operating environment
Rejected by the panel	• consumption types • sleep/wakeup scheduling • speed gap • wireless power transfer • range • BlueStar		• location privacy

The second purpose of round one was for the panelists to nominate any issues relevant to the purpose of the study that were not found in the literature review (see Table 22).

Round two questionnaire required participants to rate all issues on their importance to the future of personal area networks. Furthermore, the panelists were required to provide comments about their decisions as feedback to other panelists. Eighteen of the 19 panelists participated in round two.

In round two, panelists were also asked to vote to accept or reject the 14 issues nominated in round one. Nine issues were accepted to go on to round three (see top portion of Table 22) and five issues were rejected (see bottom portion of Table 22).

Table 22: PAN Issues Nominated by the Delphi Panel

	Success Criteria	Application Areas	Barriers/Challenges
Accepted by the panel	• usability • reliability of connection • functionality	• universal identification • agriculture • proximity sensors	• regulation and standards • embeddedness and wearability • self-organization
Rejected by the panel	• cost	• eco-PAN	• data management • environmental issues • human interface

In round three, the 18 panelists were asked to reconsider their ratings in the light of the ratings and comments from other panelists in round two, in order to achieve a consensus.

The fifteen most important issues that will determine the future of personal area networks in a ubiquitous computing world are shown in Table 23, based on analysis of round three results.

Table 23: Top Fifteen Issues that Will Determine the Future of PANs

Success Criteria	Application Areas	Barriers/Challenges
• reliability of connection	• monitoring	• security
• interoperability	• healthcare	• interference and coexistence
• usability	• smart things	• regulation and standards
• power management	• cable replacement	• self-organization
• widespread deployment	• body area network	• privacy

Implications of the Research

From a PAN developer's perspective, the results of this study are important in terms of developing new PAN systems, for example in highlighting the importance of success criteria such as interoperability and usability and challenges such as security and coexistence. Similarly, these findings offer guidance to developers in designing new PAN technologies and directing the design process. From this study, design resources can be allocated more efficiency to maximize success criteria and minimize barriers and challenges.

End users will also benefit from these findings because if PANs are properly designed and developed prior to the utilization, consumers and users will receive benefits such as better quality of services, more secure data communication, and more efficient power usage. Since PAN devices will be everywhere in the anticipated ubiquitous computing world, there will have to be a solid environment so suitably designed PANs can be used in the key application areas identified in this study – for monitoring, health care, smart things and others. Whereas developers will receive direct benefits from this study, end users will benefit indirectly.

From a research perspective, it is interesting to note that several of the most important success criteria (e.g., reliability of connection, usability) and challenges (e.g., self-organization) were not identified in the literature review. Researchers will need to pay more attention to these because the usual criteria for determining success of wireless telecommunication networks might not determine the success of personal area networks.

To barriers and challenge section, security issue is still the most significant aspect to PANs and other network technologies. Due to rapidly developing PAN technologies, regulations and standards is reasonable to become the third important barriers and/or challenges ahead. However, it is surprising to notice that self-organization has such a high ranking (the fourth) among all eight issues. A possible explanation for this phenomenon is that it would be complex or difficult if PANs do not allow self-adjustment due to the rapidly changing computing environment.

Limitations of the Study

PAN is a fast-moving area and constantly being updated with the introduction of new technologies, emerging applications, and revised standards. An important limitation of this study is that as PAN rapidly changes, the conclusions of this research study will change, and so it has would have less lasting significance than predictive studies of more traditional technologies. As suggested below, follow-up research might be necessary in a few years.

Although the size of the panel (18-19 members) was sufficient, the heterogeneity of the panelists was not ideal as 15 of the final 18 panelists were from New Zealand. Therefore, it is possible that the results have a geographic bias. This is partly offset by the issues being identified from a review of the international literature and the international experience of several of the panelists (see Appendix A). With the exception of the agriculture application area, all other issues seem to apply to an international context.

There were quite a few changes in results from round two to round three in this study. So while a probable consensus was reached, this was not confirmed in a fourth round of the Delphi panel, for reasons listed earlier. A fourth round would have determined if a definitive consensus had been achieved.

Suggestions for Future Studies

The following discussion proposes opportunities that can be included in future studies in this area.

First, as mentioned above, PAN is a dynamic technology. It would be appropriate to conduct a similar study to forecast the future prospects of PAN in three to five years. Such a study, using a similar Delphi process with different panelists, would also provide interesting comparative data and offer some longitudinal insight into this research area.

Second, a future study might utilize other research method to predict the future of PANs. This research uses experts' opinions to forecast the future trends of PANs. However, the judgments of end users could provide additional insight into whether PAN technologies will be successful or not, and in what consumer applications. Possible research methods could be survey, interview or focus groups with experienced PAN users.

Third, a final suggestion is to focus on the passive component aspect of PANs, which are represented by near field communication (NFC) and radio frequency identification (RFID) that were excluded from this study. Another possible study would be research about comparison between passive PAN technologies and active PAN technologies.

Conclusion

In conclusion, this research focused on the future prospects of PANs through three main aspects: success criteria, application areas, and barriers/challenges. By using the Delphi Method as the research methodology, three Delphi surveys were conducted and circulated to the selected group of panelists in order to obtain experts' opinions on issues identified from the international literature and nominated by the panelists. The contributions of this study is that it identified the most influential issues associated personal area networks and filled a gap in the literature, since there are no similar studies.

As an important part of ubiquitous computing world of the future, PAN technologies will be a significant part of everyday life. Comprehensive knowledge of PAN will benefit individuals researchers, professionals, and organizations to make efficient and effective decisions. This study has helped show the way ahead.

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APPENDIX A: BIBLIOGRAPHY OF PANELISTS

This Appendix identifies the name, position, company, country and short bibliographical information of 17 of the 18 panelists who participated in all three rounds of the Delphi study used in this research study. One panelist did not want to be identified except by country of residence (New Zealand).

The panelists are listed in alphabetical order, which is not related to the way they were identified in this research. Specifically, labels such as “expert 1” were based on random assignment. Accordingly, while the panelists are identified here, there contributions to the study remain confidential.

Danny Adair: Director, Unfold Limited (New Zealand). Mr. Adair has over 10 years experience in ICT field and his technical interests include GNU/Linux, software engineering, client/server architectures and Web applications. His recent work (VanStar – Open Source Mobile Sales Solution) was judged finalist in the category “Excellence in Mobile and Wireless Solutions” of the Computerworld Excellence Awards in 2006.

Mark Barlow: Technology Strategist Services, Telecom (New Zealand). Mark has over 25 years of Information Technology experience spanning programming, systems analysis, project management and high level strategic consultancy. This includes over 19 years of Internet experience dating back to even before the World Wide Web. He is a member of the PMI and has over 5,000 hours of programme & project management experience. He has managed a number of large projects and delivered strategic consultancy for companies as diverse as Telecom, Sky City, UBD, Toll, and Rongopai Wines.

Prashant Belwalkar: Sector Manager for ICT, New Zealand Trade & Enterprise (New Zealand). Prashant is responsible for the growth of telco/wireless sector in the international market.

Paul Dromgool: Enterprise Solutions Specialist, Gen-i (New Zealand). Mr. Dromgool has involved in electronics and wireless industry for 15 years including Mobile Data/3G experience at Telecom NZ for 6 years.

Vern Fotheringham: Managing Director, IP Broadband Ltd (United States). Mr. Fotheringham is recognized internationally as an industry leader and successful entrepreneur in the wireless and broadband communications industry. Throughout his career he has been a catalyst for innovation and change in the competitive telecommunications field through numerous direct entrepreneurial activities; as an advisor or influencer on many successful projects for major service providers, system vendors, software application developers and hosted service operators. He has also been active as a public policy and regulatory advocate for new telecommunications service rules and standards; and as an inventor and creator of new and innovative products and services.

Steve Greenley: IT Consultant, SolNet Solutions Ltd (New Zealand). Steve Greenley is a senior IT consultant with over 25 years of experience. He is a Chartered Engineer and has covered a broad range of IT roles including software development, systems architecture, business analysis and project management.

John Humphrey: CEO, Convergex Ltd (New Zealand). John Humphrey has worked with leading edge telecommunications technologies for many years, pioneering the markets for satellite, fibre optic, wireline and wireless products and services. His experience has provided him with a unique blend of skills that bridge all aspects of the marketing, financial and operational requirements of major telecommunications projects. Over the past two decades John has earned a reputation for the translation of sound vision into innovative telecommunications technology applications to deliver new products and services to both wholesale carrier and end user customers.

Thienne Johnson: Post-doctoral Fellow, Unicomp (State University of Campinas) (Brazil). Dr. Thienne Johnson's past research interests were on ad hoc networks routing protocols. Her current research interests are mobility management in IP networks and mobility for body area networks.

Ross Kennedy: Coaching Director, Business Facilitators Ltd (New Zealand). Mr. Kennedy is currently a business and goals coach, having arrived at that destination from working with SMEs in franchising specifically retail, Ross was involved in the establishment of the Lotteries network in 1987. He started his career as an agriculturalist, working with and educating farming students and farmers in the management and husbandry of dairy farming when the use of electronic data storage was beginning, working with farmers who at that time only had a vision for its use and value in to the industry.

Dave Parry: Senior Lecturer, Auckland University of Technology (New Zealand). Dr. Dave Parry is the founding director of the AUT RFID applications Laboratory and his research interests include the use of RFID in healthcare, information retrieval, fuzzy ontologies, health informatics, and the semantic web.

Krassie Petrova: Senior Lecturer, Auckland University of Technology (New Zealand). Ms. Petrova's research and scholarship interests are in the area of mobile computing and facilitating technologies, mobile business and applications, mobile networks and network conversion, and emerging information systems supported by ubiquitous devices.

Adrian Pike: Engineering Manager, ECKey Ltd (New Zealand). Mr. Adrian Pike is an embedded software engineer with 15 years experience. He is currently responsible for all engineering activities of a small design and development company that produces Bluetooth access control products.

Grant Pugh: Managing Director, Tracient Technologies (New Zealand). Grant is the Founding Director of Tracient Technologies. He has over 28 years experience in electronics, telecommunications and semiconductor industries both in New Zealand and in the UK. He has managed over 300 electronic and software product development projects to date. Grant has a wealth of experience providing product development skills and strategic technology assessment and new product introduction, scalable manufacture techniques and risk managed development. Grant's company designs and manufactures RFID and NFC products for the mobile enterprise.

Joseph Stuart: Business Manager, Foundation for Research, Science and Technology (New Zealand). Mr. Joseph Stuart is an accredited economic developer (AEcD NZ) working for New Zealand's largest public sector R&D investor with a particular focus on creative and ICT sector investments through TechNZ.

Philip Verstraaten: Director, Orbiz International Ltd (New Zealand). Philip manages Orbiz, a software development company that specialized in mobile and wireless technologies.

Alistair Vickers: Information System and Business Intelligence Manager, Royal New Zealand Plunket Society (New Zealand). Mr. Vickers started his IT career developing applications for WAP-enabled phones (such as location-based services guides) in Germany for Deutsche Telecom's developers, before moving to Nortel Networks where he spent some time conceptualizing IP routing protocols, together with innovative uses for Bluetooth and UMTS/3G networks.

Hiroyuki Yomo: Associate Professor, Aalborg University (Denmark). Dr. Hiroyuki Yomo's research interests are access technologies, radio resource management, and link-layer techniques in the area of short-range communications, cellular network, cognitive radio, and relay network.

APPENDIX B: ROUND ONE QUESTIONNAIRE

The Future of Personal Area Networks in a Ubiquitous Computing World

Round One Questionnaire

In round one, issues determining the future prospects of PANs are listed in three sections: success criteria, applications and barriers/challenges. As one of the panelists, you are asked to:

- Read the enclosed "Research Information Sheet" and "Delphi Method Information Sheet" to familiarize yourself with the research.
- Read the enclosed "Background Reading" carefully to answer the questions below.
- Optionally, read the enclosed "Supplement Reading" if you are unfamiliar with any of the PAN technologies.
- Complete this questionnaire.

Please write legibly in different font/color and return this questionnaire as an e-mail attachment to zhaofeicn@gmail.com no later than **25 March 2008**.

Your name: ____

Section 1: PAN Success Criteria

In this section, the primary focus is what the success criteria are in the future that will enable PAN to succeed. Please reference any articles, knowledge or experiences that influenced your opinion or might be useful for the study. Your tasks here are:

1. Determine if the following criteria are appropriate.
2. Add missing success criteria.
3. Comment on your decision and/or the discussion in the background reading.

In round two, the success criteria that selected from round one will be rated and ranked by the panelists to determine the most significant ones.

Transmission Speed

PAN technologies have various transmission speeds which influence application areas and quality of service. Will the transmission speed of a PAN technology determine its success in the future?

Retain as a success criteria? Delete? Comments:

Power Management

Currently, all PAN technologies are powered by batteries, hence all systems have limited service and coverage areas. Do you think an efficient power management will ensure the success of a specific PAN technology in the future?

Retain as a success criteria? Delete? Comments:

Consumption types

Power consumption can be divided into three main components: processing, storage and communication. These types consume different levels of power supply. Will these consumption types impact on power management, therefore influence on the future success of PANs? Which one of these will be the most critical for power management to ensure the success of PAN technologies?

Retain as a success criteria? Delete? Comments:

Sleep/Wakeup scheduling

Sleep/Wakeup scheduling is a power management protocol which ensures power efficiency according to network congestion and traffic demand. Is it an important criterion to power management and so to the future success of PAN?

Retain as a success criteria? Delete? Comments:

Speed gap

As computing speed increases, the speed gap between human users and computers is increasing as they are interacting. To utilize power more efficiently, is speed gap a critical issue?

Retain as a success criteria? Delete? Comments:

Wireless power transfer

Wireless power transfer refers to devices that absorb power from incoming radio frequency to transmit and/or respond messages. It seems to be significant especially to low power devices. Will wireless power transfer be a critical component to power management in the future?

Retain as a success criteria? Delete? Comments:

Frequency Switching

Many PAN technologies operate in the unlicensed 2.4GHz band. This raises issues of interference (as discussed in Section 3). Is this an issue that is critical to the success of PANs? A potential solution is for PAN technologies to utilize multiple radio frequencies. This could possibly provide an advantage of one technology or another. Do you agree?

Retain as a success criteria? Delete? Comments:

Range

As short-range wireless technologies, PANs have traditionally operated in small distances. However, the coverage of PANs is becoming larger and larger as these technologies advance. On the other hand, larger coverage usually means higher power supply or more dedicated devices. How critical is range to the future of PANs?

Retain as a success criteria? Delete? Comments:

Cooperative Exchange

Cooperative exchange refers to PAN devices that can establish a connection to transmit data through two or more types of PAN technologies. Is it a success criterion for PAN technologies to be capable of cooperative exchange?

Retain as a success criteria? Delete? Comments:

BlueStar

The BlueStar technology allows a Bluetooth device to become a member of a WLAN, in order to access the Internet. Do you think this type of cooperative exchange between a PAN and a WLAN is a special case of cooperative exchange that will determine the success of PANs?

Retain as a success criteria? Delete? Comments:

Widespread deployment

Although recent PAN technologies (e.g., UWB) offer a better quality of service in terms of range, speed, etc, mature wireless technologies such as the Bluetooth or infrared still dominate the device marketplace. Is widespread deployment a critical success factor for PAN technologies?

Retain as a success criteria? Delete? Comments:

Additional PAN success criteria you might suggest (please list and briefly describe):

Section 2: Application Areas

For your information, this section focus on what application areas will be the most important in the future. In this study, an important application area is considered to be utilized by widespread popularity with a large number of users. Please reference any articles, knowledge or experiences that influenced your opinion or might be useful for the study. Your tasks here are:

1. Determine if the following application areas are appropriated.
2. Add missing application areas.
3. Comment on your decision and/or the discussion in the background reading.

In round two, the application areas that selected from round one will be rated and ranked by the panelists to determine the most significant ones.

Body area network

Body area networks (BAN) are applications in which mobile devices are embedded in or carried on human bodies. However, concerns surrounding BAN's implementation focus on several issues such as the size and weight of wireless sensors and varied wireless technologies. Is body area network an application that will be important to PANs in a ubiquitous computing world?

Retain as an application area? Delete? Comments:

Healthcare usage scenario

Currently, BANs are most popular as a healthcare solution. In this application, BANs bear responsibilities in continuous health monitoring and real-time feedback. In order to establish a BAN for a patient, wireless sensors will be located closely or even planted into human body. Will healthcare usage of BANs be a critical application area for PAN technologies?

Retain as an application area? Delete? Comments:

Cable replacement

Cable replacement was the original "killer application" for wireless technologies. And still it is a great advantage for emerging PAN technologies to succeed because of the high data rate requirement in the current marketplace. Can cable replacement survive as a critical application area for PAN technologies in the future?

Retain as an application area? Delete? Comments:

Monitoring

The main characteristic of PAN monitoring systems is to share information between mobilized objects within a very short-range. Despite the use of PAN technologies in healthcare monitoring, monitoring applications can be employed as event detection, passive or active sensing and data logging or real-time monitoring. Will monitoring still be an important area for PAN technologies to be utilized?

Retain as an application area? Delete? Comments:

Convenience

PAN applications can be critical to provide convenience services such as remote control and obstacle avoidance, etc. In the future, is "convenience applications" going to be an important driving force for PAN development?

Retain as an application area? Delete? Comments:

Smart things

In the ubiquitous computing world of the future, ubiquitous computation services will be the main driving force, and the corresponding essential element would be "smart things" with embedded computers. Smart applications allow the invisibility of computational technology services in the real world. However, the challenge ahead is to deploy such unobtrusive smart environments without violating social and legal rules of people's everyday life. Will "smart things" be an important application area for PAN implementation?

Retain as an application area? Delete? Comments:

Additional PAN application areas you might suggest (please list and briefly describe):

Section 3: Barriers and Challenges to Implementation

In this section, the primary focus is to identify what the most important barriers and challenges are to PAN development and deployment. Please reference any articles, knowledge or experiences that influenced your opinion or might be useful for the study. Your tasks here are:

1. Determine if the following barriers and challenges are appropriated.
2. Add missing barriers or challenges.
3. Comment on your decision and/or the discussion in the background reading.

In round two, the barriers and challenges that selected from round one will be rated and ranked by the panelists to determine the most significant ones.

Security

Security standards for wired networks or long-range wireless network are rarely suitable since PANs devices are mobile, have no requirement for physical infrastructure and have low processing power. However, normal security concerns (e.g., authorization, availability) still apply to PANs, or do they? Is security a barrier to PAN development and deployment?

Retain as a barrier or challenge? Delete? Comments:

Interference and Coexistence

The unlicensed 2.4 GHz frequency band is shared by many PAN technologies as well as WLAN and other appliances. A main drawback is to tolerate the interference. Are interference and coexistence barriers/challenges to PAN technologies? How well will various wireless technologies coexist in the shared frequency band?

Retain as a barrier or challenge? Delete? Comments:

Privacy

As discussion in the background reading, wireless networks are the best medium to provide privacy as well as the most threatening medium to user privacy. Hidden privacy or anonymity could cause wireless networks to become a potential places to commit a crime. Is privacy a barrier/challenge to PANs?

Retain as a barrier or challenge? Delete? Comments:

Location privacy

An attacker is able to track the place and time of the communication between mobile devices by eavesdropping on transmitted data. Low-cost cryptography is necessary to prevent this problem by using a temporary random identifier. Do you think location privacy is an important barrier/challenge to PAN technologies?

Retain as a barrier or challenge? Delete? Comments:

Tradeoff between quality of service (QoS) and power efficiency

Power consumption can affect the system performance of PANs in many ways. However, because of rapidly increasing requirements in QoS and slowly developing battery capacity, it is necessary to consider the tradeoff between QoS and power efficiency in system design. Should tradeoff between QoS and power efficiency be a barrier/challenge associated with PAN implementation?

Retain as a barrier or challenge? Delete? Comments:

Environment

In the ubiquitous computing world, a mobile device might encounter many other wireless devices with different protocols and interfaces. Also, the network capacity should be considered for PAN implementation in the nature environment as the more populated network might result in less shared resources. Will the environment aspect be a barrier/challenge to PAN technologies?

Retain as a barrier or challenge? Delete? Comments:

Additional PAN barriers and challenges of implementation you might suggest (please list and briefly describe):

Thank you for your participation. My supervisor and I appreciate your precious time.

APPENDIX C: ROUND TWO QUESTIONNAIRE

The Future of Personal Area Networks in a Ubiquitous Computing World
Round Two Questionnaire

Thank you for your participation in round one. To ensure the validity of the final results, your participation in the second round is critical. Specifically, "panel burnout" is a clearly identifiable problem with Delphi Method studies – a study that ends round three with a fraction of the participants in round one has far less credibility in the research marketplace.

To assist you in completely round two easily and within the two-week deadline, considerable effort has gone into summarizing the results from round one and to make this questionnaire easy for you to submit your results for round two.

In round two, you are requested to:

- Read the enclosed "Round One Results Report" to learn of the results from round one. Briefly, the report is divided into three sections – PAN success criteria, PAN application areas and PAN barriers/challenges – that summarizes the panel's decisions to retain or delete issues in these sections plus new issues that were accepted from the panel's nominations. The report concludes with three appendices that provide detailed feedback from each panelist for each issue.
- If you need to refresh your memory about issues that were in round one, please review the "Background Reading" that is attached, for your convenience.
- For each issue that is listed in this questionnaire, please rate your judgment on its importance to the future of PAN on a 5-point scale ranging from "very important" to "not important at all" (see below).
- For each new issue that was nominated from round one, decide to retain or delete (i.e., these issues were nominated by 1 or more panelists, but a collective opinion on their inclusion is desirable).
- Please provide any appropriate comment on your decision.

The following table indicates the 5-points scale used for this study.

Scale	Description
1	Very Important
2	Important
3	Neutral
4	Unimportant
5	Not important At All

Please type in different font/color and return this questionnaire as an e-mail attachment to zhaofeicn@gmail.com **no later than 22 April 2008**.

Your Name: ________________________________

Section 1A PAN Success Criteria

In this section, the primary focus is on what success criteria will enable personal area networks to succeed in the future world of ubiquitous computing. In your comments, please reference any articles, knowledge or experiences that influenced your decision or might be useful for the study.

In round two, your tasks here are to:

1. Rate all listed criteria on a scale of 1 to 5.
2. Comment on your ratings.

Remember, if you are unclear about the criteria, refer to the background reading that was used in round one.

For your information, in round three, each panelist will be presented with the ratings from other panelists in round two and you will be asked to confirm or change your ratings in order to achieve a consensus on the most important success criteria. Your comments will help other panelists to understand how you rated each criterion.

Briefly, the success criteria assessed in this section include:
Success criteria from the literature and retained by the panel from round one:

- Transmission speed
- Power management
- Power consumption type
- Frequency switching
- Range
- Interoperability (was cooperative exchange)
- Widespread deployment

New success criteria, nominated from the panel in round one:

- Usability
- Functionality
- Reliability of connection
- Cost

Transmission speed
Transmission speed refers to the speed at which information is transferred wirelessly. PAN technologies have various transmission speeds which influence application areas and quality of service.

How important is transmission speed to the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Power management
Currently, all PAN technologies are powered by batteries. Efficient battery power utilization is rapidly becoming an important issue.

How important is power management to the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Power consumption type
Within the general area of power management is type of power consumption – for processing, storage and communication.

How important is power consumption type to the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Frequency switching
Many PAN technologies operate in the unlicensed 2.4 GHz band. This raises issues of interference (as considered in Section 3) and the ability for PANs to use multiple radio frequencies in a collaborative manner (as considered here).

How important is frequency switching to the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Range
As short-range wireless technologies, PANs have traditionally operated in small distances. However, the coverage of PANs is becoming larger and larger as these technologies advance. On the other hand, larger coverage usually means higher power supply or more dedicated devices.

How important is range to the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Interoperability (was cooperative exchange)
Cooperative exchange refers to PAN devices that can establish a connection to transmit data through two or more types of PAN technologies. A broader term is interoperability, which is the ability for PANs to transmit data to and from LANs and WANs.

How important is interoperability to the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Widespread deployment
Although recent PAN technologies (e.g., UWB) offer a better quality of service in terms of range, speed, etc, mature wireless technologies such as the Bluetooth or infrared still dominate the device marketplace.

How important is widespread deployment to the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Section 1B Nominated Success Criteria
The following success criteria were suggested by panelists in round one and have been accepted for inclusion in round two. In addition to rating the criteria (as you have been doing above), you are also asked to retain or delete as a success criterion. This is because these were nominated by 1 or more panelist, but this is the first time the entire panel has had a chance to express its collective judgment about the inclusion in the final list of criteria. If you need more information about these, consult the Round One Report, Table 2.

Usability
The aim of usability is to guide users through efficient, effective and satisfying process to accomplish their goals in using a product. Usability involves many aspects of a product such as ease of use, user satisfaction, connectivity, user interface, etc. Do you think usability is an important criterion?

Retain as a success criterion? Delete? ____________ Comments:

Regardless of your response (even if delete) please answer the following:

How important is usability to the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Functionality
Generally, functionality is the degree to which a PAN technology is able to meet the needs of the user or, as one panelist put it: "if a technology offers unique utility / functionality that is widely desired, then it will succeed". Do you agree? Do you think functionality is an important criterion?

Retain as a success criterion? Delete? ____________ Comments:

Regardless of your response (even if delete) please answer the following:

How important is functionality to the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Reliability of Connection
Increasingly PAN technologies are demanding highly reliable connections, especially multimedia connections that consist of high data capacity and fast speed. Reliability of connection is "being able to connect and stay connected". Do you agree this is an important success criterion to the future of PANs?

Retain as a success criterion? Delete? ____________ Comments:

Regardless of your response (even if delete) please answer the following:

How important is reliability of connection to the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Cost
In the literature, PAN technologies are seen as being inherently inexpensive, but “cost”, “overall cost” and aspects of cost such as “affordability” were raised by panelists. What do you think? Do you agree that cost is an important success criterion to the future of PANs?

Retain as a success criterion? Delete? ____________ Comments:

Regardless of your response (even if delete) please answer the following:

How important is cost to the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Section 2A Application Areas
This section focuses on what application areas will be the most important for the future of PAN. In this study, an important application area is considered to be utilized by widespread popularity with a large number of users. In your comments, please reference any articles, knowledge or experiences that influenced your opinion or might be useful for the study.

In round two, your tasks here are to:
1. Rate all listed application areas on a scale of 1 to 5.
2. Comment on your ratings.

Remember, if you are unclear about the application area, refer to the background reading that was used in round one.

For your information, in round three, each panelist will be presented with the ratings from other panelists in round two and you will be asked to confirm or change your ratings in order to achieve a consensus on the most important application areas. Your comments will help other panelists to understand how you rated each application area.

Briefly, the application areas assessed in this section include:
Application areas from the literature and retained by the panel from round one:
- Body area network
- Healthcare usage
- Cable replacement
- Monitoring
- Convenience
- Smart things

New application areas, nominated from the panel in round one:
- Universal identification
- Proximity sensors
- Eco-PAN
- Agriculture

Body area network

Body area networks (BAN) are applications in which mobile devices are embedded in or carried on human bodies. However, concerns surrounding BAN's implementation focus on several issues such as the size and weight of wireless sensors and varied wireless technologies.

How important is body area network as an application area in the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Healthcare usage scenario

Currently, BANs are most popular as a healthcare solution. In this application, BANs bear responsibilities in continuous health monitoring and real-time feedback. In order to establish a BAN for a patient, wireless sensors will be located closely or even planted into human body.

How important is healthcare usage as an application area in the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Cable replacement

Cable replacement was the original "killer application" for wireless technologies. And still it is a great advantage for emerging PAN technologies to succeed because of the high data rate requirement in the current marketplace.

How important is cable replacement as an application area in the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Monitoring

The main characteristic of PAN monitoring systems is to share information between mobilized objects within a very short-range. Despite the use of PAN technologies in healthcare monitoring, monitoring applications can be employed as event detection, passive or active sensing and data logging or real-time monitoring.

How important is monitoring as an application area in the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Convenience
PAN applications can be critical to provide convenience services such as remote control and obstacle avoidance, etc.

How important is convenience as an application area in the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Smart things
In the ubiquitous computing world of the future, ubiquitous computation services will be the main driving force, and the corresponding essential element would be "smart things" with embedded computers.

How important is smart things as an application area in the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Section 2B Nominated Application Areas
The following application areas were suggested by panelists in round one and have been accepted for inclusion in round two. In addition to rating the application area (as you have been doing above), you are also asked to retain or delete as an application area. This is because these were nominated by 1 or more panelists, but this is the first time the entire panel has had a chance to express its

collective judgment about the inclusion in the final list of application areas. If you need more information about these, consult the Round One Report, Table 4.

Universal identification

Universal identification, or universal ID, is similar to having a passport in a PAN device. Applications from identifying a person positively will help multiple applications such as payments, cards, driver licensing and cross border travel. Do you think this is an important application area in the future?

Retain as an application area? Delete? ____________ Comments:

Regardless of your response (even if delete) please answer the following:

How important is universal ID as an application area in the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Proximity Sensors

Devices with personal profiles will enable users to find nearby users with similar interests or to locate nearby friends ("friend finder") – both social interaction applications. Proximity sensors will also allow applications in location-based advertising and security monitoring. Do you think proximity sensors is an important application area in the future?

Retain as an application area? Delete? ____________ Comments:

Regardless of your response (even if delete) please answer the following:

How important is proximity sensors as an application area in the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Eco-PAN

PAN technologies could be applied to "eco-conscious applications which help monitor, reduce and eliminate waste – even down to being able to remote monitor electricity use at home and switch off rogue appliances". Do you agree this is an important application area in the future?

Retain as an application area? Delete? ____________ Comments:

Regardless of your response (even if delete) please answer the following:

How important is eco-PAN as an application area in the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Agriculture
This application area signifies that PAN technologies can be widely utilized in the agricultural sector. Do you agree agriculture is an important application area in the future?

Retain as an application area? Delete? ____________ Comments:

Regardless of your response (even if delete) please answer the following:

How important is agriculture as an application area in the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Section 3A Barriers and Challenges to Implementation
The primary focus of this section is to identify what are the most important barriers and challenges to PAN development and deployment. In your comments, please reference any articles, knowledge or experiences that influenced your opinion or might be useful for the study.

In round two, your tasks here are to:
1. Rate all listed barrier/challenge on a scale of 1 to 5.
2. Comment on your ratings.

Remember, if you are unclear about the barrier or challenge, refer to the background reading that was used in round one.

For your information, in round three, each panelist will be presented with the ratings from other panelists in round two and you will be asked to confirm or change your ratings in order to achieve a consensus on the most important barriers/challenges. Your comments will help other panelists to understand how you rated each barrier/challenge.

Briefly, the barriers and challenges assessed in this section include:
Barriers/Challenges from the literature and retained by the panel from round one:
- Security

- Interference and coexistence
- Privacy
- Trade-off of quality of service and power efficiency
- Operating environment

New barriers/challenges, nominated from the panel in round one:

- Regulation and standards
- Self-organization
- Data Management
- Environmental issues
- Human interface
- Embeddedness and wearability

Security

Security standards for wired networks or long-range wireless network are rarely suitable since PANs devices are mobile, have no requirement for physical infrastructure and have low processing power.

How important is security as a barrier/challenge in the deployment of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Interference and coexistence

The unlicensed 2.4 GHz frequency band is shared by many PAN technologies as well as WLAN and other appliances. A main drawback is to tolerate the interference.

How important is interference and coexistence as a barrier/challenge in the deployment of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Privacy

Wireless networks are the best medium to provide privacy as well as the most threatening medium to user privacy. Hidden privacy or anonymity could cause wireless networks to become a potential place to commit a crime.

How important is privacy as a barrier/challenge in the deployment of PANs?

Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Trade-off between quality of service and power efficiency
Power consumption can affect the system performance of PANs in many ways. However, because of rapidly increasing requirements in QoS and slowly developing battery capacity, it is necessary to consider the trade-off between QoS and power efficiency in system design.

How important is the trade-off between QoS and power as a barrier/challenge in the deployment of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Operating environment
In the ubiquitous computing world, a mobile device might encounter many other wireless devices with different protocols and interfaces. Also, the network capacity should be considered for PAN implementation in the natural environment as the more populated network might result in less shared resources.

How important is the operating environment as a barrier/challenge in the deployment of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Section 3B Nominated Barriers and Challenges
The following barriers/challenges were suggested by panelists in round one and have been accepted for inclusion in round two. In addition to rating the barrier/challenge (as you have been doing above), you are also asked to retain or delete as a barrier/challenge. This is because these were nominated by 1 or more panelists, but this is the first time the entire panel has had a chance to

express its collective judgment about the inclusion in the final list of barriers and challenges. If you need more information about these, consult the Round One Report, Table 6.

Regulation and standards
This barrier includes the lack of consistent standards (to enable interoperable PAN communications) and regulation (who will set and enforce the standards). Do you think regulation and standards will be a barrier or challenge in the future?

Retain as a barrier/challenge? Delete? ____________ Comments:

Regardless of your response (even if delete) please answer the following:

How important is regulation and standards as a barrier/challenge in the deployment of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Self-organization
Self-organization in PAN technologies reflects issues such as self-configuration and self-customization. Self-organization ensures that PANs can perform in a changing environment, especially with applications that utilize discovery and monitoring. Do you agree self-organization will be a barrier or challenge in the future?

Retain as a barrier/challenge? Delete? ____________ Comments:

Regardless of your response (even if delete) please answer the following:

How important is self-organization as a barrier/challenge in the deployment of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Data Management
The data collected from PAN implementations will have to be integrated so it can be used for generating useful information. As PANs multiply and grow, there will be an increasing quantity of data to collect, process and store. Do you think this issue will be a barrier or challenge in the future?

Retain as a barrier/challenge? Delete? ____________ Comments:

Regardless of your response (even if delete) please answer the following:

How important is data management as a barrier/challenge in the deployment of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Environmental Issues

In the ubiquitous computing future, there will be billions of PAN devices, so it is important to design PAN devices in an environmental-friendly way, including provisions for recycling many parts of the device, or disposable without harming the environment. Do you believe it will be a barrier or challenge to the future implementation of PANs?

Retain as a barrier/challenge? Delete? ____________ Comments:

Regardless of your response (even if delete) please answer the following:

How important is environmental issues as a barrier/challenge in the deployment of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Human interface

On the one hand, a human interface can be a concern if users need to set, control, read or operate these devices, principally because of their small size. However, if these devices are mostly hidden and embedded, then human interaction with them should be minimal. Do you believe it will be a barrier or challenge to the future implementation of PANs?

Retain as a barrier/challenge? Delete? ____________ Comments:

Regardless of your response (even if delete) please answer the following:

How important is human interface as a barrier/challenge in the deployment of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

Embeddedness and wearability
In a ubiquitous computing world, PAN devices will have to be embedded in clothes (body area networks), appliances (smart things) and even wristwatches, eyeglasses, etc. How can this be done without interfering with the operation of the "thing" or the user? Smaller, but related issues include heat management and robustness Do you believe this will be a barrier or challenge to the future implementation of PANs?

Retain as a barrier/challenge? Delete? ____________ Comments:

Regardless of your response (even if delete) please answer the following:

How important is embeddedness and wearability as a barrier/challenge in the deployment of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your rating (1-5):

Your comments:

This is the end of round two questionnaire.

Please return this questionnaire as an e-mail attachment to
zhaofeicn@gmail.com no later than 22 April 2008.

Thank you for your participation!

APPENDIX D: ROUND THREE QUESTIONNAIRE

The Future of Personal Area Networks in a Ubiquitous Computing World

Round Three Questionnaire

Thank you for your participation in round two. To ensure the validity of the final results, your participation in the final round is critical.

The main purpose of round three is to achieve a consensus of experts' opinion over a particular issue. In this study, consensus is defined as a degree of acceptance to all identified issues. Achieving consensus does not imply conformance; you are still asked to use your independent judgment in making your ranking in this round, but do so in light of the ratings and comments from other panelists.

Your comments about your final rating in this round are important, but optional. Panelists' comments will prove very useful to me when I am writing up the results for my thesis. (A reminder that all comments will be reported anonymously.) However, because this is the final round, comments will not be used for further decision making; so if time is an issue for you, rate without comment.

Round three requires the least time of all three questionnaires because this is more of a review-and-re-rate exercise. No new background reading is required.

In round three, your tasks are to:

- Read the enclosed "Round Two Results Report" to learn of the results from round two.
- As you complete each section – success criteria, application areas, barriers/challenges – come to this questionnaire and provide new ratings and, optionally, comments. Please type in different font/color.
- Return this questionnaire as an e-mail attachment to zhaofeicn@gmail.com **no later than 15 May 2008**.

What happens next? The results from all three rounds will be written up objectively as Chapter 4 of my thesis (Results). Then the results will be analyzed and interpreted in Chapter 5 (Discussion). After this is done (Approximately in July) I will prepare a summary of these two chapters and send this summary to all panelists who participated in round three. This summary will provide you with the results of the study and is one way I can say THANK YOU for your participation.

Fei Zhao

The Future of Personal Area Networks in a Ubiquitous Computing World

Round Three Questionnaire

Your Name: ________________________________

Section 1 PAN Success Criteria

In this section, your tasks here are to:

1. Compare your ratings for success criteria in round two with the mean and individual panelists in Table A in Appendix A of the round two report (a reminder: your expert # is included in the email message that accompanied with the report),
2. Read the comments from all panelists concerning the issue (Appendix A of the round two report),
3. Consider your rating in relation to the group mean, how the rating distribution among all panelists (see Table A in round two report) and comments. Indicate your new round three rating in this questionnaire. You may remain your rating the same or modify it. Exercise your independent judgment as a knowledgeable expert, but in light of what other panelists have rated and said in round two.
4. Your comments in round three are important but optional. We would appreciate any summary judgment, comment or justification for your rating as that will help us explain the results when writing the thesis. If your final rating is noticeably different from the group consensus in round two, your comments which explain your divergent opinion will definitely facilitate others to understand your point of view.

Briefly, the success criteria included in this section are:

- Interoperability
- Reliability of connection
- Power management
- Transmission Speed
- Usability
- Frequency switching
- Functionality
- Widespread deployment

Interoperability (was cooperative exchange)
Cooperative exchange refers to PAN devices that can establish a connection to transmit data through two or more types of PAN technologies. A broader term is interoperability, which is the ability for PANs to transmit data to and from LANs and WANs.

How important is interoperability to the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Reliability of Connection

Increasingly PAN technologies are demanding highly reliable connections, especially multimedia connections that consist of high data capacity and fast speed. Reliability of connection is "being able to connect and stay connected". Do you agree this is an important success criterion to the future of PANs?

How important is reliability of connection to the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Power management

Currently, all PAN technologies are powered by batteries. Efficient battery power utilization is rapidly becoming an important issue.

How important is power management to the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Transmission speed

Transmission speed refers to the speed at which information is transferred wirelessly. PAN technologies have various transmission speeds which influence application areas and quality of service.

How important is transmission speed to the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Usability

The aim of usability is to guide users through efficient, effective and satisfying process to accomplish their goals in using a product. Usability involves many aspects of a product such as ease of use, user satisfaction, connectivity, user interface, etc. Do you think usability is an important criterion?

How important is usability to the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Frequency switching

Many PAN technologies operate in the unlicensed 2.4 GHz band. This raises issues of interference (as considered in Section 3) and the ability for PANs to use multiple radio frequencies in a collaborative manner (as considered here).

How important is frequency switching to the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Functionality

Generally, functionality is the degree to which a PAN technology is able to meet the needs of the user or, as one panelist put it: “if a technology offers unique utility / functionality that is widely desired, then it will succeed”. Do you agree? Do you think functionality is an important criterion?

How important is functionality to the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Widespread deployment

Although recent PAN technologies (e.g., UWB) offer a better quality of service in terms of range, speed, etc, mature wireless technologies such as the Bluetooth or infrared still dominate the device marketplace.

How important is widespread deployment to the future of PANs?

Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Section 2 PAN Application Areas

In this section, your tasks here are to:

1. Compare your ratings for application areas in round two with the mean and individual panelists in Table B in Appendix B of the round two report (a reminder: your expert # is included in the email message that accompanied with the report),
2. Read the comments from all panelists concerning the issue (Appendix B of the round two report),
3. Consider your rating in relation to the group mean, how the rating distribution among all panelists (see Table B in round two report) and comments. Indicate your new round three rating in this questionnaire. You may remain your rating the same or modify it. Exercise your independent judgment as a knowledgeable expert, but in light of what other panelists have rated and said in round two.
4. Your comments in round three are important but optional. We would appreciate any summary judgment, comment or justification for your rating as that will help us explain the results when writing the thesis. If your final rating is noticeably different from the group consensus in round two, your comments which explain your divergent opinion will definitely facilitate others to understand your point of view.

Briefly, the application areas included in this section are:

- Healthcare
- Monitoring
- Smart things
- Cable replacement
- BAN
- Convenience
- Universal ID
- Agriculture
- Proximity sensors

Healthcare usage scenario

Currently, BANs are most popular as a healthcare solution. In this application, BANs bear responsibilities in continuous health monitoring and real-time feedback. In order to establish a BAN for a patient, wireless sensors will be located closely or even planted into human body.

How important is healthcare usage as an application area in the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Monitoring

The main characteristic of PAN monitoring systems is to share information between mobilized objects within a very short-range. Despite the use of PAN technologies in healthcare monitoring, monitoring applications can be employed as event detection, passive or active sensing and data logging or real-time monitoring.

How important is monitoring as an application area in the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Smart things

In the ubiquitous computing world of the future, ubiquitous computation services will be the main driving force, and the corresponding essential element would be "smart things" with embedded computers.

How important is smart things as an application area in the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Cable replacement

Cable replacement was the original "killer application" for wireless technologies. And still it is a great advantage for emerging PAN technologies to succeed because of the high data rate requirement in the current marketplace.

How important is cable replacement as an application area in the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Body area network
Body area networks (BAN) are applications in which mobile devices are embedded in or carried on human bodies. However, concerns surrounding BAN's implementation focus on several issues such as the size and weight of wireless sensors and varied wireless technologies.

How important is body area network as an application area in the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Convenience
PAN applications can be critical to provide convenience services such as remote control and obstacle avoidance, etc.

How important is convenience as an application area in the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Universal identification
Universal identification, or universal ID, is similar to having a passport in a PAN device. Applications from identifying a person positively will help multiple applications such as payments, cards, driver licensing and cross border travel. Do you think this is an important application area in the future?

How important is universal ID as an application area in the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Agriculture
This application area signifies that PAN technologies can be widely utilized in the agricultural sector. Do you agree agriculture is an important application area in the future?

How important is agriculture as an application area in the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Proximity Sensors
Devices with personal profiles will enable users to find nearby users with similar interests or to locate nearby friends ("friend finder") – both social interaction applications. Proximity sensors will also allow applications in location-based advertising and security monitoring. Do you think proximity sensors is an important application area in the future?

How important is proximity sensors as an application area in the future of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Section 3 PAN Barriers and Challenges

In this section, your tasks here are to:

1. Compare your ratings for barriers and challenges in round two with the mean and individual panelists in Table C in Appendix C of the round two report (a reminder: your expert # is included in the email message that accompanied with the report),
2. Read the comments from all panelists concerning the issue (Appendix C of the round two report),
3. Consider your rating in relation to the group mean, how the rating distribution among all panelists (see Table C in round two report) and comments. Indicate your new round three rating in this questionnaire. You may remain your rating the same or modify it. Exercise your independent judgment as a knowledgeable expert, but in light of what other panelists have rated and said in round two.
4. Your comments in round three are important but optional. We would appreciate any summary judgment, comment or justification for your rating as that will help us explain the results when writing the thesis. If your final rating is noticeably different from the group consensus in round two, your comments which explain your divergent opinion will definitely facilitate others to understand your point of view.

Briefly, the barriers/challenges included in this section are:
- Security
- Interference & coexistence
- Regulation & standards
- Privacy

- Trade-off of QoS & power efficiency
- Operating environment
- Embeddedness & wearability
- Self-organization

Security
Security standards for wired networks or long-range wireless network are rarely suitable since PANs devices are mobile, have no requirement for physical infrastructure and have low processing power.

How important is security as a barrier/challenge in the deployment of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Interference and coexistence
The unlicensed 2.4 GHz frequency band is shared by many PAN technologies as well as WLAN and other appliances. A main drawback is to tolerate the interference.

How important is interference and coexistence as a barrier/challenge in the deployment of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Regulation and standards
This barrier includes the lack of consistent standards (to enable interoperable PAN communications) and regulation (who will set and enforce the standards). Do you think regulation and standards will be a barrier or challenge in the future?

How important is regulation and standards as a barrier/challenge in the deployment of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Privacy
Wireless networks are the best medium to provide privacy as well as the most threatening medium to user privacy. Hidden privacy or anonymity could cause wireless networks to become a potential place to commit a crime.

How important is privacy as a barrier/challenge in the deployment of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Trade-off between quality of service and power efficiency
Power consumption can affect the system performance of PANs in many ways. However, because of rapidly increasing requirements in QoS and slowly developing battery capacity, it is necessary to consider the trade-off between QoS and power efficiency in system design.

How important is the trade-off between QoS and power as a barrier/challenge in the deployment of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Operating environment
In the ubiquitous computing world, a mobile device might encounter many other wireless devices with different protocols and interfaces. Also, the network capacity should be considered for PAN implementation in the natural environment as the more populated network might result in less shared resources.

How important is the operating environment as a barrier/challenge in the deployment of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Embeddedness and wearability

In a ubiquitous computing world, PAN devices will have to be embedded in clothes (body area networks), appliances (smart things) and even wristwatches, eyeglasses, etc. How can this be done without interfering with the operation of the "thing" or the user? Smaller, but related issues include heat management and robustness Do you believe this will be a barrier or challenge to the future implementation of PANs?

How important is embeddedness and wearability as a barrier/challenge in the deployment of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

Self-organization

Self-organization in PAN technologies reflects issues such as self-configuration and self-customization. Self-organization ensures that PANs can perform in a changing environment, especially with applications that utilize discovery and monitoring. Do you agree self-organization will be a barrier or challenge in the future?

How important is self-organization as a barrier/challenge in the deployment of PANs?				
Very Important 1	Important 2	Neutral 3	Unimportant 4	Not important at all 5

Your round three rating (1-5):

Your comments:

This is the end of round three questionnaire.

Please return this questionnaire as an e-mail attachment to zhaofeicn@gmail.com no later than 15 May 2008.

Thank you for your participation!

APPENDIX E: SUMMARY OF ROUND ONE RESULTS

Most experts indicated clear decisions of “retain” or “delete” and these are indicated as Y or N respectively in these tables. In a few instances, the responses were unclear or no response was made. These instances are indicated by ND for “no decision”. Panelists’ comments are not included but are available upon request.

Summarized Results of Success Criteria in Round One

Success Criteria	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12	Expert 13	Expert 14	Expert 15	Expert 16	Expert 17	Expert 18	Expert 19	Retain	Delete	No Decision
Frequency switching	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	19	-0-	-0-
Power management	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	ND	Y	Y	Y	Y	Y	Y	Y	18	-0-	1
Widespread deployment	Y	Y	Y	ND	Y	Y	Y	Y	Y	Y	Y	ND	Y	Y	Y	Y	Y	Y	Y	17	-0-	2
Transmission speed	Y	N	Y	ND	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	16	2	1
Cooperative exchange	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y	N	Y	ND	Y	ND	Y	Y	14	3	2
Range	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N	N	Y	Y	ND	Y	N	N	Y	13	5	1
Consumption type	Y	ND	Y	ND	Y	N	N	N	Y	N	Y	Y	N	Y	Y	Y	ND	Y	Y	11	5	3
Terminated Success Criteria																						
BlueStar	Y	N	Y	N	Y	N	ND	Y	ND	Y	Y	Y	N	Y	N	Y	ND	N	Y	10	6	3
Wireless power transfer	Y	ND	Y	Y	N	Y	N	N	ND	Y	Y	Y	N	N	Y	N	N	Y	Y	10	7	2
Sleep/wakeup scheduling	N	ND	N	N	N	N	Y	N	N	Y	Y	N	Y	Y	ND	Y	Y	Y	N	8	9	2
Speed gap	Y	N	Y	N	N	N	Y	N	N	Y	N	N	N	Y	N	N	N	Y	N	6	13	-0-

Summarized Results of Application Areas in Round One

Application Area	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12	Expert 13	Expert 14	Expert 15	Expert 16	Expert 17	Expert 18	Expert 19	Retain	Delete	No Decision
Smart things	Y	Y	Y	ND	Y	Y	ND	Y	Y	Y	ND	Y	Y	Y	Y	Y	Y	Y	Y	16	-0-	3
Monitoring	Y	ND	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	N	Y	Y	16	2	1
Cable replacement	Y	Y	Y	N	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	N	16	3	-0-
BAN	Y	N	Y	ND	Y	Y	Y	Y	Y	ND	Y	Y	N	Y	Y	Y	Y	Y	Y	15	2	2

Application Area	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12	Expert 13	Expert 14	Expert 15	Expert 16	Expert 17	Expert 18	Expert 19	Retain	Delete	No Decision
Healthcare	Y	ND	Y	Y	Y	N	Y	Y	Y	N	Y	ND	N	Y	Y	Y	Y	Y	Y	14	3	2
Convenience	Y	Y	Y	Y	Y	N	N	Y	Y	ND	Y	Y	Y	Y	Y	N	N	Y	ND	13	4	2

Summarized Results of Barriers/Challenges in Round One

Barrier/Challenge	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12	Expert 13	Expert 14	Expert 15	Expert 16	Expert 17	Expert 18	Expert 19	Retain	Delete	No Decision
Security	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	19	-0-	-0-
Interference and coexistence	Y	Y	Y	ND	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	18	-0-	1
Trade-off of QoS and Power	Y	Y	Y	ND	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	17	1	1
Environment	Y	Y	Y	ND	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	N	15	3	1
Privacy	Y	Y	Y	Y	N	Y	Y	N	Y	Y	Y	N	N	Y	Y	Y	ND	Y	Y	14	4	1
Terminated Barrier/Challenge																						
Location privacy	Y	Y	Y	Y	N	N	Y	N	Y	ND	ND	Y	N	Y	Y	N	Y	Y	ND	11	5	3

APPENDIX F: SUMMARY OF ROUND TWO RESULTS

Most experts indicated 1 (very important) to 5 (not important at all). In a few instances, the responses were unclear or no response was made and these are indicated by NR (no response). Additionally, for nominated issues, Y = retain and N = delete. Panelists' comments are not included but are available upon request.

Summarized Results of Success Criteria in Round Two

Success Criteria	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12	Expert 13	Expert 14	Expert 15	Expert 16	Expert 17	Expert 18	Expert19	Mean
Interoperability	3	1	1	1	1	1	3	2	2	2	1	3	1	1	1	NR	2	1	1.53
Power management	1	1	1	2	2	1	1	2	1	1	1	5	2	1	2	2	2	3	1.72
Transmission speed	2	1	1	1	2	1	2	1	2	2	2	5	1	2	1	2	3	1	1.78
Frequency switching	3	2	2	1	1	3	3	2	1	1	2	2	1	3	1	2	3	1	1.94
Widespread deployment	1	1	4	2	1	1	2	2	1	3	3	1	3	3	2	1	NR	2	1.94
Range	4	1	3	2	3	1	3	3	2	2	2	1	4	2	2	5	NR	3	2.53
Power consumption type	2	2	1	4	2	3	4	1	3	3	2	5	2	3	2	3	2	2	2.61
Success Criteria Accepted for Inclusion in Round Two																			
Reliability of connection	Y/2	Y/1	Y/2	Y/1	Y/2	N/NR	Y/2	Y/1	Y/2	Y/2	Y/1	Y/2	Y/2	Y/2	Y/1	NR/2	Y/2	Y/1	1.65
Usability	Y/1	Y/1	Y/2	Y/1	Y/2	Y/1	Y/1	Y/2	Y/1	Y/1	Y/2	Y/2	Y/2	Y/2	Y/1	Y/1	Y/2	N/5	1.67
Functionality	Y/2	Y/1	Y/2	Y/2	Y/2	Y/2	Y/1	Y/2	Y/3	Y/1	Y/1	Y/2	Y/4	Y/3	Y/2	NR/2	N/NR	N/4	2.13
Cost	Y/1	Y/2	N/3	N/1	N/4	Y/1	N/3	Y/3	N/3	Y/2	N/4	Y/2	Y/4	N/3	Y/2	NR/2	N/5	N/5	2.78

Summarized Results of Application Areas in Round Two

Application Area	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12	Expert 13	Expert 14	Expert 15	Expert 16	Expert 17	Expert 18	Expert 19	Mean
Healthcare	1	1	3	1	3	1	1	2	3	2	2	2	3	1	1	1	2	2	1.78
Monitoring	1	1	2	1	3	1	1	3	2	2	1	2	2	2	2	1	3	3	1.83
Smart things	3	2	2	1	1	3	2	3	2	1	2	3	2	2	1	1	1	1	1.83
Cable replacement	2	2	1	3	2	1	1	2	1	1	3	1	1	2	3	1	3	5	1.94
BAN	3	3	3	2	3	1	1	3	2	3	4	2	4	1	1	2	1	2	2.28

Convenience	1	2	1	4	2	3	3	2	3	1	3	3	2	3	2	2	2	3	2.33
Application Areas Accepted for Inclusion in Round Two																			
Universal ID	Y/2	Y/2	Y/2	Y/3	Y/2	Y/2	Y/2	Y/1	N/5	Y/2	N/5	Y/2	Y/2	Y/2	Y/1	NR/3	Y/3	Y/1	2.33
Agriculture	Y/2	Y/1	Y/1	Y/1	N/5	Y/1	Y/2	Y/3	Y/3	Y/2	NR/3	Y/2	N/5	Y/3	Y/1	NR/2	N/5	N/4	2.56
Proximity sensors	Y/3	NR/3	Y/2	N/3	Y/3	Y/2	Y/2	Y/3	Y/3	NR/3	Y/3	N/3	Y/2	N/4	Y/2	NR/2	Y/1	N/4	2.67
Eco-PAN	N/4	Y/1	Y/3	N/4	N/4	Y/2	Y/2	Y/4	Y/3	Y/3	Y/4	Y/3	N/5	Y/2	Y/2	NR/2	Y/3	N/5	3.11

Summarized Results of Barriers/Challenges in Round Two

Barrier/Challenge	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12	Expert 13	Expert 14	Expert 15	Expert 16	Expert 17	Expert 18	Expert 19	Mean
Security	1	2	1	1	1	1	1	1	2	1	3	2	1	1	1	2	1	1	1.33
Interference and coexistence	1	1	1	1	1	NR	2	2	2	1	2	2	1	2	1	1	3	1	1.47
Privacy	2	1	1	3	2	1	1	1	2	1	1	3	5	2	3	2	2	2	1.94
Trade-off of QoS and power efficiency	1	1	1	2	2	1	3	2	1	1	1	2	3	3	2	2	4	3	1.94
Operating environment	2	1	2	3	2	1	3	2	2	2	1	2	2	4	2	1	3	1	2.00
Barriers/Challenges Accepted for Inclusion in Round Two																			
Regulation and standards	Y/1	Y/1	Y/2	Y/2	Y/1	Y/1	Y/1	Y/1	Y/1	Y/1	Y/2	Y/2	Y/2	N/3	Y/1	NR/2	Y/4	Y/2	1.67
Embeddedness and wearability	Y/2	Y/1	Y/2	Y/2	Y/2	Y/1	Y/3	Y/3	Y/1	Y/3	N/5	Y/2	Y/1	N/3	Y/1	NR/2	Y/2	Y/1	2.06
Self-organization	N/4	Y/1	Y/2	N/1	Y/2	Y/2	Y/2	Y/3	Y/2	Y/1	Y/1	N/4	Y/1	Y/2	Y/1	NR/2	Y/5	Y/2	2.11
Human interface	Y/2	Y/1	Y/2	N/4	N/5	Y/1	N/5	Y/2	Y/1	Y/1	Y/2	N/4	Y/3	N/3	Y/3	NR/1	N/NR	Y/2	2.47
Data management	Y/1	Y/2	Y/1	N/3	N/5	Y/2	N/5	Y/3	Y/3	N/3	Y/2	N/3	N/5	Y/2	Y/2	NR/3	N/5	Y/2	2.89
Environmental issues	N/5	Y/1	Y/2	N/3	N/5	Y/1	N/5	Y/2	N/3	N/3	Y/2	Y/2	Y/3	Y/1	Y/1	NR/3	Y/5	N/5	2.89

APPENDIX G: SUMMARY OF ROUND THREE RESULTS

Most experts indicated 1 (very important) to 5 (not important at all). In a few instances, the responses were unclear or no response was made and these are indicated by NR (no response).

Summarized Results of Success Criteria in Round Three

Success Criteria	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12	Expert 13	Expert 14	Expert 15	Expert 16	Expert 17	Expert 18	Expert 19	Mean	Rank
Reliability of connection	2	1	1	1	1	1	2	1	2	2	1	1	1	2	1	1	2	1	1.33	1
Interoperability	1	1	2	1	2	1	3	1	1	1	1	3	1	1	1	2	2	1	1.44	2
Usability	1	1	1	1	1	1	1	2	1	1	2	2	2	2	1	1	2	3	1.44	2
Power management	2	2	1	2	2	1	1	2	2	1	1	1	2	1	2	2	2	2	1.61	4
Widespread deployment	2	1	1	3	1	1	2	2	1	2	3	1	3	3	2	NR	NR	2	1.88	5
Functionality	2	1	1	3	1	2	1	2	3	1	1	2	4	3	2	2	NR	3	2.00	6
Transmission speed	4	2	1	1	3	1	2	2	2	2	2	3	1	2	1	3	3	1	2.00	6
Frequency switching	3	3	1	1	2	2	3	3	2	NR	2	3	1	3	1	2	3	1	2.12	8

Summarized Results of Application Areas in Round Three

Application Area	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12	Expert 13	Expert 14	Expert 15	Expert 16	Expert 17	Expert 18	Expert 19	Mean	Rank
Monitoring	1	1	1	2	2	1	1	2	2	2	1	1	2	1	2	2	3	3	1.67	1
Healthcare	1	1	2	2	3	1	2	1	2	2	2	2	3	1	1	2	2	2	1.78	2
Smart things	3	2	2	1	1	2	2	2	2	1	2	3	2	2	1	3	1	1	1.83	3
Cable replacement	2	2	1	2	1	1	1	3	1	1	3	1	1	2	3	2	3	5	1.94	4
BAN	3	2	1	2	3	1	1	2	2	3	3	3	3	2	1	3	1	2	2.11	5
Convenience	1	1	1	2	2	NR	3	2	3	1	3	3	2	3	2	2	2	3	2.12	6
Agriculture	1	1	1	2	4	1	2	2	2	2	3	2	5	3	1	3	5	4	2.44	7
Proximity Sensors	3	2	3	2	3	2	2	2	3	3	3	3	2	2	2	NR	1	4	2.47	8
Universal ID	3	1	2	3	3	2	2	2	5	NR	5	2	2	3	1	2	3	1	2.47	8

Summarized Results of Barriers/Challenges in Round Three

Barrier/Challenge	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12	Expert 13	Expert 14	Expert 15	Expert 16	Expert 17	Expert 18	Expert 19	Mean	Rank
Security	3	1	1	1	1	1	1	1	1	1	2	2	1	1	1	3	1	1	1.33	1
Interference and coexistence	2	1	1	1	1	1	2	1	2	1	2	2	1	1	1	2	3	1	1.44	2
Regulation and standards	3	1	1	2	2	1	1	2	1	1	2	2	2	2	1	3	4	2	1.83	3
Self-organization	2	1	3	1	2	2	2	2	2	1	1	3	1	1	1	2	5	2	1.89	4
Privacy	1	2	1	3	2	1	1	1	2	1	1	3	5	1	3	4	2	2	2.00	5
Trade-off of QoS and power efficiency	3	1	2	2	3	1	3	2	1	1	1	2	3	2	2	3	4	3	2.17	6
Operating environment	1	2	3	2	4	2	3	2	2	2	1	2	2	3	2	2	3	1	2.17	6
Embeddedness and wearability	2	2	4	2	4	1	3	2	2	3	4	3	1	2	1	2	2	1	2.28	8