Hierarchical Real-Time MAC Protocol for (m,k)-firm Stream in Wireless Sensor Networks

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Abstract— **In wireless sensor networks (WSNs), both efficient energy management and Quality of Service (QoS) are important issues for some applications. For creating robust networks, real-time services are usually employed to satisfy the QoS requirements. In this paper, we proposed a hierarchical real-time MAC (medium access control) protocol for (m,k)-firm constraint in wireless sensor networks shortly called HRTS-MAC. The proposed HRTS-MAC protocol is based on a dynamic priority assignment by (m,k)-firm constraint. In a tree structure topology, the scheduling algorithm assigns uniform transmitting opportunities to each node. The paper also provides experimental results and comparison of the proposed protocol with E_DBP scheduling algorithm.**

Index Terms— **Wireless sensor networks, Medium access control, Real-time**

I. INTRODUCTION

WSN (wireless sensor networks) [1] has received significant attention recently for monitoring physical phenomena like temperature, noise, light intensity, speed, etc. In WSN a large challenge of sensor network is the limited lifetime since each sensor node is operated by a limitative battery-powered device. In order to suit to energy constrained environment, the design model to reduce energy consumption is often selected in MAC (Medium Access Control) protocol. Therefore, most of research in WSN MAC layer focuses on energy conservation [2-5]. However, such as military, factory automation and other cases, timely packet delivery is a fundamental requirement, wireless sensor network are increasingly used for time critical applications. For sensor networks, the design model to reduce energy consumption and guarantee bounded delay is often selected in MAC (Medium Access Control) layer. Hence the real-time system is often utilized for wireless sensor MAC protocol [6-9].

In real-time communication system packets that do not reach the destination before deadline contain stale information that cannot be used. For wireless sensor networks, as the natural condition and other factors, the packet loss is unavoidable. In order to suit the limited conditions, the (m,k)-firm guarantee model can be employed in WSN. A real-time stream with an (m,k)-firm guarantee requirement states that m out of any k consecutive packets in the stream must meet their respective deadlines [10]. If less than m packets meet deadline in any consecutive k packets, it is said the application experiences a dynamic failure and the current state is called failure state.

In this paper we proposed a hierarchical real-time MAC for sensor network protocol (HRTS-MAC) with (m,k)-firm constraint. For keeping latency bound and reducing energy consumption, relative to the contention mode, TDMA access scheme has natural advantage since TDMA is better for avoiding collision. HRTS-MAC is a TDMA based real-time MAC protocol for clustered hierarchical sensor networks. HRTS-MAC designed a hierarchical cluster, in one cluster the normal sensor nodes collect information from environment and transmit the information to cluster head in their own time-slot. The hierarchical cluster means that cluster header has higher energy level than normal nodes, we do not need to care about energy consumption with cluster header. This opinion is proposed since the cluster head can achieve low latency to forward received packets for guaranteeing real-time application. In one cluster, HRTS-MAC designs a fixed number of time-slots, cluster head assigns the time-slots to normal nodes which are higher priority, HRTS-MAC utilizes (m,k)-firm to choose the most suitable nodes transmit with their cluster head.

The remainder of this paper is organized as follows. In section II we discuss the related works. Section III describes the algorithm of HRTS-MAC protocol. Section IV shows the simulation results and performance evaluation of the proposed HRTS-MAC. Section V concludes this paper and also includes the further work.

II. RELATED WORKS

In packet transmission networks the real-time system is increasingly being utilized for advancing Quality of Service (QoS) requirements. In wireless sensor networks, QoS for real-time communications are often defined at the MAC and Network Layers [11]. Some solutions with (m,k)-firm guarantee model are proposed to support QoS for real-time communication requirements.

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Implicit Earliest Deadline First (I-EDF) [12] protocol is based on real-time MAC layer protocol for transmission with earlier deadline first in wireless sensor networks. The key idea consists of exploiting the periodic nature of the traffic in sensor networks. In I-EDF author assumed a cellular network structure and employed multi-channel radio sensor hardware. On MAC layer, the I-EDF can achieve using implicit prioritization instead of relying on control packets.

Distance-based Priority (DBP) [13] is based on (m,k)-firm real-time approach, which is a dynamic priority assignment mechanism. DBP scheduling is proposed to research the efficiently serve multiple streams based on (m,k)-firm constraints sharing a single server. The priority assignment algorithm is described as follows. Let 0 and 1 represent a deadline miss and meet, respectively, $s_j = (\delta^j_{i-k_j+1},\ldots,\delta^j_{i-1},\ \delta^j_i)$ is the current state s_j of stream R_j, $l_j(n,s)$ denote the position (from the right side) of the n^{th} meet (or 1) in the state s_j of stream R_j. then the priority of the next packet is designed by:

$$priority^j_{i+1} = k_j - l_j(m_j, s) + 1 \qquad (1)$$

By calculate from (1), the lower value has higher priority. If there are less than n 1's in s_j, then $l_j(n,s) = k_j + 1$, that mean the current state sj is failure (*priority* = 0), compare with successful state, the highest priority will be assigned. There is example, a stream R_j with (2,4)-firm constraint, current k-sequence state is 1110, then $l_j(n,s) = l_j(2,s) = 3$ and the $priority^j_{i+1} = 2$.

Although DBP is good for efficiently serve multiple streams by utilizing (m,k)-firm constraint, the disadvantage is also obvious. If the current k-sequence states of two or more streams are failure, the value of priority is same (priority = 0), but maybe the distance to exit the failure state is different.

Extended Distance-Based Priority scheduling (E_DBP) [11, 14] was proposed for extending the DBP mechanism and applied on wireless sensor networks. E_DBP presents a solution to solve the disadvantage of DBP which is showed in above mentioned. The priority assignment algorithm of E_DBP is described as follows. There is a stream τ_j with constraint parameter m_j and k_j in a failure state, and let $s_j = (\delta^j_{i-k_j+1},\ldots,\delta^j_{i-1},\ \delta^j_i)$ be its current k-sequence. Defining $\tilde{l}_j(n,s)$ as the position (from the right side) of the n^{th} miss in the state of s_j, then the distance to exit the failure state (priority) of a stream is designed by :

$$\emptyset^j_{i+1} = k_j - \tilde{l}_j\,(k_j - m_j + 1,\ s_j) + 1 \qquad (2)$$

For example, a stream τ_j with (4,5)-firm constraint, current k-sequence state is 01110, then $\tilde{l}_j(n,s) = \tilde{l}_j\,(2,s) = 5$ and the $\emptyset^j_{i+1} = 1$. For E_DBP, in a successful state, priority is assigned according to DBP, while in a failure state priority is assigned by (2). If just some streams τ_j are failure states, others are successful states, the packets in the stream τ_j get higher priority. If all streams are failure states at the same time, the lower value of $\emptyset$ has higher priority. If all value of $\emptyset$ is same, EDF (Earliest Deadline First) is adopted. For all cases, if the deadline are same, then FIFO.

III. ALGRITHEM OF HRTS-MAC

The HRTS-MAC protocol is a hierarchical real-time MAC for wireless sensor networks based (m,k)-firm constraint protocol. The HRTS-MAC designed a hierarchical cluster as show in Fig. 1, the cluster header has higher energy level than normal nodes. We consider a tree structure topology which is formed by clusters. As shown in Fig. 2, at the lowest level of the tree structure, cluster headers receive messages from leaf (normal nodes) and forward the messages to parent cluster heads. Their parent cluster heads receive messages from their leaf and children and forward the messages to sink.

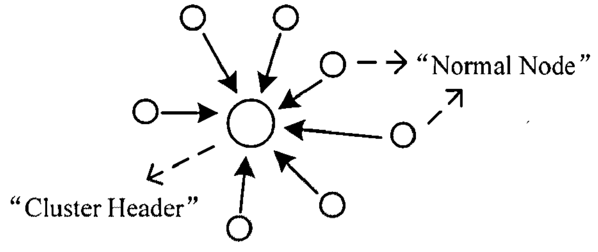

Fig. 1. Intra-cluster: a cluster with one cluster header and N number of normal nodes.

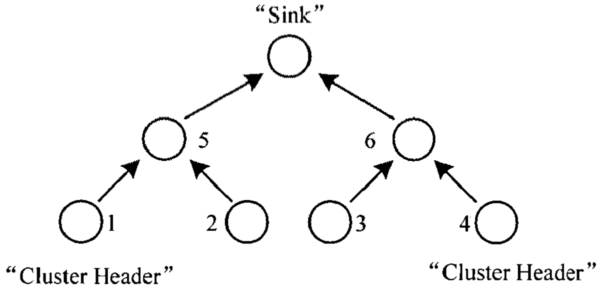

Fig. 2. Inter-cluster: transmission from lower level cluster header to higher level cluster header.

HRTS-MAC divides time into a lot of rounds. As shown in Fig. 3, a round is composed by set-up phase and transmission phase. Sensor nodes establish cluster with their cluster head in set-up phase, transmission phase is consisted of superframe, in every superframe messages can be transmitted from leaf to sink node by (m,k)-firm constraint.

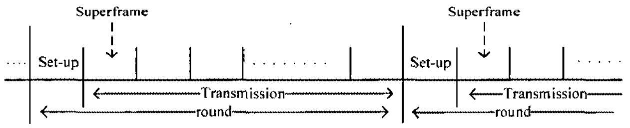

Fig. 3. Round structure of HRTS-MAC.

Initially, in the set-up phase, the cluster formation algorithm like done in LEACH. Sink node first broadcast a short message for defining duration of the round. Then cluster heads broadcast a cluster-request message, the message just includes ID of the cluster header. When normal nodes receive this message they transmit a cluster-agree message to the cluster head and join in the cluster, the cluster-agree message is also a short message that it include the node' ID and chosen cluster header's ID. If a node receives two or more cluster-request messages from different cluster header, the node elects the cluster header that it consumes the minimum transmission energy. When the set-up phase is finish, nodes will send message to sink in transmission phase.

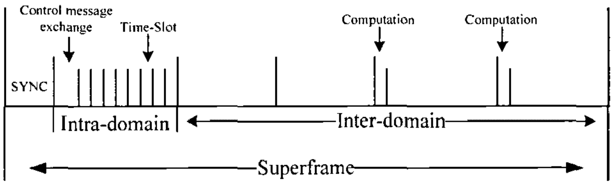

Fig. 4. Superframe structure of HRTS-MAC.

Fig. 4 shows the superframe structure of HRTS-MAC. The RTTHS superframe structure is composed of a synchronization period, intra-domain period and inter-domain period. HRTS-MAC proposes a fixed duration of superframe. During the synchronization period all nodes keep their wake up state, sink sends a time-control message to cluster header and cluster header forwards the control message to their cluster member. The time-control message indicates the start time and duration of each portion in a superframe for synchronizing transmission of every cluster. Intra-domain period is divided in control message exchange period and a fixed number of time-slots. Because the fixed number of time-slots, in one cluster if the amount of normal nodes more than the number of timeslots, the nodes transmit with their cluster header based on real-time streams with (m,k)-firm. We can use several kinds of schemes to set the number of timeslots in one superframe for adapting different application. For example, there is an algorithm for setting the amount of time-slots in intra-domain of one superframe:

NC means number of cluster heads.

$NN(i)$ means number of normal nodes in one cluster.

V means number of timeslots in the intra-domain of one superframe.

$$V = \sum_{i=1}^{NC} NN(i)/NC \tag{3}$$

In different application we should to choose the most suitable algorithm to determine the number of time-slots for adapting environmental monitoring requirements.

In control message exchange period, cluster header first broadcasts an information-request message, this message just includes ID of the cluster header. Some cluster members reply an information message if they need to transmit with cluster header. The information message is also a short message which is consist of node's ID, cluster header's ID, (m,k)-firm, remaining energy and deadline of the next packet. Cluster header determines priority based on the several parameters and establishes schedule for assigning time-slots to the normal nodes, then the cluster header sends a message to cluster members that the message includes the schedule of the cluster in this superframe. During the next period, node with data to transmit turns on its radio and sends data to cluster header over its allocated time-slot, in other time the node keeps sleep state by turning off its radio. The priority assignment algorithm based on real-time by (m,k)-firm is described in the following content:

N_j refers to the node that generate packet P_i.

P_i refers to the i^{th} packet in a stream on a node.

R_j refers to the stream on the node.

1. If the number of time-slots V equal or more than the amount of normal nodes X in a cluster, normal nodes adopt an algorithm for designing if transmit next message by (m,k)-firm.

Let $s_j = (P^j_{i-k_j+1},\ldots,P^j_{i-1}, P^j_i)$ denotes the state of the previous k consecutive packets of R_j, $l_j(n,s_j)$ denotes the position (from the right side) of the n^{th}(or 1) meet deadline in the s_j. In sensor network there is weak for transmission by reason of some influences which is induced from internal and external factors. There is a threshold L for denoting the data packet loss rate on link. Each node checks its packet loss rate on the link. If its packet loss rate is less than L, then the state of the next packet P^j_{i+1} is designed by:

If $l_j(m_j,s_j) \le k-1$, then packet P^j_{i+1} can be dropped, else if $l_j(m_j,s_j) > k-1$, then packet P^j_{i+1} will be sent.

For example, a stream R_1 with (5,8)-firm constraint, if the current state is 10001111, then the $l_1(5,s_1) = 8$, that means the position of 5^{th} meeting deadline packet is more than k-1, which is 8-1=7. Thus the next packet P^j_{i+1} will be sent. In another case, a stream R_2 with (5,8)-firm and the current state is 00111011, $l_2(5,s_2) = 6 < (k-1)$, for this reason the next packet P^j_{i+1} can be dropped for decreasing traffic and save energy.

However that if the packet loss rate of one node is equal or more than threshold L, the node will send every data packet. By reason of the weak link, packet is easy to loss in communication as a result of the influence from internal and external factors. For reducing fail (m,k)-firm state on the link, the node will transmit each data packet.

2. If the number of time-slots V less than the amount of normal nodes X in a cluster, protocol adopt an algorithm for designing which nodes can be scheduled for sending message by (m,k)-firm.

By method 1 some nodes may be excluded, drop $P_{i+1}^{j}$and go to sleep state for waiting next superframe. If the amount of normal nodes still more than the number of time-slots, then we first estimate the current state of (m,k)-firm. We denote the successful state is T and the failure state is F. The priority of successful state is higher than the failure state for sending message.

1) If current (m,k)-firm state of N_j is successful, let $s_j = (P_{i-k_j+1}^{j},\dots,P_{i-1}^{j},\ P_{i}^{j})$ denotes the state of the previous k consecutive packets of R_j, $l_j(z,s_j)$ denotes the position (from the right side) of the z^{th}(or 1) meet deadline in the s_j, then the priority of the next packet $P_{i+1}^{j}$is designed by:

$$T_{i+1}^{j}= k_j - l_j((m_j - n),s_j)+1 \qquad (4)$$

Where n can be equal from 0 to $(m_j - 1)$, initial $n = 0$, if the value of $T_{i+1}^{j}$is same between the nodes, n will add 1 for comparing previous position which meet deadline in the s_j. For example, there has two streams R_3 and R_4 with (2,4)-firm constraint, state of the two streams is 1100 and 1001, respectively. Table 1 shows the state change of k-sequence with the two streams. The k-sequence state 1 is current k-sequence state of R_3 and R_4 streams, k-sequence state 2 shows the states of the two streams which are miss deadline with the next packet P_{i+1}, k-sequence state 3 shows the states of the two streams which are meet deadline with the packet P_{i+2}. Although the two streams are miss deadline about packet P_{i+1}, when their packet P_{i+2} meet deadline, the R_3's (m,k)-firm state is failure but R_4's (m,k)-firm state is successful. Therefore R_3 should be given a higher priority. Initially calculating with (4), $l_3(2,s_3) = 4$, $l_4(2,s_4) = 4$, we get the same value of the two streams: $T_{i+1}^{3}=T_{i+1}^{4}=$ 1. Then n will add 1 and calculate again, T_{i+1}^{3} = 2, T_{i+1}^{4} = 4. By calculating, node with low value of has higher priority for transmitting the next packet P_{i+1}^{x}, thus R_3 is given a higher priority.

TABLE. 1.
THE STATE CHANGE OF K-SEQUENCE WITH R_3, R_4.

Stream	*k-sequence state 1*	*k-sequence state2*	*k-sequence state 3*
R_3	1100	1000	0001
R_4	1001	0010	0101

- For n is equal from 0 to $(m_j - 1)$, if every value of $T_{i+1}^{j}$is same, EDF is adopted.
- If all of the parameters which are mentioned above are same, the control message of N_j which is first arrive on cluster header in the control message exchange period has higher priority.

2) If current state of N_j is failure, $s_j = (P_{i-k_j+1}^{j},\dots,P_{i-1}^{j},\ P_{i}^{j})$ denotes the state of the previous k consecutive packets of R_j, $\tilde{l}_j(z,s_j)$ denotes as the position (from the right side) of the z^{th}(or 0) miss in the state of s_j, then the priority of the next packet P_{i+1}^{x} is designed by:

$$F_{i+1}^{j}= k_j - \tilde{l}_j\,(k_j - (m_j + n) + 1,\, s_j) + 1 \qquad (5)$$

Where n can be equal from 0 to $(k_j - m_j - 1)$, initial $n = 0$, if the value of $T_{i+1}^{j}$is same between the nodes, n will add 1 for comparing previous position which miss deadline in the s_j. For example, there has two streams R_5 and R_6 with (3,6)-firm constraint, state of the two streams is 000011 and 010001, respectively. Table 2 shows the state change of k-sequence with the two streams. The k-sequence state 1 is current k-sequence state of R_5 and R_6 streams, k-sequence state 2 shows the states of the two streams which are miss deadline about the next packet P_{i+1}, k-sequence state 3 shows the states of the two streams which are meet deadline about the packet P_{i+2}. Although the two streams are miss deadline about packet P_{i+1}, when their packet P_{i+2} meet deadline, the R_5's (m,k)-firm state is successful but R_6's (m,k)-firm state is failure. Therefore R_6 should be given a higher priority. Initially calculating with (5), $l_5(3,s_5) = 6$, $l_6(3,s_6) = 6$, we can get the same value of the two streams: $F_{i+1}^{5}=\ F_{i+1}^{6}$ = 1. Then n will add 1 and calculate again, F_{i+1}^{5}= 2, F_{i+1}^{6} = 3.

TABLE. 2.
THE STATE CHANGE OF K-SEQUENCE WITH R_5, R_6.

Stream	*k-sequence state 1*	*k-sequence state2*	*k-sequence state 3*
R_5	000011	000110	001101
R_6	010001	100010	000101

Different between E_DBP, in (5), node with higher value of F_{i+1}^{j}has higher priority for sending the next packet P_{i+1}^{j}. The priority assignment can avoid a long duration between two transmissions for ensuring good quality of environmental monitoring with every node, moreover, the assignment guarantee average energy consumption in a cluster. Thus R_6 is given a higher priority.

- For n is equal from 0 to $(k_j$ - m_j - 1), if every value of $F_{i+1}^{j}$is same, EDF is adopted.
- If all of the parameters which are mentioned above are same, the control message of N_j which is first arrive on cluster header in the control message exchange period has higher priority.

The transmission of inter-domain is forwarding data from cluster header to sink. As shown in Fig. 2 and Fig. 4, in the first two frames the lowest cluster heads 1,2,3 and 4 forward their data to the parent cluster heads 5 and 6. The children cluster head which is belong to different parent cluster header can transmit to their parent simultaneously. For example, in the first frame of inter-domain, children cluster header 1 transmits with its parent 5 while children cluster head 3 can transmits data to its parent 6. Then the cluster heads 5 and 6 receive data from three directions: two children and leaf itself, the last two frames of the inter-domain is proposed for designing the transmission between parent cluster header and sink, the two parent cluster headers send their data packet to sink one by one.

We assumes the duration of one frame for transmitting between parent cluster header and sink is T, it is also assumed that forwarding the data which is arrived on parent cluster header need to spend time N. There is a computation period for estimating priority at the first time of the frame as shown in Fig. 4.

For one parent cluster header if $T<N$, it will compare priority from the three data streams by (m,k)-firm as mentioned above in the computation period. By (4) and (5), if the (m,k)-firm value is same, parent cluster header will compare the other parameter which is packet generation rate. In HRTS-MAC, data packets include the packet generation rate with their source nodes. The packet generation rate is shown as an interval which is duration between two consecutively generating data packets. The interval t_j is presented by:

$$t_j = t^j_{i-1} - t^j_i \qquad (6)$$

In equation (6) $t^j_{i-1}$is the last data packet generated time and $t^j_i$is the current data packet generated time. Packet with higher value of t^j_ihas higher priority to be sent. If the packet generation rate is same, EDF is adopted. If all of the parameters which are mentioned above are same, the FIFO is adopted.

For one parent cluster header if $T>N$, then it sends a time-remaining message to another parent cluster header when its transmission is finish. Another parent cluster header can utilize the remaining time to communicate with sink node, for the cluster header if $T<N$, it can transmit more data packets to sink node.

IV. PERFORMANCE EVALUATION

To evaluate performance of HRTS-MAC, we used C program as the simulator. By the simulator we compared the probability of dynamic failure between HRTS-MAC and E_DBP. We do not show the latency value because meeting deadline is most important in real-time system. The inputs to the simulator include scheduling policy, stream parameters, and simulator directives. The scheduling policies which are E_DBP and HRTS-MAC we chose for evaluating their performance.

The scenario which we used as shown in Fig. 2, we made simulation by observing transmission of one cluster in the scenario for analyzing their performance by comparing the probability of dynamic failure. In the experiment we assume the deadline of data packets which are generated from one normal node is same. For the chose cluster, we assume the deadlines of packets which are generated from these normal nodes are lower than other packets in the scenario, thus normal nodes of the chose cluster can get higher priority for transmitting data packet in contention between inter-clusters. In the simulation we did not consider environmental factor because it cannot be controlled. The packet generate rate ensures every normal node generates one data packet in one superframe.

Fig. 5 shows the comparison of the probability of dynamic failure between E_DBP and HRTS-MAC with (5.8)-firm. In the cluster, number of normal nodes is 7, number of time-slot is 4. The deadline of packets which are generated from node 1 to node 7 is increment in the simulation. As shown in the figure, the probability of dynamic failure of HRTS-MAC is similar between normal nodes, the probability of dynamic failure maintain at about 43%. In E_DBP, the probability of dynamic failure between normal nodes is not steady. Although the probability of dynamic failure of node 1 and node 2 is lower than HRTS-MAC, other nodes are higher than HRTS-MAC. In E_DBP the node 1 can transmit all the packets to meet deadline because its deadline is earliest, but the probability of dynamic failure of other nodes is very high. Especially node 7, as a result of the latest deadline, node 7 is hard to get higher priority for transmitting data packet, therefore the probability of dynamic failure of node 7 is highest, reached 58%. Comparing with HRTS-MAC, the value of probability of dynamic failure is 15% more than HRTS-MAC.

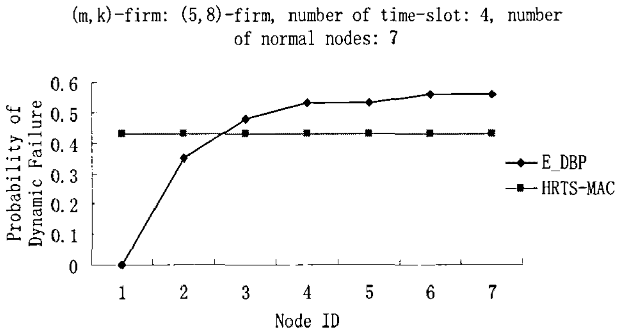

Fig. 5. Comparison of the probability of dynamic failure between E_DBP and HRTS-MAC with (5,8)-firm.

Fig. 6 shows the comparison of the probability of dynamic failure between E_DBP and HRTS-MAC with (4,5)-firm. In this case, number of normal nodes is 8, number of time-slot is 6. The deadline of packets which are generated from node 1 to node 8 is increment in this case. In the same way, the probability of dynamic failure of HRTS-MAC is similar between normal nodes, the probability of dynamic failure maintain at about 25%. In E_DBP, although the probability of dynamic failure of nodes from 1 to 4 can transmit all the packets to meet deadline, the probability of dynamic failure of nodes 5-8 is 50%, comparing with HRTS-MAC, the value of probability of dynamic failure is 25% more than HRTS-MAC.

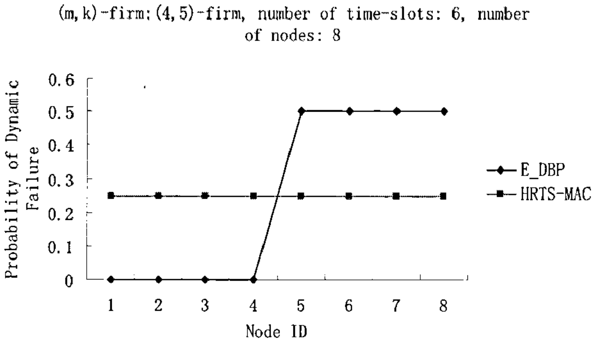

Fig. 6. Comparison of the probability of dynamic failure between E_DBP and HRTS-MAC with (4,5)-firm.

From the two cases mentioned above, the proposed HRTS-MAC protocol can average assign priority on normal nodes for transmitting data packet to cluster header, cluster header collects and forwards the data packets to sink. But in E_DBP, as a result of the uneven priority assignment, packets with the lowest deadline have lower probability of dynamic failure, but packets with higher deadline have higher probability of dynamic failure. This situation may lead to some nodes cannot sent enough valid information to sink node. In addition, because of the different probability of dynamic failure, energy consumption of normal node is also different. For example, in the first case, node 1 can transmit all the packets to meet deadline, but the node consumes more energy than other nodes. This situation will result in uneven energy consumption affect the entire network lifetime. HRTS-MAC is a good solution for the problem mentioned above.

IV.CONCLUSION AND FURTHER WORKS

In this paper, proposed a hierarchical real-time Medium Access Control (MAC) protocol called HRTS-MAC which adopt the (m,k)-firm constraint to guarantee QoS of real-time transmission in wireless sensor networks. HRTS-MAC designs a hierarchical cluster and these clusters form a tree structure topology. In order to avoid collision, HRTS-MAC employs TDMA access scheme for keeping latency bound and reducing energy consumption. The proposed protocol is based on a dynamic priority assignment which can ensure each node sent enough valid information to sink node. The simulation results show that E_DBP scheduling cannot guarantee each node provides enough valid information to customer, HRTS-MAC is a good solution for this problem.

In the further work, we will consider to research the energy constraint in the propose protocol and attempt apply real-time with (m,k)-firm constraint on multi-hop wireless sensor networks.

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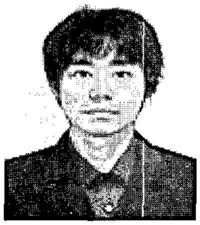

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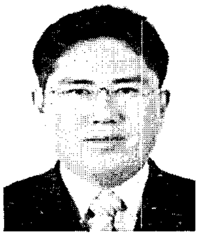

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