PAPER *Special Section on Emerging Technologies for Practical Ubiquitous and Sensor Networks*

Counter-Based Broadcasting with Hop Count Aware Random Assessment Delay Extension for Wireless Sensor Networks*

Shintaro IZUMI†a), **Takashi TAKEUCHI**†, **Takashi MATSUDA**†, ***Student Members***,
Hiroshi KAWAGUCHI†, **Chikara OHTA**†, ***and*** **Masahiko YOSHIMOTO**†, ***Members***

SUMMARY Broadcasting is an elementary operation in wireless multi-hop networks. Flooding is a simple broadcast protocol but it frequently causes serious redundancy, contention and collisions. Probability based methods are promising because they can reduce broadcast messages without additional hardware and control packets. In this paper, the counter-based scheme which is one of the probability based methods is focused on as a broadcast protocol, and the RAD (Random Assessment Delay) Extension is proposed to improve the original counter-based scheme. The RAD Extension can be implemented without additional hardware, so that the strength of the counter-based scheme can be preserved. In addition, we propose the additional algorithm called Hop Count Aware RAD Extension to establish shorter path from the source node. Simulation results show that both of the RAD Extension and the Hop Count Aware RAD Extension reduce the number of retransmitting nodes by about 10% compared with the original scheme. Furthermore, the Hop Count Aware RAD Extension can establish almost the same path length as the counter-based scheme.

key words: *sensor network, broadcast, flooding, counter-based scheme*

1. Introduction

Recent advances in micro-sensors, which integrate circuit technology and low-power wireless communications will enable the deployment of extremely small, low-cost sensor nodes. Applications of sensor networks comprising numerous such sensor nodes include remote environmental monitoring, smart spaces, military surveillance, precision agriculture [2].

A multi-hop wireless sensor network comprises multiple small wireless sensor nodes, each of which is driven by a limited battery capacity. As the number of sensor nodes increases to several hundreds or to several thousands, the persistent necessity of changing batteries would be a considerable burden. For that reason, it is highly desirable to reduce the power being used by each sensor node. A salient issue is the reduction of the amount of transmitted data because wireless communications at sensor nodes consume more power than any other activity [3], [4].

Broadcasting (diffusing a message from a source node to all the other nodes in the network) plays an important role in multi-hop wireless sensor networks. This operation is used for path establishment in most of routing protocols[5], [6]. The most straightforward solution for broadcasting is a flooding (simple flooding), in which every node in the network retransmits an unseen received message once. However, the flooding may cause serious redundancy, contentions and collisions, known as a "broadcast storm" problem [7]. This problem leads to high overheads and high energy consumption. To solve the broadcast storm problem, various efficient broadcast protocols have been proposed [8].

In this paper, we focus on the counter-based scheme which is one of the probability based broadcast schemes. Probability based schemes reduce the amount of unnecessary rebroadcasts with the cost of only slight additional hardware and without any control messages. Such features are desirable for wireless sensor networks because the cost of nodes can be reduced and wireless resource that is scarce can be saved. In [8], *probabilistic scheme* and *counter-based scheme* are shown as examples of probability based methods. In the paper, it is pointed out that the counter-based scheme has adaptability to local topologies, and more precisely node density. This fact is supported in [7] where it is shown that the counter-based scheme outperforms the probabilistic scheme in terms of reachability and saved rebroadcast. The counter-based scheme is, however, not sufficient, and there still remains room for improvement as shown in this paper.

In this paper, we propose two approaches to improve the counter-based scheme: "Random Assessment Delay Extension (RAD Extension)" and "Hop Count Aware RAD Extension (HCA-RAD Extension)." As shown in Sect. 4, the RAD Extension reduces the number of retransmitting nodes by about 10% compared with the original counter-based scheme. In compensation for reduced rebroadcast, the RAD Extension possibly finds redundant paths with more hops from a source node to the other nodes than the original counter-based scheme. This inherence will be undesirable if it is used for routing protocols because redundant paths make more nodes consume power to relay data packets. In this paper, we call the side-effect "roundabout problem."

To cope with this problem, we propose the HCA-RAD Extension. As shown in Sect. 4, the HCA-RAD Extension finds almost the same length paths as the original counter-based scheme on average while it saves rebroadcasting almost as same as the RAD Extension.

The rest of this paper is organized as follows: Sect. 2 describes the original counter-based scheme. Improved counter-based schemes are proposed in Sect. 3. Section 4 presents some simulation results. Finally, conclusions are

---

Manuscript received March 2, 2008.
Manuscript revised June 1, 2008.

†The authors are with the Graduate School of Science and Technology, Kobe University, Kobe-shi, 657-8501 Japan.

*This paper is the extended version of [1].

a) E-mail: shin@cs28.cs.kobe-u.ac.jp

DOI: 10.1093/ietcom/e91–b.11.3489

drawn in Sect. 5.

2. Counter-Based Scheme

In simple flooding, the more duplicate broadcast messages a node receives, the less effective its rebroadcasting becomes [7]. This is because the duplicate broadcast messages are likely to have been received by its neighboring nodes. This fact is involved in the counter-based scheme. In this scheme, a node which has received redundant messages more than a predefined threshold cancels to rebroadcast. The details of the original algorithm are shown below:

1. When a node receives a broadcast message for the first time, it initializes a counter and a timer to one and zero, respectively, and determines a timer threshold called "Random Assessment Delay (RAD)," the value of which is uniformly distributed between 0 and $T_{\max}$.
2. The timer increases with time. If the timer reaches the predetermined RAD (or expires), the node rebroadcast the message.
3. The node increases its counter by one every time it receives a duplicate broadcast message, and if the counter reaches the preset threshold C_{th} prior to expiry of the timer, the node halts rebroadcasting.

References [7] and [9] show that C_{th} set 4 to 6 is preferable from the viewpoint of the trade-off between reachability and saved rebroadcast. Note that the original counter-based scheme performs the same as the simple flooding in the case of $C_{\text{th}} = 1$. Further, the rebroadcast is completed within $T_{\max}$ or halted. In this sense, $T_{\max}$ can be regarded as the maximum rebroadcast delay.

The counter-based scheme can reduce the number of retransmitting nodes just like an area based scheme, with a high arrival rate maintained. And this scheme needs neither hardware like an area based scheme nor additional communication cost like a neighbor knowledge based scheme. For this reason, the counter-based scheme can be regarded as a promising broadcast algorithm for wireless sensor networks.

There are some research efforts to improve the counter-based scheme [10]–[12]. In [10], a node sets the value of the counter threshold C_{th} according to the number of its neighboring nodes. Similarly, in [11], a node sets C_{th} according to the distance from the broadcasting node to itself. In [12], the upper value of the RAD is a function of the the distance from the broadcasting node. These schemes, however, cooperate with a neighbor knowledge based scheme or an area based scheme. Such the cooperation possibly diminishes the strength of the original counter-based scheme, that is, a very little extra hardware and no control traffic. As shown in Sect. 3, there is still room for improvement without losing such features. This is our contribution in this paper.

3. Proposal Scheme

3.1 Basic Consideration

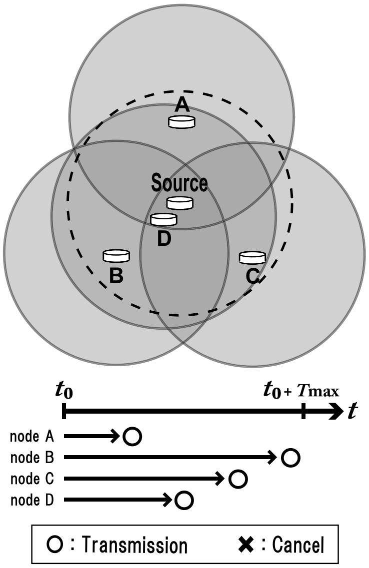

Fig. 1 An operational example of counter-based scheme (the case of one hop and $C_{\text{th}} = 4$).

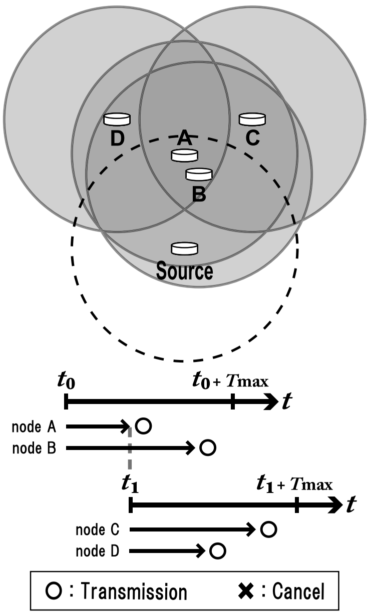

Fig. 2 An operational example counter-based scheme (the case of two hops and $C_{\text{th}} = 4$).

In this subsection, the reason why the redundant broadcast occurs in the original counter-based scheme is considered. Suppose the case of $C_{\text{th}} = 4$ and the node placement shown in Fig. 1. In this figure, the source node broadcasts a new message. Note that the rebroadcast by the node D covers only a quite small area, so that it can be in vain. This is because the node D exists near to the source node.

The original counter-based scheme can not always prevent such a redundant rebroadcast. For example, suppose that each node set its RAD after receiving the broadcast message from the source as shown in Fig. 1. In this figure, a circle denotes the communication range of the node at the center. Even though the node D will hear the same messages including the original one four times, the node D rebroadcasts since its timer expires earlier than those of the node B and C. The node D can suppress the redundant rebroadcast if the node D happens to set its RAD longer than the other nodes. Such a probability is, however, only 1/4 in this case since the value of the RAD is chosen uniformly at random. In order to increase success probability, the nodes with more redundant broadcasts had set their RAD longer. Unfortunately, however, the nodes can not predict the number of future received broadcasts at the moment of decision of the RAD.

Let us consider another example shown in Fig. 2. In this figure, the node A and B exist near each other, and they set their RAD just after receiving a broadcast message from the source. The node A's timer expires at time t_1 earlier than the node B, and then the node C and D set their RAD just after receiving the node A's rebroadcast. In the case, the node B's timer tends to expires earlier than those of the node C and D since they are invoked later than the node B's timer. The node B's rebroadcasting covers only a small area since the node A and node B exist near. Such vain effort can be avoided if both the node C and D rebroadcast ahead of the node B. This, however, happens at the probability 1/6 (See Appendix A.1).

3.2 RAD Extension

The problem considered in the previous subsection comes from the way to decide the value of RAD. In the original counter-based scheme, each node has no choice but to determine its RAD at random since it does not have any information such as the distance between the source and itself.

To mitigate this problem, we introduce "RAD Extension" to the original counter-based scheme. The RAD Extension makes nodes receiving more rebroadcasts have longer pseudo RAD. The details of the RAD Extension are shown below:

1. When a node receives a broadcast message for the first time, it initializes a counter and a timer to one and zero, respectively, and determines a timer threshold called "Random Assessment Delay (RAD)," the value of which is uniformly distributed between 0 and $\Delta T = T_{\max}/(C_{\text{th}} - 1)$.
2. The timer increases with time. If the timer reaches the predetermined RAD (or expires), the node rebroadcast the message.
3. The node increases its counter by one, and extends the RAD by ΔT every time it receives a duplicate broadcast message, and if the counter reaches the preset threshold C_{th} prior to expiry of the timer, the node halts rebroadcasting.

Similarly to the original counter-based scheme, rebroadcasting completes or halts within $T_{\max} = \Delta T(C_{\text{th}} - 1)$. This is because the initial RAD is uniformly chosen between 0 and ΔT, and the RAD could be extended at most $(C_{\text{th}} - 2)$ times.

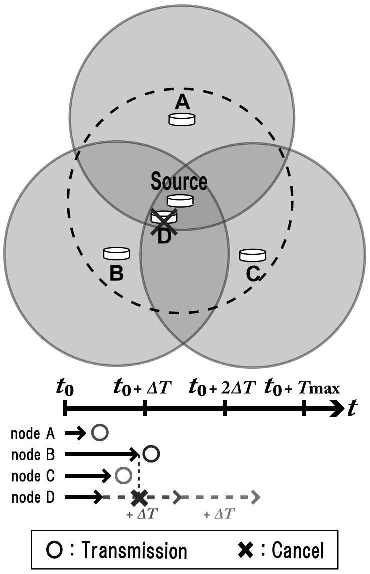

Fig. 3 An operational example of RAD Extension (the case of one hop and $C_{\text{th}} = 4$).

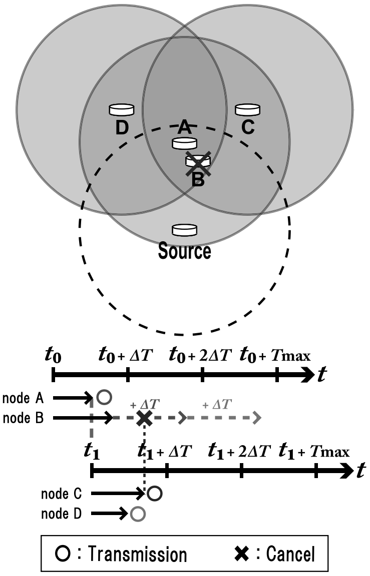

Fig. 4 An operational example of RAD Extension (the case of 2 hops and $C_{\text{th}} = 4$).

Here let us consider how the RAD Extension works in the previous examples.

Figure 3 shows an example similar to that shown in Fig. 1. The node D extends its RAD twice due to the receptions from the node A and C. The counter of the node D reaches $C_{\text{th}} = 4$ just after the reception from the node B, so that the node D halts rebroadcasting. The node D will fail only when its initial RAD is the shorter than those of the node A, B and C. Such a probability is 1/4. Thus the RAD Extension increases the success probability from 1/4 to 3/4.

Figure 4 corresponds to Fig. 2. The node B extends its RAD at time t_1 because of the reception from the node

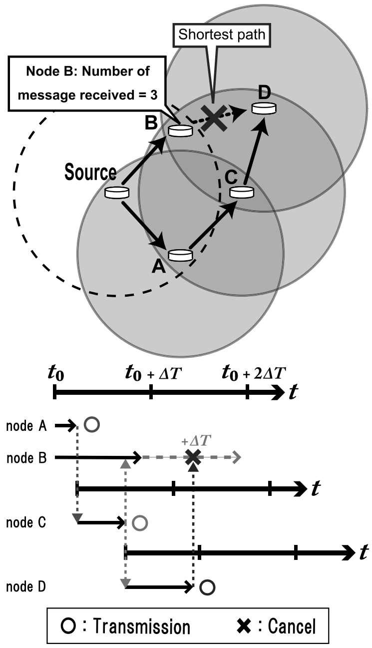

Fig. 5 An operational example of the RAD Extension (the case of path establishment and $C_{\text{th}} = 3$).

A. At the same time, the node C and D initially set their RAD between 0 and ΔT, so that their timers will expire by time $t_1 + \Delta T$ and rebroadcast. On the other hand, since the node B's timer expires after time $t_1 + \Delta T$, the rebroadcasts of the node C and D increase the counter of the node B up to $C_{\text{th}} = 4$. As results, the node B will halt rebroadcasting.

The RAD Extension has an undesirable effect in return for reducing unnecessary rebroadcasts. In this paper, we call the effect "roundabout problem."

Here let us consider how a path of successive rebroadcasts expands. In the RAD Extension, a node extends its RAD every receiving the duplicate rebroadcast. In other words, if a path happens to stick out, the node on the tip of the path will not receive so many rebroadcasts from the other nodes around itself. As a result, such a node will be given higher priority of rebroadcasting. This foments the path to expand itself, and suppresses the construction of other paths which may have smaller hops.

In Fig. 5, the three-hop path from the source to the node D via the node A and C may block the two-hop path via the node B. If the node A and C happen to rebroadcast ahead of the node B, the node B will extend its RAD so that the node D rebroadcasts before the node B. As results, the node B will halt rebroadcasting. This happens with a probability of 1/6. On the other hands, in the case of the original counter-based scheme, such a probability is only 1/24. (See Appendix A.3.)

3.3 Hop Count Aware RAD Extension

In order to cope with the roundabout problem while restructuring redundant broadcasts, we introduce the Hop Count Aware RAD Extension. For this sake, the scheme is twofold:

1. In order to reduce the average hops of the path compared with the RAD Extension, the HCA-RAD Extension gives the higher priority to nodes with the smaller hops from the source.
2. In order to reduce redundant rebroadcasts, likely to the RAD Extension, the HCA-RAD Extension gives the higher priority to node with fewer duplicate rebroadcast receptions.

Recall that the reason of the roundabout problem in the RAD Extension is that the longer path tends to expand itself. In order to slack off the rate of such the expansion, the HCA-RAD Extension makes the nodes offset their RADs to wait for the ones with smaller hops.

The details of the HCA-RAD Extension are shown below:

1. When a node receives a broadcast message for the first time, the node initializes a counter to one, and determines the initial RAD at random uniformly between 0 and $\Delta T_{\text{HCA}} = \frac{T_{\max}}{2(C_{\text{th}}-1)}$. Then the RAD is offset by (ΔT_{HCA} − *initial value of the RAD of a sender node*). Here, the *sender node* is a neighbor node which rebroadcasts the message. Note that the node to receive the broadcast message is further from the source by one hop than the node to send the broadcast message. To notify the length of the offset, the sender includes its initial RAD in the broadcast packet. Note that the initial RAD of the source node is ΔT_{HCA}.
2. If the node receives the same broadcast message during the RAD, the node increases its counter by one. Then, it cancels to rebroadcast if the counter reaches the preset threshold C_{th}; otherwise it extends the RAD by $2\Delta T_{\text{HCA}}$.
3. After the RAD expires, the node retransmits the broadcast message.

Setting ΔT_{HCA} as the half of ΔT of the RAD Extension enables to interleave waiting time among nodes with different hops but the same number of message receptions as shown in Fig. 9. Then the nodes with H hops and N message receptions have retransmitted before nodes with $H + 1$ hops and N message receptions retransmit. This interleaved waiting time prevents nodes from overtaking the ones with smaller hops.

By this extended algorithm, each node decides its rebroadcast after other nodes which have shorter hop count and fewer message reception (Fig. 9). Therefore, if the number of message reception is the same, rebroadcast probability is the same as RAD Extension. So, the number of average hop count can be reduced, without increasing the number of rebroadcast nodes from the RAD Extension.

Moreover, the rebroadcast is completed within $T_{\max} = 2\Delta T_{\text{HCA}} \times (C_{\text{th}} - 1)$ or halted. The initial value of the RAD is chosen over the range from 0 to ΔT_{HCA}. And the initial "waiting time" of a node is from ΔT_{HCA} to $2\Delta T_{\text{HCA}}$, since (ΔT_{HCA} − *initial value of RAD of a sender*) is added to

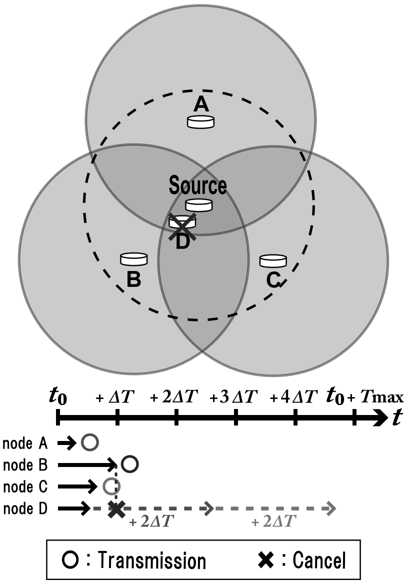

Fig. 6 An operational example of the HCA-RAD Extension (the case of one hop, $C_{\mathrm{th}} = 4$).

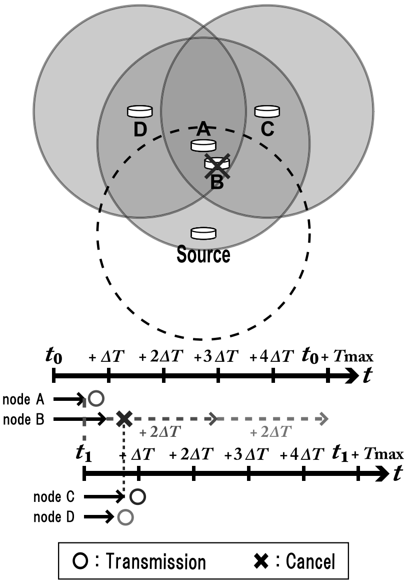

Fig. 7 An operational example of hop count aware RAD Extension (the case of 2 hops, $C_{\mathrm{th}} = 4$).

its initial RAD. Furthermore, the RAD could be extended $2\Delta T_{\mathrm{HCA}}$ at most ($C_{\mathrm{th}} - 2$) times. As results, the sum of the initial RAD and its extensions is less than $2\Delta T_{\mathrm{HCA}}\times(C_{\mathrm{th}}-1)$.

Here let us consider how the HCA-RAD Extension works in the previous examples. Figure 6 shows a similar example to that shown in Figs. 1 and 3. And Fig. 7 shows a similar example to that shown in Figs. 1 and 4. In both of the examples, the same operation as the RAD Extension was performed essentially, and redundant retransmission can be suppressed.

If the HCA-RAD Extension is used in the same situation as Fig. 5, the shortest path can be discovered as shown in Fig. 8. In this situation, the HCA-RAD Extension can certainly suppress the redundant path establishment (Appendix A.3).

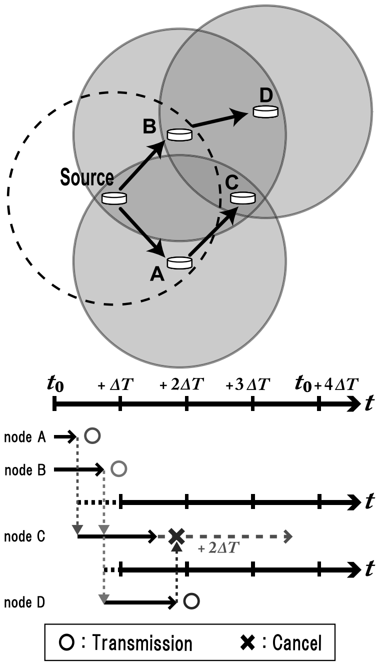

Fig. 8 An operational example of the HCA-RAD Extension (the case of path establishment, $C_{\mathrm{th}} = 3$).

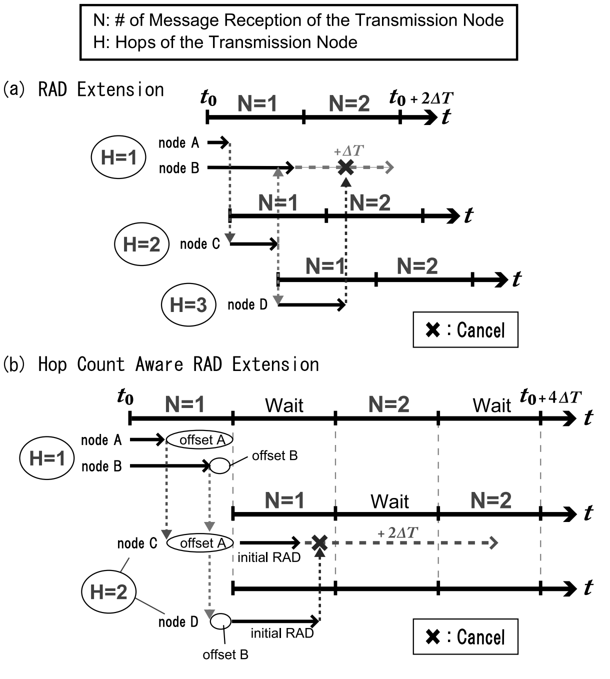

Fig. 9 The synchronization of the RAD by the HCA-RAD Extension: (a) timing diagram in Fig. 5, (b) timing diagram in Fig. 8.

In practice, the receiver node needs to know the initial RAD of the sender node in the HCA-RAD Extension. The simple method is that a node adds its initial RAD to a broadcasting message. Although it is a problem that a broadcasting message increases, the required amount of information is several bits since the range of the initial RAD is from 0 to ΔT. Moreover, if time synchronous type MAC protocols [13] or GPS are used and the system has a strict timer, the receiver node can calculate the initial RAD of the sender node using the message reception time and the time which the base station sends broadcast message. This is because, as shown in Fig. 9, operation of all the nodes is divided by ΔT.

In the next section, we show some simulation results to verify the effect of the RAD Extension.

4. Performance Evaluation

In order to verify the effects of the RAD Extension and the HCA-RAD Extension, we perform simulation experiments using QualNet [14]. In the simulation, all the broadcasting schemes are implemented in the network layer instead of MAC layer. For each parameter setting, 50 trials with different random seeds were executed and the average value of them is plotted in the following graphs.

4.1 Parameter Settings

First, we mention the parameters defined in the simulation. A simulation area is set to 100 m × 100 m or 300 m × 300 m, and sensor nodes are deployed randomly in the area. A base station is placed in the center of the simulation area, and it performs broadcasting. The transmission range is set to about 20 m. The modulation is on-off keying, and the information rate is set to 10 kbps. It is assumed that the transmission power is 800 μW, the reception power is 500 μW, the idle power is 0.5 μW [15]. LPL (Low Power Listening) [16] is used as an MAC (Medium Access Control) protocol. In LPL, the periodic wakeup time is set to 50 ms [13]. Packet size of a broadcast message is set to 48 bytes. As a result, the packet transmission time is 38.4 ms.

4.2 Simulation Results

In this paper, the number of retransmitting nodes, reachability, hop count, and latency (shown as end to end delay in the graphs) are used as performance metrics. Here, the latency is defined as the time after the base station transmits a broadcast message until the last rebroadcast is completed.

The counter-based scheme, the RAD Extension and the HCA-RAD Extension have two control parameters $T_{\max}$ and C_{th}. The longer $T_{\max}$, the less redundant broadcasts but the larger latency. The value of C_{th} controls the trade-off between the number of retransmitting nodes and reachability.

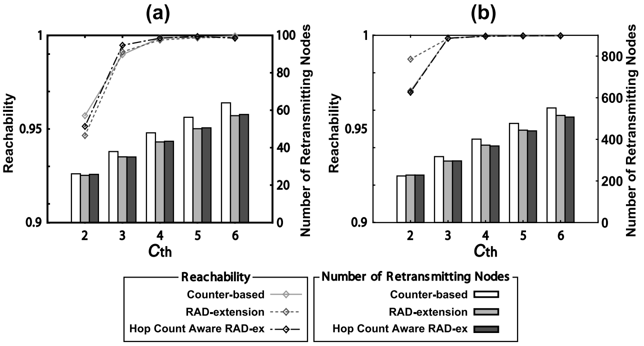

Fig. 10 Counter threshold C_{th} versus reachability and number of retransmitting nodes: (a) number of nodes = 100, field size = 100 m × 100 m (b) number of nodes = 900, field size = 300 m × 300 m ($T_{\max}$ = 15 s).

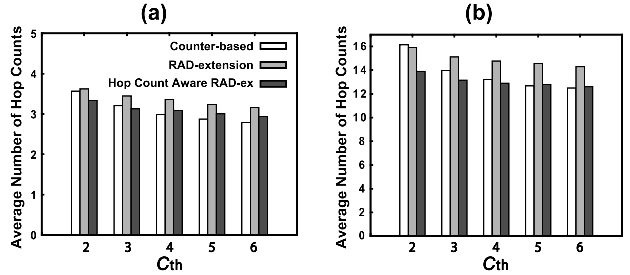

Fig. 11 Counter threshold C_{th} versus average number of hop count: (a) number of nodes = 100, field size = 100 m × 100 m (b) number of nodes = 900, field size = 300 m × 300 m ($T_{\max}$ = 15s).

First, the counter threshold C_{th} is varied. In Figs. 10(a) and 11(a), a simulation area is set to 100 m × 100 m, and the number of nodes is set to 100. The value of $T_{\max}$ should be set larger enough to restrict redundant rebroadcasts. $T_{\max}$ is set to 15s in Figs. 10 and 11. Figure 10(a) shows the number of retransmitting nodes and reachability against C_{th} in the counter-based scheme, the RAD Extension and the HCA-RAD Extension. As shown in this graph, there is no significant difference in reachability, and when C_{th} is 4 or more, the reachability is over 99.5%. On the other hand, the RAD Extension and the HCA-RAD Extension reduce the number of retransmitting node by about 10% when C_{th} is set to three or more. As mentioned in Sect. 3, when C_{th} is set to two, the number of retransmitting nodes is the same.

Figure 11 shows the average number of hop counts against C_{th}. As shown in this graph, the average number of hop counts of the HCA-RAD Extension is always fewer than the RAD Extension, and it is fewer than the original counter-base scheme when Cth is less than 4.

In Figs. 10(b) and 11(b), the network scale is increased nine times from Figs. 10(a) and 11 (a) with the same node density. Here, a simulation area is set to 300 m × 300 m, and the number of nodes is set to 900. Although the tendencies of retransmitting nodes, reachability, and hop count are the same as Fig. 11(a), the average number of hop counts of the HCA-RAD Extension is suppressed about the same as the original counter-based scheme when C_{th} is 4 or more. That is, it is shown that the effect of the HCA-RAD Extension becomes large with the network scale.

Next, the value of $T_{\max}$ is varied. Here, a simulation area is set to 100 m × 100 m, the number of nodes is set to 100, and C_{th} is set to 4. Since the transmission range is about 20 m, the node density is 12.56 m^{-2}. Figure 12 (a) shows the relationship between reachability and $T_{\max}$. It is

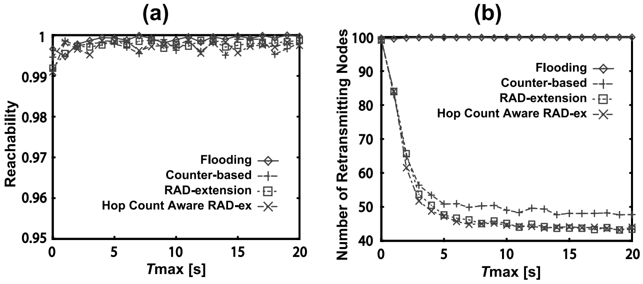

Fig. 12 Maximal value of RAD $T_{\max}$ versus (a) reachability, (b) number of retransmitting nodes (C_{th} = 4, number of nodes = 100, field size = 100 m × 100 m).

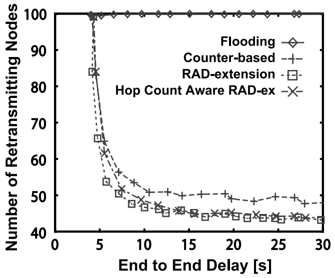

Fig. 14 Latency versus number of retransmitting nodes (C_{th} = 4, number of nodes = 100, field size = 100 m × 100 m).

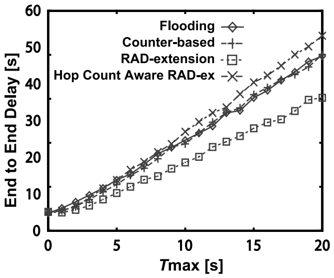

Fig. 13 Maximal value of RAD $T_{\max}$ versus latency (C_{th} = 4, number of nodes = 100, field size = 100 m × 100 m).

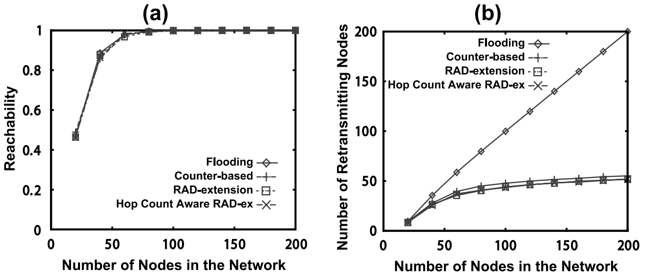

Fig. 15 Number of nodes in the network (density) versus (a) reachability, (b) number of retransmitting nodes (C_{th} = 4, $T_{\max}$ = 15 s, field size = 100 m × 100 m).

read from this figure that reachability is hardly influenced by $T_{\max}$. Then, reachability drops in the case of too small $T_{\max}$. This is because broadcast messages are transmitted by some nodes during a short period. Therefore, they tend to collide each other.

Figure 12(b) shows the relationship between the number of retransmitting nodes and $T_{\max}$. The number of retransmitting nodes cannot be reduced enough in the case of too small $T_{\max}$. This is the same reason as reachability. However, the number of retransmitting nodes decreases with the value of $T_{\max}$ in the counter-based scheme, the RAD Extension and the HCA-RAD Extension. In the simulation, the wakeup period in LPL (MAC layer) is set to 50 ms, and the transmission time of the broadcast packet is 38.4 ms. Therefore, it takes at least 353.6 ms for a node to receive four duplicate rebroadcasts so that it cancels its rebroadcast since C_{th} = 4. Since all the broadcasting schemes are implemented in the network layer in the simulation, any node can not cancel to rebroadcast after its network layer passes the rebroadcast packet to the MAC layer even if it receives the fourth duplicate packet (C_{th} = 4) before its rebroadcast. The value of $T_{\max}$ should be set a few seconds or more since about twelve nodes compete in the transmission region of a node. And the RAD Extension and the HCA-RAD Extension outperform the original counter-based scheme when $T_{\max}$ is set to 5s or more. Then $T_{\max}$ is set to 15s in Figs. 10, 11, 15 and 16.

Figure 13 shows the relationship between the latency and $T_{\max}$. In Fig. 13, the latency increases linearly with $T_{\max}$. Furthermore, the latency in the RAD Extension is smaller than other schemes, because the initial RAD is chosen in the smaller range in the RAD Extension. This fact encourages a broadcast to diffuse rapidly. Moreover, the latency in the HCA-RAD Extension is almost the same as the flooding or the original counter-based scheme, regardless of the initial RAD is chosen in the smaller range. This is because, in HCA-RAD Extension, each node decides its rebroadcast after other nodes which have shorter hop count and fewer message reception.

Figure 14 illustrates the relationship between the number of retransmitting nodes and the latency. In this figure, it is shown that the RAD Extension and the HCA-RAD Extension can suppress the number of retransmitting nodes under the condition of the same latency.

Next, the influence by node density is shown. Here, $T_{\max}$ is set to 15 s, and C_{th} is set to 4. A simulation area is set to 100 m × 100 m, and the number of nodes is set to 100. Figure 15(a) shows the relationship between the number of nodes in the network and reachability. If the node density is same, there is no significant difference in reachability.

Figure 15(b) shows the relationship between the number of nodes in the network and the number of retransmitting nodes. In the flooding, every node in the network retransmits a message. On the other hand, the number of retransmitting nodes in the counter-based scheme hardly increases even if the node density becomes high. Moreover, the RAD Extension and the HCA-RAD Extension reduce the number of retransmitting node by about 10% from the original counter-based scheme regardless of the node density.

Finally, in order to show the influence of the hops on the energy consumption, we consider the scenario of the data gathering where the sensed data packets are transfered

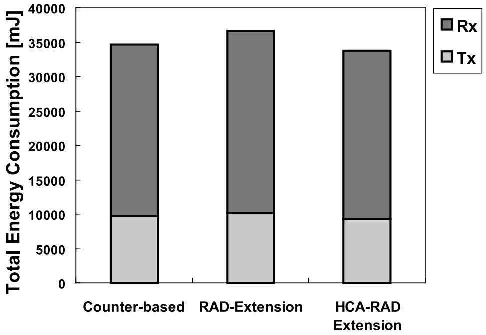

Fig. 16 Total energy consumption in the data gathering operation (C_{th} = 4, $T_{\max}$ = 15 s, number of nodes = 900, field size = 300 m × 300 m).

along the paths which are established by proposal or conventional broadcast schemes. Here, Tiny Diffusion [6] was used as a routing protocol. Figure 16 illustrates the power consumption in the whole of the network where all nodes send the their sensed data at once to the base station. C_{th} is set to 4, and $T_{\max}$ is set to 15 s. The data packet length is 48 bytes. A simulation area is set to 300 m × 300 m, and the number of nodes is set to 900. In general, the power strongly depends on the frequency of the broadcasting to the data transfer. In the figure, the power does not include that for broadcasting in order to evaluate only the established path. In this figure, it is shown that HCA-RAD Extension reduces the power consumption of the data transfer by 2.6% and 7.9% compared to the counter-based scheme, and RAD Extension, respectively. This is because HCA-RAD Extension finds a path with the smaller hops so that the fewer data transmissions and overhearings can be achieved.

5. Conclusion

In this paper, the counter-based scheme was focused on as a broadcast protocol for wireless sensor networks, and the RAD Extension has been proposed to improve the original. Simulation results showed that the RAD Extension can reduce the number of retransmitting nodes by about 10% compared with the original scheme. In addition, we propose the HCA-RAD Extension to establish shorter path from the source node to the other nodes. This algorithm succeeds in shortening the average path length to almost the same as the counter-based scheme. And the reduction of retransmitting nodes is still kept about 10% compared to the counter-based scheme.

Acknowledgment

This research work was partially supported by Strategic Information and Communications R&D Promotion Programme (SCOPE), Ministry of Internal Affairs and Communications, Japan, by a Ministry of Education, Culture, Sports, Science and Technology (MEXT) Grant-in-Aid for Scientific Research (C), No. 18500052.

References

[1] S. Izumi, T. Matsuda, H. Kawaguchi, C. Ohta, and M. Yoshimoto, "Hop count aware broadcast algorithm with random assessment delay extension for wireless sensor networks," Proc. 7th APSITT, April 2008.
[2] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: A survey," Comput. Netw., vol.38, pp.393–422, 2002.
[3] B. Krishnamachari, D. Estrinf, and S. Wicker, "Modelling datacentric routing in wireless sensor networks," Proc. INFOCOM, 2002.
[4] D. Petrovic, C. Shah, K. Ramchandran, and J. Rabaey, "Data funneling: Routing with aggregation and compression for wireless sensor networks," Proc. IEEE International Workshop on Sensor Network Protocols and Applications, 2003.
[5] C. Intanagonwiwat, R. Godinvan, and D. Estrin, "Directed diffusion for wireless sensor networking," IEEE/ACM Trans. Netw., vol.11, no.1, pp.2–16, 2003.
[6] J. Heidemann, F. Silva, and D. Estrin, "Matching data dissemination algorithm to application requirements," Proc. SENSYS, pp.218–229, 2003.
[7] S. Ni, Y. Tseng, Y. Chen, and J. Sheu, "The broadcast storm problem in a mobile ad hoc network," Proc. MOBICOM, pp.151–162, 1999.
[8] B. Williams and T. Camp, "Comparison of broadcasting techniques for mobile ad hoc networks," Proc. MOBIHOC, pp.194–205, 2002.
[9] J. Arango, A. Efrat, S. Ramasubramanian, M. Krunz, and S. Pink, "Retransmission and back-off strategies for broadcasting in multihop wireless networks," Proc. BROADNET, 2006.
[10] Y.-C. Tseng, S.-Y. Ni, and E.-Y. Shih, "Adaptive approaches to relieving broadcast storms in a wireless multihop mobile ad hoc network," Proc. ICDCS, pp.481–488, 2001.
[11] C. Chen, C.-K. Hsu, and H.-K. Wang, "DISCOUNT: A hybrid probability-based broadcast scheme for wireless ad hoc networks," Proc. VTC, 2005.
[12] C.-C. Yang and C.-Y. Chen, "Reduction of the broadcast redundancy by location awareness in mobile ad hoc networks," Journal of Computer Communications, vol.26, no.18, pp.2082–2089, 2003.
[13] M. Ichien, T. Takeuchi, S. Mikami, H. Kawaguchi, C. Ohta, and M. Yoshimoto, "Isochronous MAC using low frequency radio wave time synchronization for wireless sensor networks," Proc. ICCE, pp.172–177, 2006.
[14] "QualNet," http://www.scalable-networks.com/
[15] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient MAC protocol for wireless sensor networks," Proc. INFOCOM, vol.3, pp.1567–1576, 2002.
[16] J. Hill and D. Culler, "Mica: A wireless platform for deeply embedded networks," IEEE Micro, vol.22, no.6, pp.12–24, 2002.

Appendix: Calculation of Probabilities

A.1 Definitions

Let T_{RAD} denote the random variable of the RAD, which is governed by the *i.i.d* (independent and identically distributed) uniform distribution on the interval $[0, T_{\max}]$. Let $p_{\text{RAD}}(t)$ and $P_{\text{RAD}}(t)$ denote the probability density function and the probability distribution function of the random variable T_{RAD}, respectively. Let $T_{n\text{RAD}}$ denote the random variable of the sum of n independent RADs. Further, let $p_{n\text{RAD}}(t)$ be the probability density function of $T_{n\text{RAD}}$. $p_{n\text{RAD}}(t)$ can be calculated by using the recursive formula:

$$p_{n\mathrm{RAD}}(t) = \int_0^t p_{\mathrm{RAD}}(t-\tau)\,p_{(n-1)\mathrm{RAD}}(\tau)\tau. \qquad (\mathrm{A}\cdot 1)$$

Further let T_{RAD_i} denote the random variable of the RAD of the node i for convenience in the followings.

A.2 Probability to Suppress Redundant Rebroadcast in RAD Extension

In Fig. 2, the node A (resp. B) can be assumed to rebroadcast prior to the node B (resp. A). The unnecessary rebroadcast by the node B (resp. A) is avoided when both the node D and C rebroadcast prior to the node B (resp. A) because of $C_{\mathrm{th}} = 4$. This happens with the probability $P_{\mathrm{SRR}} \overset{\mathrm{def}}{=} \Pr\{\max\{T_{\mathrm{RAD_C}}, T_{\mathrm{RAD_D}}\} < |T_{\mathrm{RAD_A}} - T_{\mathrm{RAD_B}}|\}$. The probability density function of the random variable $|T_{\mathrm{RAD_A}} - T_{\mathrm{RAD_B}}|$ is given by

$$p_{|\mathrm{RAD_a}-\mathrm{RAD_b}|}(t) = 2\int_0^{T_{\max}-t} p_{\mathrm{RAD}}(t+\tau)\,p_{\mathrm{RAD}}(\tau)\tau. \qquad (\mathrm{A}\cdot 2)$$

Using (A· 2), the value of P_{SRR} can be calculated as follows:

$$P_{\mathrm{SRR}} = \int_0^{T_{\max}} (P_{\mathrm{RAD}}(t))^2\, p_{|\mathrm{RAD_a}-\mathrm{RAD_b}|}(t)dt = \frac{1}{6}.$$

On the other hand, the RAD Extension (Fig. 4) and the HCA-RAD Extension (Fig. 7) can certainly cancel one retransmission of the node A or node B regardless of how to choose the value of the RAD.

A.3 Probability to Establish Roundabout Path

First, let us consider the case of the original counter-based scheme shown in Fig. 5. The roundabout path from the source to the node D via the node C and D will be established when the series of rebroadcasts of the node A, C, and D finishes before the node B's timer expires. This happens with the probability $P_{\mathrm{ERP}} \overset{\mathrm{def}}{=} \Pr\{T_{\mathrm{RAD_B}} < T_{\mathrm{RAD_A}} + T_{\mathrm{RAD_B}} + T_{\mathrm{RAD_D}}\}$, which can be calculated as follows:

$$P_{\mathrm{ERP}} = \int_0^{T_{\max}} P_{3\mathrm{RAD}}(t)\,p_{\mathrm{RAD}}(t)dt = \frac{1}{24}.$$

Second, let us consider the case of the RAD Extension shown in Fig. 5. The roundabout path from the source to the node D via the node C and D will be established when the series of rebroadcasts of the node A and C finishes before the node B's timer expires. This happens with the probability $P_{\mathrm{ERP-RADE}} \overset{\mathrm{def}}{=} \Pr\{T_{\mathrm{RAD_B}} < T_{\mathrm{RAD_A}} + T_{\mathrm{RAD_B}} + T_{\mathrm{RAD_D}}\}$, which can be calculated as follows:

$$P_{\mathrm{ERP-RADE}} = \int_0^{T_{\max}} P_{2\mathrm{RAD}}(t)\,p_{\mathrm{RAD}}(t)dt = \frac{1}{6}.$$

Finally, let us consider the case of the HCA-RAD Extension shown in Fig. 8. The node C does not rebroadcast earlier than the node B since the node C extend its initial RAD by $\Delta T - t_{\mathrm{a}}$. Thus the roundabout path can not be established.

Shintaro Izumi received the B.E. degree in Computer and Systems Engineering from Kobe University in 2007. He is currently a Master's student at Kobe University. His interests include communication protocol and node architecture for sensor networks.

Takashi Takeuchi received a B.E. degree in Computer and Systems Engineering from Kobe University in 2005. He is M.E. degree from Kobe University in 2007. He is currently enrolled in a Doctoral course in Kobe University. His interests include low-power analog circuit designs.

Takashi Matsuda received a B.E. degree in Computer and Systems Engineering in 2005 and a M.E. degree in Science and Technology both from Kobe University. He is currently a Doctor's student at Kobe University. His interests include routing protocol and media access control for wireless sensor networks.

Hiroshi Kawaguchi received the B.E. and M.E. degrees in electronic engineering from Chiba University, Chiba, Japan, in 1991 and 1993, respectively, and the Ph.D. degree in engineering from the University of Tokyo, Tokyo, Japan, in 2006. He joined Konami Corporation, Kobe, Japan, in 1993, where he developed arcade entertainment systems. He moved to the Institute of Industrial Science, the University of Tokyo, as a Technical Associate in 1996, and was appointed a Research Associate in 2003. In 2005, he move to the Department of Computer and Systems Engineering, Kobe University, Kobe, Japan, as a Research Associate. Since 2007, he has been an Associate Professor with the Department of Computer Science and Systems Engineering, Kobe University. He is also a Collaborative Researcher with the Institute of Industrial Science, the University of Tokyo. His current research interests include low-power VLSI design, hardware design for wireless sensor network, and recognition processor. Dr. Kawaguchi was a recipient of the IEEE ISSCC 2004 Takuo Sugano Outstanding Paper Award and the IEEE Kansai Section 2006 Gold Award. He has served as a Program Committee Member for IEEE Symposium on Low-Power and High-Speed Chips (COOL Chips), and as a Guest Associate Editor of IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences. He is a member of the IEEE and ACM.

Chikara Ohta was born in Osaka, Japan, on July 25, 1967. He received the B.E., M.E. and Ph.D. (Eng.) degrees in communication engineering from Osaka University, Osaka, Japan, in 1990, 1992 and 1995, respectively. From April 1995, he was with the Department of Computer Science, Faculty of Engineering, Gunma University, Gunma, Japan, as an Assistant Professor. In October 1996, he joined the Department of Information Science and Intelligent Systems, Faculty of Engineering, University of Tokushima, Tokushima, Japan, as a Lecture, and there he had been an Associate Professor since March 2001. Since November 2002, he has been an Associate Professor of the Department of Computer and Systems Engineering, Faculty of Engineering, Kobe University, Japan. From March 2003 to February 2004, he was a visiting scholar in the University of Massachusetts at Amherst, USA. His current research interests include performance evaluation of communication networks. He is a member of IPSJ, IEEE and SIGCOMM.

Masahiko Yoshimoto received a B.S. degree in electronic engineering from Nagoya Institute of Technology, Nagoya, Japan, in 1975, and an M.S. degree in electronic engineering from Nagoya University, Nagoya, Japan, in 1977. He received a Ph.D. degree in Electrical Engineering from Nagoya University, Nagoya, Japan in 1998. He joined the LSI Laboratory, Mitsubishi Electric Corp., Itami, Japan, in April 1977. From 1978 to 1983 he was engaged in the design of NMOS and CMOS static RAM including a 64 K full CMOS RAM with the world's first divided word-line structure. From 1984, he was involved in research and development of multimedia ULSI systems for digital broadcasting and digital communication systems based on MPEG2 and MPEG4 Codec LSI core technology. Since 2000, he has been a Professor of the Dept. of Electrical and Electronic Systems Engineering at Kanazawa University, Japan. Since 2004, he has been a Professor of the Dept. of Computer and Systems Engineering at Kobe University, Japan. His current activity is focused on research and development of multimedia and ubiquitous media VLSI systems including an ultra-low-power image compression processor and a low power wireless interface circuit. He holds 70 registered patents. He served on the Program Committee of the IEEE International Solid State Circuit Conference from 1991 to 1993. In addition, he has served as a Guest Editor for special issues on Low-Power System LSI, IP, and Related Technologies of IEICE Transactions in 2004. He received the R&D100 awards from R&D Magazine for development of the DISP and development of a real-time MPEG2 video encoder chipset in 1990 and 1996, respectively.