社団法人　電子情報通信学会
THE INSTITUTE OF ELECTRONICS,
INFORMATION AND COMMUNICATION ENGINEERS

信学技報
TECHNICAL REPORT OF IEICE.

センサネットワークにおける緊急情報伝達アーキテクチャの実装と評価

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あらまし　社会インフラとして用いられる無線センサネットワークでは種々の情報がネットワーク内を流れるため，それらのうち緊急を要する情報を優先的に伝達する制御が不可欠である．前回の報告で，複数の単純なメカニズムを組み合わせることでイベントの規模に応じた緊急情報伝達の自律分散制御を可能にする UMIUSI アーキテクチャを提案した．今回，同アーキテクチャを市販のセンサノードに実装して 2 つのテストベッドにて実験を行い，緊急情報の到達率および遅延を評価した．その結果，UMIUSI アーキテクチャはイベントの規模に関わらず緊急情報伝達の信頼性および速達性を向上させることが示された．

キーワード　センサネットワーク，緊急情報，迅速性，信頼性

Implementation and Evaluation of an Urgent Information Transmission Architecture in Wireless Sensor Networks

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Abstract　In a wireless sensor network used as a social infrastructure, priority control is essential to prefer transmission of urgent information over other non-urgent information. In our previous report, we proposed UMIUSI (aUtonomous Mechanisms Integrated for Urgent Sensor Information) architecture, in which several simple mechanisms are combined to enable autonomous and distributed traffic control while adapting to the scale of an emergency. In this paper, we conducted practical experiments in two testbeds with off-the-shelf sensor nodes onto which we implemented UMIUSI, and evaluated the delay and loss rate of urgent information. The results showed that UMIUSI improved the reliability and latency of transmission of urgent information regardless of the scale of an emergency.

Key words　sensor networks, urgent information, fastness, reliability

1　Introduction

In a Wireless Sensor Network (WSN), a number of sensor nodes equipped with a processing unit, a radio transceiver, and sensors are deployed in a region to monitor. Environmental information detected by sensors is collected to a BS (base station) through wireless communication among sensor nodes [1]. A WSN can be used as a social infrastructure, for example, disaster warning system, building automation, public surveillance and so on. Emergency event detection is one of the most important functions in such a WSN. Urgent information, a fire alarm for example, has to be transmitted through a WSN with higher reliability and lower latency than other non-urgent information. Since the capacity of a wireless network is limited, a WSN must be capable of differentiating and prioritizing packets depending on their urgency and importance. Furthermore, in the event of a large emergency, such as an earthquake attack, a lot of nodes detect the emergency and send urgent information at the same time. A WSN should adopt mechanisms to mitigate serious congestion caused by this simultaneous packet emission.

In our previous report [2], we proposed a WSN architecture called UMIUSI (aUtonomous Mechanisms Integrated for Urgent Sensor Information) designed for prioritizing transmission of urgent information. In order to adapt to the scale of an emergency ranging from a small event like a gas leakage to a catastrophic event such as an earthquake attack, some simple mechanisms are embedded in each node, instead of a monolithic and complicated mechanism which controls its overall behavior. Those mechanisms work in different spatial and temporal levels and they autonomously and independently react to its surrounding situation locally observed.

In this paper, we conducted practical experiments in two testbeds whereas we have evaluated the performance of UMIUSI through simulation experiments in the previous paper [2]. One testbed consisted of 25 sensor nodes arranged in a grid and the other had 46 nodes deployed on a floor in practical settings. The contribution of each mechanisms employed in UMIUSI was investigated in the former, and the feasibility demonstration was the primary purpose of the latter.

The rest of this paper is organized as follows. We briefly review the outline of UMIUSI in Section 2. Evaluation of the architecture by practical experiments is presented in Section 3. Finally, we conclude this paper in Section 4.

2 UMIUSI Architecture

We assume a WSN deployed for periodic environment monitoring where a data gathering scheme to collect all sensor information to a BS and a sleep scheduling scheme to prolong the lifetime. In UMIUSI, we consider three classes of sensor information as one normal class and two emergency classes and prioritize emergency class information over normal class information. The two types of urgent information are distinguished in more important and less important.

- *Normal Class.* Any non-urgent information belongs to this class. Normal class information is gathered to a BS at regular intervals of t_{norm}.
- *Important Class.* This class is for urgent information, but an application can tolerate loss and delay of important class information to some extent. Packets belonging to this class, called important packets, can be delayed or dropped depending on the level of congestion in an emergency. The interval of emission of important packets $t_{\mathrm{imp}} < t_{\mathrm{norm}}$ is determined by an application, but could be regulated to be larger than t_{norm} to mitigate congestion.
- *Critical Class.* This class is for the most urgent and important information which requires highly reliable and fast transmission to the BS. Critical packets are emitted by a node detecting an emergency at fixed regular intervals of $t_{\mathrm{cri}} < t_{\mathrm{norm}}$, which is determined by an application.

We choose five mechanisms for UMIUSI: priority queueing, rate control by local congestion detection, retransmission, assured corridor mechanism (ACM) [3], and rate control by backpressure. These mechanisms are simple and distributed, work independently of each other, and cover all the levels

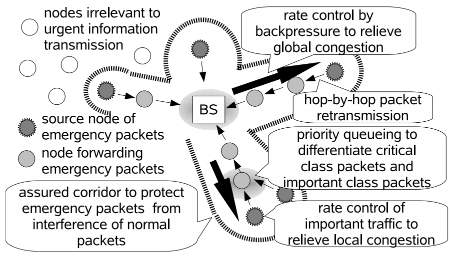

Fig. 1 The mechanisms leveraged in UMIUSI.

from node-level to network-level. Figure 1 briefly summarizes how and where they work. Refer to [2] for the detailed description of UMIUSI with simulation results.

- *Assured corridor mechanism (ACM).* The main purpose of this mechanism is to avoid loss of emergency packets caused by collisions with normal packets. In addition, ACM contributes to avoiding delay caused by sleeping nodes. ACM establishes an "assured corridor" from a source node to a BS, in which emergency packets are protected from normal packets by suppressing packet emission at nodes surrounding the path. In normal operation, all nodes are in the *NORMAL* state and operate in accordance with a data gathering scheme. Once a node detects an emergency, it moves to the *EMG_SEND* state and begins to periodically emit packets labeled as critical or important. On receiving an emergency packet for the first time, other node moves to either of the *SUPPRESSED* or *EMG_FORWARD* state. A node on the path to the BS is responsible for forwarding emergency packets to the BS. Therefore, it moves to the *EMG_FORWARD* state, cancels its sleep schedule to keep awake, and immediately relays emergency packets it receives. A node which receives an emergency packet but is not on the path moves to the *SUPPRESSED* state. A node in the *SUPPRESSED* state completely stops sending normal packets or decreases the sending rate of normal packets. Details of ACM with simulation results can be found in [3].
- *Retransmission.* In order to recover a lost emergency packet while providing differentiated services, we introduce a prioritized scheduling algorithm to hop-by-hop retransmission. When a packet is lost, the first retransmission is scheduled after a backoff. To prioritize retransmission of a critical packet, the backoff timer for a critical packet is set shorter than that for an important packet, at 0.1 and 0.2 seconds respectively in our experiments. If the first retransmission fails, one or more trials are conducted by applying doubled backoff, *i.e.*, a binary backoff scheme, until retransmission succeeds or a next-hop node goes to sleep. An emergency packet is discarded at a node when it receives the next emergency packet originating at the same source node. This is because that sensor data in the waiting packet is obsoleted

Table 1 The power consumption of nodes during 10 minutes. (mAh)

State	Node 1	Node 2	Node 3
NORMAL	8.786	8.814	8.759
EMG_FORWARD	8.795	8.834	8.778
EMG_SEND	8.795	8.836	8.779
SUPPRESSED	8.804	8.849	8.783

by the new data.

- *Priority queueing.* Each node has a priority queue for emergency packets, with which important packets are served only when there is no critical packet queued. This means that fast transmission of critical packets is accomplished at the sacrifice of longer transmission delay of important packets.
- *Rate control by local congestion detection.* To mitigate congestion in a corridor as fast as possible by local control, we introduce a rate control mechanism which is triggered by detection of local congestion. In order to keep the reporting rate of critical information at $1/t_{\mathrm{cri}}$, the rate control is applied only to important class traffic. When a source node of important packets detects congestion by, for example, monitoring packet reception rate, it increases the emission interval of important packets. As a rate control algorithm, a TCP-like AIMD (Additive Increase and Multiplicative Decrease) algorithm, such as that in [4], is empirically employed in our experiments.
- *Rate control by backpressure.* In an event of large emergency such as an earthquake, even if emission of normal packets is suppressed and source nodes of important packets regulate their emission rate, congestion cannot be fully avoided around a node belonging to multiple paths and around the BS, where many emergency packets concentrate on. We employ a backpressure mechanism for a network-level traffic control in UMIUSI. To suppress emission of important packets at their source nodes, a backpressure message is sent back to source nodes from a point of congestion by piggybacking on an emergency packet.

3 Practical Experiments

We implemented UMIUSI onto off-the-shelf sensor nodes provided by OKI Electric Industries Co., Ltd. and conducted experiments using two testbeds.

In the experiments, IEEE 802.15.4 non-beacon mode was employed for the MAC layer. The payload size of an emergency packets was 16 bytes including packet header with a class identifier, dummy sensor data, and a time stamp. For the network layer, we adopted the synchronization-based data gathering scheme [5] modified to ignore uni-directional links. It employs a tree-based routing, and timing of packet emission is the same among nodes of the same hop distance from the BS. In a normal state, all nodes adopt a sleep schedule. Nodes on the same hop distance wake up at the same time and receive packets from one-hop distant node. Then, they send packets to next-hop nodes. Finally, after overhearing packets emitted by the next-hop nodes, they go back to a sleep mode. In the experiments, we set the interval of normal packet emission t_{norm} at ten seconds, and the offset between emissions of adjacent nodes at one second. Routes from nodes to the BS dynamically changed for variations in radio environment.

For evaluation of transmission of emergency packets, we made one (small scale event) or eight (large scale event) nodes become source nodes, *i.e.*, with ACM, they moved to the *EMG_SEND* state. Each of them was scheduled to emit emergency packets at interval of $t_{\mathrm{emg}} = 0.5$ seconds, but the actual interval was up to 0.58 seconds due to implementation constraints. Source nodes went back to normal operation ten minutes later.

We first briefly consider the energy efficiency of UMIUSI. Table 1 summarises the amounts of power consumed by randomly chosen three nodes in ten minutes for each of the four states on Testbed A. It was measured by a digital power meter (Yokogawa Electric WT210) attached to a DC input of a node. We find that the difference in power consumption among four states is relatively small. Therefore the active / sleep ratio in normal operation would determine the lifetime of a node, although we did not apply any sleep schedule in the experiments due to implementation constraints. A node adopts three AAA alkaline cells with serial connection. One cell has the capacity of about 1 Ah. Thus, if we apply a sleep schedule of the active / sleep ratio of 1/600, *i.e.*, being active for one second in ten minutes, the lifetime of a node can be estimated as 11,400 hours (= 1.30 years). Once an emergency occurs and a node stays in either of *EMG_SEND*, *EMG_FORWARD* or *SUPPRESSED* states for three minutes for example, it shortens the lifetime of a node by 30 hours. Developing a sleep schedule for these states is one of our future works.

3.1 Testbed A

In Testbed A, 25 sensor nodes were arranged in a 5×5 grid topology with separation of one meter. A BS was put beside the grid with one meter separation. The transmission power was set to −27 dBm. The average delivery ratio of normal packets over ten hours experiments was around 80 %.

In order to evaluate the effect of mechanisms comprising UMIUSI, we compared five variants of combination of the mechanisms. One is KA (keep awake), in which nodes in a corridor keep awake but neither suppression of normal packets nor other mechanisms is conducted. The second is ACM,

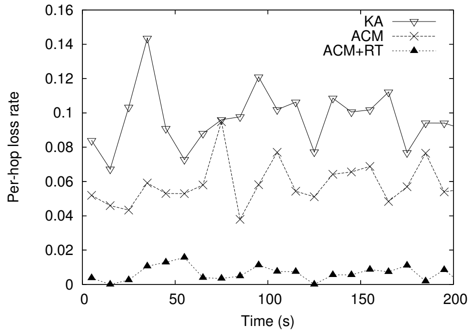

Fig. 2 The per-hop loss rate of emergency packets (small scale event).

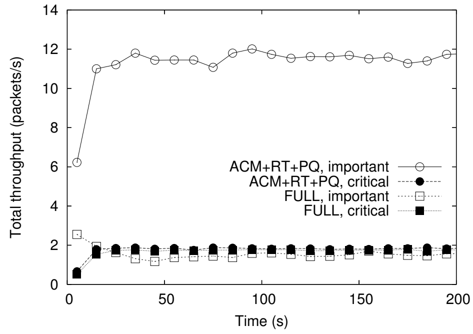

Fig. 4 The total throughput of emergency packets (large scale event).

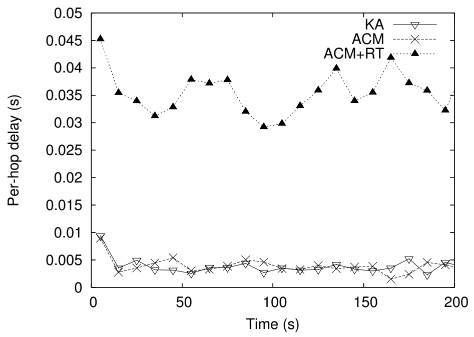

Fig. 3 The per-hop delay of emergency packets (small scale event).

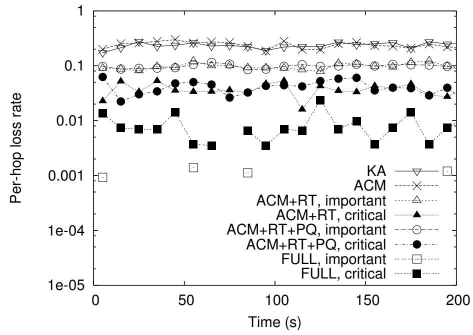

Fig. 5 The per-hop loss rate of emergency packets (large scale event).

in which an assured corridor is established by suppressing emission of normal packets. The third one is ACM+RT (retransmission), in which ACM and the retransmission are applied. For the variants with RT, the first retransmission was scheduled at 0.1 seconds after the first transmission for the critical class and 0.2 seconds for the important class, respectively. A binary backoff scheme was applied to following retransmissions. The fourth is ACM+RT+PQ (priority queueing), in which the priority queueing is additionally applied. The last one, FULL employs all of the mechanisms explained in Section 2. In FULL, local congestion detection was done by monitoring packet reception rate at each node additionally. When a node received more than 20 packets in recent two seconds, it considered that the wireless channel was highly loaded. We observed that the number of packet losses rose up sharply when the traffic exceeded this threshold in preliminary experiments. For the AIMD rate control, the parameters for multiplicative decrease and additive increase were 0.5 and 0.05 packets/s respectively taken from [4].

Since the hop distance from a node to the BS dynamically changed during the experiments, we employ the per-hop loss rate and per-hop delay as evaluation metrics. Letting n the hop distance from a source node to the BS and $p_k\,(k = 1, 2, \cdots, n)$ the per-hop loss rate in transmission of emergency packets at k-th hop, the loss rate P_n observed at the BS is given by

$$P_n = 1 - Q_n = 1 - \prod_{i=1}^{n}(1 - p_i)$$

where Q_n is the delivery ratio observed at the BS. In the experiments, packet losses were detected at the BS using a sequence number in the header of an emergency packet to obtain P_n. Then, assuming p_k is identical for all hops ($p_1 = p_2 = \cdots = p_n = p$), the per-hop loss rate p is defined as

$$p = 1 - \sqrt[n]{1 - P_n} = 1 - \sqrt[n]{Q_n}.$$

The per-hop delay d is defined as

$$d = D_n/n,$$

where D_n is time taken from emission of an emergency packet at a source node to reception of the packet at the BS. Note that, since only a clock on the hundred milliseconds scale was provided for the application layer, time error in D_n observed was 100 ms at maximum.

3. 1. 1 Small Scale Event

In the scenario of a small scale event, one critical class node became a source node of critical packets and went back to normal operation ten minutes later. We conducted experiments twice for each of randomly chosen eight nodes.

Figure 2 shows the per-hop loss rate of emergency packets averaged over the 16 experiments. In these experiments,

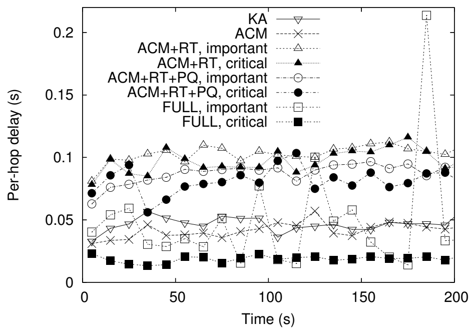

Fig. 6 The per-hop delay of emergency packets (large scale event).

suppression of normal packets became effective immediately after a node began emitting critical packets, since the hop distance to the BS was so small, 1.6 on average, that it did not take long to establish an assured corridor. With retransmission, the per-hop loss rate was further improved to be less than 1 %.

However, retransmission led to increase of the per-hop delay (Fig. 3). Even if collision was mostly avoided by the suppression, packet losses still frequently occurred (see ACM in Fig. 2) due to random channel errors. Therefore, a number of retransmissions were needed to recover those lost packets, which resulted in increase of the delay.

3. 1. 2 Large Scale Event

For the experiments of a large scale event, we considered eight sets of seven important class nodes and one critical class node. These eight nodes were moved to the *EMG_SEND* state in about ten seconds and went back to the *NORMAL* state about ten minutes later. We conducted experiments twice for each of the eight sets.

First, the total throughput of the critical and important class averaged over the experiments is illustrated in Fig 4. Here the total throughput is defined as the number of emergency packets received by the BS per second. Little difference was observed between the total throughput of ACM+RT and that of ACM+RT+PQ for both classes, thus results of ACM+RT are not shown in Fig. 4. With the rate control mechanisms, we can see that the total throughput of the important class decreased around 1.5 packets/s in 30 seconds while that without the rate control in ACM+RT+PQ was kept high at 11.5 packets/s.

The per-hop loss rate of emergency packets is illustrated in Fig. 5. Suppression of normal packets had little effect on reliability in a large emergency as can be seen in comparison between KA and ACM. Adding the priority queueing mechanism to ACM+RT was also not much helpful in this experiment settings, because paths of important and critical class traffic seldom overlapped with each other. In FULL,

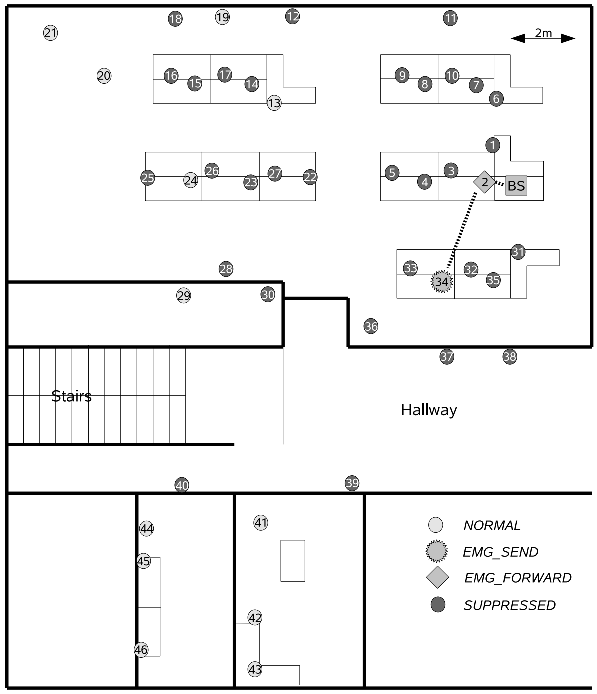

Fig. 7 A small scale event in Testbed B. The thick lines represent concrete walls and steel doors. The rectangles with thin lines represent steel desks.

the per-hop loss rate of the critical class gradually decreased as the emission rate of important class was regulated by the rate control mechanisms. Since an important class packet had more chances to be retransmitted than a critical class packet due to the prolonged interval of emission by rate control, the per-hop loss rate of the important class was smaller than that of the critical class.

Figure 6 shows the per-hop delay of emergency packets. In FULL, the per-hop delay of the critical class gradually decreased in the first 30 seconds as the important class traffic was regulated by the rate control mechanisms. The emission interval of important class packets was prolonged by the rate control mechanisms, thus waiting time to be retransmitted at an *EMG_FORWARD* node could be as long as a few seconds. Such occasional large delay caused the large variation in the per-hop delay of the important class in FULL.

3. 2 Testbed B

The purpose of the experiments in Testbed B is to verify feasibility of UMIUSI in practical settings. In Testbed B, 46 sensor nodes and a BS were deployed on a floor of several rooms and a hallway in a concrete building, as illustrated in Fig. 7. All of the five mechanisms of UMIUSI (FULL) were used, and parameters were the same as in Testbed A other than the transmission power of −7 dBm.

3. 2. 1 Small Scale Event

Figure 7 shows a snapshot where Node 34 detected an emergency. Node 34 reached the BS via Node 2 by a

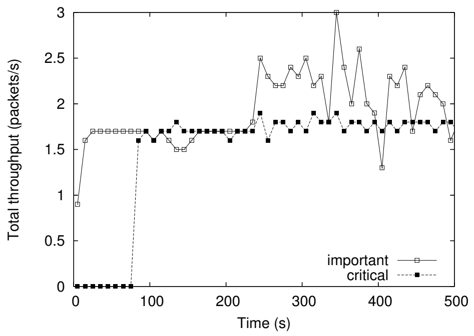

Fig. 8 The total throughput of emergency packets in Testbed B.

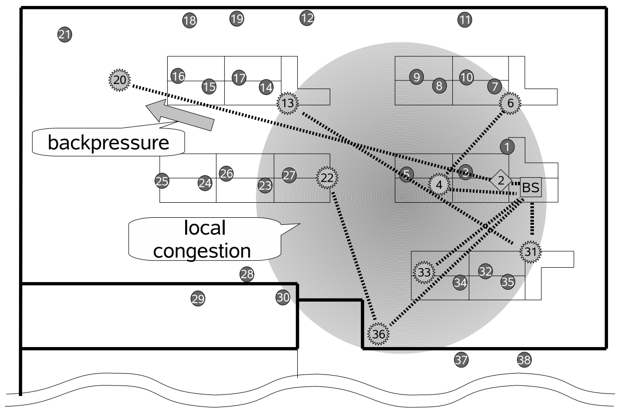

Fig. 9 A snapshot in the large scale event in Testbed B (t = 400 s).

path established by the synchronization-based data gathering scheme. Therefore, Node 2 was an *EMG_FORWARD* node in the snapshot. Nodes indicated by dark circles could hear radio signals of Nodes 2 and 34 and moved to the *SUPPRESSED* state. Due to shadowing and fading, the geographical proximity does not necessarily correspond to neighbor relation. The average per-hop loss rate over eight experiments setting Nodes 4, 7, 16, 25, 30, 34, 41, and 46 an *EMG_SEND* node was 0.37%. The average hop distance to the BS was 2.75.

3. 2. 2 Large Scale Event

Next we considered a scenario where a small scale emergency grew to become large, such as a fire. In this scenario, Node 33 first detected an event, moved to the *EMG_SEND* state, and began sending important packets at time $t = 0$. At $t = 80$ seconds, Node 4 of the critical class next detected the event, followed by Nodes 22 and 36 at $t = 240$ seconds and Nodes 6, 13, 20, and 31 at $t = 340$ seconds. These six nodes were of the important class.

When Nodes 4 and 33 were in the *EMG_SEND* state, emergency packets were directly transmitted to the BS. As shown in Fig. 8 the average throughput was about 1.7 packets/s for both nodes. After Nodes 22 and 36 detected the event at $t = 240$ seconds, local congestion occurred and the three *EMG_SEND* nodes of the important class, *i.e.*, Nodes 33, 22, and 36, reduced the emission rate in order to mitigate congestion. The total throughput of the important class was controlled around 2.3 packets/s. At $t = 340$ seconds, other four nodes newly began to emit important packets and this caused congestion around Node 2. To reduce the important class traffic at its source, Node 2 sent a backpressure to Node 20 (Fig. 9). As a result, the total throughput of the important class was kept about the same level, and there was no loss of critical class packets throughout this ten minutes experiment. The loss rate of important class packets was 0.6 %.

As shown in this experiment, traffic control developed from path-level to network-level adapting to the growing scale of emergency without any centralized control in UMIUSI architecture.

4 Conclusion

Urgent sensor information is needed to be transmitted preferentially in a WSN used as a social infrastructure. In our previous study, we presented a WSN architecture, called UMIUSI, for fast and reliable transmission of urgent information. We consider that several simple and fully-distributed mechanisms working in different spatial and temporal levels should be incorporated onto a node so that the collective control of these mechanisms offers preferential transmission of urgent information adapting to the scale of emergency.

Our claim stated above was examined by thorough practical experiments with two testbeds. The results supported our claim and showed that the architecture successfully improved the delivery ratio and the delay of emergency packets regardless of the scale of emergency.

References

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam and E. Cayirci: "Wireless sensor networks: a survey", Computer Networks, **38**, 4, pp. 393–422 (2002).

[2] T. Kawai, N. Wakamiya and M. Murata: "Design and evaluation of a wireless sensor network architecture for fast and reliable transmission of urgent information", Technical Report USN2007-14, IEICE (2007).

[3] T. Kawai, N. Wakamiya and M. Murata: "ACM: A transmission mechanism for urgent sensor information", Proceedings of the 26th IEEE International Performance, Computing, and Communications Conference (IPCCC 2007), New Orleans, Louisiana, USA, pp. 562–569 (2007).

[4] A. Woo and D. E. Culler: "A transmission control scheme for media access in sensor networks", Proceedings of the 7th annual international conference on Mobile computing and networking (MobiCom 2001), Rome, Italy, pp. 221–235 (2001).

[5] S. Kashihara, N. Wakamiya and M. Murata: "Implementation and evaluation of a synchronization-based data gathering scheme for sensor networks", Proceedings of IEEE International Conference on Communications, Wireless Networking (ICC 2005), Seoul, Korea, pp. 3037–3043 (2005).