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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) will enable communications between devices both embedded in the environment and mobile on vehicles and persons. This research determines the future prospects of PANs by examining criteria that will lead to success and barriers to implementation. An initial set of issues in each of these areas is identified from the literature. The Delphi Method is used to determine what experts believe what are the most important success criteria and barriers. Critical success factors that will determine the future of personal area networks include reliability of connections, interoperability, and usability. Important barriers that may inhibit the deployment of PAN are security, interference and coexistence, and regulation and standards.

Keywords

personal area networks, ubiquitous computing, Delphi Method

INTRODUCTION

The importance of this study lies in the assumption that in the not too distant future, ubiquitous computing will be part of everyday life. This ubiquitous computing future will depend on device-to-device communication, through personal area networks, to allow the environment and everyday things to respond to an individual's needs or operating requirements. Insight into ubiquitous computing is available in Mostefaoui, Maaamar, and Giaglis (2008), Weiser (1991), and especially Greenfield (2006). Defining the prospects for personal area networks in this ubiquitous computing world is the primary focus of this study.

The results of this research are also important because 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 of PAN implementation is crucial. 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 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:

- What are the key criteria or combination of criteria that will determine the future success of personal area networks?
- What barriers will be associated with PAN implementations?

Most studies define a PAN according to its short-range characteristic. For example, a 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 and 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).

For the most part, PAN technologies (e.g. infrared, Bluetooth, ZigBee, Ultra-wideband (UWB)) have been developed for unobtrusive computing devices that can be worn by individuals to enhance the ability to perform productive work as well as provide entertainment (Braley, Gifford, and 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 and Yow, 2002).

LITERATURE REVIEW

The principal purpose of the literature review in this study was to identify the main success criteria and barriers in the literature for consideration by a panel of experts in round one of the Delphi Method (see next section). The descriptions in this section represent only a small part of what was discovered in the literature and presented to the panel. The full literature review can be found in Zhao (2008).

Success Criteria for Personal Area Networks

Based on a review of the business-oriented literature related to PANs, the following 11 criteria were identified as potentially critical to the success of PANs:

- BlueStar architecture
- Consumption types
- Frequency switching
- Interoperability
- Power management
- Range
- Sleep/wakeup scheduling
- Speed gap
- Transmission speed
- Widespread deployment
- Wireless power transfer

At the end of the first round of the Delphi Method, the panel of PAN experts considered the following criteria to be inappropriate or not worthy of further consideration: BlueStar architecture, consumption types, range, sleep/wakeup scheduling, speed gap, and wireless power transfer. The remaining five criteria are briefly described below.

Frequency switching: Because wireless communication is so dependent on wireless frequency, efficiency in wireless frequency usage may be an important determinant of PAN success. 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 (Bahl, Adya, Padhye, and Walman, 2004).

Interoperability: In a ubiquitous computing world there will be a need for PANs to interconnect (i.e., PAN-to-PAN) in what is known as cooperative exchange. For example, ad hoc connections between Bluetooth and infrared have been proposed by Woodings, Joos, Clifton, and Knutson (2002). There will also be a need for PANs to exchange data and commands with local area or wide area wireless networks (i.e., PAN-to-WLAN or PAN-to-WWAN). An example is continuous health or sports performance monitoring in body area networks (Jovanov, 2005). Interoperability also includes the ability for all of these wireless networks to cooperate with each other and access each other's resources (Agrawal and Zeng, 2005), especially in the unlicensed 2.4 GHz ISM frequency band (Golmie, 2006).

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, and Sarwat, 2004). The main drawback of wireless technology is the limited battery life associated with wireless-enabled devices, especially when used for high capacity content delivery (e.g. multimedia) over the network (Cornea, Nicolau, and Dutt, 2006).

Transmission speed: The availability and immediacy of future network access will be magnified by high-speed wireless connectivity (Orman, 1999). PAN technologies offer different transmission speeds. A high speed PAN technology, such as UWB, is suitable for multimedia applications which require high speed combined with a high quality of service (QoS). In contrast, a low speed PAN technology, such as Bluetooth, is suitable for applications with relaxed needs for data speed and low QoS (Shinde and Borse, 2005).

Widespread deployment: As wireless technologies and wireless applications become more common and 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, and 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, and Bahl, 2005). From the commercial aspect, emerging wireless technologies' deployments are still in their infancy because routing protocols are rather complex for practical applications found in enterprise, office or home domains (Koulamas, Orphanos, Lucas, and Colin, 2004).

Barriers for Personal Area Networks

Based on a review of the business-oriented literature related to PANs, the following six issues were identified as potential barriers to the successful deployment and implementation of PANs.

- Interference and coexistence
- Location privacy
- Operating environment
- Security
- Trade-off of QoS and power efficiency
- Privacy

At the end of the first round of the Delphi Method, the panel of PAN experts considered location privacy could be included within privacy and so it was dropped from further consideration. The remaining five criteria are briefly described below.

Interference and coexistence: For similar reasons that interoperability is a success criterion for PAN success, frequency inference and network coexistence are potential barriers to widespread deployment of PANs. In a human analogy, whereas interoperability is about "networks working together cooperatively", interference and coexistence is about "networks playing together nicely". The major downside to the use of the 2.4 GHz unlicensed band used by most PAN technologies is that frequencies must be shared and potential interference tolerated, especially as more networks are choosing to use the unlicensed band to avoid the need to purchase spectrum (Golmie, 2006). For example, 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 and Zeng, 2005). One seemingly obvious 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 and 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). More complex techniques to control interference (e.g., adaptive frequency hopping, dual-mode radio switching (Prasad and Ruggieri, 2003)) or improve coexistence (e.g., variable modulation, clear channel assessment (Morrow, 2004)) can prove difficult or impossible to implement in networks with low power output and minimal processing capabilities.

Privacy: On the one hand, privacy protection is not a serious concern in PANs due to the very localized nature of their operation. However, a threat also exists because (a) PANs can disclose not only the identity of the user, but also their physical location (Karygiannis, Kiayias, and Tsiounis, 2005); (b) ubiquitous sensor technology might allow ill-intentioned individuals to deploy secret surveillance networks for spying on unaware victims (Perrig, Stankovic, and Wagner, 2004); and (c) the nature of PANs may require new interpretations of privacy in a constantly monitored world (Orman, 1999). 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).

Operating environment: A mobile device in a PAN will find a heterogeneous operational environment, encountering base stations that provide different services, protocols, and interfaces (Boulis, Lettieri, and Srivastava, 1998). PANs should be designed to accommodate energy efficiency, dynamic self-organization, and mobility in a dynamic operational environment (Chung and Kim, 2006), including difficult or changing environmental conditions (Johnson and Margalho, 2007).

Security: Security is a universal challenge associated with nearly all telecommunication networks, and personal area networks are no exception. What special security concerns are associated with PANs? First, because connectivity in a PAN is intermittent and ubiquitous, the traditional approaches for networks to authenticate users – online connectivity to an authentication or revocation server – are unworkable (Stajano and Anderson, 2002). Second, PAN system integrity can be compromised from both internal (e.g., transmission collisions and radio propagation impairment) and external sources (e.g., malicious attacks) (Lee, Zheng, and Ashel, 2006). Third, confidentiality on PANs is difficult to achieve because the computational power of PAN devices is minimal and so processing-intensive tasks such as public-key cryptography cannot be performed easily (Stajano and Anderson, 2002). However, new technologies are putting increased emphasis on security (e.g., ZigBee supports access control lists, packet freshness timers, and 128-bit advanced encryption standard (Kohvakka, Kuorilehto, Hännikäinen, and Hämäläinen, 2006)). Other, more minor, security concerns for PANS are in denial of service, non-repudiation, and freshness.

Tradeoff between quality of service and power efficiency: Quality of service (QoS) on PANs is a critical issue, especially for wireless multimedia applications that require high data transmission rates. To ensure a guaranteed QoS for coverage and speed, a sufficient power supply is essential. Besides the obvious (e.g., increasing battery power), most potential solutions focus on improving system design (Park, Raghunathan, and Srivastava, 2003).

Contribution to the Literature

Most studies about personal area networks focus on technologies (e.g., Agrawal and Zeng, 2005) or application implementation. Prasad and Ruggieri (2003) focused their work on future technology trends in various wireless communications, not success factors or barriers. A number of Delphi studies have been used to predict technological futures, including wireless telecommunication technologies (e.g., Viehland and Wong, 2007). However, no other research has studied success criteria and barriers to determine the future of personal area networks, as is done in this study.

RESEARCH DESIGN AND RESULTS

Due to space limitations, the research methodology used in this study – the Delphi Method – is explained at the same time as the results are presented.

Introduction to the Delphi Method

The Delphi Method is 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 and Ziglio, 1996). It is especially useful in forecasting situations in which statistical methods are impractical or impossible and when some form of human judgment is needed (Rowe, Wright, and Bolger, 1991).

The Delphi Method begins with convening a panel of experts who have considerable knowledge in the topic being investigated. In this study a panel of 18 experts offered a variety of perspectives from ICT companies (seven panelists), universities (four), government (three), and other commercial and not-for-profit organizations (four). Six panelists had direct experience with implementing personal area networks or PAN technologies and another eight panelists were actively involved with wireless (other than PAN) projects. Fifteen panelists were from New Zealand and one each were from Brazil, Denmark, and the United States. All three rounds of the Delphi study took place during March - May 2008.

Method and Results: Round One

In round one of the Delphi Method the panelists were sent an extensive background report on PANs and a description of the success criteria and implementation barriers found in the literature. Panelists were asked: (a) are the issues found in the literature appropriate for the purpose of the study (i.e., retain or delete), (b) are any issues missing, and (c) comment on each issue. The results are shown in Tables 1 and 2. Note that 19 panelists participated in round 1 (literature vote) and 18 panelists in round two (panel vote). Not all panelists voted on all issues.

Success Criteria	Source	Round 1 or 2	
		Retain	Delete
Frequency switching	literature	19	-0-
Interoperability	literature	14	3
Power management	literature	18	-0-
Transmission speed	literature	16	2
Widespread deployment	literature	17	-0-
Functionality	panel	15	2
Reliability of connection	panel	16	1
Usability	panel	17	1

Table 1. Success Criteria Results in Round One

Barriers	Source	Round 1 or 2	
		Retain	Delete
Interference and coexistence	literature	18	-0-
Operating environment	literature	15	3
Privacy	literature	14	4
Security	literature	19	-0-
Trade-off of QoS and power efficiency	literature	17	1
Embeddedness and wearability	panel	15	2
Regulation and standards	panel	16	1
Self-organization	panel	14	3

Table 2. Barriers Results in Round One

As described in the previous section, five of the original eleven success criteria were retained for round two and five of the original six barriers were accepted. Additionally, panels nominated (round one) and voted to accept (round 2) three new success criteria – functionality, reliability of connection, usability – and three additional barriers – embeddedness and wearability, regulation and standards, and self-organization.

Method and Results: Rounds Two and Three

In round two, panelists were provided with the results of round one, including the anonymous comments from all panelists in round one, and a questionnaire that asked each panelist to rate the importance of each success criteria and barrier to the future success of PAN on a five-point Likert scale (1 = very important; 5 = not important at all). Panelists were asked to justify their ratings in comments. The results are shown in Tables 3 and 4.

The purpose of round three was to obtain a consensus opinion from the panelists. Results from round two were sent to all panelists. Each panelist was asked to review his/her rating for each success criteria/barrier in light of the ratings and comments of the other panelists. Each panelist was asked to re-rate each issue on the same five-point Likert scale, keeping the rating the same or modifying it. The results are shown in Tables 3 and 4.

Success Criteria	Round 2		Round 3	
	Mean	Rank	Mean	Rank
Reliability of connection	1.65	2	1.33	1
Interoperability	1.53	1	1.44	2
Usability	1.67	3	1.44	2
Power management	1.72	4	1.61	4
Widespread deployment	1.94	6	1.88	5
Transmission speed	1.78	5	2.00	6
Functionality	2.13	8	2.00	6
Frequency switching	1.94	6	2.12	8

Table 3. Success Criteria Results in Rounds Two and Three

Barriers	Round 2		Round 3	
	Mean	Rank	Mean	Rank
Security	1.33	1	1.33	1
Interference and coexistence	1.47	2	1.44	2
Regulation and standards	1.67	3	1.83	3
Self-organization	2.11	8	1.89	4
Privacy	1.94	4	2.00	5
Trade-off of QoS and power efficiency	1.94	4	2.17	6
Operating environment	2.00	6	2.17	6
Embeddedness and wearability	2.06	7	2.28	8

Table 4. Barriers Results in Rounds Two and Three

In the analysis of success criteria for PANs (Table 3), there were considerable changes in means and ranks. The top three criteria stayed the same, but reliability of connection moved to top rank. There were also some changes in the bottom half of the table with both widespread deployment and functionality decreasing their means and moving up in rank.

These changes in results from round two to round three were larger than anticipated. 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) an academic 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.

Barriers for PAN implementation (Table 4) showed relatively few changes between rounds two and three, the major exception being the rise in the ranks of self-organization. This can be attributed to comments from panelists in round two that promoted this issue as a significant barrier to PAN operation.

DISCUSSION

The following paragraphs present a brief discussion of the top three success criteria and barriers that will determine the future of personal area networks, including comments provided by the panelists. A full discussion of the results for all 16 issues is available in Zhao (2008).

Success Criteria

Reliability of connection: Reliability of connection was nominated in round one by two experts, one defining it as "being able to connect and stay connected". This is understandable because increasingly PAN technologies are demanding highly reliable connections, especially multimedia connections with high data capacity and fast speed. Connection errors are most likely to occur in multiple-path connections and network capacity is another factor that influences the connectivity (e.g., interference or congestion). After being nominated in round one, its importance was highlighted by several panelists in round two (e.g., a reliable connection between wireless devices ensures "customers' satisfaction and acceptance" (expert 5) of these technologies as well as quality of service). Several experts commented that an unreliable connection would frustrate users and reduce the level of PANs acceptance by users (experts 6, 10, 18). After this strong support in round two, several other panels changed their ratings to give this criterion the lowest (most important) criteria for PAN success.

Interoperability: Interoperability is the ability for one PAN to connect to another network. The mean for interoperability actually decreased (increased in importance) between round two and three, but not as much as top-ranked reliability of connection. 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 as new technologies are emerging. 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: In round one, the single most widely nominated success criterion was usability or some form of it. 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"; and "simple, user friendly identify management and access control will be critical". In round two, 17 of the 18 panelists voted to retain it and in round three its mean decreased (increased in importance) to end ranked second equal with interoperability.

Barriers to PAN success

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). Security obtained a unanimous decision to retain in round one and security ranked as the top barrier with a mean of 1.33 in rounds two and three. These results indicate that security is considered to be the most significant barrier to deployment of personal area networks.

Interference and coexistence: 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 will be a critical challenge to any telecommunication network, including PANs, and there are many studies that focus on how to solve problems associated with interference and coexistence (e.g., Golmie, 2006; Morrow, 2004; Qiao, Choi, and Shin, 2007). In addition, several panelists (experts 5, 7, 14) commented that this is both 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 the most frequently nominated barrier in round one. 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" and "multiple protocols/technologies – no universal standard will cause huge problems and slow down the deployment". A related issue also included in here is "spectrum availability (how much can we provide PAN with available frequency?" In round two, three panelists (experts 2, 8, 12) generally agreed it will be an important barrier to the future success of PAN technologies but 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). The issue of standards (to enable interoperable PAN communications) and the closely related area of regulation (who will set and enforce the standards) is clearly viewed as a key challenge facing PAN implementation.

CONCLUSIONS

Suggestions for Future Research and Limitations of the Study

The study of personal area networks is an emerging area that is developing rapidly. As new technologies, applications, and standards appear, the underlying conditions of this research study will change, and follow-up research to update these results and offer some longitudinal insight to this research area will be necessary.

More significantly, research is required to investigate the factors that can promote the success criteria and solve the barriers. For example, reliability of connection is considered to be the top critical success factor that will determine the future of PANs, but it was identified by the panel, not from the literature. A similar comment can be made about usability and regulation and standards.

Although the size of the panel (18 members) was sufficient and the profile of the panelists was heterogeneous, the geographical composition 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, especially, the international experience (e.g., exporters, lived/worked outside NZ, international work portfolio) of most of the New Zealand panelists.

Finally, as noted above, it is desirable to determine if the results from the third round truly represented a consensus opinion by conducting a fourth round. However, it is unlikely that this would have had a material effect on the final results.

Conclusion

A high level summary of this research is presented in Table 5 – the top ten issues that will determine the future of PANs.

Success Criteria	Barriers
Reliability of connection	Security
Interoperability	Interference and coexistence
Usability	Regulation and standards
Power management	Self-organization
Widespread deployment	Privacy

Table 5. Top Ten Issues that Will Determine the Future of PANs

The contributions of this study are that it is the first study to identify (a) the critical factors that will determine the success of personal area networks and (b) the most important barriers that have the potential to inhibit the future prospects of PANs.

Personal area networks will be an important part of the ubiquitous computing world of the future, which will be experienced by most readers of this paper, and their children and grandchildren. A better understanding of the future of personal area networks will benefit individuals, researchers, professionals, and organizations who will live, work, and seek profit in this world. This study has helped show the way ahead.

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