Terminal Design without Using Receiver Circuits for Wireless Sensor Networks

Hiroaki Nose[1], Miao Bao[2], Kazumasa Mizuta[3], Yasushi Yoshikawa[4], Hisayoshi Kunimune[2], Masaaki Niimura[2], and Yasushi Fuwa[2]

[1] Nagano Prefectural Institute of Technology, Ueda-shi 386-1211, Japan
[2] Shinshu University, Nagano-shi 380-8553, Japan
[3] Epson Toyocom Corporation, Hino-shi 191-8501, Japan
[4] Seiko Epson Corporation, Suwa-shi 392-0001, Japan

Abstract. Sensor network terminals are installed in large numbers in the field and transmit data periodically by radio. Such terminals must be miniaturized, and save power so that each device can operate by battery for several years. As one way to satisfy these two conditions, in this research we propose a terminal design which eliminates the receiver circuit. Because there is no receiver circuit, circuitry can be miniaturized, and power can be saved because there is no need to consume power to receive signals. However, the terminals cannot perform carrier detection and reception acknowledgement because there is no receiver circuit. We propose following two new protocols to solve this problem.

1. Terminal transmission times are randomized to prevent frequent collisions between specific terminals due to the lack of carrier detection.
2. Since all packet losses due to collision cannot be prevented with 1, data from a number of past transmissions is included in each packet so that a later packet can provide transmission data even if a packet is lost.

In this report, we describe the proposed protocol, and evaluate its performance by simulation. Furthermore, we actually prototype the system and evaluate the prototypefs performance.

Keywords: Sensor Network, Sensor Node, Power Saving, Protocol.

1 Introduction

Sensor networks which interconnect numerous miniature sensors with built-in wireless communication capability are attracting attention as part of the effort to realize a ubiquitous network enabling easy communication anywhere, at any time, by anything. SmartDust [1] is well known as a pioneering approach in sensor network research. At present there is active research on applications in a broad range of fields including medicine/welfare, crime prevention/security, disaster prevention, and agriculture and devices are being sold as products in an increasing number of cases. Progress is particularly being made toward applications in safety monitoring systems for the elderly and ill, and monitoring of the natural environment, disaster sites and other locations.

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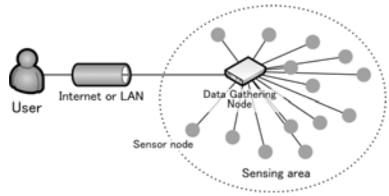

Fig. 1. Overview of system

Sensor network terminals must be small because the aim is to widely disperse them in the natural environment and attach them to mobile objects such as human. They must also save power because they are expected to be used in environments where power supplies cannot be easily secured.

The terminal devices proposed in this research have no receiver circuits, and thus enable greater miniaturization and power saving by the sensor network terminals. We also propose a protocol for lessening the effects of collisions, which occur frequently due to the lack of a receiver circuit. The effectiveness of these proposals is verified via simulation, and we also conduct an evaluation by prototyping the proposed terminals and building a sensor network.

2 Sensor Network Issues

Fig.1 shows the configuration of the sensor network. Numerous independent terminals (sensor nodes) autonomously communicate, periodically sending the information they sense to a data gathering node. Terminals may be distributed in large numbers over an extremely wide range, as would be expected in applications such as safety monitoring and disaster prevention, and it will be crucial to reduce terminal power consumption and achieve greater miniaturization.

2.1 Reducing Power Consumption

In general, terminals of the sensor network will use batteries because they will be attached to people and other mobile objects, or dispersed in the natural environment, and thus are not expected to be used under conditions where a power supply can be easily secured. If terminal size is not a problem, the issue of service life can be solved by using a combination of a photovoltaic cell and a secondary (rechargeable) battery, but the cost will be extremely high. Furthermore, if it is assumed that terminals will be attached to people and other mobile objects, size will become a problem.

Therefore, the favored approach is to incorporate a single primary battery with a comparatively small size and use it as the power supply. However, in this case battery life becomes an issue. In a sensor network where a large number of terminals are distributed over a wide range, the cost of replacing batteries will be extremely high, and this will be a problem directly affecting operation of the system. There are expected to be situations where battery replacement itself will be difficult, particularly in the case of terminals dispersed in the natural environment. To lower these costs it will be necessary to extend battery life by reducing terminal power consumption.

2.2 Miniaturization

Sensor network terminals are likely to be used in the following situations:

1. People attach terminals to their bodies, and transmit data such as their vital signs.
2. Terminals are placed in server rooms and transmit temperature of installed equipment etc.
3. Terminals transmit temperature and other data for the locations where they are installed in the natural environment.

For 1 and 2 installation space is extremely limited. When terminals are attached to the body, they should not interfere with the personfs movement, and it should be possible to wear the terminal without being aware of it. In a server room, terminals must be installed in locations with limited space, such is inside racks, and thus large terminals cannot be installed. In case 3, there are no limitations on the space for installation, but since the terminals are likely to be disposable, it would be ideal for terminals to have the least possible impact on the environment.

Thus there is a strong need to miniaturize sensor network terminals due to the way they will be used.

3 Purpose of This Research

For reducing power consumption of sensor network terminals, Wei Ye et al. have proposed an S-MAC approach where terminals efficiently enter a sleep state to suppress power consumption of wireless devices when they are on standby waiting to receive [2]. With this technique, terminals have two states (active and sleep) and communication is only possible in the active state. All terminals must simultaneously become active in order to communicate, but terminals are synchronized by broadcasting to neighboring nodes that a node is active. There are many studies deriving from S-MAC which attempt, for example, to further improve power saving performance by dynamically changing the period that a terminal is active [3],[4],[5]. A technique has also been proposed which reduces power consumption by synchronizing the times when terminals are active (using a radio clock or other accurate clock), and scheduling receive times [6].

Low Power Listing (LPL) is a common technique which does not use synchronization. The sensor nodes switch to the active state for a time at a fixed interval T, and check the transmit channel. They continue in the active state and receive packets only if the channel is in use at that time. On the other hand, transmitting nodes notify other nodes that there is a request to send by transmitting a

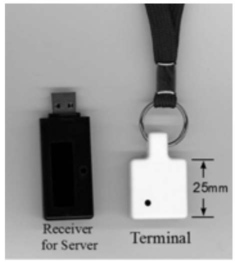

Fig. 2. Sensor terminal (right) and receiver (left)

preamble longer than T. Well known techniques based on LPL include B-MAC [7], X-MAC [8], and TICER [9].

Recently, ZigBee (IEEE 802.14.4) [10] has attracted attention as a sensor network protocol, and sensor modules are being commercialized. With ZigBee, nodes are classified into 3 types: ZigBee coordinators, ZigBee routers and ZigBee end points. Of these, only the ZigBee endpoints which do not relay information have power saving specifications.

Thus all of the sensor network protocols which have currently been proposed assume that the sensor network terminals have reception capability, and strive to reduce power consumption by efficiently suppressing power supplied to the receiver circuit.

In order to further reduce power consumption and achieve greater miniaturization, we have developed terminals without a receiver circuit, as shown in Fig.2, and we propose a sensor network using these. However, since the sensor network terminals have no reception capability, the network cannot use conventional protocols employing carrier detection. Therefore there is an increase in packet loss due to collision, and major problems arise in the overall performance of the system.

To solve this problem, we propose a new protocol for sensor networks which use sensor network terminals with no receiver circuit. This protocol is comprised of two elements: providing a random wait time before starting transmission, and redundantly transmitting past data in each packet.

This research examines the proposed protocol in detail through simulation. In addition, we implement the proposed protocol in actual sensor network terminals with no reception capability, and confirm the effectiveness of the proposed technique by conducting experiments on the data loss rate in an environment where multiple terminals are simultaneously operating.

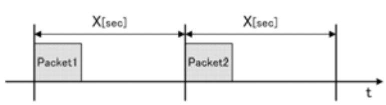

Fig. 3. Packet transmission timing

4 Proposed Protocol

4.1 Elimination of Receiver Circuit

The main role of terminals in a sensor network is to send data measured by the terminals' sensors to the data gathering server. Therefore it is rare for sensor network terminals to receive any data, and in some systems they don't receive any data at all. In the sensor network system we are developing, it was decided to eliminate receiver circuits from the sensor network terminals. This makes it possible to eliminate power consumed by the receiver circuits, thereby enabling major power savings. At the same time, it also enables miniaturization of network terminals.

4.2 Problems with Eliminating Receiver Rircuits

Generally, protocols for wireless networks perform carrier detection before starting transmission, and transmission begins after confirming that no other terminal is transmitting. To avoid collisions between transmissions starting at the same time due to simultaneous detection of the no-carrier state by different terminals, a typical approach is to provide a random wait time until the start of transmission. However, the sensor network terminals used in this system omit reception capability in order to reduce power consumption, and thus carrier detection is impossible.Thus there is no way for a terminal to check the state which other terminals are in, and the only thing a terminal can do is transmit one-way. As a result, all terminals of the system repeatedly transmit in a disorderly fashion. Transmission collisions frequently occur, and this causes a marked drop in throughput of the overall system.

Occurrence of Constantly Colliding Terminals. The sensor network terminals of this system transmit one packet at a time at a fixed time interval of X [sec], as shown in Fig.3. The beginning of the first transmission is determined simply by the time when the terminal's power was switched on, and thus transmission is asynchronous, with no relationship whatsoever to other terminals or the time etc. Therefore, if there are multiple terminals which happen to start their first transmission at the same time, their transmissions will collide every time, and there will be many terminals which can never complete their transmission.

Unconfirmed Arrival of Data. With ordinary protocols, the receiving side sends ACK to the transmitting side when a transmission has been received properly, and both sides recognize that the communication has finished successfully when the transmitting side receives this ACK. With this system, however, the terminals do not have a way to confirm that their own transmission was successful. Therefore if packet loss occurs frequently due to factors such as increasing the number of terminals, there may be a marked loss of communication quality of the overall system.

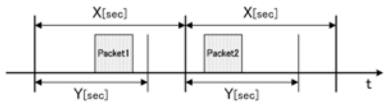

Fig. 4. Packet transmission timing with random delay times

4.3 The Proposed Protocol

This system uses terminals which cannot perform carrier detection because reception capability has been eliminated. Therefore, we propose a new protocol which avoids the aforementioned occurrence of constantly colliding terminals and ensures successful communication.

Setting of Random Delay Time. Terminals transmit once at every fixed time interval X [sec]. Therefore, as stated in 4.2, terminals which started transmitting at the same time, will continually conflict thereafter and transmission will fail. Thus a random transmit delay time T ranging from 0 - Y [sec] $(0 \leq T \leq Y)$ is provided before starting transmission, as indicated in Fig.4. In this way, the transmission timing is varied within a range up to maximum of Y each time transmission is attempted, and this makes it possible to avoid the occurrence of terminals whose transmissions constantly collide because they started transmission at the same time. Transmission once in the time X is assured by setting Y so that $X > Y + P$, where P is the time required to send a packet.

Redundant Transmission of Past Data. Since terminals cannot received an ACK from the receiving side, it is impossible for a terminal to confirm whether a packet it sent was received correctly by the gathering server. Therefore, if transmission fails due to collision with another terminal, the data which the terminal was trying to transmit will be lost. In other words, the effects due to packet loss will be extremely large. Thus, in order to handle the situation where transfer of data is not completed in a single transmission, data for the past $Z - 1$ times is added to the latest data currently being transmitted in the transmission packet so that data for Z transmissions is sent in a single packet, as

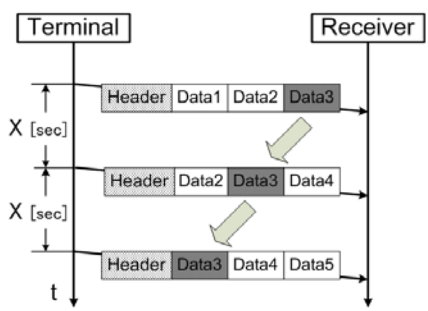

Fig. 5. Redundant transmission of packets

Preamble	WS	Terminal ID	Data1	···	DataZ	Check sum
48bit	32bit	32bit	16 × Z bit			8bit

WS : Frame synchronize
Data : Measurement data

Fig. 6. Frame format of terminal packet

indicated in Fig.5. This ensures that data arrives on the receiving side, provided that transmission failure only occurs consecutively less than Z times, and this improves transmission reliability. However, we must take into account the fact that increasing Z increases packet length, and thereby increases the probability of packet collision. (This is verified in 5.2.)

5 Evaluation

5.1 Specifications

This section describes the specifications of the system being evaluated. The frequency used is the 315 MHz band, and communication speed is 60 kbps. The format of the packets sent by the terminals is as indicated in Fig.6, with each packet consisting of a preamble, terminal ID, data fields and check sum. In order to realize the redundant transmission in the proposed protocol, the data fields contain multiple past data items in addition to the most recent data.

5.2 Evaluation of Data Loss Rate by Simulation

The data loss rate is defined as the percentage of data which cannot be received correctly by the data gathering node, relative to the number of data items generated in each fixed time interval X. The data loss rate for the proposed protocol was found by simulation. The system used for simulation was configured as shown in Fig.1, and incorporated 100 terminals. The transmission repeat time X for each terminal was set to 1 [sec], and 100 packets were sent, so the system overall was highly loaded. The start up timing of each terminal was also set to be random. For this system, Z was increased in increments of 2 from 1 to 9, and Y was increased in increments of 200 [msec] from 100 [msec] to 900 [msec], and simulation was conducted 5 times for each of these conditions. Fig.7 shows the average data loss rate, and Fig.8 the maximum data loss rate in the simulation results. In both graphs, the horizontal axis indicates the Y value, and the vertical axis indicates the data loss rate.

In Fig.7, the average data loss rates were found for all terminals in all 5 simulations, and 95% confidence intervals are also shown in the graph.

Fig.8 shows the results for maximum data loss rates. The reason for adopting the maximum data loss rate as the object of evaluation is as follows.

In the current system, the transmission timing is determined by when the power supply for each terminal is turned on. Therefore, if the Y value is 0, there will be groups of terminals whose transmitted packets are always lost due to

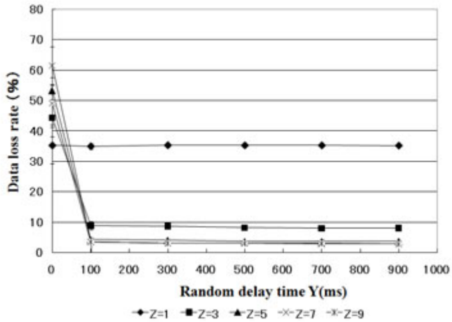

Fig. 7. Average data loss rate

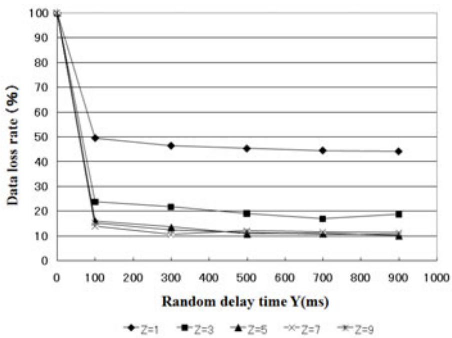

Fig. 8. Maximum data loss rate

collision. Even if a Y value is provided, variations in timing will arise depending on its value, and biases are likely to appear in the data loss rate. Therefore, even if the average data loss rate is, say, 3% under certain conditions, and that is within the permissible range for the application, a specific set of terminals may have a data loss rate of 30%, thereby resulting in problems. In the case of this system, where a bias can arise in the data loss rate between terminals, we felt there were problems with discussing protocol performance using only the average data loss rate, and thus it was decided to use both the average and maximum as a basis for evaluation.

To find the maximum data loss rate here, simulations were performed 5 times under the same conditions while varying the timing of switching on power. Then the data loss rate was found for the terminal whose loss was the greatest in all of the simulations, and the average of those values over the 5 times was taken to be the maximum.

Introduction of Random Delay Time Y. First we verified the effectiveness of introducing the random delay time Y. A major improvement due to introducing Y can be seen in both the average and maximum data loss rate. When the random delay time was not provided, the average loss rate was 30% or higher,

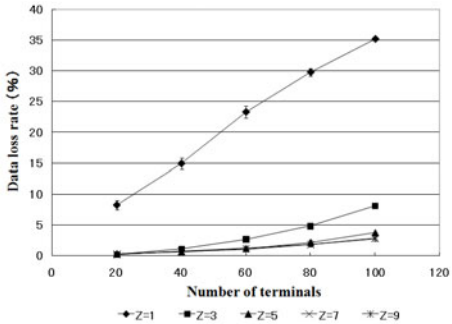

Fig. 9. Change in average data loss rate due to the number of terminals (Y = 900 [msec])

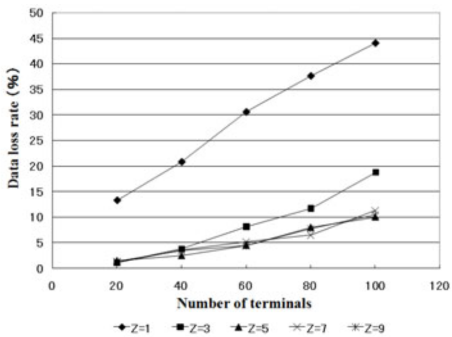

Fig. 10. Change in maximum data loss rate due to the number of terminals (Y = 900 [msec])

and the maximum loss rate was 100% due to constantly colliding terminals. In contrast, when the random delay time was introduced, the average loss rate dropped below 10% for $Z = 2$ or higher.

When $Z = 1$, introducing the random delay time Y has almost no effect on the average value. This is because a random delay time is simply added to the random transmission timing determined only by the original time the terminals were started up, and thus no significant difference was seen in transmission timing. However, for $Z = 1$ the maximum was 50% or less, and for $Z = 2$ or higher it was 25% or less. In both cases, effects due to the introduction of Y were evident. The main factor due to the introduction of Y was the elimination of constantly colliding terminals.

Also, if we look at changes in the loss rate with respect to increases in Y, almost no change is seen for the average, but a small reduction is evident for the maximum, and the loss rate reaches a minimum when Y = 900 [msec].

Introduction of Redundant Transmission of Past Data *Z*. Next, we verify the effect of introducing redundant transmission of past data Z. In the

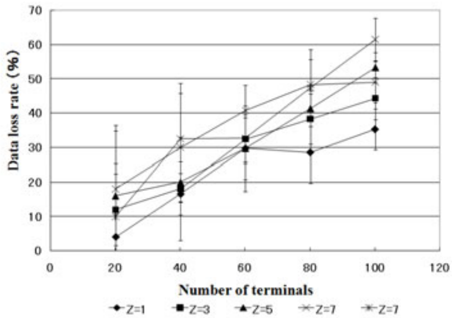

Fig. 11. Change in average data loss rate due to the number of terminals ($Y = 0$ [msec])

case where Y has been introduced, the average was about 35% for the case where Z was not introduced ($Z = 1$) in Fig.7, but it improved to about 9% for $Z = 3$, 4% for $Z = 5$, and 3% for $Z = 7$. There was also an improvement with maximum values in Fig.8. While the maximum was about 45% for the case where Z was not introduced ($Z = 1$), it improved to about 20% for $Z = 3$, 13% for $Z = 5$ and 10% for $Z = 7$.

For both the average and maximum value, introducing Z led to a major improvement in the loss rate, and the loss rate decreased as Z increased. However, when Z was 5 or more, increasing Z only led to slight improvement. This may be because increasing Z makes it possible to recover even if packets are consecutively lost, but packets get longer as Z increases, and this leads to an increase in the collision probability.

Evaluation Based on Number of Terminals. The effect of introducing Y was verified in 5.2. There it was confirmed that the effect is greatest for the maximum loss rate with $Y = 900$ [msec]. Therefore simulations were conducted to determine the change in loss rate when the number of terminals was varied from 20 to 100 under these conditions. The results are shown in Fig.9 and Fig.10. In the graphs, the horizontal axis indicates the number of terminals, and the vertical axis indicates the data loss rate. It can be confirmed from the graphs that, when Z was set to 5 or higher, both the average and maximum loss rate were held to 5% or less for up to 60 units. This loss rate may be adequate for practical use in selected applications.

For comparison, Fig.11 and Fig.12 show the average and maximum loss rates resulting from a simulation with $Y = 0$ [msec]. $Y = 0$ means that terminals which collide will continue to repeatedly collide, and therefore there is no hope of improving the data loss rate by repeating data in packets. In particular, it was confirmed that the maximum value reaches 100% when the number of terminals exceeds 40, and thus the system is not practical.

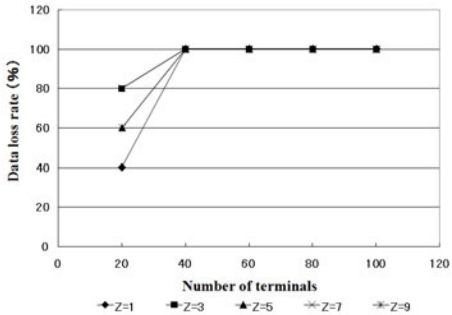

Fig. 12. Change in maximum data loss rate due to the number of terminals ($Y = 0$ [msec])

5.3 Evaluation Using Actual Equipment

Experiments were conducted by implementing the proposed technique with the actual sensor network terminals shown in Fig.2. However, since only 25 sensor network terminals could be procured for the experiment, the network load had to be increased in order to recreate the same trends as the simulations shown in 5.2. Therefore, the experiments were conducted by setting the transmission interval X of the sensor network terminals, which was 1 [sec] in the simulations, to 200 [msec]. Fig.13 shows the average loss rate, and Fig.14 the maximum loss rate, when the number of terminals was set to 10, Y was set to 20 [msec], 100 [msec] and 180 [msec], and Z was set to 1, 3 and 5. Fig.15 shows the average loss rate, and Fig.16 the maximum loss rate, when the number of terminals was set to 25. For comparison, the same simulations as in 5.2 were performed under the same conditions and both the average and maximum were recorded in the graphs. The 95% confidence intervals for each result are shown on each symbol in the graphs.

Comparing the case with 10 terminals against the case with 25 terminals, it is evident that both the average and maximum data loss rate increase as the number of terminals increase. Therefore, it was confirmed by experiments with actual equipment that increasing the number of terminals results in a drop in performance of the entire network.

The average data loss rates in experimental results with 25 units were as follows. When Y was increased from 20 [msec] to 180 [msec], data loss improved from 11% to 6.7% for $Z = 3$ and from 5.4% to 4.0% for $Z = 5$. When Z was increased from 1 to 5, there was a major reduction from 30.2% to 4.0% for $Y = 180$ [msec], and this shows the marked effect of introducing Z. For the maximum values too, increasing Y from 20 [msec] to 180 [msec] greatly reduced the data loss rate from 52.6% to 21.8% for $Z = 3$ and from 48.1% to 11.9% for $Z = 5$, thus showing that occurrence of constantly colliding terminals was effectively suppressed. Also, introducing Z improved the data loss rate, with a drop from 46.4% to 11.9% when Z was increased from 1 to 5 with $Y = 180$ [msec].

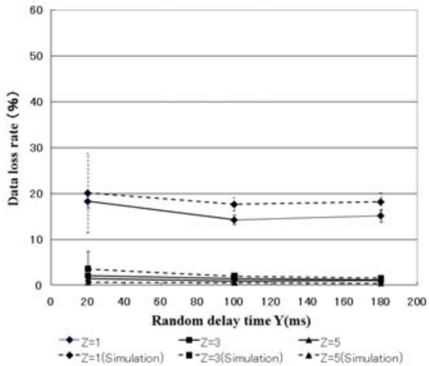

Fig. 13. Average data loss rate (10 terminals, transmission interval $X = 200$ [msec])

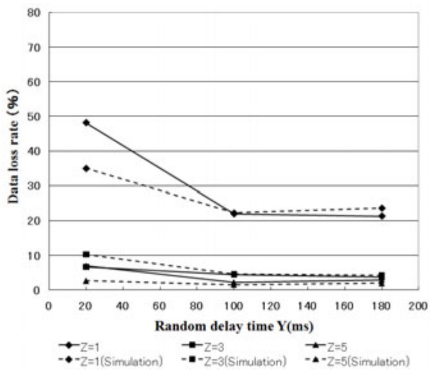

Fig. 14. Maximum data loss rate (10 terminals, transmission interval $X = 200$ [msec])

When the results of experiments using actual equipment are compared with results based on simulation, some differences are evident in the numerical values for the data loss late, but Y and Z exhibit almost the same trend of improving the data loss rate, and the evaluation of the proposed protocol via simulation in 5.2 was confirmed to be valid.

5.4 Power Consumption

Battery life was verified in two cases: when the proposed protocol was implemented and receiver circuits were eliminated, and when a receiver circuit was installed and carrier detection and ACK reception were performed.

Assuming use of an ordinary coin-cell battery, capacity was set to 225mAh, and the fixed time interval X was set to 1 [sec]. When both carrier detection and ACK reception are performed, transmission/reception operation of sensor network terminals is basically comprised of receiver module setting, RSSI, transmission and ACK reception (Fig.17). The current consumption required by each operation was measured with a prototype, and battery life was determined by

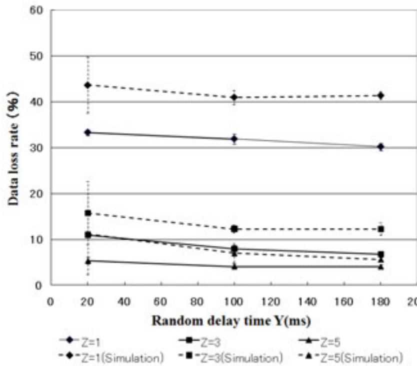

Fig. 15. Average data loss rate (25 terminals, transmission interval $X = 200$ [msec])

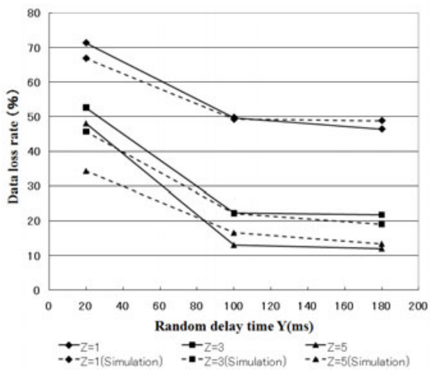

Fig. 16. Maximum data loss rate (25 terminals, transmission interval $X = 200$ [msec])

calculating based on those values. When the time and power consumption required for reception were measured using a prototype circuit, it was found, for the period from switching on power to the RFIC circuit until reception was enabled, that current consumption for the first 2.2 [msec] interval was 17 mA, that current consumption for the following 2.2 [msec] interval was 23 mA, and that after that reception was enabled. To perform carrier detection, receive processing was performed for 0.5 [msec] after this processing to switch on power of the RFIC circuit (current consumption at that time was 23 mA). Current consumption during ACK packet reception, after power switch-on processing of the RFIC circuit in the same way, was 23 mA. It was determined by measuring the prototyped circuit that the transmitter circuit required 10 mA of current consumption.

First of all, Fig.18 calculates the effect of the parameters of this protocol Y and Z on battery life, in the state with no receiver circuit. This graph shows that, when Z is varied from 1 to 10, battery life is reduced by almost half. Since

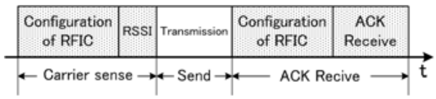

Fig. 17. Transmission/Reception modes of sensor terminal

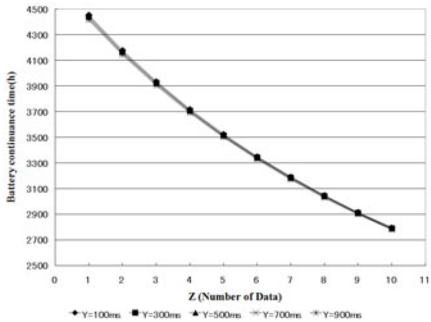

Fig. 18. Effect of introducing Y and Z on battery life

increasing Z directly increases packet length, and the time necessary for transmission increases with longer packet length, battery life may become shorter. On the other hand, even if Y is varied from 100 [msec] to 900 [msec], this only shifts the transmission timing, and has almost no effect on battery life. Some reduction in life is evident in response to increasing Y, but this is because the maximum setting of the timer for measuring the sleep state of sensor network terminals in this system is 250 [msec] and if Y exceeds that value, it is necessary to reset temporarily from the sleep state, and thus there is a slight increase in power needed to do this.

In contrast with the case with no receiver circuit, Fig.19 assumes that $Y = 900$ [msec] and calculates battery life when a receiver circuit is provided. In addition to the case with no receiver circuit, three cases with a receiver circuit are shown: carrier detection only, ACK reception only, and both carrier detection and ACK reception. In the case with no receiver circuit in the proposed protocol, life is 4500 hours for $Z = 1$ and 2800 hours for $Z = 10$.

In the cases with a receiver circuit, battery life was shortest when both carrier detection and ACK reception were implemented. In that case, life was about 650 hours for $Z = 1$, and 600 hours for $Z = 10$. In the case of carrier detection only, where life was longest, life was about 1300 hours for $Z = 1$ and 1100 hours for $Z = 10$.

This calculation was done using an extremely short fixed time interval of $X = 1$ [sec] for the sensor network, and thus, if X is assumed to be 10 [sec], it should be possible to achieve a battery life of about 5 years with $Z = 1$ and 3 years with $Z = 10$. These results confirmed that power saving can be realized by eliminating the receiver circuit.

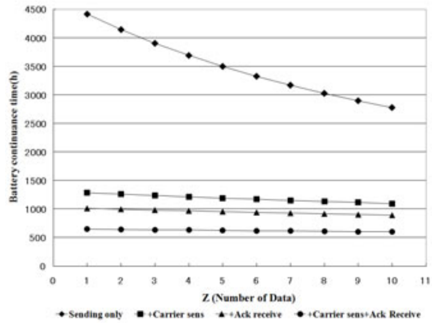

Fig. 19. Battery life with receive operation ($Y = 900$ [msec])

6 Conclusion

In order to realize a sensor network using terminal devices with no receiver circuits, this paper proposed a new protocol which does not require carrier detection or ACK reception.

If the sensor network terminals have no receiver circuits, collisions will occur frequently due to the lack of carrier detection, and constantly colliding terminals in particular will cause a marked decrease in system performance. Furthermore, since ACK reception is not performed, there is a problem due to loss of certainty regarding data arrival.

The contributions of this paper can be summarized in the following four points:

1. In transmission where carrier detection is not performed, each sensor terminal repeatedly transmits on its own, and therefore constantly colliding terminals arise. Consequently, there was a problem in that the maximum data loss rate for the sensor network reached 100%. However, by providing a random delay time when transmitting from each sensor network terminal, it was possible to improve the maximum data loss rate to 50% or less.
2. Since ACK reception is not performed, each sensor network terminal cannot confirm that the sent data successfully arrived on the receiving side. Therefore, if a packet is lost due to collision, the data in it will be lost. However, if past data is sent redundantly while also providing the random delay time in 1, then the average data loss rate can be improved to about 3%.
3. Major improvements were seen, just as in the simulations, in experiments conducted by implementing the protocols proposed in 1 and 2 in actual equipment, and the effectiveness of the proposal was confirmed.
4. Battery life of the sensor network terminals was calculated by measuring current consumption in each operation of the actual equipment. As a result, it was confirmed that eliminating the receiver circuit was effective for lengthening battery life.

Going forward, we plan to develop actual applications in fields such as agriculture, medicine and disaster prevention.

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