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Cross-Layered Approach for (m, k)-Firm Stream in Wireless Sensor Networks

Ki-Il Kim · Tae Eung Sung

Abstract As most sensor nodes are deployed to detect and transmit interesting events or phenomena around them, the real-time delivery of sensed information within a predetermined deadline becomes one of the biggest challenges in wireless sensor networks. Even though some of the recent research works have been published in specific field, they are designed to cover general purpose applications. Therefore, most of applications cannot be supported by existing schemes especially when the requirement is application-specific real-time. In order to solve this problem, we model the target application as a specific traffic, (m, k)-firm stream, which is known as hard real-time requirement, and then propose a scheme to guarantee real-time delivery. To develop these, we introduce a cross-layer design to bring collaboration between layers under the basic principle that real-time delivery will hardly achieve by independent scheme in each layer. Thus, the requirements of application are passed to lower layers and used to adjust transmission power, prioritize packets, and find the adequate path in order to meet (m, k)-firm constraints for any stream dynamically. Finally, simulation results reveal that low failure probability for real-time requirements on (m, k)-firm stream is achieved by the proposed scheme.

Keywords Real-time · (m, k)-firm · Wireless sensor networks

1 Introduction

Wireless Sensor Networks (WSNs) [1] have been proposed and studied to detect interesting events happened around them in a form of ad hoc networks, defined as self-organizing without any centralized infrastructure. Ad hoc networks indicate that a sensor node should

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K.-I. Kim (✉)
Department of Informatics, Engineering Research Institute, Gyeongsang National University,
900 Gajwa-dong, Jinju, 660-701, Korea
e-mail: kikim@gnu.ac.kr

T. E. Sung
Korea Institute of Science and Technology Information, 66 Hoegiro, Dongdaemun-gu, Seoul 130-741,
Republic of Korea

work as a network device capable of forwarding packets to destination as well as a sensing device. Since sensor networks can be considered as one specific ad hoc networks, it can get several benefits such as simple, low cost, and fast deployment. On the other hand, it is very hard to meet many requirements through sensor nodes because their power is supplied by non rechargeable battery, also wireless communication is unstable and short ranged. Despite of these constraints, sensor networks have increasingly deployed in real world in order to collect interesting information efficiently.

As many applications have emerged in wireless sensor networks, real-time data delivery becomes one of essential requirement for time-sensitive information which remains valid only before deadline is passed. Moreover, as a sensor node is designed to accommodate vector type of information such as multimedia, the importance for real-time property is emphasized nowadays. Until now, researches for real-time system have been well explored in many different systems. The good examples include industrial system, operating system, mission critical system and so on. Based on research results of previous works, many schemes have been proposed by adapting their approaches into wireless sensor networks [2]. Their major contribution is to modify existing schemes in order to meet constraints of sensor nodes as well as requirements on specific applications.

As roughly explained above, current approaches for real-time delivery are developed for wireless sensor networks by extending existing schemes. Thus, they have naturally several drawbacks to be mentioned. Most of the current schemes take only general application into account. However, it is nearly impossible to find common features between applications because of its different outstanding missions and requirements in wireless sensor networks. This implies that it is practical to develop a real-time scheme which targets specific application and extend it according to the corresponding needs in wireless sensor networks. It is also observed that most of the schemes for real-time delivery are designed on a strict layered architecture. However, when it comes to refer to previous experiences in other systems, real-time requirement cannot be met by approaches on one layer but collaboration between layers. So, it is reasonable to take a well known cross-layered design in this research area.

To meet above two research challenges, we propose new schemes to guarantee real-time data delivery in wireless sensor network while considering limitations of each node in this paper. Compared to previous works, it is possible to guarantee (m, k)-firm stream under cross-layered design principle in wireless sensor networks. We model the traffic as (m, k)-firm, a well-known example for hard real-time system. In order to meet (m, k)-firm requirement, more detailed, priority scheduling is developed by utilizing current geographic information on each node as well as sink. Power-aware scheme used to prolong network lifetime along with two different kinds of multiple transmissions for recovering unstable and short-range communication are also presented.

The reminder of this paper is organized as follows. In Sect. 2, we describe and explain related works as well as summarize the existing schemes. In the following section, we present new schemes throughout several subsections. Simulation results are presented and analyzed in Sect. 4. Finally, we make a conclusion and mention further study in Sect. 5.

2 Related Works

2.1 (m, k)-Firm Real-Time System

Real-time system is generally divided into two major categories, i.e. hard real-time system and soft real-time system. System fails if any deadline is missed in hard real-time system

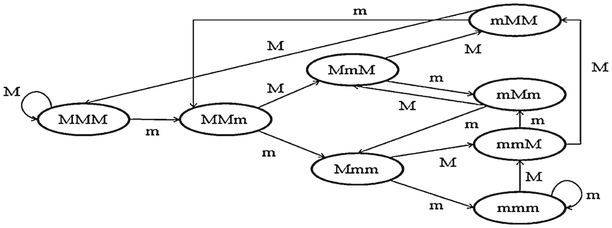

Fig. 1 DBP state diagram

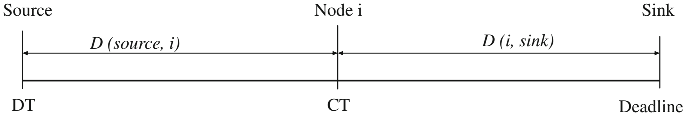

Fig. 2 Time and distance domain

where missing deadline is noticed by user but system doesn't necessarily fail in soft real-time system.

Different respective model was developed for each system,. In case of hard real-time system, (m, k)-firm model has attracted many researchers' interest [3,4]. To support this model, the (m, k)-firm scheduling policy has been studied by many researchers in the area of real-time system. A real-time stream with (m, k)-firm guarantee requirement states that at least m out of any k consecutive packets in this stream must meet their respective deadlines. When a stream fails to meet its (m, k)-firm guarantee, dynamic failure occurs and is called dynamic failure probability. The probability of dynamic end-to-end failure is then used as a measurement of the real-time stream. To guarantee (m, k)-firm requirements, distance-based priority was proposed by [3] to guarantee (m, k)-firm constraints in which higher priorities are assigned to packets which are close to the failure state. In addition, research effort in wireless networks has been studied in [4], but there is no existing research to adapt (m, k)-firm model in wireless sensor networks yet.

Distance Based Priority (DBP) [3], a detailed scheduling algorithm, has been proposed to prioritize packets of each stream represented in state machine where a DBP value depends on the current state of the stream. The state of stream is measured by identifying whether certain number of previous packets of the stream met their deadline or not. Generally, the DBP value of a stream is defined as the number of transitions required to reach a balanced state, where failing states are those states in which the number of meetings is less than m. Many research approaches based on DBP are assumed to give higher priority when DBP value of stream is relatively less. The packet from the stream with the highest priority is selected for transmission. Figure 1 shows an example of the DBP state diagram for a (2, 3)-firm stream where M and m are used to represent meeting a deadline and missing a deadline, respectively.

2.2 Current Existing Schemes for Real-Time Delivery in Wireless Sensor Networks

Current research works for real-time delivery mainly fall into network layer approach since most of delivery time is consumed in this layer. According to real-time transmission is designed to work in network layer, two kinds of approaches have been proposed. One is real-time scheduling based on priority since queuing delay is the biggest component of end-to-end delay. VMS (Velocity Monotonic Scheduling) [5] in the example of this approach in which a node takes real distance and time till expiration into account when it comes to assign priority dynamically. VMS may be implemented by queue based on multiple priorities. JiST [6] is a good example to use VMS by addressing scheduling algorithm to consider slack time and weight factor for network congestion. By analyzing the evaluation through simulations, JiST outperforms the general priority scheduling scheme in the point of failure probability.

The other scheme for real-time communication is real time routing, which is designed to find the adequate path meeting end-to-end delay. SPEED [7] is one of well-known protocols for real time routing in sensor networks. In SPEED, a node estimates the delay between itself and neighboring node to choose for real-time forwarding. Both VMS and SPEED take similar approach that geographic information is used to compute velocity on the link. Other routing approaches include Velocity-based Forwarding [8] and Real-time Power-Aware Routing [9]. In [8], each node predicts delay between itself and neighbors and then chooses one of the neighbors in order to minimize delay. Different from velocity-based forwarding, delay is calculated by routing decision algorithm in order to minimize the energy consumption in [9]. It runs power aware forwarding and transmission power management strategies. In parallel with respective approach, a network architecture for real-time delivery is VIGILNET tracking operations which is developed at University of Virginia [10]. Military operations including real-time tracking and observation are major target of VIGILNET. Mathematical model and threshold partition method were proposed to meet deadline for end-to-end delay.

3 Proposes Scheme

In this section, we propose new schemes to meet (m, k)-firm requirement in wireless sensor networks. To develop the proposed scheme, we considered following features and assumptions are concerned. (1) every sensor node can acquire accurate geographic position information through low cost equipment, (2) packets can be lost frequently by either network congestion or unreliable wireless link, (3) disjoint multiple paths between source and sink are allowed in dense deployment, (4) energy management of a node is important component to prevent network partition caused by node's complete battery drain. Corresponding to these requirements, our scheme will extend current DBP scheme in each layer by introducing new additional scheme if the current real-time service is not met by requirement. Otherwise, the current parameters are maintained.

3.1 DBP-ST (Slack Time)

Similar to previous approaches, first scheme for (m, k)-firm stream is designed for scheduling algorithm with slack time. Literally, slack time is defined as time remaining before deadline. With these constraints reason, slack time has been used for good parameter to decide the order of scheduling for buffered packets in several systems. Generally the less slack time remains, the higher priority is assigned to each packet. Moreover some research results have been introduced to assign priority of packets based on slack time in wireless sensor networks. However, since they are based on assumption that a sensor node can easily get hop distances to the sink by the help of routing protocols and other schemes, it cannot be an actually feasible approach when it comes to concern additional control overhead to achieve it. Thus, we define a slack time to be computed by real physical distance computed through geographical position information instead of relying on hop distance in previous works.

After getting the slack time, original DBP scheme is extended to prioritize each packet correspondingly. Such scheme is called DBP-ST (slack time). A scheduling algorithm to adapt new slack time definition is shown below.

$P_j = j^{th}$ packet in a queue

$S_x =$ stream that produced P_j

$ESL(P_{j)} =$ Expected slack time of packet P_j

$DBP(P_j) = DBP$ value of packet P_j

$DBPS(S_x) = DBP$ state of stream S_x and how many transitions are required between non-failing and failing state

$DT(P_j) =$ Departure time of packet P_j

CT = Current Time

$D(i, j) =$ Geographical Euclidean distance between node i and j

For each packet on a node i, performs steps 1–4

1. *For each* P_j *from* P_0 *and* P_{k-1}, *determines if the packet has missed its end-to-end deadline, such packets are then dropped where the number of total buffered packets is k.*
2. $ESL(P_j) = (CT - DT\,(P_j)) * D\,(i, sink)/D\,(source, i)$
3. *Calculate the DBP value of each packet according to DBPS* (S_x)

$$DBP(P_j) = DBPS(S_x) + \frac{ESL(P_j)}{MAX(ESL(P_1), \ldots, ESL(P_{k-1}))}$$

4. *Select* P_j *that has the lowest DBP value, called best packet*
5. *Schedule the best packet*

Step 1: If a packet cannot meet its end-to-end deadline, that it is dropped and the DBP state of corresponding stream is adjusted accordingly.

Step 2: In this step, slack time for each packet is calculated, respectively. *ESL* (P_j) is computed by using distance at current position as well as elapsed time. Even though slack time is literally defined as time difference between deadline and elapsed time, we modify this value according to the experienced delay from source to current node. The main reason to consider elapsed time is that a packet should compete with other packets in the middle of transmission. With above reason, we set the relationship between time and distance domain as Eq. (1). In Eq. (1), both time and distance are closely related to expected slack time.

$$(CT - DT) : (D\,(\text{source, i})) = (\text{Deadline } - CT) : (D\,(\text{i, sink})) \qquad (1)$$

Step 3: Given current DBP state of stream, DBP value for a packet is calculated by adding two variables. One is current status value, *DBPS* (S_x), the other is proportional slack time value among all packets.

Step 4: Once DBP values for all packets are computed, then packet with lowest DBP value is chosen as the best packet.
Step 5: Packet scheduler picks the best packet.

Even though a new scheduling scheme is presented, it is not enough to meet (m, k)-firm constraints because scheduling can provide opportunity to adjust queuing delay on each node. The proposed scheme can reduce packet loss caused by missing deadline, but the other factors remain the same. In the next subsection, we will introduce other algorithms.

3.2 DBP-PC (Power Control)

Among constraints of a sensor node, energy management, short-ranged and low data-rate wireless communication are the main concerns. Even though DBP-ST is designed to prevent the drop of consecutive packets missing deadline in same stream by controlling queuing delay, short-ranged wireless communication is another reason to cause packet drop. Since wireless communications are affected by many outside factors such as several obstacles, it is very hard to guarantee reliability through static transmission range. To remove unreliability and achieve efficient energy consumption, one possible solution is to adjust transmission power of each node dynamically according to current status of stream and battery level. To achieve above objective, a new scheme called DBP-PC (power control) is proposed. Before explaining the details about DBP-PC, it is assumed that each sensor node can adjust transmission power independently.

In DBP-PC, transmission power is determined by considering current DBP status and remaining battery level. However, since the main objective of DBP-PC is not to compute the optimal and exact transmission power level on a node, we propose a strategy, i.e., how to meet (m, k)-firm constraints by controlling power dynamically to overcome deficit of wireless communications. Moreover, it is very essential to remember that high transmission power causes quick battery drain. Thus, current remaining battery level should be included while setting transmission power. The details are described in algorithm below.

```
$E_c$ : Current battery level
$E_h, E_m, E_l$ : Predetermined Battery Level Indicator ($h$ = high, $m$ = medium, $l$ = low)
$MAX\_T_p$ = Maximum transmission power with $E_c$, $T_p$ = Transmission Power
$C$ = Constant (larger than MAX ($DBPS\ (S_x)$))
if $DBPS\ (S_x) < 0$
    if $E_c >= E_m$
        $T_p = MAX\_T_p$
    else
        $T_p = MIN\left(MAX\_T_p, T_p - T_P \times \frac{DBPS(S_x)}{2^{C-|DBPS(S_x)|}}\right)$
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10. else if $DBPS\,(S_x) > 0$
11.     if $E_c <= E_m$
12.         $T_p = MIN\left(MAX\_T_p, T_p - T_P \times \frac{DBPS(S_x)}{2^{C-|DBPS(S_x)|}}\right)$
13.     else
14.         Maintains $T_p$
15. else
16.     Maintains $T_p$
17. Transmits packet using $T_p$ in physical layer
```

The algorithm described above starts identifying the current DBP status variable in a similar way to previous DBP-ST. In case that DBP status variable becomes negative which indicates real-time service is not met, different actions are taken according to current battery level because increasing transmission power is very closely related to node's lifetime. If the current battery level is considered as sufficient, transmission power is set as maximal value. This procedure is used to improve packet delivery by strengthening transmission power as long as possible to get high SNR (Signal to Noise Ratio). Otherwise, when small amount of battery is currently available, we need to pay more attention to preventing battery complete drain. To achieve it, transmission power increases that new equation instead of maximum value as described in line 9. This equation is related to current DBP value so large value is generated if current state is far from balanced state. According to this value, transmission power gradually increases within the range of current transmission power and maximum power level.

Secondly, in case of positive DBP status, it is more important to achieve energy efficient transmission than enhancing reliability over the link, so different transmission power values are computed. When current battery level is regarded as enough, current transmission power is kept to maintain current DBP value. On the contrary, when battery level is low, then transmission power decreases in order to reduce power consumption for transmission until the DBP value is equal to balanced states. The reason for this decrease is that positive DBP status which demonstrates that packet loss is not critical for requirements. Furthermore, current power level is considered enough to cover transmission range to meet (m, k)-firm constraints. By these reasons, transmission power is reduced and tested. Last case describes when current DBP state is represented as balanced; there is no change on current transmission power level.

3.3 DBP-R (Reliability)

Even though DBP-ST reduces dynamic failure probability by reducing queuing time in the corresponding stream and DBP-PC can also achieve it by strengthening transmission power, it is not enough to guarantee to meet (m, k)-firm constraints since appropriate scheme is not concerned in network layer yet.

Additional scheme should be developed to make sure successful packet delivery especially when current DBP status is negative. To achieve this goal, DBP-R is newly developed as one of approaches in network layer. The basic idea of DBP-R is to duplicate the packet

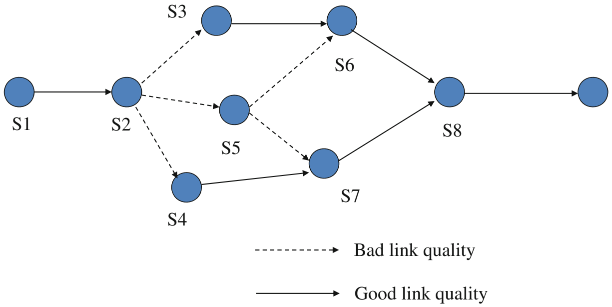

Fig. 3 Example of duplications based on link reliability

and transmit the same packets along several different links according to current state. Duplicated packets contribute to increase packet delivery ratio eventually at the sink even though some packets are lost at the intermediate node. Figure 3 shows the example of how DBP-R duplicates packets where S1 sends data to S2. When S2 receives this packet, it finds out next nodes, S3, S4 and S5. S2 selects S5 for next hop. Because the link between S2 and S5 does not have good link quality, therefore, S2 increases the number of next nodes for reliability. And, S2 sends multiple packets to them. S5 works similarly where both S3 and S4 send one packet without duplication. S8 receives data from both S6 and S7, respectively.

To develop DBP-R, it is important to implement when and how many packets are duplicated because these two factors are closely related to resource consumption. First of all, a packet is duplicated when current DBP status does not meet (m, k)-firm requirement where link reliability cannot guarantee successful packet delivery. A new terminology, *LR* (Link Reliability), is measured by exchanging beacon message periodically during predetermined period and its value is ranged from 0 to 1. For the link between node t and neighbor node r, $LR_{t,r}$ is represented as Eq. (2).

$$LR_{t,r} = \text{total number of receiving packets on a node } r/\text{total number of sending packets on a node} t \tag{2}$$

Each node compute and record this $LR_{t,r}$ between neighbor nodes independently. When a packet is chosen for transmission by DBP-R scheme, both $LR_{t,r}$ and DBP status are extracted from the header and identified. The decision algorithm is shown as follows;

```
$R_h, R_m, R_l$ = Link Reliability Indicator ($h$ = high, $m$ = medium, $l$ = low)
$NS$ = A subset of neighbors for duplications
Assumption: Link between $t$ and $r$ is primary link to transmit packets
Calculates probability $\Psi(m, k, r)$
if $DBPS\,(S_x) < 0$
    if $\Psi > R_h$
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            Transmits packet over primary link between $t$ and $r$
        else if $(R_m < \Psi < R_h) or (R_l < \Psi < R_m)$
            Determines the maximum number of duplications as much as absolute value of DBP
            Choose neighbors in an order of $LR_{t,r}$ in Eq. (4)
            Transmits each packet over link between each element in $NS$ and $t$
        else
            Broadcasts the packet
    else
        if $\Psi > R_m$
            No duplication
        else
            Determines the maximum number of duplications as much as absolute value of DBP
            Transmits each packet over link between each element in $NS$ and $t$
```

Duplication in DBP-R relies on current DBP status and specific probability Ψ which is defined as probability to meet (m, k)-firm constraints representing that m out of k packets in any stream should be delivered where measured $LR_{t,r}$ is given.

$$\psi(m,k) = \sum_{i=m}^{k} \binom{k}{i} LR_{t,r}^{i}(1 - LR_{t,r})^{k-i} \tag{3}$$

Decision algorithm for duplicated transmission is largely divided into two main parts according to current DBP status. If DBPS status is negative, then duplication is essentially needed in most cases except that current link reliability is good enough to guarantee successful delivery. In case that link reliability is too low, a packet is transmitted in a form of broadcast in order to transmit packets as much as possible. For other cases, the number of duplication should be carefully determined because communication is major cause of battery consumption. On the other hand, current transmission scheme along the primary path is maintained if the reliability is acceptable for (m, k)-firm stream.

After duplication of packet is asked, the link selection procedure begins. This procedure continues when the following condition is met or the total number of duplication is greater than absolute value of $DBPS\ (S_x)$. This can be expressed and given in Eq. (4). After deciding the neighbor set, packets are continuously transmitted.

$$\sum_{r \in \{NS\}} \psi(m,k,r) > R_h \tag{4}$$

3.4 DBP-MP (Multiple Paths)

Even though DBP-R is expected to reduce dynamic failure probability of (m, k)-firm requirement by introducing recovery scheme, this approach can be thought as a local one where multiple transmissions are limited in certain areas around the primary path. In this point,

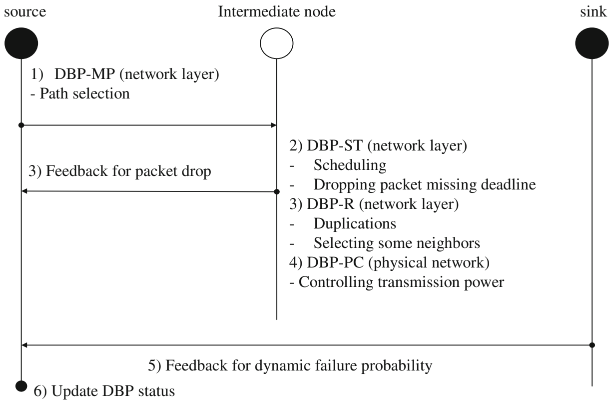

Fig. 4 The example of sequence in DBP-C

another outstanding feature in sensor networks can lead to enhance the quality of (m, k)-firm requirements. Since sensor nodes are generally deployed densely for robust operations, we can find many disjoint multiple paths from sources to sink. In order to supplement with DBP-R, a source chooses more than one path before transmitting the packets. To complete this scheme, several additional procedures should be implemented.

A step begins finding candidate paths that are expected to meet (m, k)-firm requirement. The probability that meets (m, k)-firm requirement is based on link reliability measured in DBP-R. Since a path consists of consecutive respective links from a source to destination, PR (Path Reliability) can be given in Eq. (5).

$$PR_{s,d} = \prod_{(p,q)\in x} LR_{p,q} \tag{5}$$

Although Eq. (5) provides the path reliability defined as stability of path, it is very hard to get real reliability value for all links due to control overhead as well as scalability problem. Thus, we introduce the way to use probe packets which are sent into real networks to obtain corresponding value directly instead of relying on above equation. In our scheme, probe packets copied from original packet are transmitted along different disjoint paths. After collecting and analyzing receiving packets, sink reports possible multiple paths, which can meet (m, k)-firm constraints in a form of dynamic failure probability.

3.5 DBP-C (Combined)

Until now, we propose four respective schemes to reduce dynamic failure probability in a layered concept. Even though each scheme is developed for a specific purpose, the impact will be accelerated when they are combined together in a flexible way. Based on cross layered design principle, current status on each stream, DBP status, is passed to lower layers. A source chooses more than one path among multiple paths with DBP-MP scheme. After paths selection, data packet is forwarded to the next neighbor node toward the sink. On each intermediate node, DBP-ST, DBP-PC, and DBP-R schemes are used to enhance the performance. More detailed, the best packet is chosen through DBP-ST. After determining next packet, DBP status value is used to decide how many packets are duplicated and how much energy should be used for packet transmission. Figure 4 shows the sequence of each procedure when all proposed schemes work together.

4 Performance Evaluation

We implemented our code in Qualnet simulator [11] for diverse simulations. The simulation parameter and each protocols variable are described as follows. Our simulation modeled a network of 100 nodes placed randomly within a 1,000 m × 1,000 m area. Radio propagation range for each node was 100 meters and channel capacity was 250 kbps. General CSMA (Carrier Sense Multiple Access) is used for MAC (Medium Access Control) protocols and two-ray model is for propagation models to reduce effect of MAC and physical protocol. The application for proposed simulation is SURGE, which reports the sensing information at the rate of predetermined period. Without any mention, the mean period of a stream is 50 ms inter-arrival time between packets in a stream. Simulation parameters are derived from sQualnet model [12] which is obtained by datasheet from MICA2 motes [13]. The MICA2 has the CC2420 radio chip, which is made by ChipCon and ZigBee compliant. It operates at 2.4 GHz band and has a link capacity of 250 kbps using spread spectrum and OQPSK modulation for tolerance to interference. The CC2420 has a maximum outdoor range of 125 m with a maximum current draw of 17.4 mA (0 dBm). These ranges are based on the reception strength threshold. In this way, the simulation model is compliant to actual sensor networks model.

Each simulation is executed for 20,000 s. Multiple runs with different seed numbers were conducted for each scenario and obtained data was averaged over those runs. Furthermore, the 95% confidence intervals on the mean are computed. Simulation is conducted to identify that each proposed scheme can contribute to performance improvement. This implies that each proposed scheme is compared to general scheme respectively. And then, combined scheme, DBP-C, is evaluated and compared to two existing schemes. Finally, discussion for simulation works is presented to demonstrate our analysis and motivation of our works.

4.1 Impact of Slack Time

The first experiment is chosen to compare the performance of DBP-ST with general DBP-scheme as well as priority scheme. General DBP scheme indicates that a priority is assigned by referring to DBP distance to balanced state. The lower DBP distance an application has, the higher priority is assigned to a packet belong to corresponding stream. Furthermore, general priority scheme is compared to DBP-ST. The priority of each packet is not changed in the middle of transmission as well as priority is set in order that it is equal to value (m/k) in general priority scheme. For the comparison, we adapt three different applications with (1, 1)-firm, (2, 3)-firm, (3, 5)-firm constraints. The priority of each stream is set an order of (1, 1), (2, 3) and (3, 5). For each stream, we set five different connections between source and sink were selected randomly. Thus, fifteen respective streams were employed in this scenario. The simulation result is illustrated in Fig. 5.

The above Fig. 5 shows that slack time contributes to reducing dynamic failure probability for each stream with (m, k)-firm constraints. For (1, 1)-firm stream, all schemes have high dynamic failure probability. Since (1, 1)-firm is the good example for strict hard real-time system, the failure probability of (1, 1) shows the higher value than other two streams. Another noticeable point is that the probability decreases when slack time is considered for scheduling in DBP-ST. This is closely related to another outstanding feature in sensor networks. Since all sensed information is supposed to be delivered to the sink, there is high probability for the packet to be dropped near the sink due to heavy congestion. In DBP, the best packet is chosen only according to the DBP status where slack time is another parameter concerned in DBP-ST. So, delay on congestion situation is reflected and considered when calculating

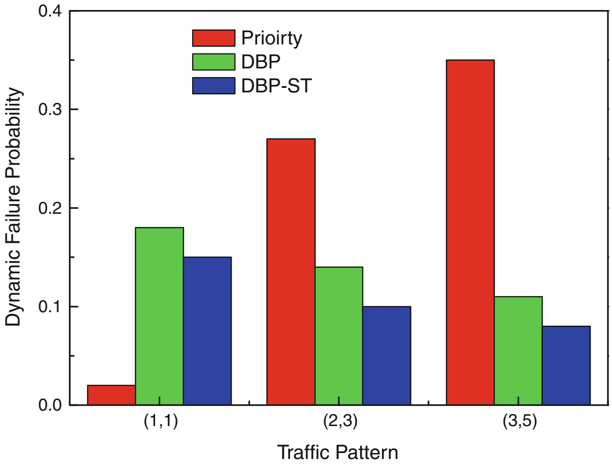

Fig. 5 Impact of slack time (inter arrival time: 50 ms)

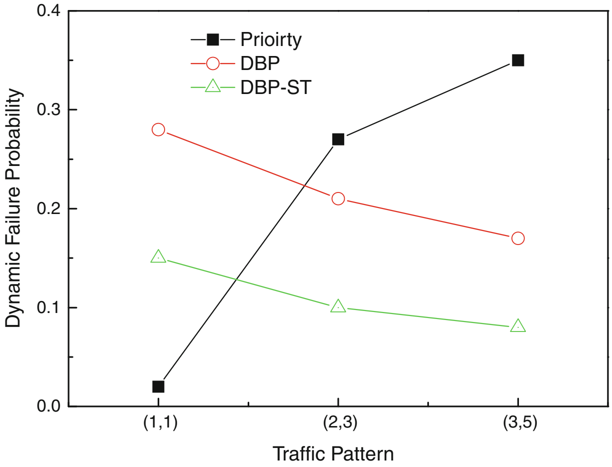

Fig. 6 Impact of slack time (inter-arrival time: 20 ms)

slack time in DBP-ST. This stats that if long time is elapsed for a packet, higher priority is given to compensate this delay. This factor contributes to making difference between DBP and DBP-ST. Another weak point of DBP is that there is no scheme to prioritize packets with the same DBP status. If the DBP status in each stream is the same, their scheduling follows general FIFO (First-In First-Out) principle. This means that DBP cannot prioritize each packet in a desirable way.

Since (1, 1) stream has the highest priority and is considered as the best packet during transmission. Therefore, the dynamic failure probability of (1, 1) streams reveals the lowest value. However this advantage causes starvation problem to other streams with low priority. The rapid increase in dynamic failure probability proved this fact in Fig. 5. The both probability of (2, 3) and (3, 5) are almost doubled to DBP-ST.

Figure 6 shows the relationship between impact of slack time and traffic load by increasing traffic load. The probability becomes high when packet inter-arrival time decreases to 20 ms

Table 1 Impact of power control

Traffic pattern	Dynamic failure probability		Network lifetime	
	DBP-PC	DBP	DBP-PC	DBP
(1,1)	0.171	0.18	570.21	400.42 s
(2,3)	0.118	0.14		
(3,5)	0.093	0.11		

Table 2 The number of duplicated packets at the sink

Traffic pattern	DBP-R	DBP
(1,1)	1.13	1
(2,3)	1.17	
(3,5)	1.12	

for all streams,. The interesting point worthwhile mentioning in Fig. 6 is that other schemes reveal drastic performance degradation while the DBP-ST performance is slightly down. Consequently, measured high failure probability in Fig. 6 implies that both existing priority and DBP based scheme are not suitable for scheduling algorithm for (m, k)-firm stream in wireless sensor networks due to their static strategies.

4.2 Impact of Power Control

For this comparison, we prepared scenario where transmission power is adjusted by DBP-PC dynamically according to DBP status as well as current battery level. On the other hand, transmission power is adjusted by referring to current battery level in DBP. We compare two main performance parameters, dynamic failure probability and network lifetime. In this paper, network lifetime is defined as the time until any area is not covered by any sensor nodes. This would be the first time when there is a gap in coverage. Following assumption is taken for the battery,. The battery starts with a fixed capacity and some amount of battery is deducted from the remaining capacity for each transaction that a node does (transmission, reception of a packet, carrier sensing). For simplicity, the total capacity to begin with is assigned by small value and the units are mA-hour. We adapt MICA2 as hardware model for current simulation. The following table show the simulation results for DBP-PC.

Even though dynamic failure probability in DBP-PC is not improved as much as DBP-ST case, therefore network lifetime is extended to 42%. Since battery is very important resource for each sensor node, the proposed approach is required to extend lifetime by reducing power consumption. Furthermore, iterative operation of DBP-PC is expected to detect suitable value for transmission power in stable state.

4.3 Impact of Reliability

The new scheme, DBP-R, is proposed to reduce the failure probability through duplicated transmissions at the intermediate node. In order to compare DBP-R with DBP, let R_h, R_m, and R_l be 80, 50 and 30%, respectively. We make use of well-known MintRoute routing protocol [14] to establish the path toward the sink. In MintRoute, beacon message is exchanged between neighboring nodes every 2 ms. Other simulation environments are the same as DBP-ST and DBP-PC.

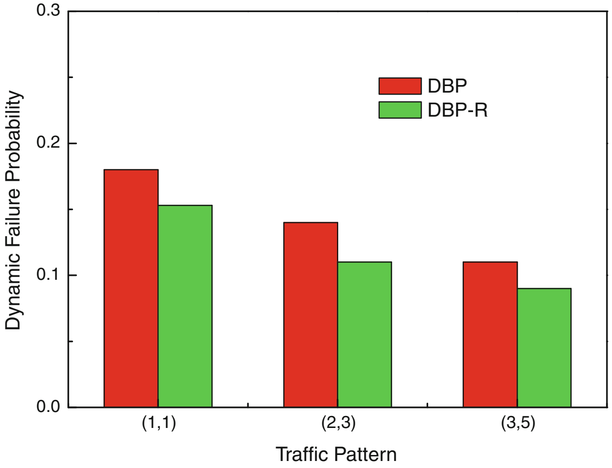

Fig. 7 Impact of duplications

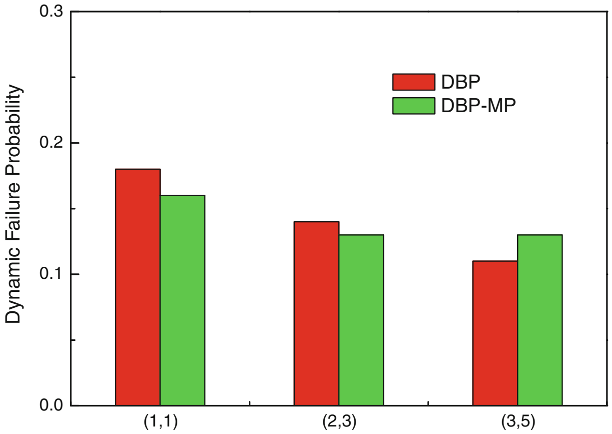

Fig. 8 Impact of multiple paths (*light* traffic)

Duplications lead to reducing dynamic failure probability in most cases of simulations. Particularly, the failure probability for (1, 1)-firm stream decreases by duplications. Duplications can supplement the packet loss in the middle of transmission. Even though the probability for (1, 1) in general priority scheme and DBP-R shows little difference, additional transmission can be effective for each scheme where priority scheduling is not applied. For other cases, the probability is reduced according to the same reason. But as duplications consume the bandwidth and battery, additional control overhead should be concerned. Table 2 demonstrates the analysis of simulation.

Above Table 2 shows the how many duplicated packets are delivered at the sink. Since the duplications are determined with link reliability and predetermined requirement for reliability, there is no meaning to compare the number of duplicated packets in any traffic pattern with others. Rather it is very interesting to obtain low probability with little overhead.

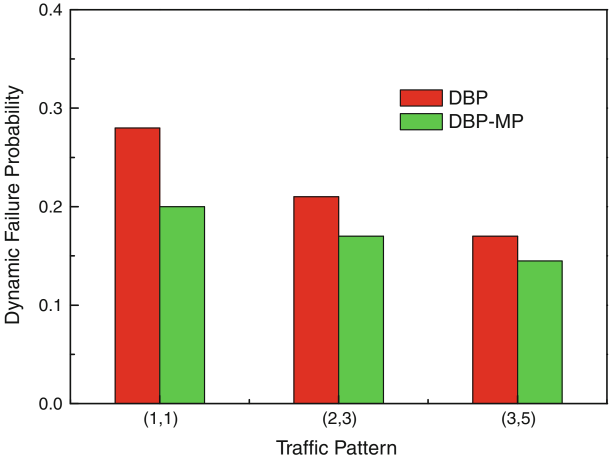

Fig. 9 Impact of multiple paths (*Heavy* traffic)

4.4 Impact of Multiple Paths

Even though reduced probability is proven in Fig. 7, the DBP-MP is designed to solve real-time delivery scheme in whole networks rather than local scheme such as DBP-R. The performance enhancement of DBP-MP is accomplished by two features. One is exact analysis for packet loss and the other is multiple transmissions along different paths. The simulation results support our assumption and demonstrate relevant operation.

The DBP-MP plays more important role in improving performance where heavy traffic is loaded. In heavy traffic, more packets are dropped due to network congestion. In original DBP, without notification of this circumstance, each node runs scheduling, power control, and reliability scheme based on current DBP status, respectively where congested area is detected by DBP-MP and packets are transmitted along the uncontested multiple paths.

4.5 Comparison with Existing Protocols

The comparative evaluation is conducted by introducing SPEED [7] and POWER-SPEED [15]. The reason to select SPEED is the simplicity by employing geographic routing concept and many citations in this research area. Also, POWER-SPEED is evaluated in the main point of efficient energy consumption while supporting real-time service.

All protocols in the case of (1,1)-firm stream showed low dynamic failure probability since any packet delivered beyond the deadline affects probability as we can find in Fig. 10. Both SPEED and POWER-SPEED show lower probability than DBP-C because they are not developed for (m, k)-firm stream basically. In addition, high dynamic failure probability is brought from the following fact. Since each node dynamically adjusts priority according to DBP value on the intermediate node in the proposed scheme, this can lead to reducing the waiting time on the queue. Moreover, while other two protocols concern remaining time for deadline, the proposed scheme estimates that how much time will be taken to the sink. Depending on this time, some packets will not be forwarded so it can prevent the network congestion. Also, multiple path and reliability scheme can lead to distribution of the packets along the different links. On the contrary, SPEED and POWER-SPEED take the best metric link as the next hop continuously without regard to requirement. This indicates that the same

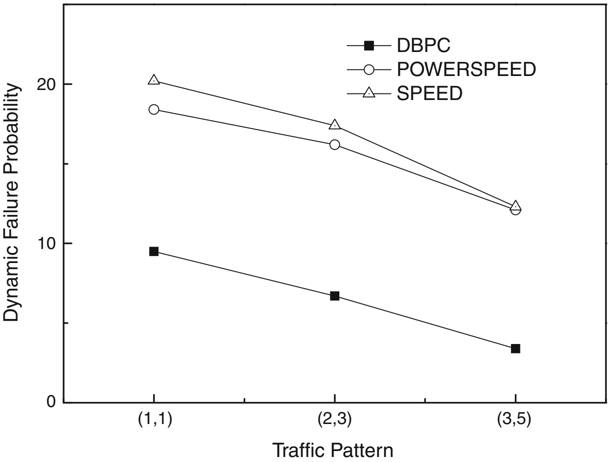

Fig. 10 Comparative evaluation for dynamic failure probability with SPEED and POWER-SPEED

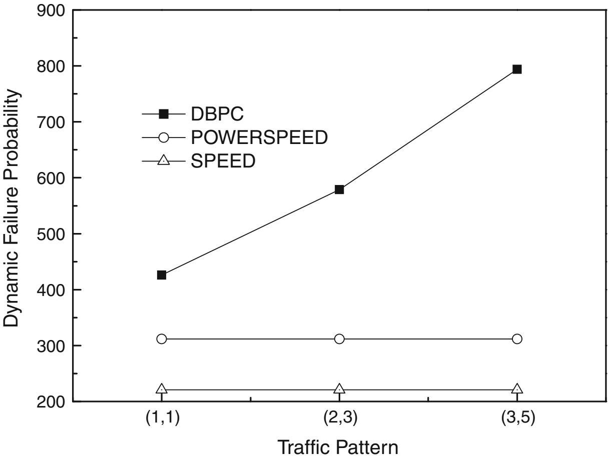

Fig. 11 Comparative evaluation for network lifetime with SPEED and POWER-SPEED

next hop is usually chosen for all traffic loads. Also, since SPEED and POWER-SPEED mostly rely on the beacon messages to measure link quality, sometimes it is not suitable for actual data packet. On the contrary, since link cost is actually measured by actual probe data packets, more reliable links are chosen in the proposed scheme. In summary, as all components of DBP-C scheme are mostly based on current DBP status value, process to return balanced state is accomplished in each layer. This implies that the time taken for this process will be shorter and shorter because the impact of cross-layer design exceeds the improvement of respective scheme.

The lifetime of networks is compared and illustrated in Fig. 11. In Fig. 11, DBP-C shows a longer lifetime than other protocols for (1,1)-firm stream. Several reasons to extend lifetime in the proposed scheme is followings. Unlike SPEED, DBP-C can distribute the traffic load along multiple paths and can prevent the battery drain on the specific node. This feature makes lifetime of the proposed scheme longer than SPEED. In addition, as compared to

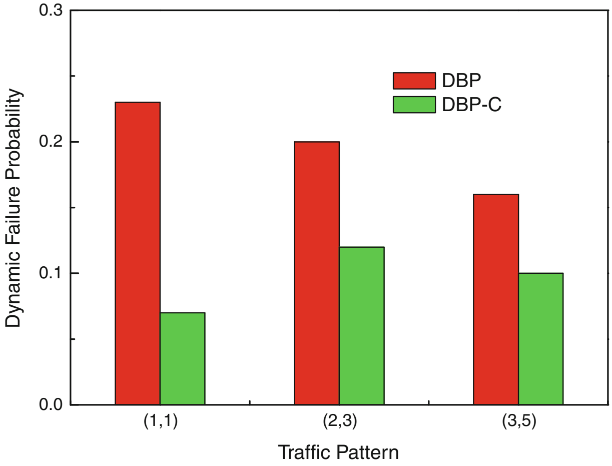

Fig. 12 Simulation results for DBP-C and DBP

POWER-SPEED, longer network lifetime is observed in the proposed scheme. This is accomplished by considering battery level when we apply our respective algorithm. This procedure contributes to balancing battery consumption among nodes. Other factor to affect network lifetime is reliable path. Unreliable link estimated through beacon message cause the number of retransmission on the data link layer and requires additional energy consumption. However, this problem is avoided by adjusting requirement in the DBP-C. On the contrary, both SPEED and POWER-SPEED do not show the difference as for traffic pattern because they are not designed to be aware of application-specific requirement. Since POWER-SPEED adapt similar approach to DBP-PC by adjusting transmission range dynamically, therefore it can reduce power consumption for longer network lifetime than SPEED.

4.6 Discussion

The performance of each scheme is evaluated through diverse simulations. Each scheme contributes to improving dynamic failure probability slightly. However the degree of improvement made by each scheme is limited as explained before. Figure 12 shows the simulation results of DBP-C and DBP. We can identify the drastic performance enhancement in DBP-C in this figure. This fact implies that cross-layered approach is essential for real-time stream and performance enhancement in wireless sensor networks. The information passed across layers makes high performance, where several constraints of node and communications are known. Furthermore, our scheme can be combined in a different way flexibly according to available function in networks and administrator's policy. For example, multiple paths and power control scheme can be combined if network congestion happen frequently and energy conservation is the biggest concern.

In the point of failure probability, DBP-ST, DBP-R, and DBP-MP show better performance than DBP-PC because the main objective of DBP-PC is to extend network lifetime while meeting (m, k)-firm constraints. Even though DBP-PC employs complex scheme to adjust transmission power independently, it causes high additional overhead. Moreover, if the network environments are subjected to be changed unexpectedly and continuously, it takes long time to reach balanced state. This means that this kind of networks can be unsuitable for real-time delivery. Since other three schemes have different respective goals, it is very hard to make an order. Rather, they should be combined and work together to enhance performance.

In terms of additional overhead, DBP-ST includes the computing complexity for slack time. However, this complexity is bounded as $O(1)$ complexity through simple computation. The overhead of DBP-PC is described above. DBP-R adds procedure for the duplications of each packet. The duplication is not complicated procedure but the number of duplication is another consideration. As each transmission is conducted by utilizing available resource, it is desirable to reduce the number of duplications. Similar procedure to DBP-R is also taken in DBP-MP. However, overhead on DBP-MP is larger than DBP-R because each procedure to find out disjoint path and maintain them is not trivial one. Due to the assumption of DBP-MP, we did not consider them in this paper.

We can make rough conclusion by comparative evaluation with SPEED and POWER-SPEED. Even though both existing protocols have been proposed for general real-time services, it is not suitable for application-specific requirement as mentioned in introduction. Also, these protocols only concerns one service at a time, the performance decreases when multiple services are requested. Moreover, both cross-layered design and dynamic adjustment based on current QoS status make the DBP-C better than existing protocols.

5 Conclusion

Despite of increasing demands, the research for real-time system is at the initial stage in wireless sensor networks. The main reasons for slow development in this research field are the constraints of each node and unsuitable approaches based on previous work under strict layered concept. To overcome these problems practically, we suggest and propose new schemes which are designed to meet their respective objective. These include packet prioritization, long network lifetime, high reliability, and congestion awareness. However, the most important goal in this paper is to efficiently meet (m, k)-firm constraints.

Each scheme is described through new algorithm and evaluated by simulation results. By analyzing simulation results, we found out that performance is mostly improved when cross layered design principle is applied to meet requirements. However, as our scheme is to propose strategy rather than exact algorithm to get optimal value, detailed procedure remains as further study. Also, more simulation works will be conducted to extend current algorithms and develop analysis model through feedback.

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Author Biographies

Ki-Il Kim received the M.S. and Ph.D. degrees in computer science from the ChungNam National University, Daejeon, Korea, in 2002 and 2005, respectively. He is currently with the Department of Informatics, Gyeongsang National University. His research interests include routing for MANET, QoS in wireless network, multicast, and sensor networks.

Tae Eung Sung received M.S. degree in Electrical Engineering from the University of Texas at Austin, Austin, TX, in 2004 and Ph.D. from Cornell University, Ithaca, NY, in 2009, respectively. His research interests are cooperative transmission techniques (with MIMO OFDM space-time coding) in large sensor networks.