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Hop Count Aware Broadcast Algorithm with Random Assessment Delay Extension for Wireless Sensor Networks

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***Abstract*—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 hardwares 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 hardwares, 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.**

I. 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 [1].

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 hundred or to several thousand, 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[2][3].

Broadcasting (diffusing a message from a source node to all 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[4][5]. 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[6]. This problem leads to high overheads and high energy consumption. To solve the broadcast storm problem, various efficient broadcast protocols have been proposed[7].

In this paper, we focus on the counter-based scheme which is one of the probability based broadcast methods. Probability based methods reduce the amount of unnecessary rebroadcasts with the cost of only slight additional hardware and without any control messages. Such features are desirable for sensor networks because the cost of nodes can be reduced and wireless resource that is scarce can be saved. In [7], *probabilistic scheme* and *counter-based scheme* are shown as examples of probability based methods. It is pointed out that counter-based scheme has adaptability to local topologies, and more precisely node density. This fact is supported in [6] where it is shown that counter-based scheme outperforms probabilistic scheme in terms of reachability and saved rebroadcast.

The contribution of this paper is to improve the counter-based scheme by controlling random assessment delay (RAD). In this paper, this improvement is called "RAD Extension." As shown in Section IV, the number of retransmitting nodes is reduced by about 10% compared with the original counter-based scheme. In addition, we propose the additional algorithm called "Hop Count Aware RAD Extension (HCA-RAD Extension)" to establish shorter path from the source node. In data gathering type application, the shorter path length is preferable to reduce power consumption since the number of data relay nodes is increased due to the redundant path. In the HCA-RAD Extension, the average length of the path established by the RAD Extension can be reduced to almost the same as the counter-based scheme. And the reduction of retransmitting nodes is kept still about 10% compared to the counter-based scheme.

The rest of this paper is organized as follows: Section II describes the original counter-based scheme. Improved counter-based schemes are proposed in Section III. Section IV presents some simulation results. Finally, conclusions are drawn in Section V.

II. COUNTER-BASED SCHEME

In simple flooding, a node with the large number of received messages has a little area which can be newly covered by its rebroadcast[6]. So, the more messages a node receives, the less benefit of its rebroadcast becomes. This fact is involved in the counter-based scheme. A node with 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 broadcasting message for the first time, the node initializes a counter to one, and sets a Random Assessment Delay (RAD) at random uniformly between 0 and $T_{\max}$.
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 $C_{\rm th}$.
3) After the RAD expires, the node retransmits the broadcast message.

References [6] and [8] show that $C_{\rm th}$ 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 $C_{\rm th} = 1$. 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[9][10][11]. In [9], a node sets the value of the counter threshold $C_{\rm th}$ according to the number of its neighboring nodes. Similarly, in [10], a node sets $C_{\rm th}$ according to the distance from the broadcasting node to itself. In [11], 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 cooperations possibly diminish the strength of the original counter-based scheme, that is, a very little extra hardware and no control traffic. As shown in Section III, there is still room for improvement without losing such features. This is our contribution in this paper.

III. Proposal Scheme

A. Basic Consideration

In this subsection, the reason why the redundant broadcast occurs in the original counter-based scheme is considered. For example, suppose the case of $C_{\rm th} = 4$ and the node placement shown in Figure 1. In this figure, the source node starts to broadcast. In this situation, the broadcast by the node D is almost futility, that is, the newly covered area is small. 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 Figure 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 RAD 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 0.25 in this case since the value of 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.

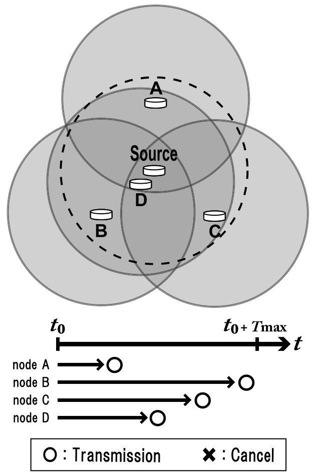

Fig. 1. An operational example of the counter-based scheme (the case of one hop, $C_{\rm th} = 4$).

B. 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, the node initializes a counter to one, and sets a RAD at random uniformly between 0 and ΔT.
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 $C_{\rm th}$; otherwise it extends the RAD by ΔT.
3) After the RAD expires, the node retransmits the broadcast message.

Note that the counter-based scheme with the RAD performs the same as the original in the case of $C_{\rm th} = 2$. This is because rebroadcast will be canceled if even one duplicate message is received during the RAD.

Similarly to the original counter-based scheme, the rebroadcast is completed within $T_{\max} = \Delta T(C_{\rm th} - 1)$ or halted. The reason why the rebroadcast delay is bounded by $T_{\max}$ can be explained as follows. The initial value of the RAD is chosen over the range from 0 to ΔT. Further the RAD could be extended ΔT at most $(C_{\rm th} - 2)$ times.

As results, the sum of the initial RAD and its extensions is less than $\Delta T \times (C_{\mathrm{th}} - 1)$.

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

Figure 2 shows a similar example to that shown in Figure 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 $C_{\mathrm{th}} = 4$ 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 0.25. Thus the RAD Extension increases the success probability from 0.25 to 0.75.

As mentioned above, the RAD Extension is expected to reduce unnecessary rebroadcasts even if not perfect.

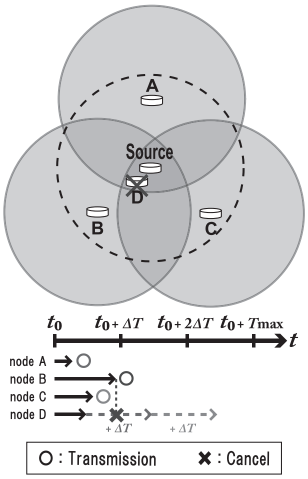

Fig. 2. An operational example of the RAD Extension (the case of one hop, $C_{\mathrm{th}} = 4$).

C. Hop Count Aware RAD Extension

In this subsection, we introduce the Hop Count Aware RAD Extension to reduce the average path length compared with the RAD Extension. If a path to the source node is roundabout, the number of nodes which relay data increases. Therefore, useless rebroadcast of message occurs.

In the RAD Extension, a node extends its waiting time every receiving the same rebroadcast. In other words, if a node happens to rebroadcast and lengthens the path, the node in the front of the path will rarely receive the rebroadcasts from the other nodes around itself. This foments the path to extend itself. So the RAD Extension tends to give higher rebroadcast priority to a node with the large number of hop (that is, far from a base station). Such the rushing extension of the path may suppress those of preferable paths with smaller hops. As a result, it is possible for the RAD Extension to make the average path length get worse (Figure 3).

In order to cope with this problem, the HCA-RAD Extension gives high transmission priority to the node with small number of hop, without changing the transmission priority by the number of message reception given by the RAD Extension. The details of the HCA-RAD Extension are shown below:

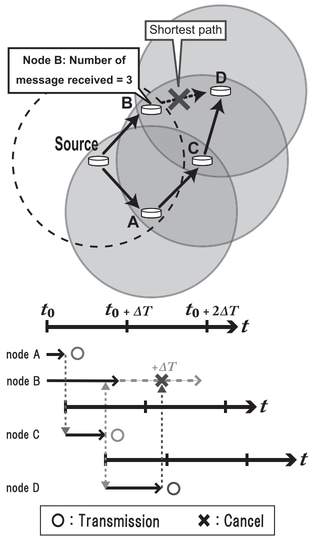

Fig. 3. An operational example of the RAD Extension (the case of path establishment, $C_{\mathrm{th}} = 3$).

1) When a node receives a broadcast message for the first time, the node initializes a counter to one, and sets a RAD at random uniformly between 0 and ΔT. In addition, (ΔT − *initial value of the RAD of a sender node*) is added to the RAD.
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 $2\Delta T$.
3) After the RAD expires, the node retransmits the broadcast message.

There are two characteristics of this algorithm. First, a node extends the RAD by $2\Delta T$ whenever receiving a duplicate message. The second characteristic is that a node adds (ΔT - initial value of the RAD of a sender) to its initial value of the RAD, when the node receives a message for the first time.

By this extended algorithm, each node decides its rebroadcast after other nodes which have shorter hop count and fewer message reception (Figure 4). 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 $T_{\mathrm{max}} = 2\Delta T \times (C_{\mathrm{th}} - 1)$ or halted. The initial value of the RAD is chosen over the range from 0 to ΔT. And the initial "waiting time" of a node is from ΔT to $2\Delta T$, since (ΔT − *initial value of RAD of a sender*) is added to its initial RAD. Furthermore, the RAD could be extended $2\Delta T$ at most $(C_{\mathrm{th}} - 2)$ times. As results, the sum of the initial RAD and its extensions is less than $2\Delta T \times (C_{\mathrm{th}} - 1)$.

Here let us consider how the HCA-RAD extension works in the previous examples. Figure 5 shows a similar example to that shown in Figures 1 and 2.

In this example, the same operation as RAD extension was performed essentially, and redundant rebroadcast can be suppressed. If the HCA-RAD extension is used in the same situation as Figure 3, the shortest path can be discovered as shown in Figure 6.

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[12] 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 figure 4, operation of all the nodes is divided by ΔT.

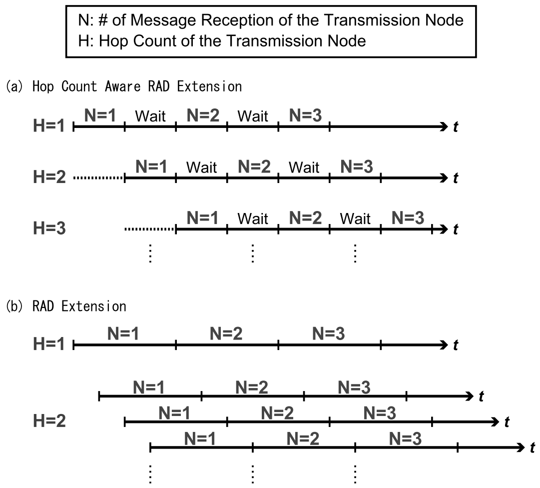

Fig. 4. Distribution of the transmission timing by the number of hop count and the number of message receiving

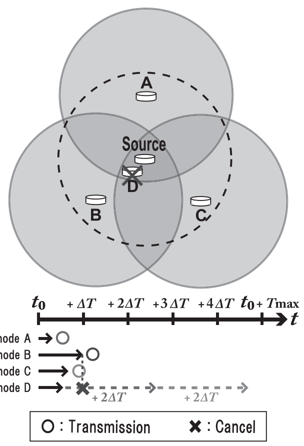

Fig. 5. An operational example of the HCA-RAD extension (the case of one hop, $C_{\mathrm{th}} = 4$).

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

IV. PERFORMANCE EVALUATION

In order to verify the effects of the RAD Extension and the HCA-RAD Extension, we performs simulation experiments by using QualNet[13]. For each parameter setting, 50 trials with different random seeds were executed and the average value of them are plotted in the following graphs.

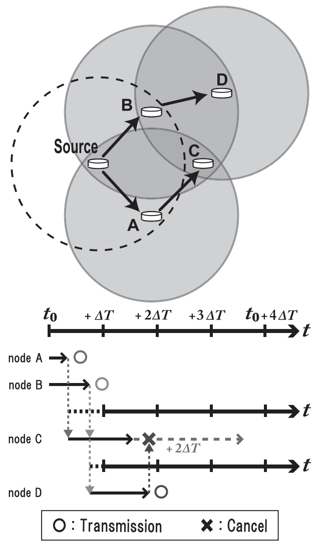

Fig. 6. An operational example of the HCA-RAD extension (the case of path establishment, $C_{\mathrm{th}} = 3$).

A. Parameter Settings

A simulation area is set to $100\mathrm{m} \times 100\mathrm{m}$, 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 $20\mathrm{m}$. It is assumed that the transmission power is $800\mu\mathrm{W}$, the reception power is $500\mu\mathrm{W}$, the idle power is $0.5\mu\mathrm{W}$, and the battery capacity of each sensor node is $500\mathrm{mJ}$[14]. LPL (Low Power Listening)[15] is used as an MAC (Medium Access Control) protocol. Packet size of a broadcast message is set to 48 bytes.

B. 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 collisions but the larger latency. The value of C_{th} controls the trade-off between the number of retransmitting nodes and reachability.

First, the counter threshold C_{th} is varied. Figure 7 shows the number of retransmitting nodes and reachability against C_{th} in the counter-based scheme, the RAD Extension and the HCA-RAD Extension. In this graph, the number of nodes is set to 100, and $T_{\max}$ is set to 15 s. 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 Section III, when C_{th} is set to two, the number of retransmitting nodes is the same.

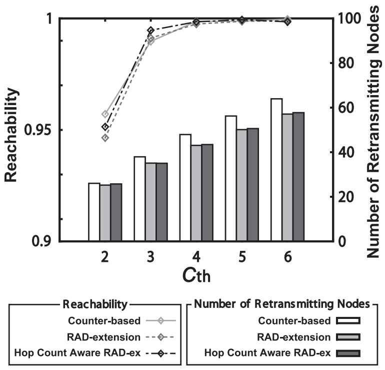

Fig. 7. Counter threshold $C_{\rm th}$ versus reachability and number of retransmitting nodes (number of nodes = 100).

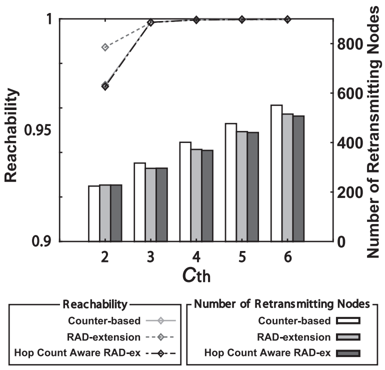

Fig. 8. Counter threshold $C_{\rm th}$ versus reachability and number of retransmitting nodes (number of nodes = 900).

Figures 9 and 10 show the average number of hop counts against $C_{\rm th}$. Here, $T_{\max}$ is set to 15 s. In Figure 9, the number of nodes is set to 100. 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 $C{\rm th}$ is less than 4.

In Figures 10 and 8, the network scale is increased nine times from Figure 7 and Figure 9 with the same node density. Although the tendencies of retransmitting nodes, reachability, and hop count are the same as Figure 9, the average number of hop counts of the HCA-RAD Extension is suppressed about the same as the original counter-based scheme when $C_{\rm th}$ 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, the number of nodes is set to 100, and $C_{\rm th}$ is set to four. Figure 11 shows the relationship between reachability and $T_{\max}$. It is 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 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

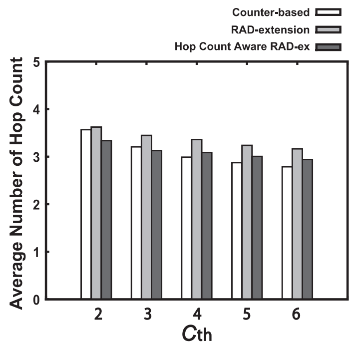

Fig. 9. Counter threshold $C_{\rm th}$ versus average number of hop count (number of nodes = 100).

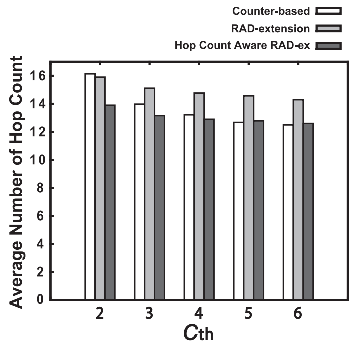

Fig. 10. Counter threshold $C_{\rm th}$ versus average number of hop count (number of nodes = 900, field size = 300 $\times$ 300).

with the value of $T_{\max}$ in the counter-based scheme, the RAD Extension ans the HCA-RAD Extension. And the RAD Extension and the HCA-RAD Extension outperform the original counter-based scheme when $T_{\max}$ is set to 5 ms or more.

Figure 13 shows the relationship between the latency and $T_{\max}$. In Figure 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.

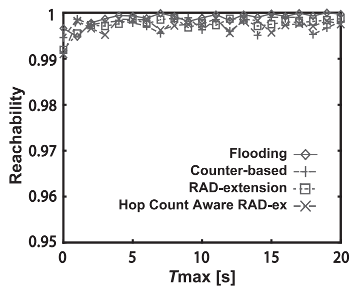

Fig. 11. Maximal value of RAD $T_{\max}$ versus number of reachability ($C_{\rm th} = 4$).

Figure 14 illustrates the relationship between the num-

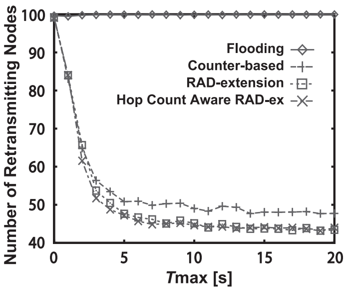

Fig. 12. Maximal value of RAD $T_{\rm max}$ versus number of retransmitting nodes ($C_{\rm th} = 4$).

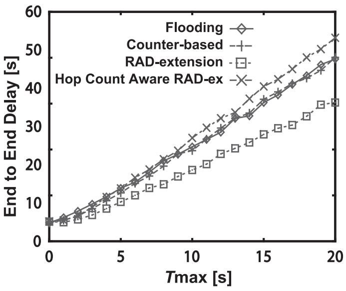

Fig. 13. Maximal value of RAD $T_{\rm max}$ versus latency ($C_{\rm th} = 4$).

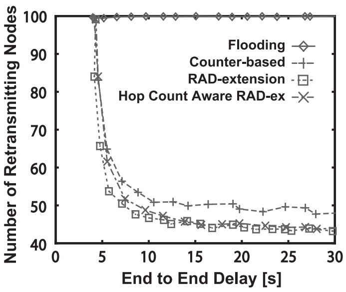

Fig. 14. Latency versus number of retransmitting nodes ($C_{\rm th} = 4$).

ber 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.

V. 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.

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