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A Forwarding Scheme for (*m,k*)-firm Streams Based on Local Decision in Wireless Sensor Networks

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***Abstract*— As the technology of multimedia sensor networks is desired in large numbers of applications nowadays, real-time service becomes one of the most important research challenges. Even though lots of related works have been conducted to meet this requirement in several ways, the specific traffic model for real-time has not been taken yet. Thus, it causes lack of adaptability of those approaches in real deployment. To solve this problem, in this paper, we model the application via (m,k)-firm streams which have weakly hard real-time property. And then, a novel forwarding scheme based on modified DBP (Distance-Based Priority) is proposed by considering local-DBP and stream DBP together. Local-DBP can contribute to identify the detailed causes of unsatisfied quality, that is, network congestion or wireless link failure. Simulation results reveal that (m,k)-firm is a good traffic model for multimedia sensor networks and the proposed scheme can contribute to guarantee real-time requirement well.**

***Index Terms*— (*m,k*)-firm Stream, Wireless Sensor Networks, Real-Time, Forwarding Scheme**

I. INTRODUCTION

SINCE the technology is rapidly developed in wireless sensor networks (WSNs) in the past decade, application-specific requirements have gained significant importance in the last few years. Wireless Multimedia Sensor Networks (WMSNs) is one of those technologies which are highly desired for their broader and higher quality of information. The availability of complementary metal-oxide semiconductor (CMOS) camera and small microphones make it possible that WMSNs is not only capable of gathering data information but also the multimedia information from the surrounding environment [1]. However, it is more difficult to meet requirements than typical WSN due to natural weakness on a node or wireless communication. Despite of these constraints, one of the main research challenges is to guarantee real-time requirements since the timeliness feature of multimedia streams is a very important property. In order to enhance QoS (Quality of Service) of real-time delivery, real-time routing and real-time scheduling have been proposed. However, the traffic models employed by these schemes are so simple that they cannot be directly applied to adapt specific application requirements.

In this paper, we propose a novel application based on (*m,k*)-firm model, which is usually used for real-time message streams. A real-time message stream is said to have an (*m,k*)-firm guarantee requirement if at least *m* out of any *k* consecutive messages from the stream must meet their deadlines to ensure adequate QoS [4]. The concept of (*m,k*)-firm is appropriate for wireless sensor networks to guarantee messages in a real-time stream to be delivered to their destination as they are expected, within the deadline constraints. For instance, applications in multimedia sensor networks require that audio/video signal should be sent as a stream of message packets across the network [8]. Due to the inherent timeliness feature of the audio/video signal, the packets must reach the destination within the associated deadline to avoid end-to-end dynamic failure, which significantly influences QoS [2].

In WMSNs, since packets which do not reach the destination on time are not available in reconstructing the multimedia signal, many schemes have been proposed in literature, to guarantee the deadline of all messages in a stream [3-7]. SPEED [3] introduces a real-time communication protocol which provides desired delivery speed across the sensor networks through a combination of feedback control and non-deterministic geographic forwarding. However, it doesn't take message deadline of real-time stream into account, which may consequently lead to severe end-to-end dynamic failure. Hamdaoui and Ramanathan proposed a scheduling policy called Distance-Based Priority (DBP) [4] to better service multiple real-time streams, each with its own (*m,k*)-firm guarantee requirement. Instead of assuming that all messages reach their destination in one hop, DBP-M [2] is extended to deal with streams which the messages traverse more than one hop to reach their destinations, by providing a local-deadline to exploit the ability of many streams to tolerate occasional deadline misses. Although these schemes present both scheduling and routing algorithm to guarantee real-time delivery for (*m,k*)-firm stream model, to the best of our knowledge, they have only targeted to adapt to wireless sensor networks, without considering the inherent timeliness relationships between packets of multimedia streams.

Motivated by above problem and needs, our new

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scheme is developed by DBP concept and enhancing the existing scheme through a novel forwarding algorithm combined with fault detection and control. Both node congestion and link failure are distinguished by this new scheme, called local-DBP, and various forwarding decisions will be made while considering real-time local-DBP status and stream DBP together.

The rest of this paper is organized as follows. In Section II, the proposed scheme is mainly described. The simulation results are shown and analyzed in following Section. The conclusion will be presented in Section IV.

II. PROPOSED SCHEME

In order to meet (*m*,*k*)-firm requirement, the proposed approach consists of two phases. One is called *Potential Nodes Discovery*, and the other is *Forwarding Scheme Adjustment*. The details of each component are explained as below.

A. Potential Nodes Discovery

Since packets in real-time streams will be delivered towards the sink, potential downstream nodes are required to provide not only high reliability of transmission, but also ability of meeting the timeliness requirement. The potential nodes discovery phase is to seek available intermediate node which is supposed to deliver interested event information through multi-hop forwarding to sink.

To find potential forwarding nodes, a source node, *i*, initiates a transmission by informing its neighbors when it has packets to send. It is achieved by broadcasting a request to downstream nodes. The request has the following information: (Source Node Position, intermediate Node Position, Sequence Number, Deadline). Source node sends *k* request messages in total, to implement initial link quality estimation between neighbor nodes. Upon receiving this request, each neighbor of node *i* records its own position to the Intermediat Node Position field of the request and then broadcasts it again. Each intermediate node counts the number of successfully receiving requests within deadline, *M*, thus the value of (*M*/*k*) indicates the initial link quality between upstream node and corresponding downstream node.

Once sink receives discovery request message, it first checks if it misses the required deadline; if not, sink directly sends back an ACK (Acknowledgement) to the last hop it receives request from. Each node receiving this ACK will check local neighbor table, and unicasts the ACK to that neighbor as informing that it's one of potential downstream nodes. A full neighbor table will be generated after all ACKs have been sent back to source node, with entries information of potential downstream nodes that may relay packets within deadline. In addition, we use periodic beaconing for exchanging location information and node energy condition to indicate network topology change and energy consumption status.

B. Forwarding Scheme Adjustment

After receiving first ACK message from sink, a source node can start transmission of packets. If there are multiple paths, all packets are delivered to one downstream node which received the first ACK, as meeting real-time requirement outweighs all other considerations. While packets transmission is going on, the main component of our scheme, link quality estimator - local-DBP is employed to estimate real-time link quality and detect link failure. Denoting the local-DBP value of upstream node *i* as *L-DBP$_i$*, it is determined as follows:

$$L-DBP_i = k - m - c_j + f_j \qquad (1)$$

In Eq. (1), *k* and *m* are defined by requirement of (*m*,*k*)-firm stream, c_j indicates the congestion level and f_j indicates link failure level of downstream node *j*, respectively.

Each time after current upstream node *i* sends one packet to downstream node *j*, it starts an RTT (Round Trip Time) timer and listens to the link between downstream node, waiting for ACK and periodic energy beaconing. There are two different results of this packet: (1) in case of receiving periodic energy beacon from downstream node, upstream node *i* can determine that there's no node failure happened with node *j*, and if node *i* receives ACK within an RTT, which shows good conditions of node *j* and the link between *i* and *j*, *L-DBP$_i$* keeps the same; otherwise, c_j +1 and *L-DBP$_i$* -1; (2) in case of not receiving periodic energy beacon, upstream node *i* can determine that node *j* is in failure mode, and after an RTT period, f_j – 1 and consequently *L-DBP$_i$*-1. This link quality estimator can distinguish congestion and link failure as different fault, thus upstream node may infer the traffic condition of downstream transmission, and make appropriate forwarding decision according to it, as shown in Algorithm 1.

STEP 1: In this step, we use single hop delay as the metric to approximate the status of a node. Delay is measured at the upstream node which timestamps the packet sending to network and calculates the round trip delay of this packet when receiving the ACK. At the receiver side, the duration for processing an ACK is put into the ACK packet. The single hop delay is calculated by combining the newly measured delay with previous delays via the exponential weighted moving average (EWMA) [10]. Delay estimation is better than average queue size or buffer size for representing congestion level of nodes in the case of transmitting packets of real-time streams.

Algorithm 1: Selection for Forwarding Node

Pseudo-code executed by node *i* in each round

L-DBP($S_{(x)}$): local-DBP of data stream x
NS: candidate downstream node set of *j*
N: next hop
$EMTT_{ij}$: estimated multiple-hop transmission time from node *i* to sink
CTT_{ij}: spent time from source node to node *i*
n_j: number of candidate nodes in node set
σ: expected single hop delay
P: probability of forwarding to each node

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for all nodes $j$ within the transmission rage of node $i$
    if $(M_j/k) > (m/k)$ && $EMTT_{ij} <$ (deadline – $CTT_{ij}$) then
        $NS = NS \cup \{j\}$
    end if
end for
if $L\text{-}DBP(S_{(x)}) > 0$ then
        no change with $N$
else
    if $L\text{-}DBP(S_{(x)}) == 0$ then
        $N = \text{arg\_max}\{E_j\}$
              $j \in NS$
    else
        if $L\text{-}DBP(S_{(x)}) == c_j$ then
            $n_j = \min(|L\text{-}DBP(S_{(x)})|, NS)$
            for node $j$ from 1 to $n_j+1$
                $N = \text{arg\_min}\{EMTT_{ij}\}$
                   $j \in NS$
            end for
            for node $j$ from 1 to $n_j+1$
                $\sigma_j = 1/RTT_{ij}/2$
                $P_j = \sigma_j / \sum\sigma_j$
                   $j \in NS$
            end for
        else
            if $L\text{-}DBP(S_{(x)}) == f_j$ then
                $n_j = \min(|L\text{-}DBP(S_{(x)})|, NS)$
                for node $j$ from 1 to $n_j$
                    $N = \text{arg\_max}\{M_j/k\}$
                       $j \in NS$
                end for
            else
                broadcast packet
            end if
        end if
    end if
end if
```

STEP 2: Though single hop delay estimation, EMTT (Estimated Multi-hop Transmission Time) can be approximated by multiplying single hop delay with the number of hops from current node *i* to sink. Another time-related parameter CTT (Current Transmission Time), which indicates the spent time from source node to current node *i*, is recorded and subtracted from deadline to figure out how much time is left to relay this packet. For all potential downstream nodes of node *i* in its neighbor table, only those who can satisfy both $M/k > m/k$ and $EMTT < deadline - CTT$ will be chosen to participate in NS (Neighbor Set) of node *i*.

STEP 3: After NS is built, it is entirely possible that *L-DBP* value decreases over time and being near zero due to dynamic network traffic load condition and complex shared media nature of wireless network. Our new forwarding scheme will work by that time. In case that *L-DBP*($S_{(x)}$) is equal to 0, upstream node will change the next hop to the node with highest energy level among all nodes in NS; in case that *L-DBP*($S_{(x)}$) is less than 0, if decrease is caused by only congestion or link failure, upstream node will make forwarding decision for load balancing or limited redundancy, according to estimated time cost and reliability, respectively; otherwise, if *L-DBP*($S_{(x)}$) decrease is caused by both congestion and link failure, upstream node will broadcast packet to guarantee timeliness and reliability by the greatest extent.

As a combination of local-link quality estimator and local-fault controller, this forwarding scheme can efficiently detects node congestion and link failure, and react to figure out solutions immediately. Simulation results show that it adapts the (*m,k*)-firm real-time stream model well.

III. PERFORMANCE EVALUATION

A. Simulation Model and Environment

The results of empirical evaluation of the proposed scheme are presented in this section. The evaluation is performed by a simulator written in C language. Our simulation models a network with 100 sensor nodes placed in an area in grid-pattern. The distance between two nodes has a maximum value of 250 meters as the diagonal. The source node is set five hops away from sink along the shortest path. The inputs to the simulator include deadline for packets of streams, (*m,k*)-firm constraints. In this simulation, we have three different applications with (2,5)-firm, (3,5)-firm, (4,5)-firm constraints. In all three applications, packets are dropped if it is determined that they have already missed their end-to-end deadline, which is set to be 12ms. Two simulations are generated according to traffic load and total link failure ratio of employed nodes, and all details are presented as follows. For reasonable comparison, we choose probability of end-to-end dynamic failure as performance measure, which significantly affects QoS of real-time streams.

B. Analysis of Simulation Results

In the first simulation, we compare probability of end-to-end dynamic failure of three applications, under different traffic ratios as shown in Fig. 2. Traffic ratio is the ratio of primary stream traffic among all cross traffic. The cross traffic is simulated as having additional message streams at each node, as shown in Fig. 1.

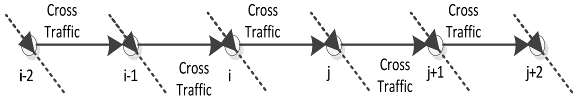

Fig. 1. Nodes status with cross traffic.

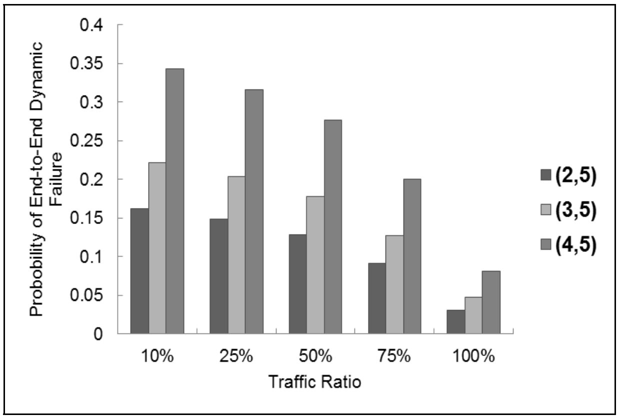

Fig. 2. Probability of end-to-end dynamic failure under different traffic ratio.

In the first simulation, with the same packet deadline, probabilities of end-to-end dynamic failure of all three applications show a monotone decreasing trend while traffic ratio approaching 100%. As it is defined before, traffic ratio indicates the traffic load on one node, therefor, the bigger this value, the lighter traffic load the node contains. Since in the proposed scheme, when congestion happened in overloaded nodes, the forwarding scheme may efficiently estimate the performance degradation caused by congestion, and if the performance cannot meet required (*m,k*)-firm, load balancing scheme will be operated immediately. Simulation result demonstrates that this mechanism can avoid congestion level becoming worse, and consequently reduces end-to-end dynamic failure. Applications with (2,5)-firm and (3,5)-firm show good performance that the maximum probability of dynamic failure of those nodes which are under very heavy load (e.g. 10%), is about 0.2. Even though the requirement of (4,5)-firm application is quite strict, the result still shows that the probability of dynamic failure is within the range of acceptance.

In the second simulation, also with the same packet deadline, probabilities of end-to-end dynamic failure of three applications are measured with link failure ratio, as shown in Fig. 3. This simulation is operated to show the robustness and reliability of the proposed scheme. Links in sensor networks are considered to be failure-prone [11], causing network partitions and dynamic changes in network topology. In the case of real-time streams, link failure will lead to severe unreliability in packets transmission, which may cause deadline miss and finally end-to-end dynamic failure. To avoid link failure becoming worse, limited redundancy mechanism takes great part in the proposed scheme. Results in Fig. 3 demonstrate that it's available to control the performance degradation caused by link failure, even if the requirement is strict as (4,5)-firm. Other applications especially (2,5)-firm performs well in all level of link failure.

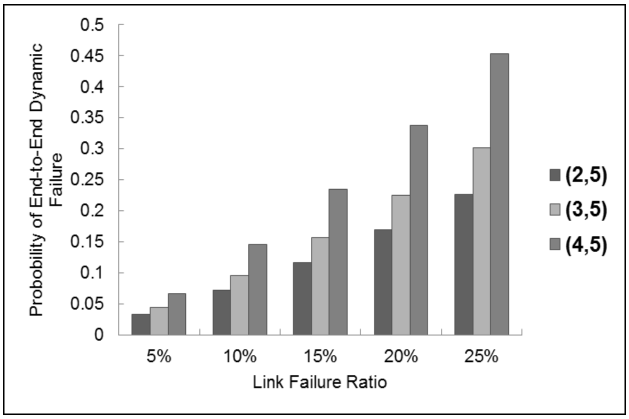

Fig. 3. Probability of end-to-end dynamic failure with different link failure ratio.

IV. CONCLUSION AND FUTURE WORK

In order to support real-time service in WMSNs, some research works have been proposed. However, general traffic model is not desirable in real deployment. In this paper, we proposed a new QoS-aware forwarding scheme which is developed based on (*m,k*)-firm streams model. It consists of a link quality estimator, called local-DBP, to monitor the real-time link status, detect and distinguish congestion from link failure; a forwarding decision making algorithm, which can efficiently evaluate performance degradation by information of local-DBP, and make appropriate decisions to achieve load balancing or limited redundancy, for solving problems. Finally, simulation results show that the proposed scheme meets the requirements of real-time streams in sensor networks to some amounts.

Related to this work, other metrics for load balancing and link failure will be concerned. Also, study for performance evaluation will be done through various topology as well as adjustable parameter to find out the strength and weakness of proposed one.

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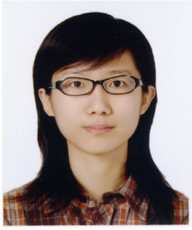

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