Multi-constrained Soft-QoS Provisioning in Wireless Sensor Networks

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***Abstract*— Due to the inexpensive cost and small size of the sensor node, sensor networks are densely deployed for most applications. In the application oriented wireless sensor networks, traffic is usually mixed with time-sensitive packets and reliability-demanding packets. Hence, routing regardless of the packet characteristics is not efficient. Our goal is to provide soft-QoS to different types of packets since accurate path information can be hardly obtained in wireless networks. In this paper, we utilize the multiple paths between the source and sink pairs for QoS provisioning. Unlike E2E QoS schemes, soft-QoS mapped into links on a path is determined based on local link state information. Through the estimation and approximation of path quality, traditional NP-complete QoS problem is split into many small problems. The idea is to formulate the problem as a probabilistic programming, then based on some approximation technique, we convert it into an integer programming, which is much easier to solve. The resulting solution is also one to the original probabilistic programming. Simulation results demonstrate the effectiveness of our approach.**

I. INTRODUCTION

Though small in size, interconnected sensor nodes are capable of accomplishing various applications, such as habitat monitoring, surveillance or emergency alarm. Sensor nodes report the sensed information to the sink, which is usually stationary. Depending on different applications, generated packets show diverse attributes. For periodic humidity record packets, as long as it arrives at the processing center or sink, path delay is not critically important. On the other hand, for multimedia packets, i.e. video streaming packets, if most of them are received in critical time, some loss is acceptable. Another kind of traffic poses strict requirements on both delay and reliability. For example, for a danger warning packet, it should be delivered to the destination as soon as possible without loss. So QoS routing is an important issue in application oriented wireless sensor networks.

In this paper, both reliability and delay are the concerned QoS constraints, in which reliability is defined as the packet delivery ratio. Prone to link changes and failures, sensor networks are not reliable [13]. In wired networks, QoS routing with multiple constraints is well-studied. However, unlike wireless networks, reliability is not a key factor in wired networks. Existing literatures in the field of wireless sensor networks focus on a single service metric, such as reliability, delay or energy. Both single path routing and multipath routing have been proposed to solve the problem. However, very few of them consider multiple QoS constraints in sensor networks.

Multiconstrained routing suffers from time complexity and/or space complexity. For wireless networks, complete and accurate state information is not available due to the time-varying traffic and link quality. Uncertainty makes QoS routing an even tougher problem than in wired networks. Only soft-QoS provisioning is attainable in notoriously unpredictable wireless communications. It is known that finding a path subject to two or more additive constraints is NP-complete [1]. Therefore solving the problem in a heuristic and approximate way is the only reasonable approach. An exciting news from [1] is that topologies leading to an NP-complete behavior of the MCP(Multiple Constraints Problem) problem are less likely to appear, and the worst case complexity of the MCP problem depends on the correlation among the constraint weights.

In our view, delay is time constrained, yet re-

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liability can be enhanced via path diversity. In this sense, we exploit the time-space efficiency to meet the various characteristics of packets. Many schemes have been proposed to improve reliability based on multipath routing or packet redundancy. Most of them provide heuristic methods without analytical results on the performance. Nevertheless, our routing algorithm design is distinct from them as we formulate the problem in an analytical way. Our goal is to fulfill the soft-QoS requirements in sensor networks. In this context, soft-QoS is defined as guaranteeing the QoS requirements with probability, an approximation of hard-QoS with probability approaching 1. Soft-QoS follows naturally from the inherent random link characteristics of wireless ad hoc and sensor networks. In this paper, we first formulate the end-to-end soft-QoS problem as a stochastic programming. Then a distributed routing algorithm is proposed based on the linear programming, which is a deterministic approximate of the end-to-end problem. Our proposed routing algorithm is hop-based, so it is scalable to network size and convenient to implement. In addition, it circumvents the formidable computation complexity of MCP problem.

The rest of the paper is organized as follows. Section II discusses previous work on related topics. Section III describes the E2E QoS problem definition and bottlenecks of the problem. Section IV presents the model and formulation for delay-reliability constrained QoS routing problem. Section V illustrates the simulation and discusses the simulation results. Section VI concludes the paper.

II. RELATED WORK

In wired network, many papers have proposed exact or heuristic algorithms targeted at MCP or MCOP(Multi-constrained Optimal Path) problems [1] [4] [7] [5]. However, wireless sensor networks differ from wired networks in nodes' limited energy, memory and computation capabilities, and link characteristics. So those methods are not applicable. A scheme to minimize the cost for delay constrained real-time traffic, while maximize the throughput for non-real-time traffic is proposed in [11]. Chen and Nahrstedt [2] tackle the QoS problem distributively with bounded number of searching paths. Many papers exploit multipath routing to achieve QoS in wireless ad hoc and sensor networks. Based on per-hop channel error rate, which is assumed to be constant across the entire network, the number of outgoing forwarding paths is determined to achieve desired reliability [6]. To combat unreliability, Tsirigos and Hass employ diversity coding and distribute packets over multiple disjoint paths [3]. Gaussian approximation of path success probability, which is tight when the number of paths is sufficiently large, is maximized to reconstruct the original information. Felemban and et al. addressed both time and reliability constraints in [16]. However, they just use the average link delay and reliability to make routing decisions, so the scheme is not able to adapt quickly under time-varying link conditions. Our paper formulates the problem in a more rigorous way and use both the first and second moments for routing. In [9], Bhatnagar et al. classify paths based on their route lengths. Thus, critical queries go through paths with minimum lengths, and the rest of the traffic is spread uniformly in the network. The algorithm proposed by Das et al [10] adaptively discovers routes before the occurrence of route errors while transmitting a large volume of data. So it dynamically finds out a series of multiple paths to complete the data transfer. Both disjoint multipath and braided multipath algorithms are explored in [15]. Comparing disjoint multipaths to braided multipaths, braided multipaths have higher resilience to failures with less overhead. Reliability is of great concern in wireless sensor networks due to the fact that sensors are susceptible to failures. Experiments provide some insight into the behavior of link reliability with regard to physical and MAC layers [14].

III. PROBLEM DEFINITION OF E2E QOS MULTIPATH ROUTING

Among the two QoS constraints to be explored in this paper, reliability is more difficult to address. Reliability can be characterized by packet delivery ratio, which is defined as the ratio of number of unique packets successfully received by the sink to the number of packets generated by source nodes. For a given path *p*, the end-to-end reliability can be computed as follows:

$$\prod_{(i,j)\in p} r_{ij}, \tag{1}$$

where r_{ij} is the reliability of link (i,j) on path p. Since reliability is multiplicative, a variation in any one of the link on *p* would change the end-to-end reliability remarkably. Also, as the number of hops on the path increases, the E2E reliability decreases. Usually the number of hops in large scale sensor networks is much larger than those in ad hoc networks. So it imposes a severe problem on reliability. For the same *p* to achieve an E2E reliability of 90%, the geometric mean of reliability of all six links on a six-link path *p* has to be 98%, which is very restrictive in wireless communications. If the E2E reliability degrades so much that no route can meet the QoS requirement, multipath routing seems to be the only method to enhance the E2E reliability.

A. *Problem Definition of E2E QoS*

If at least one route is able to provide the needed QoS requirement, then we could easily obtain a feasible path. However, if some constraint is so aggressive that no single route alone is capable of QoS provision, two different cases are possible. For delay constraint, if a constraint value, say, d_1, which is associated with a data packet, is so restrictive that every path between the source and destination has a delay larger than it, then no path is able to deliver the packet within d_1. There is no feasible path for constraint value d_1. For the other metric, reliability, it is a different case. If there is no single feasible path for a constraint value, say r_1, we can resort to multipath routing. Carefully choosing a subset of existing paths, the packet with constraint r_1 is transferred on all those paths. Although an individual path cannot achieve the performance goal, multiple paths may meet it aggregately. The assembly efficiency of multiple paths is a great boon to unreliable sensor networks. Obviously, there exist many feasible combinations. To save the energy cost, the set with the minimum number of paths is chosen as the forwarding set. We argue that sending a packet on more paths induces more energy cost, because more duplicate data packets have to be transmitted. Also more paths introduce more contentions. Even some paths in the set may have more hops, it is still more energy efficient to deliver packets over a few paths. First of all, the question of how to quantify the reliability achieved by a subset of paths needs to be addressed. Then how to choose the energy efficient path set subject to the delay constraint is our main focus. Denote d the sink, which is assumed to be stationary. Let $P(s,d)$ denote the path set of P possible paths from a source node s to d. Each path p_j in $P(s,d)$, $j = 1, 2, \ldots, P$, is associated with delay d_j and reliability r_j.

Problem Definition: Given delay requirement D and reliability requirement R, find multiple paths that satisfy the requirements simultaneously, so that

(1) $d_j \leq D$, each path has a delay no greater than D;

(2) $1 - \prod_{j=1}^{P} (1 - r_j) \geq R$, the aggregate reliability is no less than R.

For clarity, notation used in the paper is explained in Table. I.

TABLE I

NOTATION

l_{ij}	link from node i to node j
h_i	hop count from current node i to the sink
α	soft-QoS probability for delay
β	soft-QoS probability for reliability
L_i^d	hop requirement for delay at node i
L_i^r	hop requirement for reliability at node i
D_i	actual delay of the packet arriving at node i
R_i	reliability requirement assigned to the path through node i
$\mathbf{d}_{ij}$	delay of link l_{ij}, described as a random variable
$\mathbf{r}_{ij}$	reliability of link l_{ij}, described as a random variable
x_j	decision variable of whether link (i,j) is used
d_{ij}	mean of $\mathbf{d}_{ij}$
r_{ij}	mean of $\mathbf{r}_{ij}$
Δ_{ij}^d	standard deviation of $\mathbf{d}_{ij}$
Δ_{ij}^r	standard deviation of $\mathbf{r}_{ij}$

B. *Bottleneck of E2E QoS*

Though E2E QoS problem described in the previous subsection yields the exact optimal routing solution, it is subject to many inextricable challenges. First, wireless links are susceptible to fading, interference, and traffic variation. Therefore it is almost impossible to obtain the exact instantaneous link state information. So path information, which is accumulated along all links on it, is even more unpredictable. Change of a single link on a path would launch the update of the path information throughout the network, or network wide flooding on some occasions. Hence, sometimes periodic information exchange mechanism is used to mitigate the effect of inaccurate information. However, there is a trade-off between the exchange period and accuracy. If the period is long, information may not be precise. On the other hand, if the period is too short, a large amount of overhead is engendered. Second, keeping path metrics consistent at all nodes is a formidable problem. Since it takes some time for updates to propagate across the network, some nodes refresh their path information with the new updates, while other nodes still use the obsolete information to make routing decisions. A packet going through nodes with asynchronous path information may miss QoS requirement. Especially for large scale sensor networks, this problem is extremely severe because it is tough to refresh all nodes in a short interval. Third, storage of voluminous E2E path information is dreadfully memory demanding. Possible paths between two nodes may be numerous, whereas a sensor node is equipped with very limited memory. Furthermore, manipulation of E2E information is computationally burdensome for sensor nodes. The complexity is beyond the computation and energy tolerance of sensors.

Preceding reasons shed light on link based QoS routing. Per hop information is convenient to acquire and maintain at a low overhead cost. Neighbor information is enough to make routing decisions, which saves a large amount of computation. Thus, sensor nodes are free of intricate computation. For those superior features of per hop routing, we propose to approximate path quality based on link quality.

IV. MODELING AND PROBLEM FORMULATION OF DISTRIBUTED QOS ROUTING

Due to the inherent random characteristics of wireless links, soft-QoS provisioning based on link quality is practical. In this section, a distributed soft-QoS multipath routing algorithm which is an approximate of the end-to-end one is to be addressed. Since we use link quality to estimate path quality, the associated requirement to be satisfied at each hop needs to be derived.

A. Requirement Partition

Local link metrics and distance to the sink in terms of hop count are used to estimate the path metric. Local link metrics are much easier to acquire and scalable to the network. By uniformly partitioning current requirements at all downstream hops, we can obtain the hop requirements. If the hop requirement can be achieved at each hop, the end-to-end QoS requirement can also be met. A node satisfies the hop requirement by selecting next hop nodes based on link conditions. The additive form of delay allows the total available delay to be evenly divided at each hop. On the other hand, the reliability is multiplicative as indicated in (1). Consequently, it takes power form of the requirement. Denote L_i^d and L_i^r as the hop requirements for delay and reliability at node i respectively, h_i as the hop count from node i to the sink, D_i as the actual delay experienced by a packet at node i. As the path from node i to the destination is composed of h_i links, the partitioned requirements at node i can be:

$$L_i^d = \frac{D - D_i}{h_i} \tag{2}$$

$$L_i^r = \sqrt[h_i]{R_i} \tag{3}$$

By introducing D_i and h_i into calculation, the hop requirement for the delay can be adaptively adjusted according to the actual experienced delay over preceding links. Overestimate of delay requirement would tighten the hop delay requirement at downstream nodes, while underestimate would relax the requirement. R is collectively satisfied by several paths, R_i is denoted as the portion of the reliability requirement assigned to the path through node i. R_i is decided by the upstream node of i. As a packet advances towards the sink, h_i at nodes closer to the sink becomes more accurate. h_i can be easily obtained at the initialization stage, when every node exchanges messages with neighbors to obtain local information.

B. Approximate Problem

In wireless networks, delay and reliability tend to fluctuate with time. To model this phenomenon, we assume that the link delay and reliability are random processes $\mathbf{d}_{ij}(t)$ and $\mathbf{r}_{ij}(t)$. Time index t is omitted for simplicity in the following discussion. We assume that links are independent in terms of delay and reliability, and the link delay and the reliability are mutually independent. Our goal is to develop a method so that both delay and reliability are assured with high probability. We only employ the first and second moments of delay and reliability in our derivation. The approximate problem to be addressed based on local information is formulated as:

$$\text{minimize} \sum_{j\in N(i)} x_j$$

$$\text{subject to } P(x_j\mathbf{d}_{ij} \le L_i^d) \ge \alpha, \text{ for } L_i^d > 0, \quad (4)$$

$$P\left(1-\prod_{j\in N(i)} x_j(1-\mathbf{r}_{ij}) \ge L_i^r\right) \ge \beta, \quad (5)$$

$$x_j = 0 \text{ or } 1, \forall j \in N(i)$$

where $x_j's$ are the decision variables, and $\mathbf{d}_{ij}$ and $\mathbf{r}_{ij}$ are the delay and reliability of link l_{ij} at the routing decision instant respectively. This is a probabilistic integer programming problem. In the original problem definition, the nonlinear programming problem is to be solved only at the source based on end-to-end information. In contrast, the approximate problem is to be solved at all intermediate nodes since it is based on hop information. The next two subsections attempt to reduce the computation complexity of the approximation constraints respectively, thus making the approximate solution more appealing.

C. Probabilistic Delay Constraint

Denote d_{ij} the mean of $\mathbf{d}_{ij}$, which is the measured link delay. Let $(\Delta_{ij}^d)^2$ denote the variance of $\mathbf{d}_{ij}$, as defined in subsection IV-E. To guarantee that the delay requirement is satisfied with probability no less than α, we must have

$$P(x_j\mathbf{d}_{ij} \le L_i^d) = P(x_j\mathbf{d}_{ij} \le \frac{D-D_i}{h_i}) \ge \alpha \quad (6)$$

or

$$P(x_j\mathbf{d}_{ij} \ge L_i^d) \le 1-\alpha \quad (7)$$

We estimate the probability according to one-tailed version of Chebyshev's inequality:

$$P\left(\mathbf{X}-m_x \ge a\right) \le \frac{\sigma_x^2}{\sigma_x^2+a^2},\ a>0$$

which yields:

$$P\left(x_i\mathbf{d}_{ij} \ge L_i^d\right) \le \frac{x_j^2{(\Delta_{ij}^d)}^2}{x_j^2{(\Delta_{ij}^d)}^2+(L_i^d-x_jd_{ij})^2},\ L_i^d-d_{ij}>0 \quad (8)$$

This implies that if d_{ij} satisfies

$$\frac{x_j^2{(\Delta_{ij}^d)}^2}{x_j^2{(\Delta_{ij}^d)}^2+(L_i^d-x_jd_{ij})^2} \le 1-\alpha$$

then (6) is also valid. Because $x_j = 0$ or 1, $x_j^2 = x_j$. Simplifying the above equation, we obtain

$$x_j(\frac{\alpha}{1-\alpha}{(\Delta_{ij}^d)}^2+2L_i^dd_{ij}-d_{ij}^2) \le (L_i^d)^2,\ L_i^d-d_{ij}>0 \quad (9)$$

As the deterministic estimate for (6), (9) is linear and solvable. Note that Chebyshev bound is rather loose, so the solution space of (9) is smaller than the original one. Tuning α to an appropriate value to relax the solution space, could get feasible solutions to the original problem. So we add a nonnegative multiplicative factor $\omega < 1$ to it. $\alpha' = \omega\alpha$ is used in computation in (9). However, there is a tradeoff between the solution space and precision. A small α would include a larger solution space, at the risk of increasing the probability of expired packets. To achieve the best performance, this tuning parameter has to be carefully chosen.

D. Probabilistic Reliability Constraint

In our approximate problem, link reliability is an additive constraint, whereas delay is a bottleneck constraint, which is determined by the minimal one. Therefore, reliability is more complicated to deal with than delay. The current measured value of reliability r_{ij} is the time average of all finished transmissions. Assume that link reliability, $\mathbf{r}_{ij}$, is a random process with mean and variance r_{ij} and ${(\Delta_{ij}^r)}^2$ without specific p.d.f. Inequality (5) is a nonlinear constraint, which is unsolvable for capability restricted sensors. Simplifying the constraint to a linear function is more efficient. The original problem is reduced to selecting a set of paths meeting the partitioned reliability requirement at every time instant. Observe that the total reliability requirement can be achieved by multiple links

$$L_i^r = \sqrt[h_i]{R_i} = 1-\prod_{j\in N(i)}(1-x_jR_{ij}) \quad (10)$$

With this formula, the link reliability requirement can be easily obtained. But there may exist multiple solutions without regard to feasibility. So we add some constraints to restrict the solutions to the feasible ones.

Then the reliability requirement is satisfied if

$$\begin{aligned} P\left(\mathbf{r} \geq L_i^r\right) &= P(\bigcup_{j\in N(i)} x_j\mathbf{r}_{ij} \geq x_j R_{ij}) \\ &= \prod_{j\in N(i)} P(x_j\mathbf{r}_{ij} \geq x_j R_{ij}) \geq \beta \end{aligned} \tag{11}$$

The equation holds because the reliability of each link is independent. Denote $E[\mathbf{r}_{ij}] = \mu(\mathbf{r}_{ij}) = r_{ij}$, $\sigma_{ij}^2 = (\Delta_{ij}^r)^2$. Let $\mathbf{r}'_{ij}$ be the sum of all previous transmissions over link l_{ij}. The pth transmission either succeeds or fails, so it's reasonable to model a single transmission as a Bernoulli trial ξ_p, whose realization is either 1 or 0. Assume all transmissions are independent, then

$$\mathbf{r}'_{ij} = \sum_{p=1}^{M} \xi_p = M\frac{\sum\limits_{p=1}^{M} \xi_p}{M} = M\mathbf{r}_{ij} \tag{12}$$

where M is the number of transmissions over link l_{ij}. Note that $\mathbf{r}'_{ij}$ is not a binomial distribution because each ξ_p has different success probability. As M goes large, $\mathbf{r}'_{ij}$ is approximately Gaussian distributed according to the Central Limit Theorem, $\mathbf{r}'_{ij} \sim N(Mr_{ij}, M^2(\Delta_{ij}^r)^2)$.

Take the logarithm on both hands of the inequality (11),

$$\sum_{j\in N(i)} \log\left(P\left(x_j\mathbf{r}_{ij} \geq x_j R_{ij}\right)\right) \geq \log\beta \tag{13}$$

Observe that

$$\log P(x_j\mathbf{r}_{ij} \geq x_j R_{ij}) = \begin{cases} \log 1 = 0, \text{when } x_j = 0 \\ \log P\left(\mathbf{r}_{ij} \geq R_{ij}\right), \text{when } x_j = 1 \end{cases}$$

So we can rewrite (13) as

$$\sum_{j\in N(i)} x_j \log\left(P\left(M\mathbf{r}_{ij} \geq MR_{ij}\right)\right) \geq \log\beta \tag{14}$$

As $M\mathbf{r}_{ij} = \mathbf{r}'_{ij}$ is Gaussian distributed, we have

$$P\left(M\mathbf{r}_{ij} \geq MR_{ij}\right) = P\left(\mathbf{r}'_{ij} \geq MR_{ij}\right) = Q\left(\frac{MR_{ij} - Mr_{ij}}{M\Delta_{ij}^r}\right) \tag{15}$$

Substitute (15) into (14)

$$\sum_{j\in N(i)} x_j \log\left(Q\left(\frac{R_{ij} - r_{ij}}{\Delta_{ij}}\right)\right) \geq \log\beta \tag{16}$$

where

$$\prod_{j\in N(i)} (1 - x_j R_{ij}) \leq 1 - L_i^r \tag{17}$$

Again, take logarithm on both sides of (17)

$$\sum_{j\in N(i)} x_j \log(1 - R_{ij}) \leq \log(1 - L_i^r)$$

Notice that the Q-function in (16) is actually a constant, hence the constraint is linear. Now both inequalities are linear. These two inequalities constitute deterministic linear constraints for reliability. Combined with (9), the path selection problem is formulated as the following deterministic integer programming problem:

Problem Formulation: At each node i,

$$\text{minimize} \sum_{j\in N(i)} x_j$$

subject to

$$x_j\left(\frac{\alpha}{1-\alpha}(\Delta_{ij}^d)^2 + 2L_i^d d_{ij} - d_{ij}^2\right) \leq L_i^{d^2}, \text{ when } L_i^d - d_{ij} > 0 \tag{18}$$

$$\sum_{j\in N(i)} x_j \log\left(Q\left(\frac{R_{ij} - r_{ij}}{\Delta_{ij}}\right)\right) \geq \log\beta, \tag{19}$$

$$\sum_{j\in N(i)} x_j \log(1 - R_{ij}) \leq \log(1 - L_i^r) \tag{20}$$

$$x_j = 0 \text{ or } 1, \ \forall\ j \in N(i)$$

$$0 \leq R_{ij} \leq r_{ij}, \ \forall\ j \in N(i)$$

The new optimization problem is a deterministic estimate of the problem formulated in (5). There are many efficient algorithms to solve this integer programming problem. Note that the minimum distance to the sink of each node, in terms of hop count, is included in the neighbor table to eliminate loops. A node only opts for neighbors with fewer hop counts to the sink as eligible successor nodes, which avoid loops.

E. Calculation of Δ_{ij}^d and Δ_{ij}^r

Adaptive values of Δ_{ij}^d and Δ_{ij}^r may provide better estimates of path performance than the fixed ones due to the dynamic link conditions. A simple method is to determine current $\Delta_{ij}^d(t)$ and $\Delta_{ij}^r(t)$ based on previous values of $d_{ij}(t-1)$, $r_{ij}(t-1)$, and $\Delta_{ij}^r(t-1)$, and current values of $d_{ij}(t)$ and $r_{ij}(t)$. In real wireless networks, the link delay and reliability at successive time instants are correlated in time. The variance of the two constraints ought to embody time correlation in link quality. Therefore, our estimation mimics RTT estimation for timer management in TCP.

$$\Delta_{ij}^{d}(t) = (1-\rho)\Delta_{ij}^{d}(t-1) + \rho|d_{ij}(t) - d_{ij}(t-1)| \quad (21)$$

$$\Delta_{ij}^{r}(t) = (1-\gamma)\Delta_{ij}^{r}(t-1) + \gamma|r_{ij}(t) - r_{ij}(t-1)| \quad (22)$$

Tunable forgetting parameter μ and γ smooths the variations of d_{ij} and r_{ij} in time. For realistic wireless sensor networks, this is reasonable because current link state depends on historical link state.

F. Algorithm for MCMP

Our goal is to utilize the multiple paths to augment network performance with moderate energy cost. Thereupon, the objective function is to minimize the number of paths, as indicated in the Problem Formulation.

There are many existing algorithms [12] which can be applied to solve our linear integer programming. Table II outlines an efficient algorithm to solve our problem.

TABLE II

MULTIPATH ROUTING ALGORITHM

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0.  Delay-reliability Constrained Multipath Routing Algorithm
1.  $candidate = \{l_{ij} | h_j < h_i, j \in N(i)\}$;
2.  $forwarding = \emptyset$;
3.  $L_i^d = \frac{D-D_i}{h_i}$;
4.  if ($L_i^d \leq 0$)
5.      discard the packet and return;
6.  else
7.      $L_i^r = \sqrt[h_i]{R_i}$;
8.  Update $\Delta_{ij}^d(t)$ and $\Delta_{ij}^r(t)$ using equations (21) and (22);
9.  while ($candidate \neq \emptyset$){
10.     if (inequality (18) holds for $d_{ij}$ and $\Delta_{ij}^d(t)$){
11.         add link $l_{ij}$ to forwarding;
12.         $candidate = candidate - l_{ij}$}};
13. Applying the branch and bound algorithm to solve
    the reliability constraint in the Problem Formulation
    in the reduced solution space given by candidate.
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Lines 1 to 7 initialize values to be used in the following computation. Line 8 to 12 check the eligibility of each link and decides the forwarding sets. As described in section IV-C, they check the feasibility of links with delay constraint. Line 13 solves the optimization problem constrained by the reliability constraint in the solution space obtained in the preceding steps.

V. SIMULATION AND RESULTS

Our interest is to examine the feasibility of our approximate method of probabilistic modeling of unknown link delay and reliability in wireless sensor networks. Comparison is conducted with single path routing(SP), braided multipath routing [15] and God routing. God routing is defined as the routing algorithm that each node is aware of the instantaneous link delay and reliability, and selects multiple paths based on the exact knowledge, which is usually not available in reality. God routing serves as an ideal routing algorithm, thus its performance is the upper bound that is attainable by multipath routing. The closeness to God routing presents the efficacy of MCMP algorithm. The single path routing just selects an individual path, if any, which can fulfill the QoS requirement. In braided multipath routing, multiple paths are discovered at the path establish stage. Sink chooses the best path as primary path, others as alternate paths when the primary one fails. In our simulation, the best path is the one with the shortest delay between the source and sink pair. The performance difference between MCMP and single path routing or braided multipath routing reflects the performance improvement gained through MCMP.

The simulation is based on Parsec [17] developed by UCLA, which provides discrete-event simulation capability. The simulations are performed on a uniform topology consisting of 50 nodes spread in a square area of $100m \times 100m$. Sink is at the top left of the field. The transmission range of all nodes is 25m. Success probability of each transmission is randomly picked from [0.8, 1], which implies that the link reliability ranges from 0.8 to 1. Link delay is also randomly distributed in the range of [1, 50]ms. The link delay is the elapsed time for successfully transmitting a packet after receiving it. So it includes queuing time, contention time, transmission time, retransmission time and propagation time. As MCMP does not assume and utilize the distribution of link delay for routing decision, it can be applied to network with any link delay distribution. Here we choose uniform distribution following the popular simulation or numerical models in [2] [7] and [3]. Link states randomly vary at all transmission instants. The delay requirement is uniformly distributed between 120 to 260ms with an interval of 10ms. Likewise, the reliability requirement uniformly ranges from 0.7

to 1 with an interval of 0.05. Each simulation run randomly selects ten nodes to generate packets at the speed of 1 packet/second. Data packet has a fixed size of 150bytes. Each simulation lasts for 60 minutes.

A. Performance Metrics

Evaluated performance metrics include on-time packet delivery ratio, packet delivery ratio, expiration ratio, and average packet delay. On-time packet delivery ratio is the number of packets successfully received satisfying the QoS requirement to the total number of generated packets. Packet delivery ratio is the ratio of the number of packets successfully received to the total number of the generated packets. On-time packet delivery ratio exhibits the performance of packets with different delay requirements. While the packet delivery ratio demonstrates the performance of packets with different reliability requirements. Expiration ratio is the ratio of the number of packets that arrived at the sink violating the delay requirements to the total number of generated packets. The average packet delay is the average end-to-end delay experienced by successfully received packets. We investigate the performance metrics against delay and reliability requirements separately.

B. Simulation Results

The following figures show the simulation results, in which both the probability of delay and reliability constraint α and β in (19) are set to 95%. To display the relationship between performance metrics and QoS requirements, figures are shown separately with respect to delay and reliability. Results demonstrate that MCMP outperforms single path routing remarkably, and approaches approximately 95% of which for God routing.

Fig. 1 illustrates that packets with slack delay requirements have a higher on-time delivery ratio. The superior on-time delivery ratio of MCMP over single path routing and braided multipath routing validates the potentness of multipath routing. Owing to enhanced reliability, much more packets are received successfully at the sink node. MCMP improves performance by more than 50% over braided multipath routing. Without precise knowledge of link delay and reliability, MCMP has a slightly lower on-time delivery ratio than God routing.

Fig. 2 exhibits the distribution of expiring ratio. Note that the average expiring ratio is lower than $1 - \alpha = 5\%$, because some packets are lost or discarded before arriving at the sink. Expiring ratio of MCMP drops as delay requirement increases, due to the same reason as on-time packet delivery ratio vs. delay requirement. For delay requirements above 180ms, the expiring ratio is negligible, as they have a large solution space. Single path routing and braided multipath routing has a minute expiring ratio because most packets from distant nodes have been discarded or lost before arriving at the sink. For single path routing, the majority of received packets are from nodes within a short distance to the sink, so delay requirement is easy to satisfy.

Fig. 3 indicates the average end-to-end delay by successfully received packets. As God Routing has full knowledge of link states, it spans delay better than MCMP. Although the tuning parameter is used to confine the expiring ratio to a relatively small value, the algorithm is still a little conservative in estimating end-to-end delay. Consequently, delay is restricted in a small range compared to God routing. This explains that some packets are dropped at intermediate nodes, resulting in a lower packet delivery ratio compared to God routing. Hence, there is a tradeoff between the expiring ratio and on-time delivery ratio. Single path routing drops most of the packets generated farther away from the sink and has the smallest delay among three algorithms. Only packets originated in a few hop distance to the sink can be received. Braided multipath routing also has the least end-to-end delay because it uses the shortest paths.

Fig. 4 manifests the reliability performance of packets with different reliability requirements. The packet delivery ratio is almost the same for all reliability requirements, because they achieve the highest reliability constrained by α and β. The reliability performance of God routing also confirms of this. As implied by God routing, the achievable reliability is around 99%. MCMP attains the reliability around 96% with small expiring ratio. Hence, MCMP achieves 95% of the delivery ratio as we set it as β. Due to the relatively low link reliability, single path routing has to drop most packets due to multihop paths. Although braided multipath routing uses several alternate paths as backup to recover from packet loss, it just use one path to transfer packets, so the end-to-end reliability is inferior com-

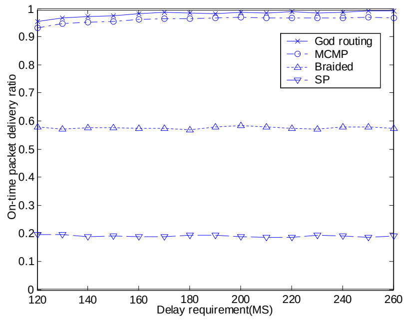

Fig. 1. On-time packet delivery ratio vs. delay requirement

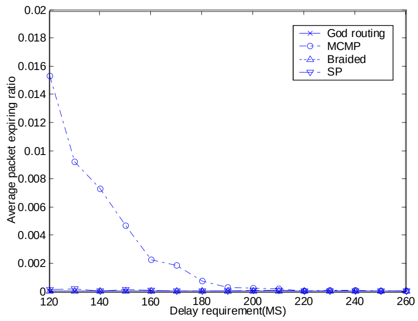

Fig. 2. Average packet expiring ratio vs. delay requirement

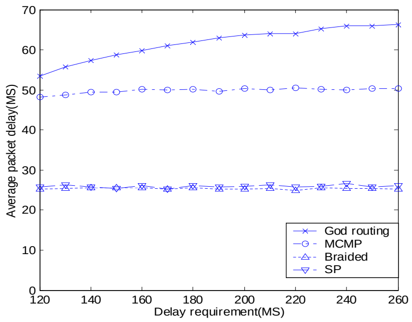

Fig. 3. Average End-to-End packet delay vs. delay requirement

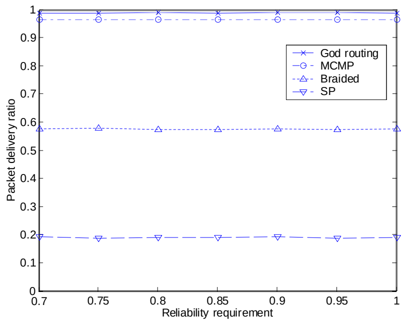

Fig. 4. Average packet delivery ratio vs. reliability requirement

pared to MCMP. Simulation results show that our MCMP algorithm prominently enhances the QoS routing performance without accurate link condition information. Although MCMP loses some of the packets due to its conservative partial solution space, it still approaches the optimal performance.

VI. CONCLUSION AND FUTURE WORK

In this paper, we propose a probabilistic modelling of link state for wireless sensor networks. Based on this model, an approximation of local multipath routing algorithm is explored to provide soft-QoS under multiple constraints, i.e. delay and reliability. Inherent computation complexity and prohibitive overhead associated with multiconstrained QoS routing problem pose serious challenges. Our MCMP routing algorithm trades precise link information for sustainable computation, memory and overhead for resource limited sensor nodes. Simulation results validate our scheme as its performance achieves near optimal performance. Though some feasible paths are excluded from solution space, the approximation algorithm still yields impressive outcome.

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