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An architecture for (*m*, *k*)-firm real-time streams in wireless sensor networks

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Abstract Despite increasing demand of application specific requirements in wireless sensor networks, lots of research is still going on under assumption of general requirement without considering specific traffic model as well as several constraints. To address this issue, we have already introduced a new real-time application with (*m*, *k*)-firm model and developed communication protocols for multimedia sensor networks. But, scalability problem and lack of architecture for (*m*, *k*)-firm stream are major research challenges that remain unsolved. Based on corresponding demands, in this paper, we propose a new integrated architecture for (*m*, *k*)-firm stream in wireless sensor networks with following functions, that is, flow aggregation based on compositional hierarchical model, velocity based routing protocol, hybrid medium access control protocol, and congestion control scheme. Simulation results are given to prove the suitability of the architecture and performance improvement under several scenarios.

Keywords (*m*, *k*)-firm stream · Wireless sensor networks · Compositional hierarchical model

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1 Introduction

In recent decades, people interact with the physical world and get useful information in easy way from different areas by the help of research works conducted in wireless sensor networks (WSNs). In each work, feasible application might be interested in different sensory data in which creates different requirements in terms of quality of service (QoS) and reliability. For example, in a military surveillance system, the detection of a target must be transmitted to the base station as an alert within a very short time period. Fire detection also requires the packets to reach the monitoring station timely so that the fire-fighters could keep aware of current fire conditions. However, despite application specific property, many schemes proposed till now has assumed general requirements. This fact may cause poor adaptability problem when it comes to deploy them in the real world. To defeat problem, recent schemes tend to be designed according to specific application requirements. For example, a sensor network for health-care environment uses video transmission as sensory modality to identify patients' behavior [1].

However, it is a great research challenge to support QoS in WSNs since WSNs differ dramatically from the traditional network systems such as wired networks or IP-based wireless networks. This is mainly because of lossy, unstable link connections and limited resource constraints. By considering these harsh constraints, many research works have been proposed to develop new architectures and communication protocols instead of adapting the existing schemes into WSNs. Nevertheless, there is little chance of deployment in real world if different application requirements are needed. Thus, suitable traffic model and architecture are required for multimedia sensor networks.

Based on these research motivation, we have proposed architecture and communication protocols for multimedia service in WSNs. Main contributions of the our previous research work were to introduce (m, k)-firm model in multimedia sensor networks at the first time. Due to the inherent constraints and lossy link connections of WSNs, it is impractical to fulfill hard real-time tasks in WSNs. Thus, a probabilistic guarantee is required by being tolerant for some deadline missing so that the time-out packets are still useful and system would not crash in multimedia sensor networks. Furthermore, firm real-time that sets the criterion between hard real-time and soft real-time is the optimal system over multimedia sensor networks while considering the inherent features of WSNs and application requirements. To meet these requirements, we proposed several communications protocols largely focusing on routing protocol. In addition, priority scheme and simple congestion control scheme were proposed to improve QoS. However, despite proposed scheme, some problems remain unsolved yet. They include scalability problem for flow based approach so severe service degradation is expected for increased number of flows in the networks. Moreover, this will speed up battery consumption and network partition at earlier time. Moreover, the most important problem is lack of architecture to integrate the respective protocols in each layer such as [2]. Also, traffic model and congestion control scheme to maintain QoS need to be revised for existing coarse-grained approach.

To solve mentioned deficiencies of our previous work, in this paper, we propose a new architecture to combine respective approaches. More detailed, multiple sub-stream models are defined for one (m, k)-model and one of them is selected for current network environment. Each stream is distinguished by differentiating parameters and priorities. As for real-time routing protocol, well-known velocity based routing protocol such as SPEED is modified for (m, k)-firm stream by selecting next hop depending on reliability over wireless link and balanced chance for next hop. And, data aggregation based on compositional model for (m, k)-firm stream is accomplished at the intermediate node in order to reduce complexity as the number of flows increases. At last, current contention-based medium access control (MAC) protocol is replaced by hybrid one to meet (m, k)-firm stream. These all schemes are integrated in one architecture and evaluated by the simulation results.

The rest of this paper is organized as follows. We review existing literatures in Sect. 2 and elaborate the proposed scheme in Sect. 3, respectively. In Sect. 4, we present the simulation results and analysis. Conclusion of the paper with open issues is given in Sect. 5.

2 Related work

Due to several constraints, a WSN protocol should minimize the energy consumption and overhead as well as delay requirement when it is dealing with some mission-critical applications [3, 4]. Specially, as the multimedia services are required in wireless sensor networks, the techniques should consider not only energy efficiency and reliability but also timeliness to avoid dynamic failure of QoS and to facilitate specific service guarantees [5]. In this point, video transmission schemes over IEEE 802.11e networks [6, 7] and peer-to-peer media stream [8] can be good guidances to develop suitable scheme. Furthermore, multimedia service leads to develop remarkable applications in medical sensor networks and body area networks [9–12] where strict QoS requirements are given. Following above research trends, existing schemes for real-time communications are mainly categorized into general and application-specific such as (m, k)-firm, approach. Thus, in this section, we briefly review the existing schemes in two areas.

2.1 Communication protocols for real-time applications, congestion control and data aggregation

Most of communication protocols in real-time application have focused on routing protocol, MAC protocol, and congestion control. First, SPEED [13] and its variants such as MMSPEED [14] and real-time fault tolerant routing protocol called FT-SPEED [15], were well-known soft real-time routing protocol. They estimate the transmission speed between current node and candidate nodes and then tries to establish a transmission path with all relay nodes maintaining a desired delivery speed. Recently, new routing protocols considering real-time requirement and other properties together have been proposed. For instance, real-time power-aware (RTPA) [16] routing protocol supports real-time application in energy efficient way. Opportunistic real time routing (ORTR) [17] also takes delivery of data under time constraints with efficient power consumption into account. Furthermore, Simultaneous Attentive Energy Routing Protocol (SAERP) [18], real-time and robust routing protocol (RTRR) [19] and Potential-based real-time routing (PRTR) [20] have addressed energy efficiency and other metrics such as robustness. In addition to mentioned routing protocols, more research works have been introduced and analyzed in [21]. Also, as for the addressed metrics, it is meaningful to identify their impact and related solution in other networks [22–25].

In addition to routing protocol, MAC protocol is closely related to real-time applications. For the real-time MAC protocols, two literatures [26, 27] have classified the existing protocols and presented comparison results in various aspects such as duty cycle [28, 29]. Moreover, real-time X-layer protocol (RTXP) [30], relies only on local information by using an opportunistic routing scheme in order to increase the packet delivery ratio. Emergency response-MAC (ER-MAC) [31] was designed to provide the flexibility to adapt to traffic and topology change as a hybrid of the TDMA and CSMA approaches. When emergency event happens, monitoring node changes its behaviors to deliver events within deadline. In addition, fair access for MAC protocols was mentioned in [32] for tightly bounded performance.

Furthermore, real-time delivery is affected by congestion control scheme. There are two recent survey papers [33, 34] worthwhile mentioning. In their work, state-of-the-arts for congestion control were well described and explained. Among them, Event to Sink Reliable Transport [35] is one of well cited research work as a novel transport solution to achieve reliable event detection with minimum energy expenditure and congestion resolution. Also, a priority based congestion control protocol was proposed in [36] that is designed for multimedia application in WSNs.

Finally, there are many published literatures for data aggregation which is one of great different features with other typical networks. Since data aggregation can be improved with reduced data size, many approaches have taken data compression scheme while considering node's constraints [37–40]. Specially, data model such as power-law decaying as well as combining grey model and Kalman filter were considered to be adapted in WSNs. Also, network coding is another applicable way to reduce data size [41]. Furthermore, coverage problem related to network lifetime was mentioned in [42, 43].

2.2 (*m*, *k*)-firm stream in WSNs

The concept of (*m*, *k*)-firm was defined as follows: a real-time message stream is considered to have an (*m*, *k*)-firm guarantee requirement that at least *m* out of any *k* consecutive messages from the stream must meet their deadlines, to ensure adequate QoS [44]. Based on this concept, a priority assignment technology called Distance Based Priority (*DBP*) was developed to arbitrate between the streams in a system. For each stream, the system maintains a state of the recent history of captured deadline meet and miss. Then the state is denoted as *DBP* value of the stream.

Related to (*m*, *k*)-firm stream in WSNs, most of related research work was conducted by our research group, with the exception of scheduling scheme explained as the last one. Our first research for (*m*, *k*)-firm was routing protocol. We proposed a new geographic routing protocol and a scheduling algorithm to support (*m*, *k*)-firm streams. Both a priority-based scheduling and a geographic forwarding scheme based on delay, distance, and remaining slack time was proposed and analyzed by simulations results [45]. Followed by this work, a local transmission status indicator based on stream Distance-Based Priority(*DBP*), called *L_DBP* (local-DBP) was proposed in [46] to monitor the statement of delivery to the next hop and indicate network faults such as congestion and link failure during transmissions. By the contributions of both *L_DBP* and stream *DBP*, a novel geographic routing protocol was proposed to meet the requirements of real-time streams, by making routing decisions while considering timeliness and reliability features together [47]. However, due to no consideration of energy consumption, a new protocol was developed to enhance forwarding decision by taking into account of packet end-to-end deadline, node condition and remaining energy of next hop [48].

In addition, we introduced a cross-layer design to bring collaboration between layers under the basic principle that real-time delivery will hardly be achieved by independent schemes in each layer. Thus, the requirements of application are passed to lower layers and used to adjust of transmission power, prioritize packets, and find the adequate path in order to meet (*m*, *k*)-firm constraints for any stream [49]. And then, traffic modeling for (*m*, *k*)-firm stream was introduced at the first time in [50].

Recently, we have devised a real-time routing protocol for (*m*, *k*)-firm streams based on Local Status Indicator(*LSI*) under the fault recovery mechanisms to make a complete scheme for QoS guarantee of real-time applications. The proposed routing protocol calculates optimal forwarding decision based on three metrics: packet deadline, *LSI* which is regarded as node condition, and remaining power of a sensor node. Through both routing protocol and fault recovery mechanisms, the proposed scheme showed high performance in successful packet delivery ratio and deadline meet ratio, which have been studied and reported through simulations in [51]. Other related scheme for (*m*, *k*) is a channel-aware scheduling algorithm to support real-time applications in wireless multimedia sensor networks [52]. It provides packet partitioning and real-time delivery. Packet partitioning combines static assignment and dynamic adjustment while considering the channel state in order to minimize the number of mandatory packets delivered in a bad channel state to avoid dynamic failure. In addition, automatic repeat request technology was introduced to enhance the reliability of real-time delivery.

3 Proposed architecture for (m, k)-firm stream in wireless sensor networks

3.1 Real-time flow model

A real-time flow, denoted by F_i, is a set of periodic message stream from a source node i to a sink node. For the simplicity, we assume that there is one flow between source and sink. Furthermore, continuous or time-driven sensing application such as nuclear stations monitoring is assumed. The message deadline is denoted by D_i. In addition, each flow has a dynamic priority P_i according to both Distance Based Priority (*DBP*) and new parameters. Both m_i and k_i are determined by the application requirement for stream. As a result, a new real-time stream is defined as $F_i = ((m_i, k_i), D_i, DBP_i, P_i)$. *A source node sends a data packet carrying* F_i *information*.

However, different from our previous work where only one level m and k is used to represent F_i, we employ multiple streams. That is, one stream can be presented by a set of multiple sub-streams that have different service demands. Thus, any (m_i, k_i) requirement in F_i is defined as $(m_i, k_i) = \{(m_1, k_1) \cup (m_2, k_2) \cup (m_3, k_3) \cup ...(m_n, k_n)\}$ where n represents the maximum number of quality levels and k^{th} stream has better quality than l^{th} stream in F_i if k is less than l. It is controlled in a way of adjusting sensing period where better quality stream is defined to have the shorter period. For the delivery of stream, one of them is selected according to rule at any time. Also, quality level and priority are changed in round based. So, any packet in j^{th} round under this model carries following information, that is, $(m_i^j, k_i^j, D_i, DBP_i^j, P_i^j)$ after quality level is set by the proposed scheme. But, for the simplicity, we use F_i instead of F_i^j for explanation in the remaining part.

3.2 Overview of proposed architecture

The proposed architecture consists of five main procedures such as (1) stream selection and prioritization, (2) stream aggregation based on compositional model, (3) velocity based routing protocol, (4) MAC protocol and queue management, (5) congestion control. The Fig. 1 shows the example of node type and their actions. The example scenario for (m, k)-firm stream in our architecture is as follows.

With the original (m_1, k_1)-firm stream, a source node, i, sends real-time packets carrying information of F_i. This packet is forwarded to a sink node through new routing protocol and MAC protocol. And then, a sink node measures whether a packet is delivered within the deadline. Based on history on previous packets as much as k, it computes *DBP* value at this time. However, a sink node does not send *DBP* value whenever it receives the packet. Rather, periodic round approach is employed. So, at every round, round *DBP* is computed by adding all *DBP* values within the round. Upon getting *DBP* value, the round *DBP* value for each flow is back to the source. This *DBP* value is used to assign priority of each stream as well as select the possible $((m_i^j, k_i^j)$ requirement among the n available streams for next round. New (m, k)-firm requirement is selected either when round *DBP* value is reported or any request message issued by congestion control scheme arrives. Also, a priority of stream is assigned and then is dynamically changed according to the number of passed hops for prioritization between sourced and transit packet.

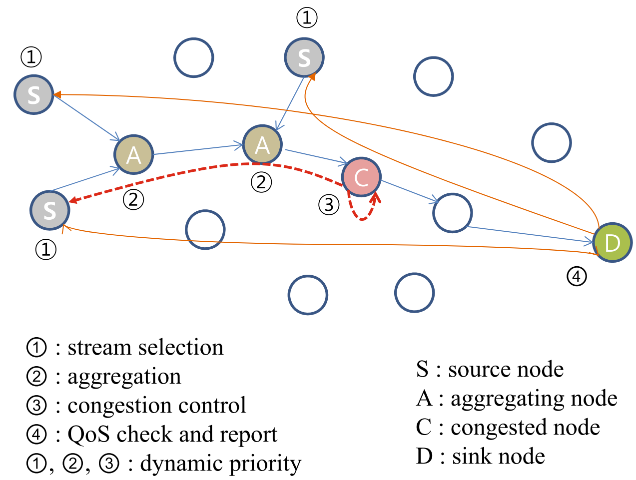


Fig. 1 Overview of operations in proposed architecture

After deciding the quality level and priority, each packet is delivered by communication protocols for (m, k)-firm stream which operate based on priority of each packet. For the data forwarding, next hop is selected by considering current priority and link reliability. Also, in order to reduce the delay and guarantee real-time delivery in MAC layer, hybrid MAC protocol consisting of contention-free and contention-based is used. A packet with higher priority is considered to be forwarded toward the reliable link over contention-free with TDMA based slot. On the other hand, low priority packet is transmitted in contention based way. However, their backoff time to avoid collision is determined by the priority. Finally, different from our previous work, since flow based approach causes scalability problem, we introduce data aggregation at the intermediate node under compositional real-time model [53] which guarantees multiple real-time streams by ensuring aggregated one real-time stream. We explain each stream one by one in following sections.

3.3 Stream selection and prioritization

Since multiple streams for one (*m*, *k*)-firm are newly defined, it is required to distinguish each stream and keep its information for current level. For this, we add one more variable, l. So, current (m, k)-firm model is extended to cover (m, k, l). According to l, a new (m, k) requirement and message period is set. Usually, longer sensing period is given to stream having greater l. For the selection of l, the following rule is applied. First, l starts from 1, the best quality level, in all streams. And then, l is changed according to value of round *DBP* which is reported by the sink. More detailed, l increases by one when two negative *DBP* values are reported in two consecutive rounds and the latter *DBP* is less or equal than former one. Otherwise, it is maintained. On the other hand, when two consecutive positive round *DBP* values are back to the source and latter *DBP* is greater or equal than former one, l decreases by one until it reaches 1. The main reason to consider two consecutive rounds is to avoid drastic degradation and frequent level change. Also, since all communication protocols are based on this priority, one more chance for current level is given. However, if it is not enough, level is supposed to be changed. Otherwise, current level is regarded suitable for current network environments so degradation is not accomplished. Another case of stream change is done by congestion control scheme explained in later section.

Additionally, the priority of stream is closely related to current level and *DBP* value as given below. With decreasing values, the stream gets higher priority. This priority is changed at every round. Furthermore, negative priority is only generated when negative *DBP* value is observed so two values are considered to have the same sign.

$$P_i = \begin{cases} DBP_i \times l_i & \text{if } DBP_i < 0 \\ (DBP_i + 1) \times l_i & \text{otherwise} \end{cases}$$

Based on this definition, the highest priority is assigned when the current level reaches the highest one and *DBP* value does minimum one. In case that the *DBP* value is zero, we add constant value, one, with current level in order to distinguish and identify current level. Also, the priority of a packet is dynamically adjusted in hop-by-hop. Since we prioritize transit packet over source packet, higher priority is given to the transit packet by considering H_i which represents number of passed hop from the src_i. In order to meet our priority rule that the least value has the highest priority, either multiplication or division is performed to initial priority which is presented by $P_{original}$ and preserved for this round.

$$P_i = \begin{cases} P_{original} \times H_i & \text{if } P_{original} \leq 0 \\ \dfrac{P_{original}}{H_i} & \text{otherwise} \end{cases}$$

3.4 Stream aggregation based on compositional model

Due to resource constraints and large number of flows, flow based approach is not suitable for WSNs in that it causes huge amount of overhead. Thus, some applications introduce how to reduce the traffic or number of communications in several ways such as data aggregation at the intermediate node to solve scalability problem. Similar to these technologies, we propose stream aggregation scheme for (*m*, *k*)-firm stream through compositional model with hierarchical scheduling framework. In this model, if one composed stream is guaranteed to meet requirement, it iteratively can meet respective requirements of composing stream.

Based on this model, multiple F_i are aggregated as a new stream. To build new composed stream, it is required to define a new stream by considering parameters in each flow. The proposed procedure is performed with two flows. If there are more flows to be aggregated, repeated aggregation is done. If two separate streams, F_i and F_j are given, a new stream is denoted by setting each parameter for flow as below to decide a new (*m*, *k*)-firm stream.

$$F_l = \begin{cases} m_l = m_i + m_j + \min(k_i - m_i, k_j - m_j) \\ k_l = k_i + k_j \\ P_l = \min(P_i, P_j) \end{cases}$$

Since new aggregated flow should not violate requirement of the two composing streams, m is more important parameter than k. K in aggregated flow is simply defined by adding two k values. On the other hand, m is considered to have $\min(k_i - m_i, k_j - m_j)$. By this value, any drop packet in new stream does not violate the original two streams (*m*, *k*)-firm requirements. In case of priority, it is determined to take minimum value of them to guarantee real-time delivery.

Furthermore, any two flows cannot be aggregated for all cases at the any intermediate node. For the aggregation, we define our aggregation rule. First, two flows should have the similar deadline or remaining time to the sink. If two flows have great difference in remaining time which can be computed by D_i and elapsed time, they cannot be aggregated since deadline is not negotiable property. Second, data aggregation is only accomplished when newly defined m_l is less than equal k_l. If these two conditions are met, it is possible to aggregate two flows.

3.5 Routing protocol

In order to remove strong dependency on state information of flow and handle packets in a round, we propose a new routing protocol for (*m*, *k*)-firm stream under tree architecture. It chooses the adequate next hop with limited state information while considering current requirement and link reliability in distributed way to prevent node failure due to concentrated selection as relay node. And, it works in a round based operation. If a new round starts, the suitable next hop is chosen by the proposed routing protocol. Since this procedure starts from each source node, selected next hop will be parent in a tree. So, tree with sink as a root is constructed by the routing protocol accordingly. And then, this tree structure is used for for data forwarding until one round is expired.

Even though new routing protocol is based on velocity, however, two different approaches are taken for (m, k)-firm stream. First, according to priority which is based on *DBP* value and current level of stream, it is determined to consider link reliability for next hop selection or not. Second, in order to prevent one node from being selected by multiple nodes, the node with the highest velocity is not always chosen for next hop. Rather, we build the possible links set and then choose one in a set randomly. The Algorithm 1 shows the data forwarding procedure.

Algorithm 1 describes two main tasks for data forwarding. First task is to build the set with adjacent nodes which provide faster velocity than requirements. This set is used to evaluate the neighboring nodes to provide the real-time service. Upon constructing the set, the second task is to choose the appropriate next hop for forwarding. This is mainly divided into three cases depending on a packet priority. First case is that the priority is less than predetermined threshold. In this case, it is required to choose the most reliable and the fastest link to prevent packet drop. To accomplish this task, the highest velocity link is chosen and then its reliability is compared with current (m, k)-firm requirement. If two conditions are met, corresponding link is used for data forwarding. Otherwise, that link is excluded and next high reliable link is compared. Through these procedures, it is guaranteed to select the best link to support (m, k)-firm stream. Second case is for negative priority which indicates the requirement is not met. In this case, reliability is also concerned but final selection procedure is done randomly. If a node

Algorithm 1 Data Forwarding

$F_i \leftarrow$ flow of packet
$n \leftarrow$ number of neighbors
$\delta \leftarrow$ threshold
$m, k \leftarrow m_i^j$ in packet, k_i^j in packet
Compute the velocity for all neighbor nodes at node k, $V(k,i) = \frac{distance(k,i)}{delay(k,i)}$

for $i \leftarrow 1, n$ **do**
    if $((V(k,i) > V(source, sink))$ **then**
        $NS_k \leftarrow NS_k \bigcup \{i\}$
    end if
end for

tmp = NS_k
if $(P_i \le \delta)$ **then**
    for $i \leftarrow 1, \|tmp\|$ **do**
        $j \leftarrow \arg\max_{i \in tmp}(V(k,i))$
        if $(PDR_{i,j} > (m/k))$ **then**
            $next\_hop = j$
        else
            $tmp \leftarrow tmp - \{j\}$
        end if
    end for
else if $(P_i > \delta$ and $P_i < 0)$ **then**
    for $i \leftarrow 1, \|tmp\|$ **do**
        if $(PDR_{i,j} > (m/k))$ **then**
            $canst = canset \bigcup \{j\}$
        end if
    end for
    $next\_hop \leftarrow$ random_select(canst)
else
    $next\_hop \leftarrow$ random_select(NS_k)
end if

is chosen for data forwarding in many times, its battery is drained quickly rather than others. Thus, random selection is used to balance the energy consumption and guarantee the suitable link for (m, k)-firm. The last case is for positive priority. In this case, there is loose constraint for next hop which can meet velocity without regard to reliability. Among these nodes, a node is randomly selected as shown in Algorithm 1.

3.6 MAC protocol and queue management

After deciding the next hop by the proposed scheme, a packet is queued into the buffer implemented between network and MAC layer. In the proposed scheme, we use two queues at each node; one for traffic with negative priority and another for positive one as shown in Fig. 2. Without regard to sourced or transit traffic, all packets with negative priority are with same queue. In a queue, a packet is ordered based on its priority. If the priority is the same, a packet with less *DBP* is handled earlier than a packet with great one. If a queue is full, we drop a packet with the lowest priority because it is most likely to have slight impact on requirements and perform congestion control scheme in next section.

In addition to priority queue, we proposed hybrid medium access control protocol to meet (m, k)-firm requirement. *The frame of this hybrid MAC protocol consists of contention-free and contention-based slots with duration* t_s and t_c, respectively, as depicted in Fig. 3. Contention-free slot is reserved for packets in negative priority queue and operates in TDMA protocol in order to meet real-time requirement. Also, in the contention-based frame, backoff time to avoid congestion is adjusted according to current priority. *By this way, low priority stream is supposed to wait longer access time than high priority*. The backoff period (BP) of packet in F_i for contention based is determined as follows. So, a node sets backoff time as any random value ranged from 0 to BP_i and waits their transmission until the timer is expired.

$$BP_i = \begin{cases} t_{ic} \times 2^{P_i} & \text{when a packet is not aggregated} \\ t_{ac} \times 2^{P_i} & \text{otherwise} \end{cases}$$

The slot allocation is done by parent node that is selected for next hop by routing protocol. The proposed MAC frame structure consists of individual and aggregated flow in both contention-free and contention-based period. A contention-free slot reserves slots as much as sum of child nodes m values. Thus, the frame duration is adjusted according to requirement.

3.7 Congestion control

If any pakcet is dropped from the queue, congestion control scheme begins. Congestion control is to adjust the (m, k)-firm stream level to reduce the incoming traffic. To perform the congestion control, it is required to determine which node adjusts the traffic and how to request it. The below Algorithm 2 shows the operation to remove the congested sensor node.

Algorithm 2 Congestion Control at node n

$priority \leftarrow P_i$ of drop packet at node n
if $(priority < 0)$ **then**
  $j \leftarrow$ source of drop packet
  if $(j == n)$ **then**
    $(m_n, k_n, l_n) \leftarrow (m_n, k_n, \max(max\_level, l_n + 1)$
  else
    Send $Level\_Adjustment\_Request$ to node j
  end if
else
  $(m_n, k_n l_n) \leftarrow (m_n, k_n, l_n + 1)$
end if

For any packet drop, two different actions are taken according to the priority of packet. If the priority is less than 0, it indicates that the flow involving this packet has the lowest priority since the priority scheduling is assumed. Thus, it is reasonable to adjust the corresponding flow. To achieve this, we identify the source of drop packet. If the packet is generated from current node, we adjust the traffic level of current (m, k)-firm stream on the node by increasing it. Otherwise, *Level_Adjustment_Request* message is sent to the source. On the other hand, if the priority of packet is greater than 0, all flows are in the satisfactory level. So, level adjustment is done in current node because transit packet has higher priority than source packet.

Fig. 2 Queue structure

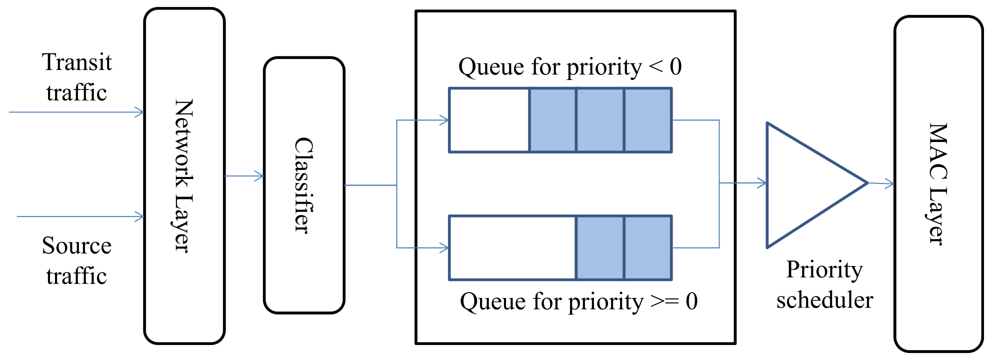
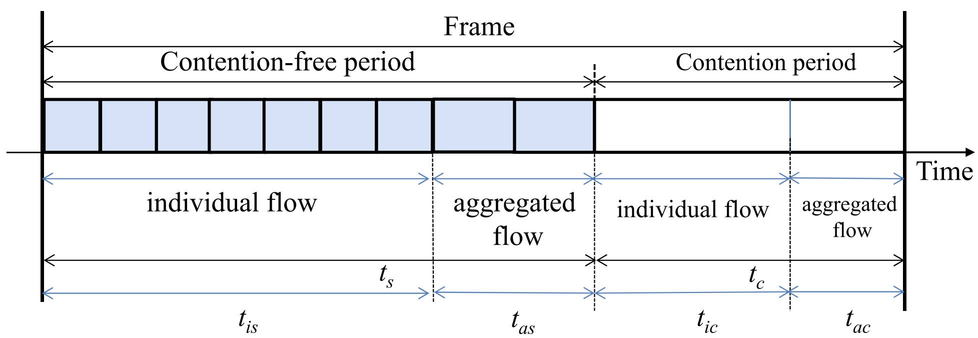


Fig. 3 Proposed MAC frame structure



4 Performance evaluation

Performance of the proposed scheme is proved by simulations. We use ns-2 as the simulator. The simulation terrain is set as a 200m × 200m field. Sink is located at the lower right corner of the field so that the end-to-end hop-count ranges from 4 to 9 hops with an average of 6 hops. Each node has a radio range of 40m. Propagation model is set to be Two-Ray Ground where protocols for physical is set to be wireless-phy in ns-2. For the application, there are one and three levels for each stream and the message period becomes doubled for next level. *Deadline for real-time packet on each node is set by considering average-link-delay and number of shortest hops, respectively*. The comparative protocols are original SPEED and our previous works [50]. For the example of multiple levels for one (m, k)-firm stream, it is defined in $(m,k) = \{(4,5) \cup (3,4) \cup (2,3)\}$ where initial period of sensing of (4,5) is set to 250 msec so other two streams are set to 500 msec and 1 sec, respectively. Since (4,5) is more strict requirement than others, we employ the three levels correspondingly.

Evaluation result is presented as stream dynamic failure ratio (SDFR) and network lifetime. The former refers to the timeliness of individual packet, which is considered as the most important feature in real-time application while the latter does the elapsed time until the region of interest is completely within the sensing range of at least one sensor node. For the mentioned performance parameters, we use three scenarios. First, we increase number of source nodes with fixed event period. Second, we have the decreasing event period with fixed number of source nodes. Finally, we gradually increase the background traffic load.

4.1 Simulation results

First, we compare two performance parameters as the number of source nodes increases from 10 to 30 % as depicted in both Figs. 4 and 5. In both figures, NewThree represents proposed new architecture with three levels and NewOne does one with single level. SPEED and Previous indicate original SPEED protocol and our previous work [50], respectively.

For the SPEED and our previous protocol, we employ TDMA MAC protocol to meet real-time delivery for fair comparison. However, as you can see in Fig. 4, it is obvious that the proposed scheme shows the superior performance to two comparative schemes even though little difference is measured when one level is implemented. More detailed, as the number of source node increases, great difference is observed. Since SPEED has no congestion control scheme, it suffers from congested node which makes long delay at intermediate node. On the other hand, since new architecture as well as previous one allows us dynamic control for traffic, congestion is likely to be released. However, different from our previous work that performs coarse grained rate control depending on *DBP*, new architecture shows the better performance by introducing multiple streams. In addition, as for comparison one

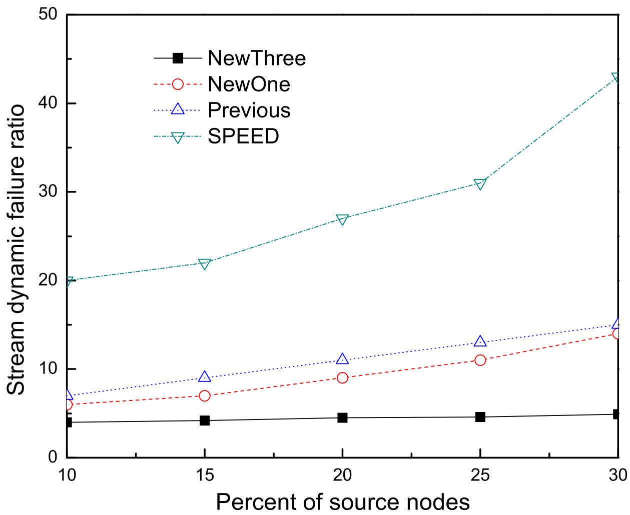


Fig. 4 Stream dynamic failure ratio as a function of increasing source nodes

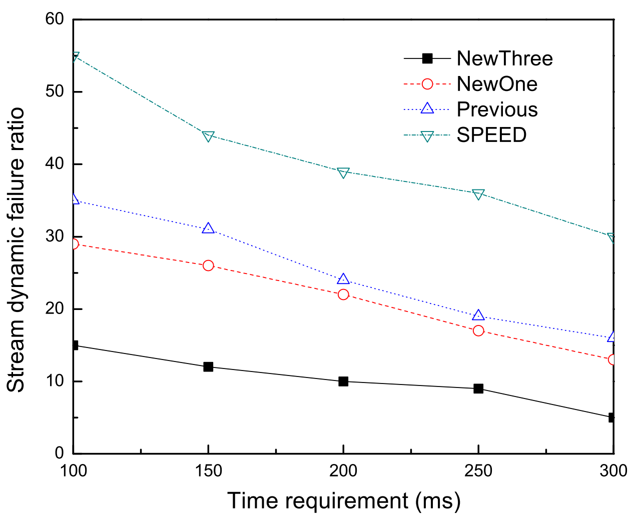


Fig. 5 Stream dynamic failure ratio as a function of time requirement

level and previous work, data aggregation and MAC protocol are major influencing sources for improved performance. Even though congestion control is not available in NewOne, data aggregation and hybrid MAC prevent scalability problem so drastic degradation of performance is not observed. On the other hand, when 30 % nodes become source node, great difference are measured in SDFR. This implies that the proposed architecture solve the scalability problem in our previous work which flow based approach has been taken. Moreover, the new architecture has little influence on the number of source node by selecting multiple streams and prioritizing scheme that affects routing and MAC protocol. This is obvious when we compare three level and one level stream. Another point worthwhile mentioning is prioritization of transit packet in the proposed scheme. By giving higher priority to transit packet,

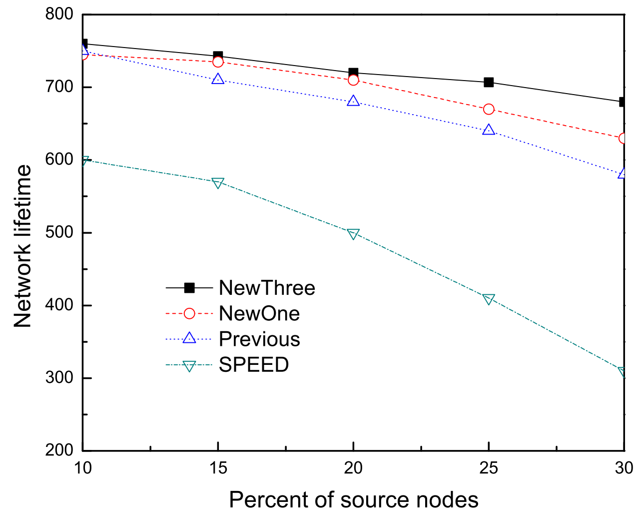


Fig. 6 Network lifetime as a function of increasing source nodes

packets in (m, k)-firm stream along long path have significantly lower failure ratio than one in previous work.

Another analysis for new schemes is presented here. Generally, it is more likely to select the best next hop node in SPEED for their decision. Even though multiple nodes are available for next hop to meet real-time delivery within deadline, the one node with the greatest value is chosen by many nodes in SPEED. This means that the battery of this node is drained quickly so network lifetime become short. Although this node becomes dead, similar situation is repeated for remaining nodes. This is very harmful for network lifetime as depicted in Fig. 6. To prevent this problem, in our previous work, remaining battery is additionally considered to select next hop. However, as you can see in Fig. 6, it is not enough to achieve the similar level with new one. This is because the largest battery node is repeatedly selected in our previous work. Based on this simulation results, we can identify advantage of random selection in possible set on new architecture in this problem. In this Fig. 6, lifetime is defined as elapsed time until 50 % node become dead. As the number of source node increases, we can recognize the decreased time due to increased traffic load. In addition to this short lifetime, another important problem is network connectivity. If a node becomes dead, in worst case, network connectivity is severely damaged. So, it is important to balance energy consumption among nodes.

Simulation result for varying time requirement is illustrated in Fig. 5. Generally, longer time requirement leads lower stream dynamic failure ratio. However, SPEED reveals the greater variances for SDFR than other comparative protocols. There are two reasons for this. First, it is because that time and distance are the factors to decide forwarding in SPEED. So, their impact on the performance is larger than ours. Second, concentrated traffic load on one node with the highest velocity is another source of high SDFR. This implies that distributed selection for forwarding node greatly contributes to reduced number of congested nodes and delivery time. Moreover, NewThree shows the least difference between time requirement due to multiple streams with different traffic rate. As compared to NewOne, multiple streams and rate adjustment in New-There are main factors to decrease SDFR. Our previous work reveals the acceptable level but lower SDFR than new proposed scheme. Multiple transmission in previous work depending on *DBP* value complements the degrade performance but flow based approach hinders significant performance improvement. Finally, when time requirement is set to 100ms, all protocols show the higher SDFR since absolute given available time is not enough.

In addition to evaluation for time and number of sources, we measure the impact of round based approach. Since (m, k)-firm constraints are supposed to be measured for consecutive packets, *the proposed scheme is expected to have side effect of round based approach where the parameters such as DBP are preserved during one round.* This is useful to reduce overhead, however, harmful for long response time. *We measure SDFR with varying the period for one round in Fig. 7 where Round **M** represents **M** second for one round period.* The two worse cases are observed when round period is set to 0.25 and 10 second, respectively. First, 0.25 second means that a sink node reports the *DBP* value whenever packet is delivered. Thus, it is enable to take appropriate action according to current situation. However, this makes the performance worse by causing unstable networks. For example, data aggregation and slot allocation is not allowed in this case. Also, routing protocol has additional control overhead to select the next hop as similar to flow based approach in previous work. On the other hand, 10 second is too long to reflect current quality and network environments due to accumulated *DBP* during long period. On the other hand, the best performance is observed when period is set to 5sec rather than 1sec. This is dependent on the our (m, k)-firm model in simulation where the period of third level is set to 1 sec. When the third level stream is chosen at any round, it corresponds to all responses for every data packet. Thus, its performance is not good as described above.

Followed by simulation of increased number of source nodes, we vary the message period and measure their impact on SDFR. By setting the short message period, more traffic is inserted into the networks so we can identify how the comparative protocols attempt to meet real-time requirement in Fig. 9. In this simulation, the 15 % node is source node and message period is ranged between 50 and 200 msec. As illustrated in Fig. 8, the similar pattern to increased number of source nodes is observed. As the message period become shorter and shorter, higher SDFR is obtained. Different from simulation for increased number of source node, data aggregation effect is not available since there is no change of flow. This indicates that congestion control and priority scheme have great impact on performance enhancement. Specially, higher priority of transit packet over source traffic contributes to reduction of the resource waste by preserving used resource for the packet, we can identify its influence on SDFR. More detailed, if a packet which already passed several hops is lost, network resource used for this packet becomes useless. Thus, preventing transit packet from being drop affects SDFR to some degree.

Last simulation result is to measure the robustness against for background traffic. While message period is used to control amount of traffic for (m, k)-firm stream, background traffic is used to measure how the proposed scheme handle congested situation caused by other traffics.

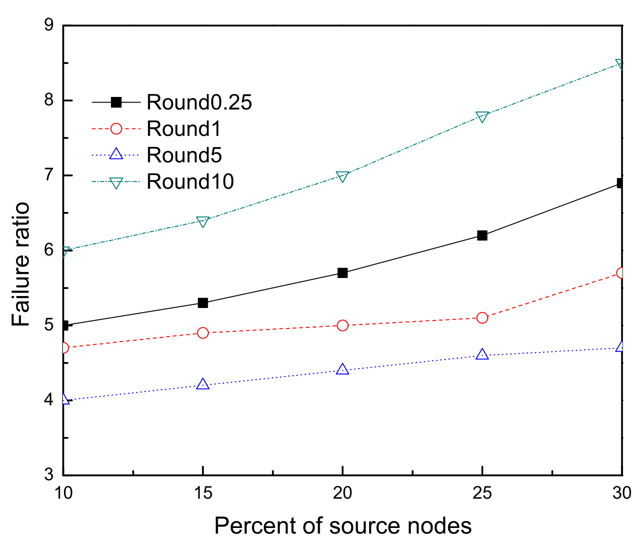


Fig. 7 Stream dynamic failure ratio as a function of round duration

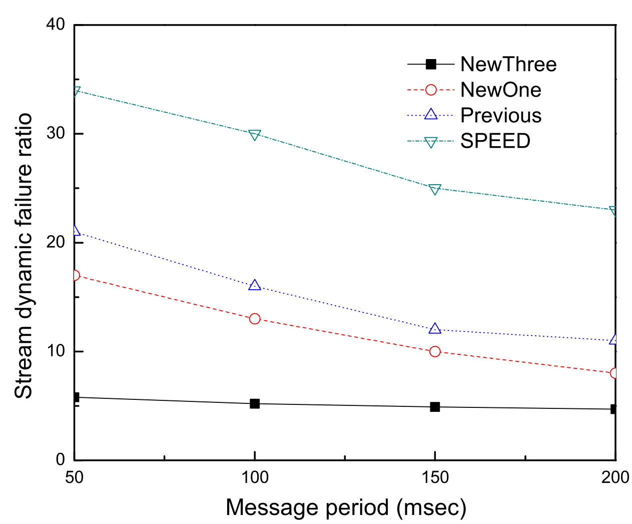


Fig. 8 Stream dynamic failure ratio as a function of message period

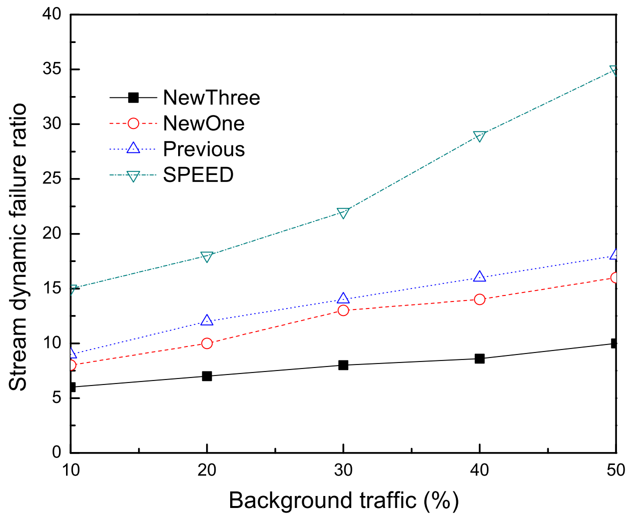


Fig. 9 Stream dynamic failure ratio as a function of background traffic

Background traffic increases from 10 to 50 percent of link capacity in a flow which consists of the same source nodes. As the traffic increases, all protocols show the higher SDFR in Fig. 9. Since the background traffic is transmitted along the same path, SDFR is affected by how to avoid the congestion and distribute the traffic accordingly. Through this analysis, SPEED needs to include the congestion control scheme. Also, network lifetime is closely related to this simulation result. Any hole or partial network connection brings longer end-to-end delay due to rerouteing around the hole. Since the increased background traffic leads to shorten network lifetime, energy aware properties in new schemes and previous one make the SDFR high.

5 Conclusion and future work

In this paper, we proposed a new communication architecture for (m, k)-firm stream in wireless sensor networks. To achieve this, we extended the our previous protocols to include multiple streams and prioritization. Also, data aggregation was performed to reduce the overhead of flow based approach in our previous work. *Moreover, congestion control scheme that is essential for real-time delivery is elaborated in fine-grain way*. In parallel with proposing new respective protocols, in this architecture, we presented how to integrate them into one architecture and define their operational procedures accordingly. Through the simulation results, we verified that it is likely to solve the scalability problem and achieve the improved performance in several aspects through the proposed architecture.

The further research work will go to focus on congestion control to include interference aware scheduling over the wireless link. Also, rate control and traffic shaping are another research challenge to guarantee the real-time delivery in further work. In the point of network architecture, combination clustering and data aggregation will be one of promising research challenges.

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Conflict of interest The authors declare that they have no conflict of interest.

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