Parametric Routing for Wireless Sensor Networks

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Abstract. Developing an ideal routing protocol that satisfies various wireless sensor network applications is difficult due to their different requirements. In this paper, we propose a parametric routing protocol that considers performance parameters such as time, reliability, and energy to satisfy various circumstances of wireless sensor network applications. Based on a geographic algorithm, the proposed protocol calculates each node's routing costs for three performance parameters and negotiates to select the next node. The framework supports adaptive service as well as scalability because the mechanism requires only neighboring nodes' information. The experiment shows that the proposed protocol provides adaptive services for various sensor networks applications.

1 Introduction

Applications in wireless sensor networks are developed in diverse fields; hence specifically-designed routing protocols for each application are required. For instance, object tracking applications such as Countersniper System [1] or Cricket System [2] need a real-time routing protocol, whereas a structural monitoring application [3] requires a reliable network protocol and an energy-efficient routing protocol is necessary for an environment monitoring system. One protocol in wireless sensor networks may not operate properly in another application.

Popular operating systems in wireless sensor networks such as TinyOS [4] and SOS [5] use a single image or loadable module to install software on sensor hardware. TinyOS is compiled with all required libraries, including a routing protocol and the single image, is generated. SOS offers a loadable module technique to install libraries efficiently. For those operating systems, application developers should understand details of the routing protocol. Moreover, they probably design and implement their own routing protocols. Thus, a general protocol considering various domains and simple APIs is required.

In this paper, we propose a parametric routing protocol that considers several performance domains such as time, reliability, and energy consumption. For the time domain, the protocol calculates a cost between the current node and the destination, the distance between the next node and the destination, and packet delay time. A link quality indicator, transmission success ratio, and buffer overflow are used for reliability. The protocol predicts a node's lifetime, based on battery residual, cutoff voltage and energy consumption rate. The key of the proposed parametric routing is the negotiation algorithm. When an application sets parameters using simple APIs ("care" or "don't care"), the current node selects the next one using the negotiation algorithm. Therefore, the proposed routing protocol operates different applications with desirable performance. Moreover, removing reinstallation of routing protocol reduces overhead for the code dissemination.

The remainder of the paper is organized as follows. Section 2 discusses related work. In Section 3, the details of parametric routing are introduced. The experimental results are discussed in Section 4. Finally, Section 5 concludes the paper with a discussion of future work.

2 Related Work

Routing protocols in wireless sensor networks have general requirements such as real-time, reliability, energy efficiency, depending on the characteristics of applications. Much research on routing protocols [6]-[13] has been conducted to satisfy these requirements, but they hardly cover all three requirements.

Protocols considering only one of those requirements are as follows. SPEED [6] and RAP [7] focus on time domain only. SPEED selects the next node in terms of speed estimation calculated by the distance from the current node to the destination, the distance from the next node to the destination, and transmission delay. It also provides a backpressure technique to prepare the failure of the next node. RAP is designed for burst real-time traffic. The mechanism calculates a cost from the distance from the current node to the destination, deadline and packet traveling time from the source to the current node. Thus, a packet traveling a longer distance receives higher priority. Woo et al. [8] propose a reliable routing protocol that calculates an average of transmission success ratio over a certain time period to select the next node. ReInForM [9] is a multi-path routing providing reliability. A user selects a reliability level and the protocol estimates a number of next nodes satisfying users' expectation. Energy aware routing mainly focuses on maximizing the network lifetime. Chung's protocol [10] decides a path, based on the Bellman-Ford Algorithm, with transmission energy and residual energy. LEACH [11] is proposed to reduce transmission power by data aggregation and rotating a role of cluster header. However, the cluster structure causes other problems.

From the QoS point of view, some research has dealt with two domains. MMSPEED [12] is a routing protocol deliberating both time and reliability issues. The main idea to select a next relay node is adopted from SPEED [4] and ReInForM [9]. An energy-aware QoS routing protocol [13] sets a path depending on the energy consumption factors. Later, the protocol uses different queues to minimize collision for packets requiring real-time. However, the reliability issue is not considered in the protocol.

3 Parametric Routing Protocol

In this section, we present a parametric routing protocol that considers the key metrics of wireless sensor networks: time, reliability, and power issue. The following subsections discuss the system architecture, routing components, and the routing algorithm.

3.1 System Architecture

Fig.1 illustrates the system architecture for the parametric routing protocol. The system consists of user APIs, estimation components, the negotiation protocol, and greedy algorithm, and neighbor table manager. Before sending packets, a user should decide which domains are cared and set parameters through APIs. In order to select candidate nodes, the parametric routing uses the greedy forwarding routing method [14], which selects the nearest node from the destination. The difference between [14] and the greedy forwarding method we use is that the greedy algorithm of the parametric routing chooses multiple nodes that are near the destination. After choosing the candidates, estimation components, which are time, reliability and energy domain, calculate a domain cost based on information from a neighbor table. Finally, negotiation algorithm analyzes the cost of each domain and selects the next relaying node.

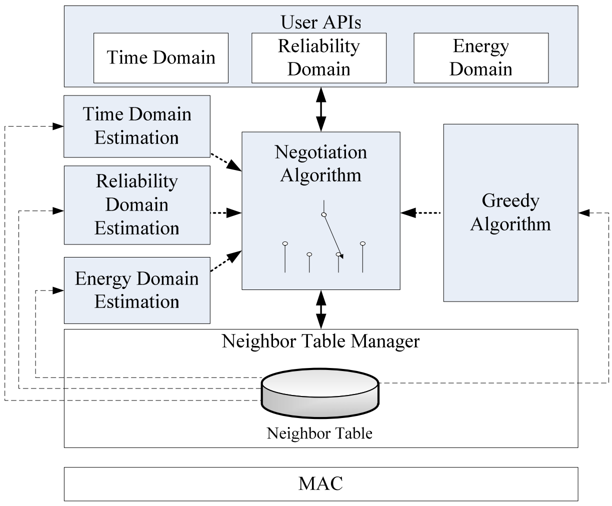


Fig. 1. Architecture for parametric routing protocol

The parametric routing works via negotiation among three independent domains of time, reliability and energy. Hence, the negotiation algorithm should make use of neighbor information, and the neighbor table manger plays the key role. A neighbor table has important information for parametric routing protocol, and the table is handled by the neighbor table manager. The manager periodically monitors the status of its neighbors and stores information in the neighbor table. The detailed scenario is as follows: The manager periodically broadcasts query to one-hop neighbors. Upon receiving the query, the neighbors send a reply message which includes its geographical position, delay time, LQI (Link Quality Indicator) and battery level. The manger node then updates the neighbor table with the new statistics, and provides latest information to the routing module via appropriate function calls shown in Table 1. This mechanism is similar to the beaconing which is commonly found in many routing protocols.

Table 1. Function calls for neighbor table manager

Component of Parametric Routing	Function Calls of NTM	Description
Time Domain Estimator	get_position()	Position of a neighbor node
	get_delay()	Delay time from receiving to sending
Reliability Domain Estimator	get_rate0	Delivery success rate of a neighbor node
	get_lqi()	Link quality of a neighbor node
Energy Domain Estimator	get_battery()	Battery level of a neighbor node

3.2 Routing Components

The negotiation algorithm for parametric routing protocol uses three components: time, reliability, and energy estimation. The estimation component for time uses the idea from SPEED [4]. Fig. 2 and Equation 1 explain how to calculate speed from distance information. Distance is calculated by subtracting the distance Ci to the destination D from the distance source S to destination D. Delay is packet relaying time at Ci.

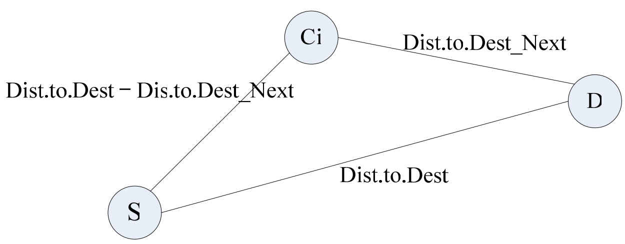


Fig. 2. Measurement distance of SPEED

$$Speed = \frac{Dist.to.Dest - Dist.to.Dest\_next}{delay(C_i)} \quad (1)$$

For reliability, the estimation component uses link quality indicator (LQI) and delivery success rate to select the reliable node as the next node. According to IEEE 802.15.4 [15], LQI is calculated by the ratio of the number of received packets to the error bits. Relay success rate is defined as the ratio of the number of received packets that should be relayed to the number of packets transmitted successfully within a certain time. In Equation 2, a reliable node is calculated by multiplying LQI to delivery success rate. That is, the estimation component considers not only network-wide reliability (LQI) but also local reliability (delivery success rate). Therefore, it accurately estimates the possible packet loss.

$$ReliableMedium = LQI \cdot DeliverySuccessRate \quad (2)$$

The estimation component considering energy uses battery residual to distribute packets to several nodes. Using the battery consumption rate, time to reach the cutoff voltage can be predicted. Based on the previous information, nodes can find the better energy-efficient paths to extend network lifetime.

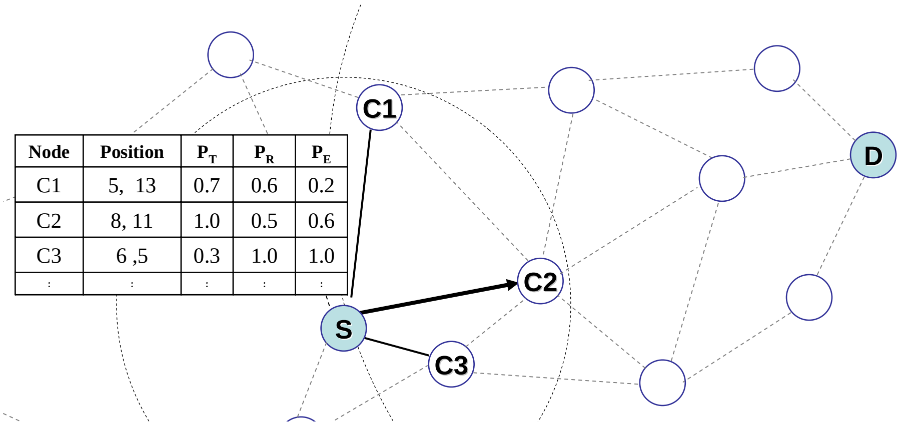
$$V_{cutoff} = V_{current} - \frac{\Delta V}{\Delta t} \times LifeTime \quad (3)$$

$$LifeTime = \frac{(V_{current} - V_{cutoff}) \times \Delta t}{\Delta V} \quad (4)$$

According to Equation 3, the cutoff voltage is calculated by subtracting predicted voltage consumption from current voltage for remaining lifetime. Equation 4 is derived from Equation 3. Lifetime in Equation 4 is the predicted operating time to send and receive packets. Therefore, finding the node that has the highest lifetime brings the extension of network lifetime.

3.3 Negotiation Algorithm

The application determines the class where each packet should be sent with three parameters. The Application API is defined as *net_set_value (int time, int reliability, int energy)*. The parameters of the function determine each domain to consider. The application uses the function to setup the required domains of following packets. Each parameter is set to CARE or DONT_CARE. Candidate nodes are selected through the geometric forwarding algorithm with its neighbor table. Our algorithm considers the parameters of domain marked CARE and chooses the next node that is superior in CARE domain. On the other hand, the algorithm does not consider the DONT_CARE domain. Hence, a packet including DONT_CARE domains possibly travels good or bad performed nodes to a destination with information about those domains.



Node	Position	P_T	P_R	P_E
C1	5, 13	0.7	0.6	0.2
C2	8, 11	1.0	0.5	0.6
C3	6 ,5	0.3	1.0	1.0
:	:	:	:	:

Fig. 3. Selection of the next node of parametric routing protocol

In order to process the negotiation, parameters of speed, reliable-medium and lifetime need to be adjusted in to the same metric. We express the performance by calculating the relative proportion of the value to the maximum cost of each domain metric. We use the largest domain value among the candidates as the maximum value of the domain and calculate the proportion P to the basis. Maximum value of candidates is used since the negotiation algorithm is not for guaranteeing the path but for best-effort. Equation 5 shows the calculation for proportion P.

$$P_{domain}(candidate) = \frac{Cost(candidate)}{MaxCost(\forall candidates)} \quad (5)$$

Fig. 3 shows an example of the parametric routing protocol. C1, C2 and C3 represent the candidates selected by the greedy algorithm among the neighbors of S. When the time domain values of candidates are 7, 10 and 4, the speed performance proportion P_T of candidates are 7/10, 10/10 and 3/10. Hence, C2 is the most appropriate node in the time domain. P_R and P_E, which represent the performance proportion of reliability and energy domains, are computed using the same method.

Users may set CARE to more than two domains when they want all the CARE domains to be satisfied. However, it is difficult to find a node that guarantees the best performance for all domains. We choose the node that has the largest weight through negotiation.

$$P_{sum}(candidate) = \sum_{i \in domain} P_i(candidate) \quad (6)$$

$$P_{difference}(candidate) = \sum_{i \in domain \cap \{j\}^c} \left| P_j(candidate) - P_i(candidate) \right| \quad (7)$$

$$W(candidate) = P_{sum}(candidate) - P_{difference}(candidate) \quad (8)$$

```
FOR each candidates in candidate list
begin
  FIND the maximum cost in each domain;
end
FOR each candidates in candidate list
begin
  P_domain := cost of each domain / maximum cost of each domain;
  CHOOSE a domain D1 which is marked CARE
  FOR each domain D2 which is marked CARE
  begin
    P_sum(candidate) := P_sum(candidate) + P_D2(candidate);
    P_difference(candidate) := P_difference(candidate) + P_D1(candidate) –
  P_D2(candidate);
  end
  W(candidate) := P_sum(candidate) – P_difference(candidate);
end
FIND a next node in candidates having the maximum W randomly;
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Fig. 4. Negotiation Algorithm of Parametric Routing

Equation 6 shows the summation of P in CARE domains for a candidate. P_{SUM} is used to find the candidate node that has the highest performance. $P_{difference}$ in Equation 7 is the summation of differences between all of the domains marked to CARE. A node with large difference among its CARE domains makes it difficult to satisfy the user's demand. Equation 8 shows the weight for final node selection. Fig. 4 shows the algorithm to select the next node with the weight. The general idea of the algorithm is to find the node that has high total performance and small performance differences among the domains. The algorithm works properly with one CARE domain since the $P_{difference}$ would be 0 in this case.

Suppose a user sets all the domains to CARE in the situation described in Fig. 3. P_{SUM} of each candidate is calculated as $P_T(C1) + P_R(C1) + P_E(C1) = 1.5$, $P_T(C2) + P_R(C2) + P_E(C2) = 2.1$ and $P_T(C3) + P_R(C3) + P_E(C3) = 2.3$. $P_{difference}$ of each candidate is calculated as $P_T(C1) - P_R(C1) + P_T(C1) – P_E(C1)\ P_R(C1) – P_E(C1) = 1.0$, $P_T(C2) - P_R(C2) + P_T(C2) - P_E(C2) + P_E(C2) – P_R(C2) = 1.0$ and $P_R(C3) - P_T(C3) + P_E(C3) - P_T(C3) + P_E(C3) – P_R(C3) = 1.4$. The final weights of each candidate are W(C1) = 0.5, W(C2) = 1.1 and W(C3) = 0.9. According to these results, our algorithm chooses C2 as the next node. The candidate C2 has higher performance on time domain and lower performance on reliability and energy domains than C3. However, the difference of total performance between C2 and C3 is insignificant and the domain performances of C2 are even.

The proposed parametric routing protocol provides various parameters for setting up the packets' requirements and operates appropriately for demands of various applications of wireless sensor networks through negotiation algorithm. The protocol is scalable because it selects candidates based on greedy forwarding algorithm.

4. Experiments

In this section, we validate the negotiation algorithm and analyze the path of packets delivery by actual experiments. We use RETOS [16] on Tmote Sky from Moteiv. RETOS is an operating system that is currently being developed in our laboratory. For updating neighbor table, a query is sent every 30 seconds by the table manger. The application changes the parameters in every second as shown in Table 2 and sets the cut-off voltage to 2V. The nodes are arbitrarily deployed in 4x4 grids. The length of each side of the little squares is 30cm. To prevent one hop communication between node number 1 and node number 6, we adjust the RF power to -35dBm. The minimum value of delta-V, in Equation 4, is set to 0.001 to prevent it from reaching 0. We analyze the experimental results of the proposed parametric routing for each domain and the effect of the negotiation. In the experiment, the situation has four different requirements. Packets are transmitted from node number 6 to the sink node.

Fig. 5 (a) shows the packet path when the time domain is set to CARE. Most packets are sent to nodes 2 and 3, which are the farthest nodes from node 6. However, the delivery time of each node is continually changed, as shown in Fig. 6 (a). Although node 5 is closer to node 6 than nodes 2 and 3, it is selected as next node of node number 6 because it has a significantly smaller packet delivery delay time. Node number 4 has less selectivity because it is close to node 6 and generally has a similar delay time as compared to the other nodes.

Fig. 5 (b) shows the result when the reliability domain is set to CARE. The decisive factor for the performance cost is LQI since the relay success rate in the node is 100%. As shown in Fig. 6 (b), the quality of the link begins to stabilize after 120 seconds. The nodes are evenly selected as the next node. Fig. 5 (c) shows the routing path that considers the remaining battery power. Most of packets are transmitted to node number 4 because it has the highest battery power. Few packets are delivered to node number 5 in the period of 570 seconds. This is because the delta-T in Equation 4 of node 5 grows relatively bigger than that of node 4 by the voltage drop of node 5. The delivery path is return to node number 4 after the period. Fig. 5 (d) shows the result when all the domains are set to CARE. Since node number 3 has good performance in the time and reliability domains and normal performance in the energy domain, more than half of the packets are sent to node 3. Table 2 shows the effect of the experiment. When the time domain is considered, the delivery time is relatively low because the SPEED algorithm considers not only the distance but also time. Since the algorithm does not consider the quality of link, relative success rate decreases. When all of the domains are considered, the delivery time is similar and the success rate is lower than the cases just considering the reliability domain. The delivery time is longer and success rate is higher than the case when the time domain is considered. According to Table 2, general performance is decreased when all domains are considered; however, we can see that node number 2 is excluded as a next node because it has the lowest battery power. In other words, the negotiation operates properly.

Table 2. Delay time and success rate of each requirement

Requirement (Time, Reliability, Energy)	Delivery time (ms)	Delivery Success Rate (%)
(CARE, DONT_CARE, DONT_CARE)	7.91	77
(DONT_CARE, CARE, DONT_CARE)	8.17	90
(DONT_CARE, DONT_CARE, CARE)	8.62	91
(CARE, CARE, CARE)	8.18	86

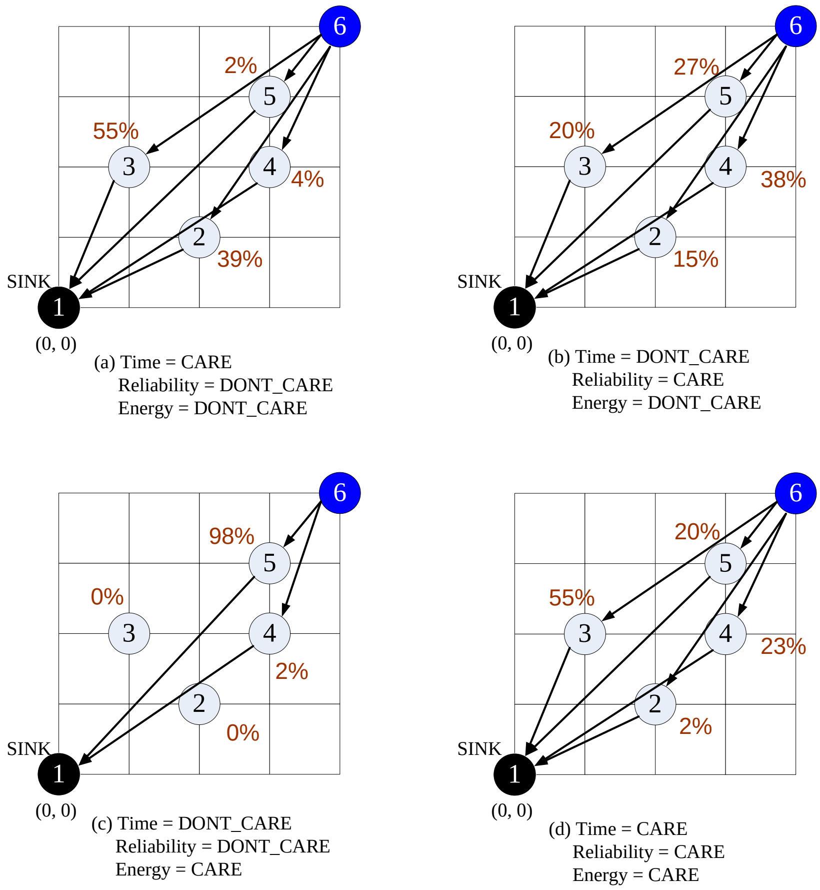
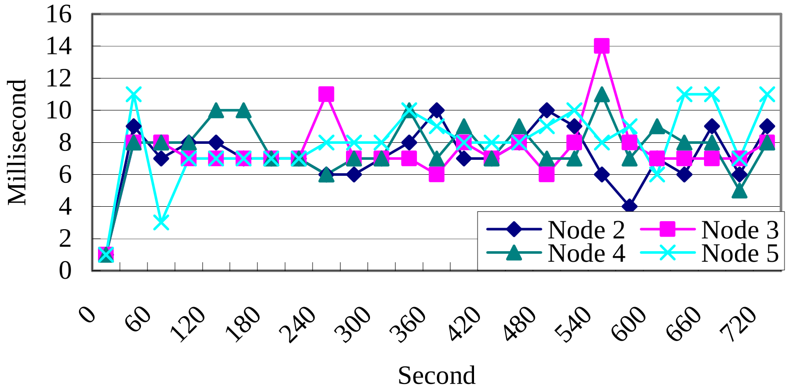
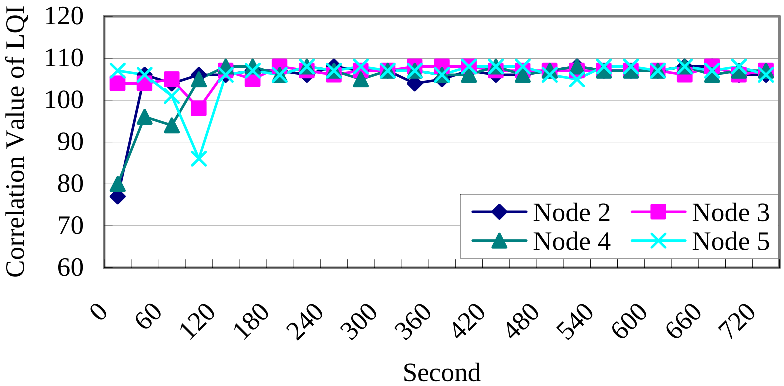


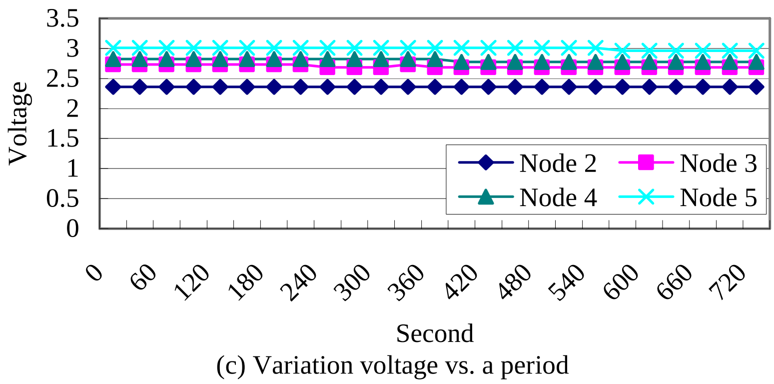
Fig. 5. Routing path and proportion of relaying



(a) Variation of delay time vs. a period



(b) Variation of Correlation Value of LQI



(c) Variation voltage vs. a period

Fig. 6. Battery level is stable, but LQI and delivery time continually change

5. Conclusion and Future Work

The proposed parametric routing offers the best-effort service when applications have a request in one domain and adaptive service when applications have requirements in two or three domains by means of computing cost in time, reliability and energy domains that applications generally request. Thus, the application programmer is relieved from developing their own routing protocols, and it is cost effective to disseminate code because parametric routing can support three domains and be loaded on a sensor node as a module. The parametric routing recognizes the state of nodes in the networks, real-time packets are transmitted fast, packets for reliability are transmitted more reliably and energy aware packets are transmitted following a path that consists of nodes having enough energy. If a packet requires "care" about all domains, parametric routing negotiates with them and offers appropriated service. The negotiation algorithm we proposed can be applied to more parameters. Thus, parametric routing is possibly expended with a cost estimation algorithm of a domain that sensor network applications require is newly suggested.

In our future work, we plan to study how differentiated service for the time and reliability domain can be supported precisely by packets having different requirements in the same network, such as periodic and alert packets of an application, and fill the buffer of a node. One possible approach is priority based multiple queues.

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