Wide Area Ubiquitous Network: The Network Operator's View of a Sensor Network

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ABSTRACT

This article describes a network concept called the wide area ubiquitous network (WAUN) and its research activities. WAUN is a network for sensors and actuators, and can support low-end wireless terminals, which are expected to be used for new applications. Among the many types of R&D being performed in the WAUN project, this article focuses on the feasibility of its basic feature and target. The basic feature is "wide coverage using very-low-power-consumption terminals," and its specific target is a "5-km cell radius using 10-mW transmission power terminals with a battery life of 10 years." The results of a basic field experiment and a laboratory experiment suggest that the target seems to be feasible using wireless technologies such as diversity reception (with additional future effort to improve the packet error rate for use in business districts) and LSI technologies such as a power switch fabricated in a CMOS/SOI LSI.

INTRODUCTION

Several decades have passed since the computer was invented, and computers are now deeply embedded in our daily lives. Concepts such as "computer located anywhere" by K. Sakamura and "ubiquitous computing" by Mark Weiser advocated in the 1980s have become targets that we should try to achieve, and a huge number of papers have been published [1]. For example, the Japanese government has formulated a "u-Japan" plan, where "u" stands for ubiquitous services, and it is launching a "u-Japan" program to achieve the objectives of the plan. Ubiquitous small networked computers, including sensors and actuators, will enable us to be networked anywhere and anytime with anybody and anything to enjoy a convenient life. That is, in the society of the future, various types of devices will be distributed everywhere, and they will be networked [2, 3]. As a result, health care will be improved, environmental destruction and earthquake damage will be reduced, and so on.

The feasibility of such concepts strongly depends on recent developments in network technology, including wireless technology, as well as in electronics and micromechanics. In particular, it is believed that establishing sensor networks in an ad hoc manner without a network infrastructure is a promising approach. Nevertheless, this article proposes and discusses an approach based on a network infrastructure newly developed for sensor networks in order to stimulate the discussion of sensor networks and take steps toward the implementation of the ubiquitous network society.

NEW APPLICATIONS

As described in the previous section, applications using ubiquitously networked devices will be implemented in the society of the future. Furthermore, we expect such applications to include ones that cannot even be imagined now.

One of the main targets of next-generation applications is to monitor and immediately manage the situation and status of individual objects and persons through the use of computerized information processing and storage. Some examples of new applications we are investigating are (Fig. 1) [4]:

- Medicine dosage management could be performed by detecting the removal of tablets from a package. Medicine is sometimes used incorrectly. In particular, elderly people forget to take medicine. As a result, medical costs increase, and doctors cannot judge whether medicine is effective.
- Business cards that have already been distributed could be updated. Business cards are distributed at business meetings, but their information soon becomes obsolete due to, for example, restructuring in a company. Business cards with a simple e-paper display having a wireless transceiver and a Power Paper battery would enable updating the information.
- Name stamp management could be performed by detecting the use of a name stamp. In many business situations as well as many private situations, Japanese people

use name stamps in the manner that signatures are used in western countries. In particular, if we could detect and manage the use of name stamps in business situations, the computerization of office work would be greatly helped.
- The opening of an envelope or a page of a book/catalog could be detected. A mail order business making use of this technology could detect that a consumer may be interested in a product catalog or a product on a page of a catalog.
- The opening of a package could provide usage evidence. This would enable us to easily count stock in an inventory that has or has not been used. It could be used as evidence for a tax agent and could help inventory management.

Here, we should note that these new applications are implemented by very small simple sensors or actuators that are networked. They are very low-end telecommunication terminals. This will result in a different future network vision from those based on the assumption that most terminals will have high performance and rich functions, such as personal computers. However, these applications could require an extremely large number of terminals.

■ **Figure 1.** *Examples of new applications.*

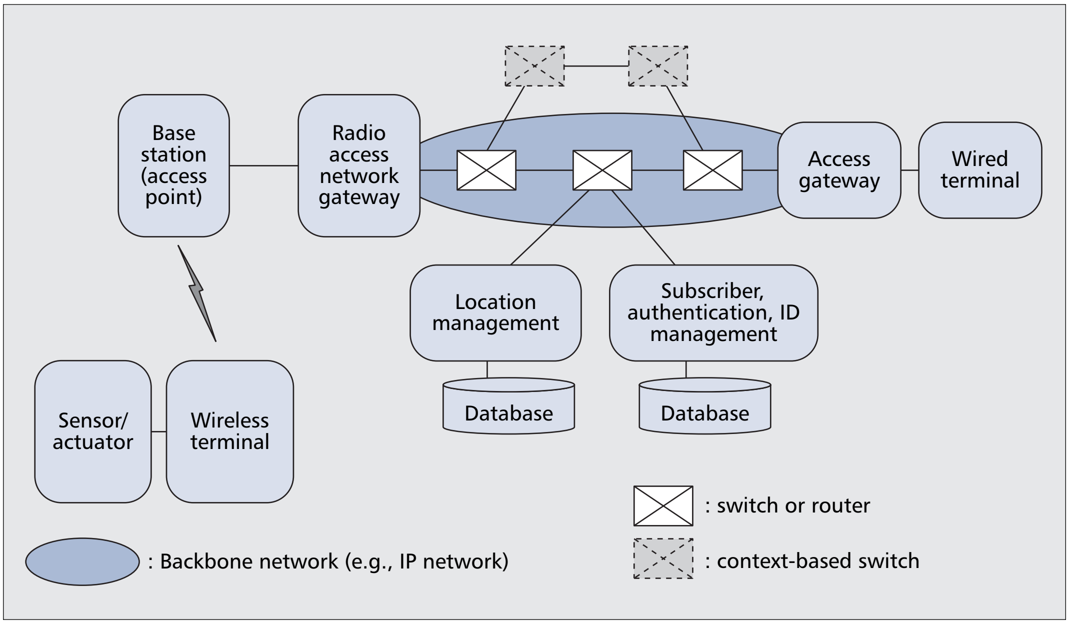
Wide Area Ubiquitous Network Concept and Technical Issues

To support the applications mentioned above and to create a ubiquitous network society in the 2010s, we started a research project called the Wide Area Ubiquitous Network (WAUN). The network has a wireless access network to support low-end telecommunication terminals equipped with sensors or actuators. This network covers areas that are not covered by a personal area network or body area network accompanying a cellular phone or by the home network with a home gateway connected to a backbone. This makes it possible to detect when a patient takes medicine while outside his/her home and when a person receiving a package opens it in his/her home as well as to detect environmental destruction by using distributed chemical sensors.

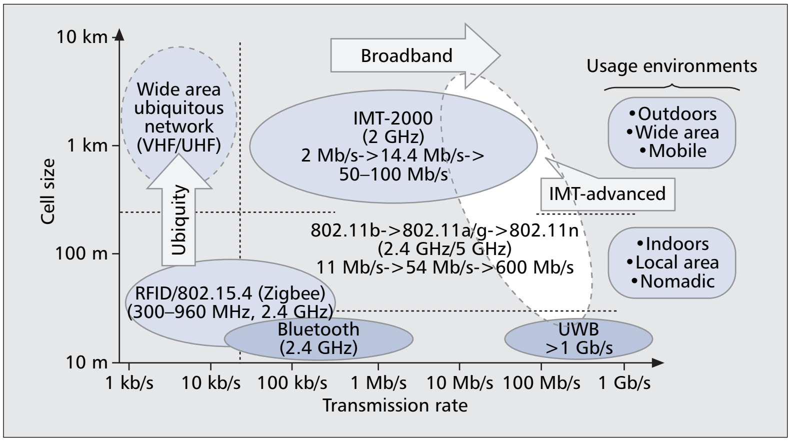
From the viewpoint of an existing network provider, we consider that the WAUN wireless network should have a wide cell with a radius of several kilometers. There are two main reasons for this. First, if the cell radius is r times larger, the number of base stations (access points, referred to as APs hereinafter) can be reduced to $1/r^2$ and the capital expense of the wireless system is reduced to nearly $1/r^2$. Second, most network providers have their own buildings containing data cables and electric power supplies every few kilometers. Thus, if the wireless range of WAUN is more than a few kilometers, an existing network provider can make full use of it for cabling the APs, with the result that capital expenses can be minimized. The bandwidth required for these applications is narrow, so additional cables are not needed, or an overlay network on the existing network owned by the network provider is enough.

Note that a new network provider might choose the mesh network approach [5–7] because the cost of cables and ducts connecting APs can be reduced and the local backhaul network can be established at a reasonable cost. Furthermore, an existing cellular operator might collocate the AP for WAUN at its base station sites for its cellular services. However, from the viewpoint of existing and new network providers as well as cellular operators, the cell radius should be as large as possible to reduce the initial infrastructure cost during the initial stage of WAUN services because service ubiquity is essential. If the amount of traffic or number of users increases, we must either reduce the cell radius to accommodate more traffic, which is just what happened with cellular networks, or increase the number of channels, which is only possible if the frequency is available.

In addition to a wide coverage area, in order to support the creation of a ubiquitous network society, WAUN needs to satisfy at least the following requirements: scalability regarding the number of terminals, terminal mobility, support for low-capability terminals, security, economy, and a very small and low-power-consumption transceiver for the wireless terminal for WAUN. Therefore, our WAUN project is conducting research to satisfy all these requirements. The research areas include the network system, wireless system, wireless terminal, and application areas. Specifically, the network system area covers a scalable location management mechanism, an efficient authentication mechanism for low-end terminals over a low-speed wireless link, dynamic ID management to prevent tracking by



■ **Figure 2.** *Example of wide area ubiquitous network configuration.*



■ **Figure 3.** *Technical trends of various wireless systems.*

an unauthorized person, congestion control for a huge number of low-activity-ratio terminals, quality of service (QoS) control and traffic class definition, and context-based switching mechanisms [4] (Fig. 2). The wireless system area covers antenna design, cell design and diversity technology for large ubiquity under low transmission power, efficient media access control for various types of application traffic, and a scheduling mechanism for various QoS requirements. The wireless terminal area covers large-scale integration (LSI) and circuit design technology for low-power-consumption terminals, thin-film implementation of the terminal, thin-film-type batteries, and an operating system for low-end terminals. The application area covers application programming interfaces, application development environments, and tools. Among them, this article focuses on the wide cell coverage of a wireless system using terminals having very low power consumption and describes the results we have achieved, because this is the fundamental requirement for WAUN concept feasibility.

Wide-Range Wireless System of WAUN

Requirements for the WAUN Wireless System

Considering the above-mentioned requirements for WAUN, the network needs a unique wireless system that is totally different from conventional wireless systems such as third-generation (3G) cellular systems (i.e., IMT-2000) and Zigbee-like multihop wireless systems. How is the wireless system of WAUN different from conventional wireless systems? As shown in Fig. 3, cellular systems and wireless local area networks (WLANs) have been evolving toward higher transmission speeds and larger capacity (i.e., broadband access covering wide and local areas, respectively). On the other hand, radio frequency identification (RFID) and Zigbee have been attracting a significant amount of attention for new services such as inventory management and logistics management. The features of those wireless networks include short range, low transmission rate, and very long battery lifetime or batteryless operation. The wireless system of WAUN will evolve from one with short range to larger coverage (i.e., toward “wide area and ubiquitous coverage”), but not toward broadband.

There are some conventional low-rate wireless packet data networks that are similar to the proposed WAUN, such as Mobitex [8] and ReFLEX [9]. The main system parameters of conventional low-rate wireless packet data networks are listed in Table 1. Mobitex is a terrestrial mobile radio system designed for packet-switched data communications; it first began operating in 1986. The original concept was a private network, and it evolved into a public mobile radio service. Mobitex can be used for a variety of applications such as messaging using the UHF band. However, since Mobitex was developed about 20 years ago, the technologies

	Two-way pager	Wireless packet	
System	ReFLEX	Mobitex	DataTAC
Transmission power	Up to 1 W	Up to 2 W	Up to 2 W
Frequency	900 MHz	400, 800, 900 MHz	800 MHz
Transmission rate	Downlink: up to 25.6 kb/s Uplink: up to 9.6 kb/s	8 kb/s	4.8-19.2 kb/s
Modulation	4 FSK	GMSK	4 FSK
FEC	Downlink: (21,32) BCH Uplink: Reed Solomon Code (31,23)	(21,8) Hamming code	R = 3/4 trellis coding/Viterbi decoding
Duplexing	FDD	FDD	FDD

Table 1. *Main parameters of conventional low-rate wireless packet data networks.*

Taking into account recent advances in wireless technologies, such as modulation and coding, diversity, antennas, and large-scale MMICs using CMOS devices, we consider the feasibility of achieving WAUN's target service area coverage of 5 km using a WT with 10-mW transmission power.

used in it are relatively old-fashioned. For example, it uses Gaussian-filtered minimum shift keying (GMSK) with forward error correction (FEC) based on a Hamming (12,8) code and provides a raw bit rate of 8 kb/s. Therefore, the transmission power of the wireless terminal is 2 W, which is high. Another example is the two-way paging system called ReFLEX. Like Mobitex, ReFLEX uses a less powerful FEC, such as BCH, and Reed Solomon coding, and needs a high output power of 1 W. DataTAC is similar to REFLEX and Mobitex, so it needs relatively high transmission power.

Design Approach for the WAUN Wireless System

The key design challenge of WAUN is to lower the transmission power from the 1–2 W range to 10 mW for the uplink, that is, from the wireless terminal (referred to as WT hereinafter) to the AP, to achieve a long battery lifetime while keeping the coverage area wide. As WAUN aims to provide new ubiquitous services and its terminals will be attached to anything and/or anyone, 10 mW transmission power for the WT is desirable because unlicensed use of wireless devices with such low transmission power is allowed in Japan and many other countries. This is a major difference from the conventional low-rate wireless data networks in Table 1.

Taking into account recent advances in wireless technologies, such as modulation and coding, diversity, antennas, and large-scale monolithic microwave integrated circuits (MMICs) using complementary metal oxide semiconductor (CMOS) devices, we consider the feasibility of achieving WAUN's target service area coverage of 5 km using a WT with 10 mW transmission power. Note that we focus on the uplink in this article. One of the most important conditions of the WAUN wireless system is the frequency to be used. To meet the requirements of low transmission rate, wide coverage, and long battery lifetime, we assume that the VHF or UHF band will be used because the propagation loss is relatively small, and a large bandwidth will not be necessary for low-rate wireless networks. In addition, as we describe later, there will be some room in the VHF/UHF bands as a result of the introduction of digital TV because its frequency utilization efficiency is much higher than that of conventional analog TV.

If the WT has only 10 mW transmission power, the AP must have excellent reception performance. There are two technical approaches to improving reception performance: a powerful FEC technique and diversity reception. Note that most of the burden should fall on the AP because we need to reduce the WT's power consumption as much as possible by simplifying its implementation.

For powerful FEC, possible alternatives include convolutional coding and Viterbi decoding, turbo-coding, and low density parity check (LDPC) coding. Regarding the diversity at the AP, we assume a reception diversity based on maximal ratio combining using 2- or 3-branch antennas at the AP to improve reception performance. As the antenna diversity reduces the received level variation due to Rayleigh fading, we can dramatically improve the FEC coding gain at the AP. Thus, the combination of diversity and FEC is essential to improve the packet error rate (PER) performance of the wireless uplink. Considering the coding complexity at the WT, LDPC does not seem appropriate because its coder is much more complicated than convolutional coding and turbo coding. Considering the above-mentioned points, in the prototype system, we used $R = 1/2$, $K = 7$ convolutional-coding-Viterbi-decoding for its lower latency than turbo coding.

For the modulation scheme, we used quadrature phase shift keying (QPSK) and coherent detection. Possible alternatives to QPSK if we need to lower the high-power amplifier backoff at the WT are $\pi/4$ QPSK, GMSK, and offset QPSK. As the theoretical bit error rate performances of the modulation schemes are almost the same in a linear channel, QPSK was tentatively chosen for the prototype wireless system. The antenna gain of the WT was assumed to be 0 dBi in the case of external antennas and –16

Frequency band	280 MHz
Output power of wireless terminal	10 mW
Modem	QPSK-coherent detection
Transmission rate	9600 bit/s
Forward error correction	Convolutional coding and Viterbi decoding
Diversity	2- or 3-branch maximal ratio combining diversity
Antenna gain	Access point: 10 dBi Wireless terminal: –16 dBi for internal antenna 0 dBi for external antenna

■ **Table 2.** *Main system parameters of the prototype wireless system of WAUN.*

dBi in the case of internal antennas. The antenna gain of the AP was assumed to be 10 dBi.

The main system parameters of the prototype wireless system based on the above-mentioned design trade-off are shown in Table 2.

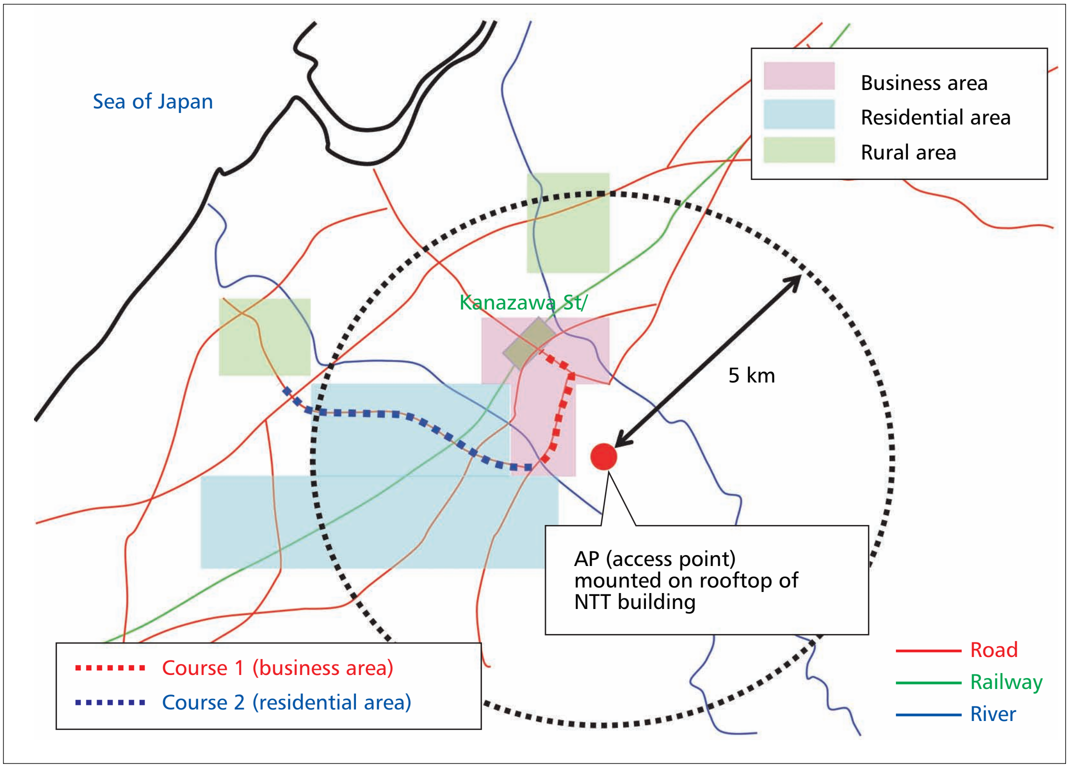
In addition to the physical layer described so far, the technical challenge for the medium access control (MAC) layer is to accommodate a huge number of WTs in the uplink of one frequency channel because the traffic per WT is very small. Another challenge for the MAC layer is to achieve high throughput when so many light-traffic WTs are connected to the AP. Considering the wide cell range for the WAUN wireless system, we need to investigate the reservation-based MAC scheme as well as the contention-based MAC scheme. According to the preliminary MAC design consideration, centralized control MAC seems promising to avoid intracell interference, where AP manages all of the time slots in time-division multiple access (TDMA)-based WAUN. We assume a cellular network approach to mitigate the intercell interference in WAUN. In fact, there are various design choices in MAC and wireless networking including interference issues, and further study is required. We have been continuing R&D efforts, and some results can be found in [10].

Field Experiment using Prototype Wireless System

Outline of Field Experiment — We have developed a prototype wireless system for WAUN. The main system parameters are shown in Table 2. The prototype was designed to enable us to evaluate wireless link performance in an actual propagation environment.

Using the prototype wireless system, we conducted a field experiment in the city of Kanazawa, Japan, to investigate the technical feasibility of the wireless system for use with WAUN [11]. A map of Kanazawa, which includes business, residential, and rural areas, is shown in Fig. 4. The target cell size of the wireless system for WAUN has a 5 km radius. The red circle indicates a distance of 5 km from the AP.

A WT was set up in the measurement vehicle with its antenna on the vehicle's roof due to the limitation of the measurement vehicle. The AP was set on the roof of the NTT building. The AP consisted of three antennas equipped



■ **Figure 4.** *Map of Kanazawa and examples of field test course for feasibility study of the wireless system of WAUN.*

for 3-branch maximal ratio combining diversity reception. The AP antennas were separated from each other by 20 m. The WT antenna height was 3.5 m (including the height of the vehicle), and the AP antenna height was 70 m (including the height of the building). Note that the WT antenna gain was –16 dBi because we assumed a WT using an internal antenna with a size of 5 × 3 × 1 cm^3 for the first-generation terminal. The WT antenna gain of –16 dBi was calculated from the size of the internal antenna. To simulate the WT antenna gain loss due to its small size, a 16-dB attenuator was inserted at the WT. In addition, to simulate the propagation loss difference between WT antenna heights of 3.5 m and 1 m, we inserted a 5-dB attenuator at the AP because the WT is expected to be used mostly at a height of 1 m. The 5-dB height gain loss was calculated using the Okumura-Hata formula.

The measurement vehicle drove through Kanazawa to measure the received level and PER with/without diversity. The packet size was 12 bytes or 96 bits.

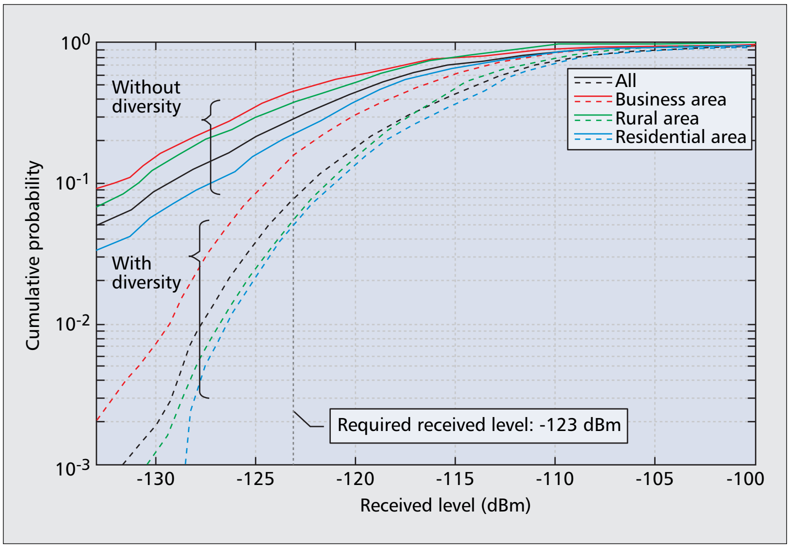


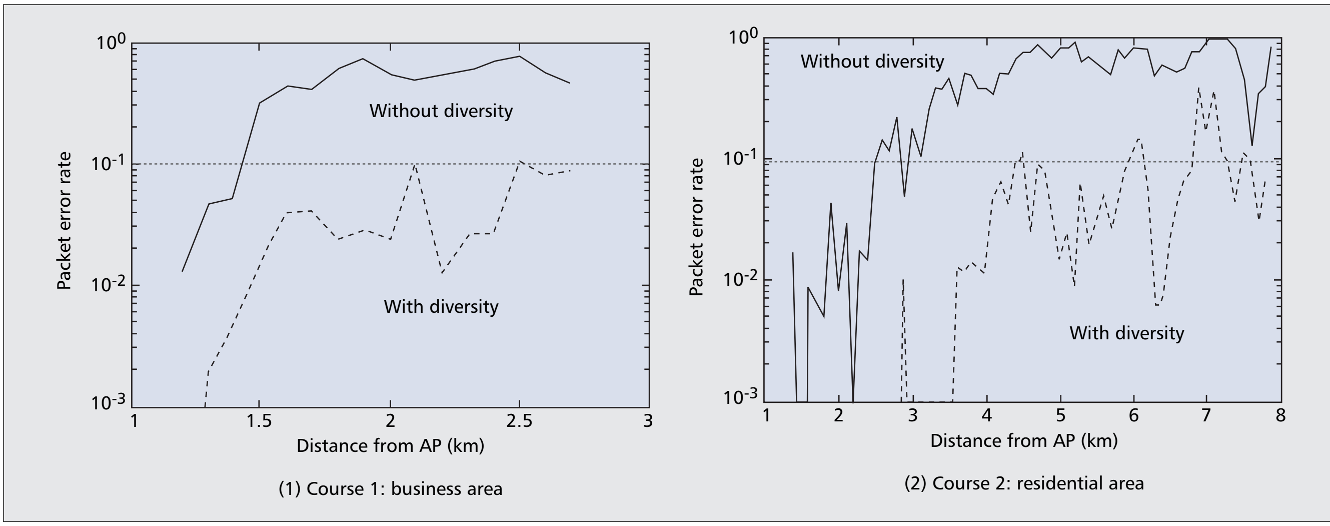
Figure 5. *Cumulative probability of received level measured in field experiment in Kanazawa-city.*

Experimental Results — Cumulative probability as a function of the received level measured at the AP is shown in Fig. 5 [11]. Measured data were recorded together with the time at the AP, and location data together with the time were recorded at the vehicle. By converting the recording times to locations, we could map the received level at the AP according to the movement of the vehicle. Measured data were categorized into three groups — business, residential, and rural areas — according to the map of Kanazawa in Fig. 4. The received level required to achieve a cumulative probability or service availability of 10^{-1} was –123 dBm when diversity was applied. The received level was measured at the AP with and without diversity reception. As shown in Fig. 5, –123 dBm was achieved in 70 percent of the overall area and only 50 percent of the business area when diversity was not used. However, when 3-branch maximal ratio combining diversity was used, the received level was greatly improved, and –123 dBm could be achieved in 90 percent of the overall area and 85 percent of the business area. Note that the received level of –130 dBm without diversity is equivalent to that of –123 dBm with diversity to achieve a cumulative probability or service availability of 10^{-1}.

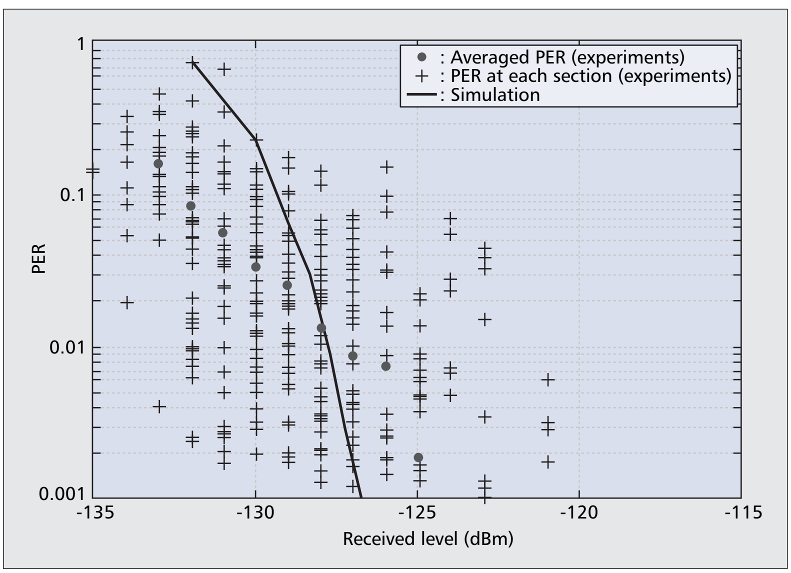
Examples of measured PERs as a function of distance from the AP in a business area (course 1) and in a residential area (course 2) are shown in Fig. 6 [11]. The physical routes are shown in Fig. 4. For course 1, when diversity was used, a PER of 0.1 could be achieved when the distance from the AP was less than 2.5 km. However, when diversity was not used, a PER of 0.1 could be achieved within 1.4 km of the AP. For course 2, the maximum range for which a PER of 0.1 could be achieved was less than 3 km without diversity but 6 km with diversity.

Figure 7 shows overall PER performance as a function of the received level without diversity at the AP in the field experiment, where PERs were measured along measurement courses about 40 km long, including business, residential, and rural areas in Kanazawa. Raw PERs and the overall average PER at each received level are plotted in Fig. 7. Simulation results for 3-branch maximal ratio combining diversity are also shown for reference, where the computer simulation was carried out assuming zero antenna correlation, Doppler frequency of 10 Hz, and carrier-to-noise ratio (CNR) = 0 dB when the received level was –130 dBm. One of the reasons for the PER performance degradation of the experimental results compared to the simulation results could be related to the cross-correlation among the three AP antennas. As shown in Fig. 7, when the received level was greater than –130 dBm, or the received CNR was greater than 0 dB, an average PER of 0.1 seemed to be achievable, although the worst PER was around 0.3. (Note that CNR = 3 dB was achievable as the average CNR at a distance of 5 km from the AP, based on the link budget calculation using the Okumura-Hata formula and system parameters shown in Table 2 [4].)

The field experiment results shown in Figs. 6 and 7 demonstrate that a 10-mW wireless terminal can be used for the proposed WAUN concept, while maintaining the target wide area coverage (i.e., a radius of about 5 km) if the combination of diversity and FEC is used. Even if the output power is as small as 10 mW, the coverage area can be as large as 5 km from the AP. Of course, we need to seek a novel solution to improve the PER performance, especially in business areas, where severe shadowing due to tall buildings is encountered. Site diversity or a gap filler will probably be necessary to cope with the severe shadowing encountered in business areas. Note that we need to consider further propagation loss such as penetration loss due to building walls when WT is used indoors. Field experiment results of site diversity for WAUN as a countermeasure to combat severe shadowing is reported in [12].



■ **Figure 6.** *Examples of measured PERs as a function of distance from the AP in field experiments.*



■ **Figure 7.** *Overall PER performance as a function of the received level in field experiments.*

LOW-POWER AND THIN-FILM WIRELESS TERMINAL OF WAUN

Although there are many technical issues for sensor network terminals [13], one of the major challenges for WAUN terminals used for the new applications described previously is low power consumption. If low power consumption is achieved, it will allow us to use a film-type battery and make super-slim terminals, which are appropriate for these new applications.

The wireless terminals for the target applications do not need to communicate frequently like cellular phone systems do, so we can reduce power consumption by decreasing the activity ratio. As shown in Fig. 8, we set the activity ratio a few orders of magnitude smaller than that of conventional cellular phone systems, which is usually around 0.01. Our target activity ratio was less than 0.0001, which corresponds to a few seconds of communication per day.

The power consumption of a terminal using CMOS LSIs is generally expected to be proportional to the activity ratio. However, we should note that power consumption is no longer proportional to the activity ratio in our target usage condition because the static leakage current of CMOS LSIs becomes the dominant factor in power consumption. The lower limit is determined by the leakage current of terminals based on conventional CMOS LSIs, as shown Fig. 8 (10 mW in the active mode and 50 μW in the sleep mode were assumed). In addition, static leakage always increases with temperature. Since the terminal will be used in various outdoor environments, tolerance of environmental temperatures is a major issue to be considered.

One of the most promising solutions is multithreshold CMOS on silicon on insulator (SOI) technology [14, 15]. This utilizes a power switch that supplies an operating current to circuits in active mode and cuts the leakage current in sleep mode. Using a power switch fabricated in a CMOS/SOI LSI, we experimentally examined whether the power switch could reduce the leakage current to less than 40 nA at device temperatures as high as 100°C while having a sufficiently high current drivability of more than 100 mA. If the activity ratio for intermittent operation is less than 0.0001 and the power consumption during operation is 10 mW or less, the average power consumption is reduced to about 1 μW, even including the power consumed in a real-time clock circuit for time management. As a result, long-term operation of 10 years or more is possible using a 100-mW/h-capacity coin-type lithium battery.

Extremely low power consumption also allows us to use a film-type battery as the power supply, so the terminal, which consists of a single-chip transceiver LSI, the battery, and a few other passive devices, can be integrated into a thin film, as illustrated in Fig. 9. This will help the wireless terminal to be ubiquitous and will also help the implementation of the next-generation applications described previously. We are now developing not only the LSI but also technology for mounting components on such a film integrated with a thin film battery and antenna. The film we plan to use is less than 100 μm thick and flexible.

Global Deployment and Frequency Issues

WAUN is a mobile network dedicated to sensor and actuator applications, so we should consider global deployment issues, just like those affecting cellular networks. Furthermore, the wireless terminal must be extremely inexpensive because the proposed network is intended for new applications, as mentioned previously. This means we must avoid complexity in the wireless terminal, especially that resulting from the need to handle different frequency allocations. To allow a low terminal cost while supporting global roaming, we need to secure a common frequency band for WAUN use on a global basis.

Fortunately, many countries are considering the introduction of digital TV within a few years. As digital TV is very efficient in frequency spectrum utilization, it does not require as much frequency spectrum as analog TV. Therefore, it may be possible to introduce a new type of wireless system using the VHF and/or UHF bands, which are currently used for analog TV broadcast. For example, in Japan the government has started discussing the reallocation of the frequency spectrum currently used for analog TV broadcasting services to new services [16].

Conclusion

Research on networking sensors and actuators and implementing new applications to make a wide area ubiquitous network was described. The basic feature of WAUN is wide coverage with very low power consumption. Therefore, we set a concrete though challenging target of a 5-km range with 10-mW transmission power for a wireless terminal with a 10-year battery life and performed a field experiment to determine the feasibility of satisfying this target. Simultaneously, to reduce the power consumption, we studied terminal implementation technologies, mainly ones using a power switch fabricated in a CMOS/SOI LSI, and experimentally determined that the power switch can reduce the leakage current to less than 10 nA at room temperature. This result implies that under our assumed usage conditions, a battery life longer than 10 years is possible.

This article considered an approach based on network infrastructure, although most research efforts and attention are paid to the other approach of setting up sensor networks in an ad hoc manner without a network infrastructure. The latter approach is promising in areas where there is insufficient wired network infrastructure or insufficient regular demand and for newcomers who do not have them. However, the former approach can make full use of the existing wired network assets to offer stable services at reasonable costs even without introducing the wireless mesh network. In addition, it can avoid technical issues related to the mobile ad hoc network such as the power consumed when a terminal is used as a mobile switching node, the security threat to mobile switching nodes, and the unstable service area or routing due to too many mobile nodes having excessive freedom of movement. Therefore, these two approaches should be used appropriately.

To commercialize WAUN within a few years, we will initiate a global standardization process. We believe that WAUN is worth discussing as a candidate system using the VHF/UHF band, which, although globally used for TV broadcast at present, will become available within a few years. We hope that this article stimulates research on networks like WAUN or wide-range wireless systems with low power consumption and their applications.

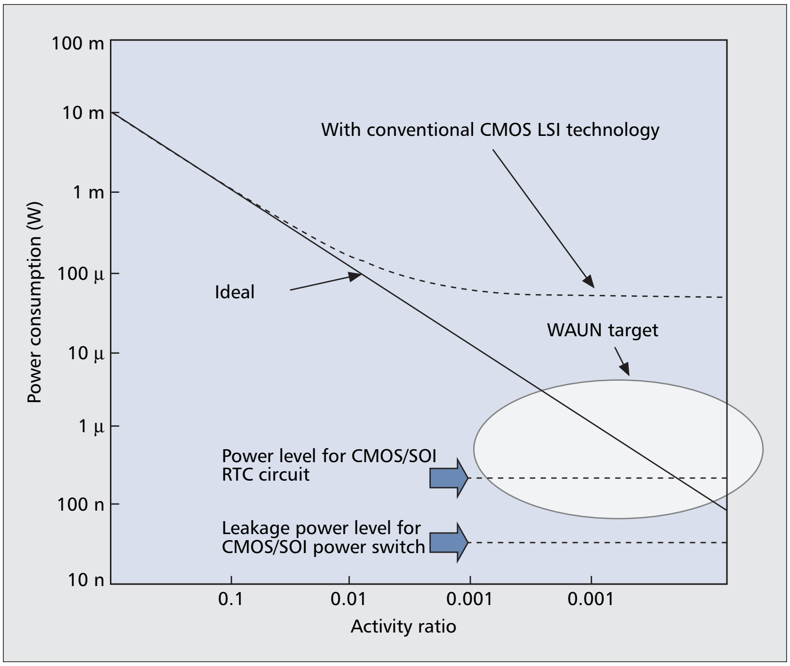


Figure 8. *Power consumption of the WAUN terminal as a function of activity ratio.*

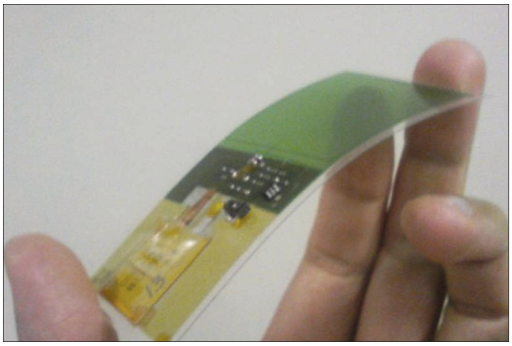


Figure 9. *Conceptual prototype of a future thin-film terminal.*

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BIOGRAPHIES

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