POLICY-BASED ENERGY EFFICIENT DATA REPORT METHOD FOR MULTI-MODE WIRELESS SENSOR NETWORKS

Kosuke YAMAZAKI (KDDI R&D Laboratories Inc., 2-1-15 OHARA FUJIMINO-SHI SAITAMA 356-8502, JAPAN, ko-yamazaki@kddilabs.jp), Issei KANNO (KDDI R&D Laboratories Inc., 2-1-15 OHARA FUJIMINO-SHI SAITAMA 356-8502, JAPAN, is-kanno@kddilabs.jp), Yuji IKEDA (KDDI R&D Laboratories Inc., 2-1-15 OHARA FUJIMINO-SHI SAITAMA 356-8502, JAPAN, yj-ikeda@kddilabs.jp), Hiroyasu ISHIKAWA (KDDI R&D Laboratories Inc., 2-1-15 OHARA FUJIMINO-SHI SAITAMA 356-8502, JAPAN, ishikawa@kddilabs.jp)

ABSTRACT

Multi-mode wireless sensor networks (MM-WSNs) consist of tiny sensor nodes (SNs) equipped with multiple radio access technologies within their very limited resources. The availability of multiple radio systems can expand accessibility and fast response toward/from each SN. However, without a suitable radio system selection method on each SN, the MM-WSN lifetime will be shortened due to redundant power consumption. In this paper, we propose a new radio system selection method, which switches between two types of metrics for the system selection, one is for energy-efficiency and the other is for maximizing the transmission data rate. Moreover, a method involving switching of these policies according to SN's remaining battery power is adopted. We show that both of accessibility and response can be improved by controlling MM-WSN lifetime.

1. INTRODUCTION

A great advantage of the software defined radio (SDR) technique is the fact that multiple radio access systems can be installed on simple hardware[8]. This feature becomes more important, especially when SDR is applied to embedded and power-critical systems, e.g. machine-to-machine networks or embedded sensor networks. Within the latter, hardware cost should be minimized and complete hardware replacement by adding and updating radio access systems is very difficult. One typical application of an embedded system is a wireless sensor network (WSN), which consists of a huge amount of tiny sensor nodes (SNs) with very limited resources. SNs are usually located in untouchable areas, e.g. on street lights [1][2][3] , in a desert island [4][5] or in deep sea [6] and the number of deployed sensor nodes tends to be huge [7]. With this in mind, changes to radio access systems incur huge costs. The SDR technique can reduce these dramatically, while also allowing SNs to use multiple radio access systems with even simple hardware. To date, we have proposed multi-mode wireless sensor network (MM-WSN) architecture to expand accessibility and a swift response toward/from each SN[9]. There, the available radio communication systems include not only multi-hop systems, i.e. short range ones like WiFi, Bluetooth or ZigBee, but also single-hop, long range radio communication systems like cellular or wireless broadband systems. Here, SNs with multiple systems are called as Multi-mode SNs (MM-SNs), which can use suitable radio access systems accordingly to report the measured data. Each radio access system has its own characteristics in terms of power consumption and transmission data rate and then a proper radio system selection method can achieve high-speed data transmission even with low power consumption. Our proposed method uses the energy consumption value to send a single bit data. The value diminishes when the system can transmit data at a higher data rate with smaller power consumption. In other words, the system with the lowest value can report data the most power-effectively. However, this value considers only power-effectiveness. At that time, the data transmission rate may be treated as the secondary importance. In this paper, we propose a new radio system selection metric to maximize the transmission data rate. Moreover, a switching method between two types of metrics according to MM-SN's remaining battery power is adopted.

The rest of this paper is organized as follows. In section II, details of MM-WSN and MM-SN are shown. In section III, a problem related to power consumption is identified and a new radio system selection method is proposed. In section IV, the effectiveness of our proposal is shown through computer simulations. Finally, in section V, we conclude this paper and show future works.

2. MULTI-MODE WIRELESS SENSOR NETWORKS

An overview of MM-SN is shown in Figure 1

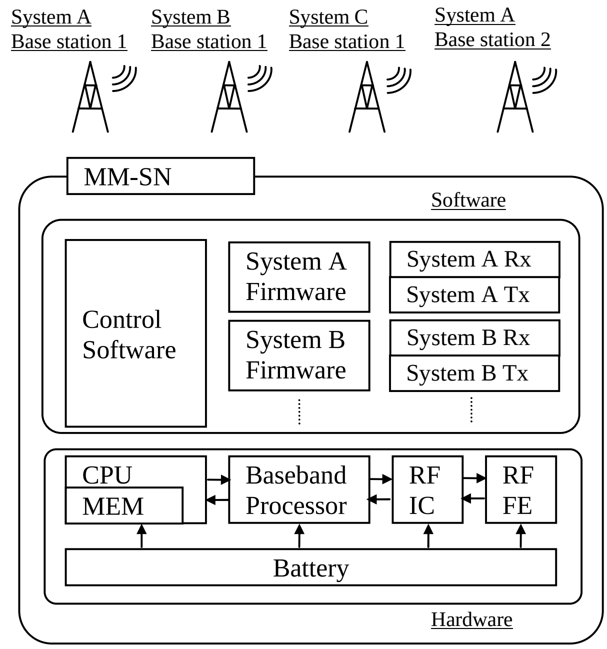

Figure 1 An overview of MM-WSN and MM-SN. All radio systems are implemented on the "Baseband Processor" solely by software. "Control Software" has the responsibility to decide an executed system on the MM-SN. Basically, MM-SN is battery-driven and can be freely located.

In Figure 1, three types of radio access systems usable by MM-SN, A, B and C, are deployed. MM-SN consists of five parts, a CPU, Baseband Processor, RF-IC, RF-Front End (RF-FE) and battery. The CPU controls the loading/storage/execution of firmware on the baseband processor. Based on the type of firmware, suitable RF-IC and RF-FE characteristics, e.g. center frequency, bandwidth and so on, are configured and then realized by pre-installed software.

To retain the deployment flexibility of most MM-SNs, they should be battery-driven. Therefore, MM-SN should select a radio access system with sufficient care of power consumption. Moreover, a sufficient transmission rate should be ensured to fulfill the rush requirement for data.

3. RADIO ACCESS SYSTEM SELECTION METHOD

In Figure 2, an example of MM-WSN as well as the required power consumption and available transmission data rate of each radio system are shown.

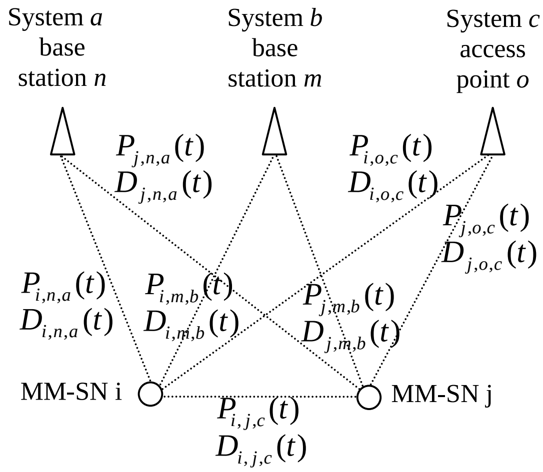

Figure 2 An example of MM-WSN and the required power consumption and available transmission data rate of each radio system. MM-SN *i* and *j* are SNs and there are three base stations, each of which provides different radio systems. Both MM-SNs are within the coverage of each system and select the best suitable system among a, b and c.

MM-SN i and j illustrated in Figure 2 can utilize radio access systems a, b and c. To save power consumption for data report, each MM-SN must determine a used system among them.

To consider the transmission rate and power consumption at the same time, we adopt an energy consumption value to send a single bit data as a metric of each radio access system. This value is calculated according to equation (1):

$$E_{i,n,a}(t) = P_{i,n,a}(t) / D_{i,n,a} \quad (1)$$

Here, $E_{i,n,a}(t)$ means the energy consumption value [J/b] required for MM-SN i to send a single bit for base station n via system a at time t. $P_{i,n,a}(t)$ means the power consumption value [W] for MM-SN i to communicate with base station n via system a at time t. $D_{i,n,a}(t)$ means the transmission data rate [bps] for MM-SN i to send data for base station n via system a at time t.

The energy consumption for multi-hop transmission is calculated as the sum of two types of energy consumption; one is from "sender" MM-SN to "relay" MM-SN and the other is from "relay" MM-SN to some base station or access point. For example, in Figure 2, $E_{i,j,c}(t)$ is calculated as follows:

$$E_{i,j,c}(t) = P_{i,j,c}(t) / D_{i,j,c}(t) + E_{j,m,b}(t) \quad (2)$$

Here, system b is the most power-effective system for MM-SN j to report the measured data. The value of $E_{j,m,b}(t)$ is shared with MM-SN i. Notice that only MM-SN with more battery capacity than "sender" MM-SN can be "relay" MM-SN".

In accordance with the above mentioned algorithm, power-effective system selection is achieved. However, when MM-

SNs have a power supply or sufficient battery capacity, their requirement may be the highest data rate system, despite the increased power consumption involved.

An enhanced system metric is applied whereby an MM-SN with sufficient remaining battery power can use the high-speed data transmission system, even with higher power consumption. In other words, if the expected remaining battery capacity after the data report exceeds a pre-determined threshold, e.g. $\alpha(0.0 \le \alpha \le 1.0)$ of the initial level, the radio access system with the highest transmission data rate should be used, even if it does not have the lowest value of energy consumption to send a single bit. Energy inefficient systems will be selected only when the remaining battery power is sufficient, whereupon data transmission times can be improved.

5. PERFORMANCE EVALUATION

5.1. Simulation setup

In Figure 3, a simulation layout is shown.

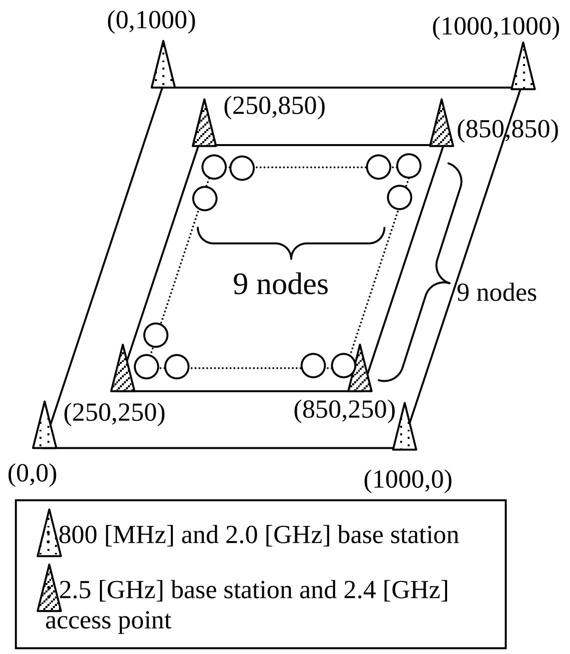

Figure 3 Simulation layout. 4 base stations and access points for each frequency band, 800[MHz], 2.0[GHz], 2.4[GHz] and 2.5[GHz] are located. Sensor nodes capable of using all the frequency bands are located in a reticular pattern.

The frequency bands of available radio access systems are 800[MHz], 2.0[GHz] and 2.5[GHz]. The transmission power for each system is calculated in open-loop fashion, namely a higher output level (power consumption) is required to keep the arriving signal level above receiver sensitivity at base stations or access points. Moreover, when multiple signals on the same frequency band arrive at the same place and time, significant interference causes the SINR (Signal-to-Interference Noise Ratio) to deteriorate. We assume that this SINR level variation impacts on the throughput. These assumptions are summarized in TABLE I.

TABLE I SIMULATION PARAMETERS

Number of nodes		81
Battery capacity		10,000[mWs]
Number of BSs		4 base stations for each system and 4 access points for 2.4[GHz]
Propagation model		Free-space propagation loss $10\log_{10}(4\pi d/\lambda)^n[dB]$ n = 3 (800 [MHz], 2.0[GHz], 2.5[GHz] n = 2 (2.4[GHz])
Available radio access system frequencies		800 [MHz], 2.0 [GHz], 2.5 [GHz] and 2.4 [GHz]
Noise		AWGN
Shadowing		5 [dB]
800 [MHz]	Transmission data rate	76.8 [kbps] ~ 2.4 [Mbps]
	Power Consumption	MAX: 2013 [mW]
2.0 [GHz]	Transmission data rate	153.6 [kbps]~ 4.8 [Mbps]
	Power Consumption	MAX: 2,013 [mW]
2.5 [GHz]	Transmission data rate	64 [kbps] ~ 12.288 [Mbps]
	Power Consumption	MAX: 2,500 [mW]
2.4 [GHz]	Transmission data rate	240 [kbps]
	Power Consumption	MAX: 115.5 [mW]

The listed “Power Consumption” values in TABLE I are for the maximum transmission output level. This output level is calculated by adding propagation loss [dB] to the base station sensitivity [dBm]. Therefore, as a node is getting nearer to a base station, propagation loss becomes smaller and then output level and power consumption can be kept lower.

The transmission data rate varies depends on the SINR. For example, the data rate of 800[MHz] system shown in TABLE I, when SINR becomes lower than -5.0 [dB], becomes only lower than 76.8 [kbps]. However, when SINR becomes more than 0.0 [dB], 921 [kbps] data rate is available. When SINR becomes more than 5.0 [dB], 1.843 [Mbps] can be used. When SINR becomes more than 10.0 [dB], the available data rate becomes the highest, 2.4 [Mbps]. These adaptive data rate assumption is adopted with all of systems except to 2.4 [GHz] system. There is assumed to be no interference on only 2.4 [GHz] throughputs by applying perfect CSMA/CA as the multiple access method.
The methods compared are listed below:

- HYBRID
Our main proposal method. Among 800[MHz], 2.0[GHz], 2.4[GHz] and 2.5[GHz], a suitable system is used to report data according with the algorithm described in section III.
- SH (Single-Hop)
Among 800[MHz], 2.0[GHz] and 2.5[GHz], the most power effective system is selected.
- MH (Multi-Hop)
Only a 2.4[GHz] system is available and the next hop should have the smallest value for equation (2).

The measured data size to be reported can be easily changed according to content. If considerably detailed information is required, the data size will be huge. In this section, the influence is confirmed when the data size changes. In our setup, the smallest case is 187 [KB], the second smallest 1.125 [MB] and the largest 18 [MB]. The capacity of each battery is set as 10,000 [mWs].

5.2. Battery Lifetime Comparison

At first, to confirm power effectiveness, the ratio of battery-remaining SNs versus all SNs, referred to as the Possibility of Survival (POS), is evaluated. This value is calculated the number of battery-remaining SNs divided by total initial SNs number, 81. Here, the battery capacity threshold, α , is set as 1.0, e.g. each MM-SN uses only equation 2 to select the suitable system. Evaluation result is shown in Figure 4.

In SH, the POS line smoothly declines while the number of report times increases. MM-SNs located at significant interference areas (near the center of space) expend far greater energy to report data and the battery capacity is swiftly exhausted. Conversely, MM-SNs in the smaller interference area consume less energy to report data, whereupon their battery capacities last longer. Consequently, the POS line of SH declines gently. In HYBRID and MH, MM-SNs in the center area tend to use a 2.4 [GHz] system to avoid significant interference. The data is sent toward other MM-SNs in areas of reduced interference and reported

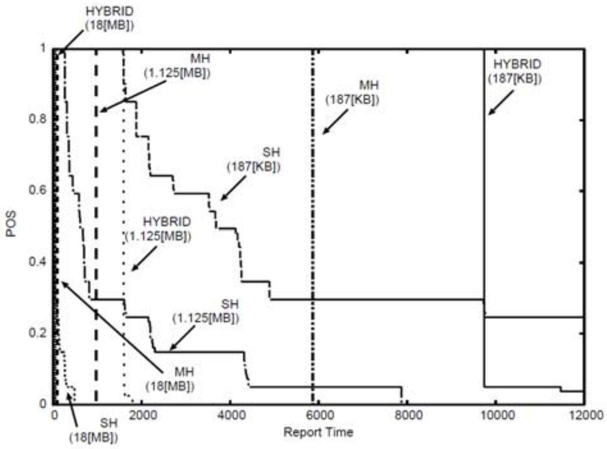

Figure 4 POS (Probability of Suvival) results. On SH, POS smoothly deteriorates over time. Conversely, in HYBRID and MH, POS drops sharply, since fair power consumption between MM-SNs is achieved. The HYBRID lifetime is clearly extended much further than that of MH by reducing the additional relay load to other MM-SNs.

with less energy consumption. Therefore, in HYBRID and MH, fair battery usage is realized. Moreover, HYBRID uses an SH system and reduces the redundant load on other MM-SNs. Moreover, it emerges that our proposal improves the whole network lifetime fairly by reducing additional load to other MM-SNs. Next, the total energy consumption until 5,000 time reports is captured in Figure 5.

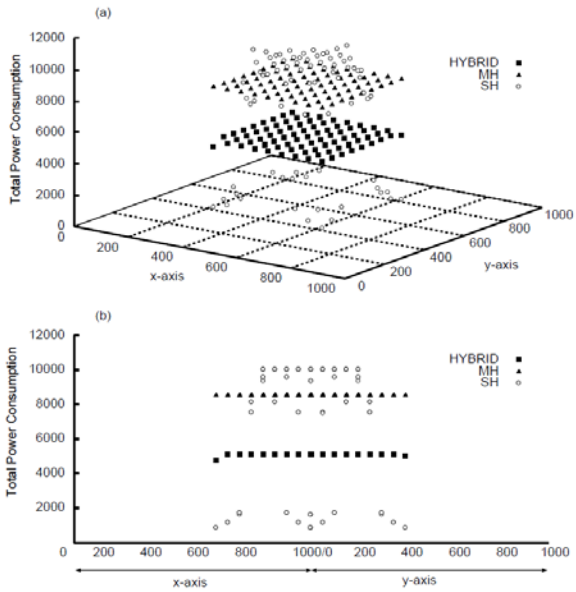

Figure 5 Total energy consumption up to 5,000 reports. (a) a three-dimensional spatial map and (b) shows the projected figure of (a) along the diagonal line.

From Figure 5, in SH, it is confirmed that the nearer MM-SN is located to the center, the greater the energy consumption required. This is because MM-SNs are located near the center where there is significant interference, the transmission data rate declines and more total energy consumption is required in order to complete the data transmission. Even in such cases, HYBRID allows an MM-SN to use multi-hop data transmission toward another MM-SN with better radio conditions and then achieves small and fair energy consumption through the network. In MH, the same trend can be found as HYBRID, but the total volume is much higher than HYBRID. Next, the data transmission time is measured in order to evaluate the amount of delay (Figure 6).

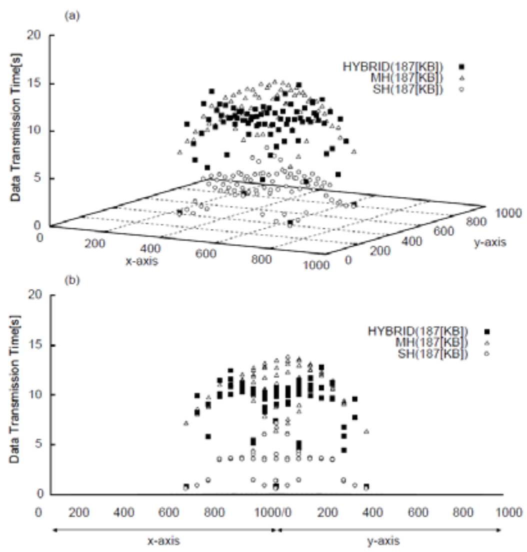

Figure 6 POS results when each node can select a radio system with the highest transmission data rate, regardless of the power consumption value provided the node has sufficient remaining battery power, up to ratios of 0.2, 0.5, and 0.7 of the initial battery capacity respectively.

In SH, the fastest data report is achieved due to the higher transmission data rate of a single-hop radio access system. On the other hand, MH requires the data report through a multi-hop relay and then the data transmission time becomes longer in proportion to the number of hops. In HYBRID, the performance is in-between all others, better than MH but worse than SH.

To improve data transmission time in HYBRID, we have set a battery threshold, α, whereby each MM-SN can select the radio system with the highest transmission data rate, regardless of the power consumption value, provided the MM-SN has sufficient remaining battery power. In this evaluation, α is set as 0.2, 0.5, 0.7 and 1.0. A result is shown in Figure 7

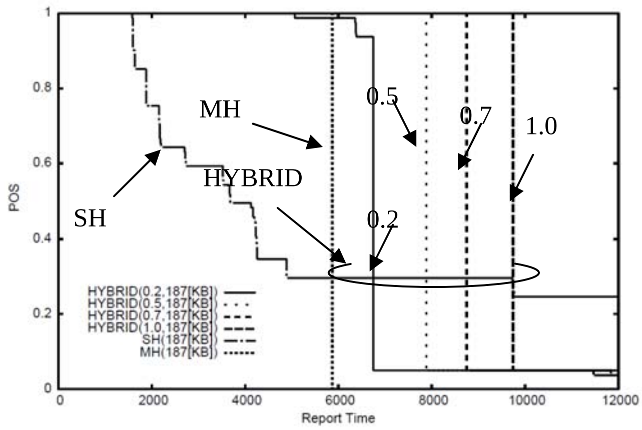

Figure 7 POS results when each node can select a radio system with the highest transmission data rate, regardless of the power consumption value provided the node has sufficient remaining battery power, up to ratios of 0.2, 0.5, and 0.7 of the initial battery capacity respectively.

From Figure 7, it can be found that the smaller α becomes, the smaller the number of possible reports becomes. This is because a smaller α value means that more MM-SNs can select higher transmission data rate systems, which shortens the lifetime of the network.

Next, an influence on data transmission time from a battery threshold is evaluated. In TABLE II, the results of the data transmission time are shown.

TABLE II AVERAGE TRANSMISSION TIME [S]

	187[KB]	1.125[MB]	18[MB]
HYBRID(α =0.2)	5.94218	36.38123	708.6916
HYBRID(α =0.5)	7.481484	45.37724	872.3481
HYBRID(α =0.7)	8.265845	51.34823	961.5154
HYBRID(α =1.0)	9.342731	58.00353	1042.378
SH	3.084443	18.12089	292.3042
MH	10.76609	64.54522	1027.17

From TABLE II, when α becomes smaller, the average transmission time also follows suit, hence network responsibility can be improved by considering the remaining battery capacity of each MM-SN.

6. CONCLUSION AND FUTURE WORKS

In this paper, we have described multi-mode wireless sensor networks (MM-WSN). The availability of multiple radio access systems, e.g. not single systems, shows great potential to solve various WSN issues, despite the risk of redundant power consumption. From a hardware perspective, the SDR technique can reduce this drawback due to the lack of additional hardware equipment required. From a software aspect, through certain computer simulations, it becomes clear that our proposed radio access system selection method can solve these problems.

As future works, the influence on throughput due to multiple users accessing a single specific system must be considered, when a huge number of MM-SNs access the same base station via the same system.

7. REFERENCES

[1] Rohan Murty, Geoffrey Mainland, Ian Rose, Atanu Roy Chowdhury, Abhimanyu Gosain, Josh Bers, and Matt Welsh, "CitySense: A Vision for an Urban-Scale Wireless Networking Testbed", the 2008 IEEE International Conference on Technologies for Homeland Security,Waltham, MA, May 2008.

[2] CitySense - An Open, Urban-Scale Sensor Network Testbed, http://www.citysense.net/

[3] BerlinRoofNet, http://sarwiki.informatik.hu-berlin.de/BerlinRoofNet

[4] Alan Mainwaring, Joseph Polastre, Robert Szewczyk, David Culler, John Anderson, "Wireless Sensor Networks for Habitat Monitoring", 1st ACM international workshop on Wireless sensor networks and applications 2002.

[5] Robert Szewczyk, Alan Mainwaring, Joseph Polastre, John Anderson and David Culler, "An Analysis of a Large Scale Habitat Monitoring Application", ACM SenSys'04

[6] Iuliu Vasilescu, Keith D Kotay, Daniela Rus, M. Dunbabin and Peter I Corke, "Data Collection, Storage, and Retrieval with an Underwater Sensor Network", SenSys'05, November 2–4, 2005

[7] Prabal Dutta, Mike Grimmer, Anish Arora, Steven Bibyk and David Culler, "Design of a Wireless Sensor Network Platform for Detecting Rare, Random, and Ephemeral Events", the 4th international symposium on Information processing in sensor networks, 2005

[8] Kosuke YAMAZAKI, Toru KITAYABU, Yuji IKEDA, Issei KANNO and Hiroyasu ISHIKAWA, "AN IMPLEMENTATION OF NOVEL MULTI-BAND/MODE SDR PLATFORM FOR SIMULTANEOUS MULTIPLE RADIO COMMUNICATION SYSTEM", SDR Forum 09, Wasington D.C. USA, Dec. 2009

[9] Kosuke YAMAZAKI, Issei KANNO, Yuji IKEDA and Hiroyasu ISHIKAWA, "Proposal of a Radio Access Selection Method for Enhancing Node Availability in Multi-Mode Wireless Sensor Networks", The 6th International Wireless Communications Mobile Computing Conference (IWCMC 2010), Cane France, 2010