

## PAPER

# Multi-Constrained QoS Geographic Routing for Heterogeneous Traffic in Sensor Networks

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**SUMMARY** Sensor networks that carry heterogeneous traffics and are responsible for reporting very time-critical important events necessitate an efficient and robust data dissemination framework. Designing such a framework, that can achieve both the reliability and delay guarantee while preserving the energy efficiency, namely multi-constrained QoS (MCQoS), is a challenging problem. Although there have been many research works on QoS routing for sensor networks, to the best of our knowledge, no one addresses the above three service parameters all together. In this paper, we propose a new *aggregate routing* model and a distributed aggregate routing algorithm (DARA) that implements the model for achieving MCQoS. DARA is designed for multi-sink, multipath and location aware network architecture. We develop probabilistic models for multipath reliability constraint, sojourn time of a packet at an intermediary node and node energy consumption. Delay-differentiated multi-speed packet forwarding and in-node packet scheduling mechanisms are also incorporated with DARA. The results of the simulations demonstrate that DARA effectively improves the reliability, delay guarantee and energy efficiency.

**key words:** sensor network, multi-constrained QoS, heterogeneous traffic, geographic routing, delay-differentiated packet forwarding

## 1. Introduction

In Wireless Sensor Networks (WSNs), sensor nodes report the sensed data packets to the sink and based on the type of application, these packets may have diverse attributes: time-critical (TC) and non time-critical (NTC), loss-tolerant or loss-intolerant etc. In such heterogeneous traffic environment, the TC packets correspond to suddenly happened important events that typically require high data delivery ratio (i.e., reliability), while the NTC packets carry periodic environmental parameters like regular values of temperature, humidity, airflow, etc. that relax on both end-to-end packet delay and reliability. For example, in forest monitoring application, a data packet with temperature value of below 50°C may be regarded as NTC packet, whereas a data packet with above 100°C could probably mean a forest fire and hence it pertains to TC packet. Similarly, events like radiation leakage or moving object tracking in the battle field produce TC packets that must be reached at the sink within a certain time limit. The sudden surge of such TC traffics (along with other periodic NTC traffics) from hundreds of sensor nodes makes the reliable and timely event perception

much difficult for many reasons [1]–[3]. Also, achieving the energy efficiency is a critical concern in wireless sensor network protocol design [4], [5], [11].

Our goal is to design a data dissemination framework that can achieve both the reliability and delay guarantee while preserving the energy efficiency, we name it as multi-constrained QoS (MCQoS). We define reliability ( $R$ ) as the ratio of the number of unique packets received by the sink to the number of packets sent from the source nodes; and, given an application delay requirement  $D$ , the delay guaranteed service means that the time delay,  $d$ , experiences by any packet to reach its destination from the source is less than  $D$ . A routing scheme is said to be energy efficient if it ensures both low average energy consumption over time and smaller standard deviation of energy consumption of nodes.

Designing an efficient routing protocol for sensor networks that are responsible for reporting very time-critical important events poses the following constraints—routing should be shortest path, deadline-driven and energy aware. Recently, there have been several pioneering studies on achieving multi-constrained QoS in sensor networks [2]–[4]. However, these works either do not consider the reliability [2] or energy [3] or have abstract and/or restrictive assumptions on the underlying routing structure [4], which limits their scope of applicability.

In this paper, we propose a MCQoS geographic routing scheme that considers three service parameters—reliability, delay guarantee and energy efficiency. It defines an *aggregate routing function* based on three metrics: geographic progress towards the destination, residual energy and expected sojourn time of a packet at the receiving node. Rather than simple greedy forwarding (GF), we propose selective greedy forwarding (SGF) to reduce energy consumption and interference. SGF facilitates TC packets to travel faster than NTC packets. We develop probabilistic models for multipath reliability constraint, sojourn time of a packet at an intermediary node and node energy consumption. We then propose a distributed aggregate routing algorithm (DARA) that finds a forwarder node with the maximum *aggregated weight*. DARA does not maintain any global state information. It is a fully localized algorithm, i.e., each sensor node performs localized routing decisions, yet the collective outcome ensures almost homogeneous energy dissipation rates keeping on-time reliable data delivery. Reliability is increased by sending duplicate packets from source nodes, if necessary. The proposed routing scheme supports

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both the static and dynamic network topologies.

We have carried out extensive simulations in *ns-2.30* to evaluate the performance of DARA algorithm. The results of the simulations depict that DARA outperforms state of the art MCQoS routing protocols in terms of reliability, end-to-end packet delay, network lifetime and workload overhead. The rest of the paper is organized as follows. Section 2 discusses on the challenging issues of achieving MCQoS in WSN and Sect.3 presents the proposed aggregate routing model, probabilistic analysis and DARA algorithm. The effective data delivery strategies for achieving MCQoS are proposed in Sect.4 and the performance evaluation is carried out in Sect.5. Section 6 concludes the paper.

## 2. Multi-Constrained QoS: Challenging Issues

The challenging issues of achieving MCQoS in sensor networks are described in the following subsections.

### 2.1 Multi-Constrained Hard-QoS vs. Soft-QoS

Due to the seemingly contradictory relationship amongst the service parameters, it is not possible to find a solution that minimizes all the parameters (hard-QoS) [1]. For instance, the use of shortest route from source to sink is most desirable to providing delay guaranteed service, but this approach puts additional burden on a set of nodes in terms of energy utilization. Adopting link layer ARQ mechanism at each hop with higher retry count values may increase the reliability [3], but doing so increases the energy consumption as well as per node packet delay. Therefore, we look for some tradeoffs among the constraints to achieve soft-QoS provisioning.

### 2.2 Single-sink Multipath vs. Multi-sink Multipath Routing

Single-sink multipath routing [3],[4] is not applicable for provisioning MCQoS as the data packets converge somewhere near the sink as in Fig. 1(a), which increases traffic contention and average packet delay. Therefore, we advocate that the use of multi-sink multipath routing (Fig. 1(b)) is more suitable as it splits the large burst of data into several smaller bursts flowing through spatially separated nodes.

### 2.3 Cluster-Based vs. Location-Based Architecture

For multi-constrained QoS provisioning, cluster based backbone networks are not suitable, mainly due to the following two reasons: *first*, huge overhead of route construction and reconstruction, especially for large scale networks and *second*, disruption of network service during path refreshment violates QoS for both the delay and reliability guarantees. On the other hand, in location-based network architecture, no prior path setup or path recovery mechanisms are required, nodes can forward packets to a neighbor closer to the base station and packets can eventually be delivered to

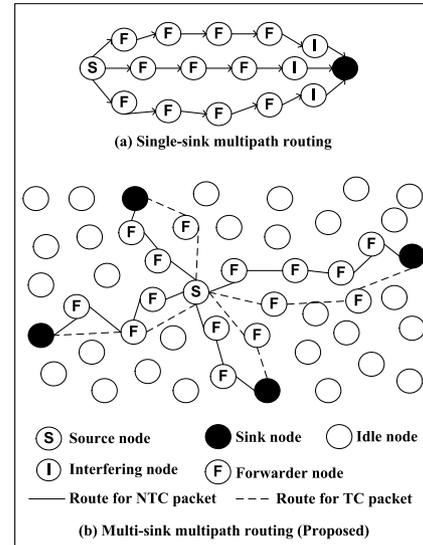


Fig. 1 Single-sink multipath and multi-sink multipath routing.

the destination without requiring any global state information [5]–[8]. Such network architecture provides with high scalability and robustness.

### 2.4 Pitfalls in Existing Works

In geographic routing, the most popular routing metric is the progress speed, which looks for a neighbor node geographically closest to the destination [6]–[8]. This simple greedy approach gives the least hop route from the source to the destination. But, if all the packets are routed over this route, a small set of nodes will be overburdened in terms of energy and network load. Energy-aware QoS geographic routing [2], in selecting the next hop node, assigns more priority to the delay factor for emergency packets and to the energy factor for less aggressive packets.

MMSPEED [3] is a novel packet delivery mechanism, where routing is driven by two parameters — the geographic progress speed of a packet from node  $i$  to  $j$  towards the final destination  $k$ ,  $Speed_{i,j}^k$ , and the end-to-end total reaching probability (TRP). In MMSPEED, node  $i$  forwards a packet to its downstream node  $j$  whose  $Speed_{i,j}^k$  value is higher and TRP is greater than some threshold. But, unfortunately the calculation of  $Speed_{i,j}^k$  does not consider the residual energy and expected sojourn time at target node  $j$  and TRP is calculated on the assumptions that (i) packet loss rate in each of the following hops will be similar to the local loss rate of the current node and (ii) for each of the following hop, the geographic progress to the destination will be similar to the current progress. Hence, the routing function of MMSPEED does not reflect the real dynamics of sensor network, where achieving energy efficiency and minimizing per node packet delay are the main hurdles of MCQoS routing.

Multi-constrained multipath (MCMP) routing [4] uses link delay and reliability as routing decision parameters in single-sink multipath network (Fig. 1(a)). Packets are du-

plicated at each hop by solving optimization problem. But, this approach considers neither residual energy nor progress speed. Hence, packets may get routed to a node which is highly congested and/or energy critical.

### 3. Proposed Aggregate Routing Model and Algorithm

#### 3.1 Basic Idea

The basic idea is to allow the TC data packets to go through the shortest route and the NTC traffics to follow a longer route keeping the shortest route free for TC packets. DARA algorithm finds most suitable forwarder nodes towards each sink for both the TC and NTC packets. The number of duplicate packets at each source node is calculated by solving an optimization problem. Forwarder nodes schedule the packet with the least delay-deadline value first and subsequently the other packets.

#### 3.2 Network Model

We consider a densely deployed large scale sensor network in which  $S$  identical sensor nodes and  $M$  sinks are uniformly distributed (Fig. 1(b)). The nodes and sinks know their geographical locations either via GPS (Global Positioning System) or other location determination techniques [10]. Each sensor node broadcasts BEACON messages to its single-hop neighbor nodes, each after  $d_{beac}$  units of time, which carry the node's  $(x, y)$  position, residual energy ( $E_{residual}$ ), and expected sojourn time of a packet ( $E[\delta]$ ). A node also learns location of the sinks by receiving location update broadcast messages from them<sup>†</sup>. Thus each sensor node knows geographical locations of all sinks and its neighbor nodes. This information is required by the proposed routing algorithm, DARA.

We assume that the radio transmission range ( $R_{tx}$ ) of all sensors is equal and there is no hole in the network [5]. Each node has the equal initial energy ( $E_{initial}$ ). The distance between any pair of nodes,  $i$  and  $j$ , is the Euclidian distance between them, denoted as  $dist(i, j)$ . Modified 802.11 MAC protocol is used. DARA uses two additional fields in the header of each data packet: type of service (ToS) and time to live (TTL) fields. The value of the ToS field is set to 1 for TC packets, 0 otherwise. TTL field represents the delay deadline of a packet and it varies from application to application. We also assume that the sinks are connected via an external network to a data collection center, which takes the controlling decisions based on the collected data packets. Therefore, it is sufficient that any of the sinks receives one copy of the transmitted packet. We consider that events can occur anytime at any point of the network with equal probability and detection of each event is reported by sensor nodes for a fixed small amount of time  $\tau$ , as shown in Fig. 2. The latter assumption is valid since it is unnecessary to report an event occurrence for a longer period of time. Two events,  $Z_k$  and  $Z_{k+1}$ , are randomly separated by 0 or more

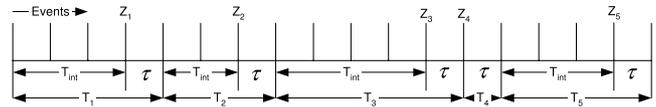


Fig. 2 Event durations and intervals between them.

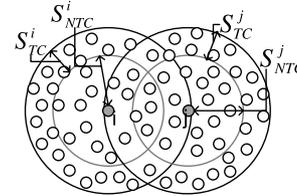


Fig. 3 Disjoint sets of downstream nodes for TC and NTC packet delivery.

event periods.

#### 3.3 Selective Greedy Forwarding (SGF)

For each node  $i$ , we define two disjoint sets of nodes for heterogeneous traffic dissemination (Fig. 3). Let  $S^i_{TC}$  be the set of node  $i$ 's candidate downstream nodes for delivering TC packets and all members in this set are within distance  $r_{TC}$  from node  $i$ ,  $\frac{2R_{tx}}{3} < r_{TC} \leq R_{tx}$ . Similarly,  $S^i_{NTC}$  represents the node  $i$ 's set of candidate downstream nodes for delivering NTC packets and all members of this set are within  $r_{NTC}$  distance,  $0 < r_{NTC} \leq \frac{2R_{tx}}{3}$ . If two nodes  $i$  and  $j$  are neighbors of each other, for a densely deployed network, the following two conditions must hold:

- (i)  $S^i_{TC} \cap S^j_{TC} \neq \phi$  and (ii)  $S^i_{NTC} \cap S^j_{NTC} \neq \phi$

Therefore, for multi-sink and multipath routing, the node  $i$  and  $j$  may be downstream nodes of each other for different flows.

#### 3.4 Reliability Constraint Analysis

In the case of SGF (Sect. 3.3), the minimum hop distance from node  $i$  to any sink  $m$ , located at distance  $dist(i, m)$ , can be calculated as follows.

$$h_{TC}(i, m) = \left\lceil \frac{dist(i, m)}{R_{tx}} \right\rceil, \text{ for TC packets}$$

$$h_{NTC}(i, m) = \left\lceil \frac{dist(i, m)}{\frac{2R_{tx}}{3}} \right\rceil, \text{ for NTC packets} \quad (1)$$

Irrespective of the type of packet, let we consider that the node  $i$  is at least  $h(i, m)$  hops away from the sink  $m$ . If some link layer ARQ mechanism is adopted and maximum retry limit is  $t$  at each hop, then the probability that the packet reaches the sink is given by

<sup>†</sup>It is reasonable to assume that sinks are powerful enough to reach all nodes of the network by broadcasting location update messages [11]. In the case the nodes and sinks move, the frequency of these location update messages will be increased by the sinks dynamically.

$$P_x = \prod_{j=1}^{h(i,m)} [1 - (1 - p_x^j)^{t+1}] \quad (2)$$

where,  $p_x^j$  is the probability that a transmission is success at  $j$ th hop of a multi-hop route  $x$ . This probability  $P_x$  represents the ultimate reliability of the route, because a high probability of success indicates a more reliable route. If the required reliability,  $R$ , is higher than the offered reliability of a route, then the only feasible way to achieve the reliability is to send multiple copies of the same data packet towards different sinks, so that the aggregate reliability might meet  $R$ . If all  $M$  sinks are selected as destinations, then the probability that at least one copy is successfully received is

$$P_f = 1 - \prod_{x=1}^M (1 - P_x). \quad (3)$$

If  $N$  packets are sent, and  $X$  packets are received by the sinks, then the random variable  $X$  has a *binomial distribution* and the *pmf* is given by

$$P(X = k) = \binom{N}{k} P_f^k (1 - P_f)^{N-k}. \quad (4)$$

Suppose, the required reliability  $R$  is achieved whenever  $L$  packets are received by the sinks out of  $N$  packets sent, then we have  $R = L/N$ . To achieve this,  $X$  must be greater than or at least equal to  $L$ . Therefore, the probability that the reliability requirement is met,  $P_R$ , is given by

$$\begin{aligned} P_R &= \sum_{k=L}^N P(X = k) \\ &= \sum_{k=L}^N \binom{N}{k} P_f^k (1 - P_f)^{N-k}. \end{aligned} \quad (5)$$

### 3.5 Modeling Sojourn Time of a Packet

We model a sensor node as an M/G/1/K queue (Fig. 4).

Based on the assumption that events can occur anytime at any point of the network with equal probability and each event persists for  $\tau$  units of time, we find the probability of occurring at least one event at a particular point of the network is equal to  $g\tau$ , where  $g$  be the Poisson rate of data generation at a point in the network. Thus, the data generation probability of a sensor node, within one sensing period, is equal to  $g\tau A$ , where  $A$  is the sensing coverage area of a sensor. We also assume  $n$  the number of total source nodes for which a sensor is forwarding data packets is Poisson distributed. Therefore, due to the superposition property of the Poisson process and the equal data generation probability of nodes, the arrival process of a node is also Poisson and it is

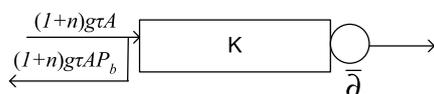


Fig. 4 An M/G/1/K model of a sensor node.

equal to  $(g\tau A + ng\tau A)$  i.e.,  $(1 + n)g\tau A$ . The service time requirements have a general distribution with mean  $\bar{\delta}$ . The *pmf* of the total number of packets in the node has the following expression

$$P[N = n] = \frac{(1 - \rho)\rho^n}{(1 - \rho^{K+1})} \quad (6)$$

where,  $\rho$  is the traffic intensity and is equal to  $(1 + n)g\tau A\bar{\delta}$ . An arrival will be blocked if the total number of packets in the node has reached a predetermined value  $K$ . Therefore, the service model can handle at most  $K$  packets at a given time. The probability of blocking is denoted as  $P_b$ . Hence, the rate of blocked packets is given by  $(1 + n)g\tau AP_b$ . From Eq. (6), we can derive the following performance metrics: average sojourn time of a packet, throughput and blocking probability. Since the blocking probability  $P_b$  is equal to the probability that there are  $K$  packets in the node, i.e., the node is full, it is given as follows.

$$P[N = K] = \frac{(1 - \rho)\rho^K}{(1 - \rho^{K+1})} \quad (7)$$

The node throughput  $H$  is the rate of packets transmitted successfully. When the node reaches at equilibrium,  $H$  is equal to the rate of accepted packets,

$$H = (1 + n)g\tau A(1 - P_b). \quad (8)$$

The sojourn time of a packet is defined as the time from the packet insertion into the interface queue until the notification of successful transmission. It includes the queuing delay, *backoff* timeout, contention period, and retransmissions due to error or collision. Therefore, following the Little's law, we can calculate the expected sojourn time of a packet as in Eq. (9).

$$E[\delta] = \frac{E[N]}{H} = \frac{\rho^{K+1}(K\rho - K - 1) + \rho}{ng\tau A(1 - \rho^K)(1 - \rho)} \quad (9)$$

The parameter  $\bar{\delta}$  in our model is to be estimated. We assume that the average sojourn time for a certain arrival rate can be estimated from measurements. The estimation at node  $i$ ,  $\hat{\delta}_i$ , is obtained by maximizing the likelihood function of the observed average sojourn time (Appendix B).

### 3.6 Node Energy Consumption Model

Based on the assumption that the node energy is consumed mainly due to the transmission or reception of data packets and duration of each event reporting is a fixed small time  $\tau$ , we can develop an energy consumption model of a sensor node as follows. The energy consumed for each TC and NTC packet transmission is calculated as follows [11]

$$\begin{aligned} e_{TC} &= (e_{te} + e_{ta}R_{tx}^\alpha) \times L_{TC} \\ e_{NTC} &= \left( e_{te} + e_{ta} \left( \frac{2R_{tx}}{3} \right)^\alpha \right) \times L_{NTC} \end{aligned} \quad (10)$$

where,  $e_{te}$  is the energy per bit needed by the transmitter

electronics,  $e_{ta}$  is the energy consumption of the transmitting amplifier to send one bit over one unit distance,  $L_{TC}$  and  $L_{NTC}$  are the packet sizes of the TC and NTC packets in bits, respectively, and  $\alpha$  is the path loss factor depending on the radio frequency environment and is generally between 2 and 4. However, the energy per bit needed by the receiver electronics,  $e_{re}$ , does not include the energy consumption due to amplification and is same for both TC and NTC data bits. So, the energy consumed for each packet reception is given as follows

$$e_r = e_{re} \times [L_{TC}I + L_{NTC}(1 - I)] \quad (11)$$

where,  $I$  is an indicator variable;  $I = 1$  for TC packets and 0 otherwise. A significant amount of energy is also dissipated by a sensor node while it overhears the transmission of packets from other nodes. The energy consumed to read header of a packet is given as follows

$$e_{rh} = e_{re} \times L_{header} \quad (12)$$

where,  $L_{header}$  is the length of the header of a packet in bits. As described in Sect. 3.5,  $(1 + n)g\tau A$  represents the probability of total data traffic passing through a node. Therefore, the probabilistic amount of energy dissipated by a node due to data traffic during  $z$ th event period is given by

$$E_{dissipated}^z = e_{TC} \times (1 + n)g\tau AI + e_{NTC} \times (1 + n)g\tau A(1 - I) + e_r \times ng\tau A + e_{rh} \times \Gamma \quad (13)$$

where,  $\Gamma$  is the number of data packets overheard during the event period. If a node senses, overhears and carries data traffic for  $Z$  number of events, then the residual energy of the node can be calculated as Eq. (14).

$$E_{residual} = E_{initial} - \sum_{z=1}^Z E_{dissipated}^z \quad (14)$$

Moreover, if an event is preceded by  $Y$  non-sensing periods (Fig. 2), then the discrete random variable  $Y$  has a geometric distribution and its pmf is given as follows.

$$P(Y = y) = (1 + n)g\tau A[1 - (1 + n)g\tau A]^{y-1} \quad (15)$$

The cdf of the time interval ( $T_{int}$ ) between two successive events is given by

$$P(T_{int} \leq y\tau) = \sum_{k=0}^y (1 + n)g\tau A[1 - (1 + n)g\tau A]^{k-1} = 1 - [1 - (1 + n)g\tau A]^y. \quad (16)$$

Hence,  $T_{int}$  is an exponentially distributed random variable. If  $E_{residual}(t_1)$  and  $E_{residual}(t_2)$  be, respectively, the residual energy of a node after time  $t_1$  and  $t_2$  (where,  $t_2 > t_1$ ), then the energy difference  $E_{diff} = E_{residual}(t_1) - E_{residual}(t_2)$  is a Poisson distributed discrete random variable. Since  $E_{residual}$  can never be increased with time and its decrement over time is Poisson distributed, it can be modeled as a Pure-Death CTMC.

### 3.7 Distributed Aggregate Routing Algorithm (DARA)

Using BEACON messages each node  $i$  learns  $(x, y)$  position, residual energy ( $E_{residual}$ ) and expected sojourn time of a packet ( $E[\delta]$ ) of all neighbor nodes. Our intention is to forward data packets to a downstream node which gives higher geographic progress, lower sojourn time and/or has the higher residual energy. To accomplish this, we use aggregated weight of these routing metrics. We define the aggregated weight of a candidate downstream node as the sum of individual normalized weights of its above parameters. The node  $i$  calculates the normalized geographic progress of a packet towards a sink  $m$  for each candidate downstream node  $j$  as follows

$$NGPROG(i, j, m) = \frac{dist(i, m) - dist(j, m)}{dist(i, m)} \cdot \hat{r}_{ij} \quad (17)$$

where,  $\hat{r}_{ij}$  represents the estimated reliability of the link  $(i, j)$ , which is measured as the ratio of the number of packets received by the downstream node  $j$  to the number of packets sent by the upstream node  $i$ . We assume that each node  $i$  can measure  $\hat{r}_{ij}$  using the exponential weighted moving average (EWMA) formula [4], and this is reasonable because the link reliability at successive time instants are correlated in time (i.e., current link state depends on historical link states). Note that, in Eq. (17), only the downstream nodes  $j$  that satisfy the condition  $dist(i, m) > dist(j, m)$  are considered. The node  $i$  calculates the normalized residual energy for each candidate downstream node  $j$  as follows.

$$NRE(j) = \frac{E_{residual}^j}{E_{initial}^j} \quad (18)$$

Also, the node  $i$  can calculate the normalized expected sojourn time of a packet at each candidate downstream node  $j$  as follows

$$NDELAY(j) = \frac{E[\delta_j]}{TTL_{initial}} \quad (19)$$

where,  $TTL_{initial}$  is the initial TTL value of the packet to be transmitted. In our simulation, we set 200 ms for TC packets and 400 ms for NTC packets, respectively, as their initial TTL values.

Now, the problem of routing a packet from the source node to the destination sink clearly boils down to the problem of finding the downstream node that produces the maximum *aggregated weight*. The node  $i$ , in DARA, for delivering the TC and NTC data packets towards a sink  $m$ , respectively, finds the downstream node with maximum *aggregated weight* using the following equations

$$DN_{TC}(i, m) = \max_{j \in S_{TC}^i} (\alpha \cdot NGPROG(i, j, m) + \beta \cdot NRE(j) + \gamma \cdot (1 - NDELAY(j))) \quad (20)$$

$$DN_{NTC}(i, m) = \max_{j \in S_{NTC}^i} (\alpha \cdot NGPROG(i, j, m)$$

$$+\beta.NRE(j) + \gamma.(1 - NDELAY(j))) \quad (21)$$

where,  $\alpha$ ,  $\beta$  and  $\gamma$  are nonnegative weight factors conditioning that  $\alpha > \beta > \gamma$  and  $\alpha + \beta + \gamma = 100$ . Thus, the normalized geographic progress parameter has the highest weight while expected sojourn time gets the least weight factor. The analytical analysis and our extensive simulation results, performed in *ns-2.30*, conclude that for a densely deployed network, setting  $\alpha = 70$ ,  $\beta = 20$ , and  $\gamma = 10$  produces the best results.

The rationale to define and maximize the *aggregated weight function* in Eq. (20) and Eq. (21) is as follows. The aggregated weight is a linear combination of three parameters. The first parameter  $NGPROG(i, j, m)$  represents how much geographic progress a packet can make towards the destination sink  $m$ . In Eq. (17), the factor  $\hat{r}_{ij}$  is correspond to the quality of the link  $(i, j)$ . Therefore, maximizing Eq. (17) means maximizing the packet transmission efficiency. If several candidate downstream nodes have the same residual energy and expected sojourn time of a packet, maximizing Eq. (20) or Eq. (21) decreases the number of hops a packet has to travel before it reaches at the destination, which in turn decreases both the energy consumption and end-to-end packet delay. The second parameter  $NRE(j)$  represents the fraction of energy available at downstream node  $j$ . This part contributes to ensure the balanced energy consumption by the nodes. The third parameter  $NDELAY(j)$  corresponds to the expected fraction of lifetime of a packet that may be spent at the candidate downstream node  $j$ . The lower the value is, the better the packet transmission efficiency is. Even though, in Eq. (20) and Eq. (21), the least weight is given to this parameter, it plays an important role in (i) achieving well traffic load distribution among the nodes and (ii) restricting a sender from delivering data packets to a highly loaded node. Finally, the distributed aggregate routing algorithm (DARA) that finds the downstream nodes for each sink is presented below.

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### DARA Algorithm

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At each node,  $i$ :

1. **Initialization:**
2. **for** each sink  $m$
3.     **set**  $DN_{TC}(i, m) = \phi$  and  $DN_{NTC}(i, m) = \phi$
4. **broadcast** BEACON message
- 5.
6. **loop**
7.     **wait** (until node  $i$  receives a BEACON
8.         message from some neighbor node  $j$ )
9.     **add** node  $j$  to either  $S_{TC}^i$  or  $S_{NTC}^i$  //see Sect. 3.3
10.    **for** each sink  $m$
11.     **calculate**  $NGPROG(i, j, m)$ ,  $NRE(j)$  and
12.      $NDELAY(j)$  using Eq. (17), Eq. (18) and Eq. (19),
13.     respectively.
14.     **update**  $DN_{TC}(i, m)$  or  $DN_{NTC}(i, m)$
15.     using Eq. (20) or Eq. (21), respectively.
16. **if** (node  $i$  finds that it has to send BEACON msg.,

17.    *i.e.*,  $d_{beac}$  expires — see Appendix A)
  18.    **broadcast** BEACON message
  19. **forever**
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## 4. Achieving Multi-Constrained QoS

DARA algorithm provides each node  $i$  with the most suitable next hop node for each sink  $m$ . We denote the sets of all these  $M$  downstream nodes as  $DN_{TC}(i)$  and  $DN_{NTC}(i)$  for forwarding TC and NTC packets, respectively. Now, the time has come to propose the effective data delivery strategies for the node  $i$  that can meet our goal.

### 4.1 Achieving Reliability

To increase the reliability, we propose that only the source node sends multiple copies of a packet (packet duplication), if required, towards multiple sinks while the intermediate nodes forward the received copy only towards the destination sink. Therefore, once the members of the sets  $DN_{TC}(i)$  and  $DN_{NTC}(i)$  are identified, the next problem is to minimize the degree of packet duplication,  $\zeta_i$ , which is defined as follows

$$\zeta_i = \sum_{j=1}^M I_j, \quad \forall j I_j \in DN_{TC}(i) \text{ or } DN_{NTC}(i) \quad (22)$$

where,  $I_j$  is an indicator variable;  $I_j = 1$  if the node  $j$  is selected, 0 otherwise. As  $\hat{r}_{ij}$  represents the estimated reliability of the link  $(i, j)$ , the optimization problem can be formulated as follows.

$$\text{Minimize } \zeta_i \quad (23)$$

Subject to :

$$1 - \sum_{j=1}^M (1 - I_j \hat{r}_{ij}) \geq R, \quad \forall j I_j = 0 \text{ or } 1 \quad (24)$$

The solution to the above optimization problem is quite easy to implement. The source node  $i$  sorts all the candidate downstream nodes  $j$  according to their  $\hat{r}_{ij}$  values in descending order. Then it takes downstream nodes  $j$  from the sorted list one after another until the condition in Eq. (24) satisfies. Therefore, the adequate number of duplicate packets are transmitted in the network and the above solution is not computationally expensive, *i.e.*, it is suitable for energy-constrained sensor networks.

### 4.2 Achieving Delay Guarantee

DARA algorithm ensures that TC packets travel much faster than NTC packets. Even though this delay-differentiated multi-speed packet forwarding mechanism minimizes a certain amount of delay for TC packets by decreasing the number of hops in between the source and the destination nodes, it does not minimize the queuing delays of TC packets at

forwarder nodes. To reap the full benefit of it, we propose the delay-differentiated in-node packet scheduling mechanism that gives higher priority to the TC packets.

As shown in Fig. 5, Dynamic Packet Classifier (DPC) stores an incoming packet in either of the two priority queues,  $PQ_{TC}$  and  $PQ_{NTC}$ , based on the ToS field of the packet. Packets are prioritized with their delay-deadline values—lower the TTL value, higher the priority. DDPS (Delay-differentiated Packet Scheduling) unit schedules the highest priority packet first and continues to schedule packets from  $PQ_{TC}$  until it finds the head of line (HOL) packet of  $PQ_{NTC}$  has lower TTL value than that of  $PQ_{TC}$ . To avoid starvation problem, we adopt aging technique in both the queues. One key advantage of using this double queuing mechanism is that the number of TC packet drops due to buffer overflow is not influenced by the low priority NTC packets.

We borrow the approach of MMSPEED [3] for updating the delay deadline value of a packet and packet dropping policy at each downstream node, which does not require any global clock synchronization.

### 4.3 MAC Layer Additional Functionality

We propose two separate queues for TC and NTC packets in the MAC layer also, as shown in Fig. 5. NTC packets are served only when there is no TC packet in the queue. End-to-end (E2E) delay of TC packets is further reduced by modifying 802.11 MAC functions as follows. At the beginning of TC packet transfer, a node waits only SIFS period of time (rather than DIFS) before transmitting a RTS packet. If the medium is found to be busy after the expiry of *backoff* timer, the contention window value is randomly chosen from the range  $0 \sim \frac{CW_{min}}{2}$  (rather than from  $0 \sim CW_{min}$ ). We turn off *post backoff* timer [2] till all the TC packets are transmitted. The above modifications assign higher priority to TC packets in two levels: inter-node and intra-node and thereby ensures lower E2E delay. As described in Sect. 3.7, link reliability for each downstream node is estimated at MAC layer and passed to DARA unit of network layer. We use a reliable

multicast protocol (for instance, reliable multicast delivery in MMSPEED [3] or BEMA [16]) for the source nodes as they require transmitting a packet to multiple next hop nodes reliably.

Partitioning the candidate downstream nodes into two disjoint sets  $S_{TC}^i$  and  $S_{NTC}^i$  also allows us to use control mechanism for transmission power adjustment to save battery and reduce interference [9], [13].

## 5. Performance Evaluation

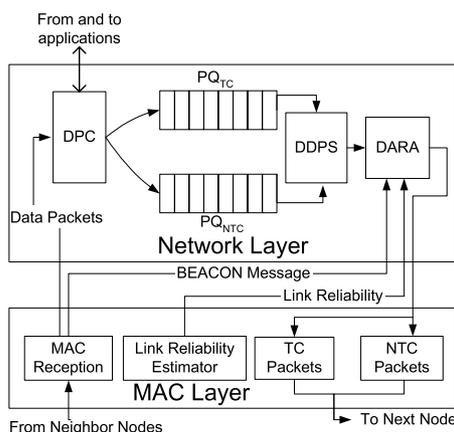
We have done extensive simulations in *ns-2.30* [17] to evaluate the performance of the proposed load and energy balanced shortest path routing algorithm, namely DARA. We have also implemented MMSPEED [3] and MCMP [4] routing algorithms to compare with DARA.

### 5.1 Simulation Setup

The simulation environment parameters are listed in Table 1. However, values of some parameters are different in MMSPEED and MCMP. For the implementation of MMSPEED, we have used EDCF MAC parameters listed in Table 2 of [3]. Similarly, in the implementation of MCMP, we have used the same values of constant parameters (e.g.,  $\alpha$ ,  $\beta$ ) as was used in [4]. But, unlike in MCMP, we have used estimated values of the link reliability and link delay for the sake of fair comparison with DARA. Finally, we have ex-

**Table 1** Simulation parameters.

Parameter	Value
Terrain	1000 m × 1000 m
Sensor nodes	1000
Node distribution	Uniform random
Trans. radius	100 m for TC packets 66 m for NTC packets
Initial energy	50 Joule
Data rate	512 kbps
Buffer size	30 Packets
Payload size	32 Bytes
PHY, MAC headers	192 bits, 184 bits, respectively.
RTS, CTS packets	208 bits, 112 bits, respectively.
ACK packet	128 bits
Time slot, DIFS, SIFS	10 $\mu$ s, 34 $\mu$ s, 10 $\mu$ s, respectively.
$CW_{min}$	31
$CW_{max}$	1023 for NTC packets 511 for TC packets
Max. retry limit	1–6
$\alpha, \beta, \gamma$	$\alpha = 70, \beta = 20, \gamma = 10$
Transmit power	$7.214e^{-3}$ Watt
Rcv. signal threshold	$3.65209e^{-10}$ Watt
PHY error model	Uniform random
Bit error rate	$10^{-3}$
FEC strength	1
Required reliability	0.8
$TTL_{initial}$	200 ms for TC packets 400 ms for NTC packets
Simulation time	300 seconds
Sink	4 sinks, sink 1 at location [48, 1], 2 at [0, 967], 3 at [965, 18] and 4 at [961, 991].



**Fig. 5** Delay-differentiated in-node packet scheduling (DDPS).

ecuted the above three algorithms for the same traffic settings as follows: 120 nodes are randomly selected as source nodes; out of them 100 nodes generate NTC packets at the rate of 4 pkts/sec, for 1 second duration at every 30 seconds interval. The rest 20 nodes generate TC packets during 50–100thsec. and 200–250thsec., at a very high rate, 10 pkts/sec. Unless otherwise specified, the sensor nodes and sinks are stationary after the deployment.

## 5.2 Performance Metrics

The performance metrics used are defined as follows.

**Reliability:** It is the ratio of the total number of unique packets received by the sinks within the delay-deadline to the number of packets generated by all the source nodes. The higher the value is, the better the transmission efficiency is.

**Average end-to-end packet delay:** End-to-end delay of a single packet is measured as the time difference between when the packet is received at the sink from its generation time at the source node. Delays experienced by individual data packets are averaged over the total number of individual packets received by sinks. The lower the value is, the better the performance is.

**Energy efficiency ( $\eta$ ):** It is measured as the ratio of total amount of energy dissipated by all source and forwarder nodes to the number of unique packets received by sinks. Therefore, in this paper, the *energy efficiency* is represented by the average amount of energy expenditure for each successful packet reception. If the same amount of total energy is dissipated by any two protocols then the protocol that has higher delivery ratio (i.e., reliability) will perform better than the other one. Note also that higher the  $\eta$  value is, lower the protocol efficiency is and vice-versa.

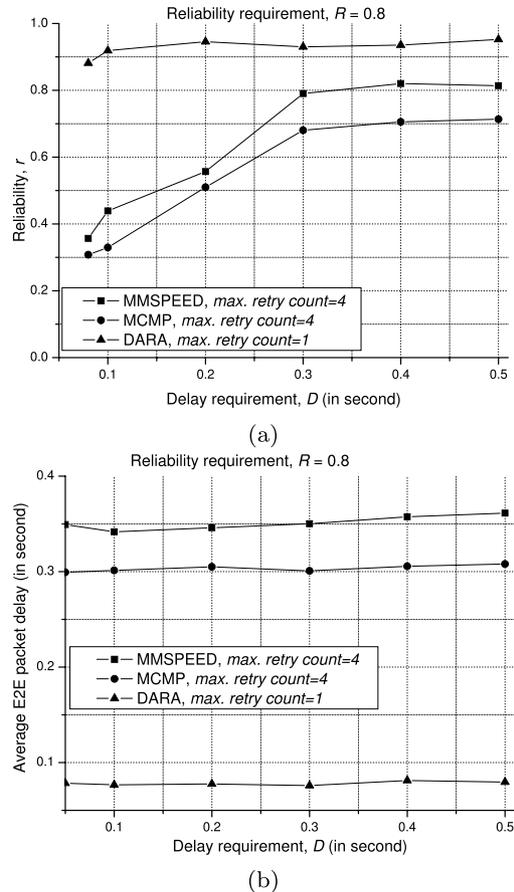
**Standard deviation of residual energy ( $\sigma$ ):** It gives the average variance between the residual energy levels on all nodes, and is measured by Eq. (25).

$$\sigma = \sqrt{\frac{1}{S} \sum_{i=1}^S (E_{residual}^i - \mu_{residual})^2} \quad (25)$$

where,  $E_{residual}^i$  and  $\mu_{residual}$  are, respectively, the residual energy of node  $i$  and mean residual energy for all nodes. Therefore, the value of  $\sigma$  indicates how well the energy consumption is distributed among the sensor nodes. The smaller the value is, the better the capability the routing protocol has in balancing the energy consumption.

**Control packet overhead:** The number of BEACON messages generated by DARA, NINFO (neighbor information) packets generated by MCMP and location update and back-pressure packets generated by MMSPEED during the whole simulation period are counted to compare the workload overhead incurred by the control packets. Therefore, the lower the value is, the higher the protocol performance is.

**Packet duplication overhead:** It is measured as the ratio of total number of duplicate data packets transmitted all over



**Fig. 6** (a) Reliability and (b) average E2E packet delay for different E2E delay-deadlines.

the network during the whole simulation period to the total number of data packets generated by all the source nodes. We have expressed this workload overhead in percentage.

**Energy consumption overhead:** It is measured as the total amount of energy dissipated by sensor nodes for transmission and reception of control packets and duplicate packets.

**Network lifetime:** We define lifetime of a network as the length of time from the network deployment until the first node drains out of its energy among all  $S$  nodes<sup>†</sup>.

## 5.3 Simulation Results

According to graphs of Fig. 6(a), even with very aggressive delay-deadline packets (100–200 ms) and retry count value 1, DARA provides with more than 93% reliability, which is much higher than that of MMSPEED and MCMP. This result is achieved as: (i) buffer drop is greatly reduced in DARA (since it is load adaptive), (ii) SGF and transmission power control reduce collision drops, and (iii) DDPS reduces packet drops due to deadline failure. Finally, the

<sup>†</sup>This is a meaningful measure in the sense that failure of first node is an indication of the remaining limited network lifetime or in some other deployments, it can make the network become partitioned and further services be interrupted.

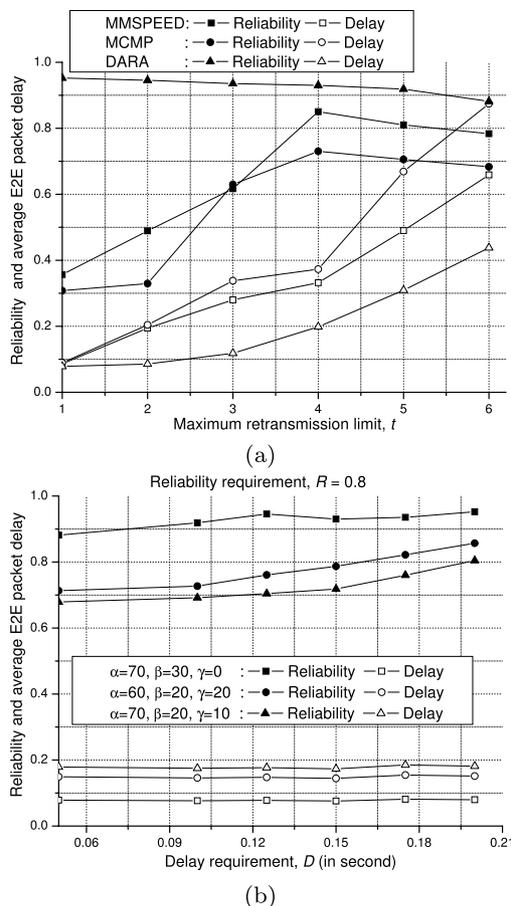


Fig. 7 Reliability and average E2E packet delay for different (a) retransmission limits and (b) weight factors.

reliability is also increased by adequate number of packet duplications at source nodes. Figure 6(b) shows that the average E2E packet delay is significantly reduced in DARA, since it uses multiple sinks. Also, the combined effort of DDPS, modified MAC and load adaptive routing further decreases the E2E packet delay. Hence, the results conclude that the proposed MCQoS routing scheme ensures faster and more reliable event detections.

The graphs in Fig. 7(a) and Fig. 7(b) depict that, in all approaches, average packet delay increases with increased retransmission limits, but it remains almost constant for various delay requirements. Note that the values of Y-axis in Fig. 7 represent ratio for the reliability and time in second for the delay. The interesting result, found in Fig. 7(a), is that DARA gives high reliability at retry count value 1 only, while both MMSPEED and MCMP requires retry count value 4 to produce better results and also the reliability decreases with retry count values greater than 4. The rationale behind this result can be explained as below. DARA splits the large burst of data into several smaller bursts flowing through spatially separated nodes, hence the collision probability decreases. Moreover, as opposed to MMSPEED and MCMP, DARA takes care of the traffic load of receiving node and thus it tries to avoid packet forwarding to a highly

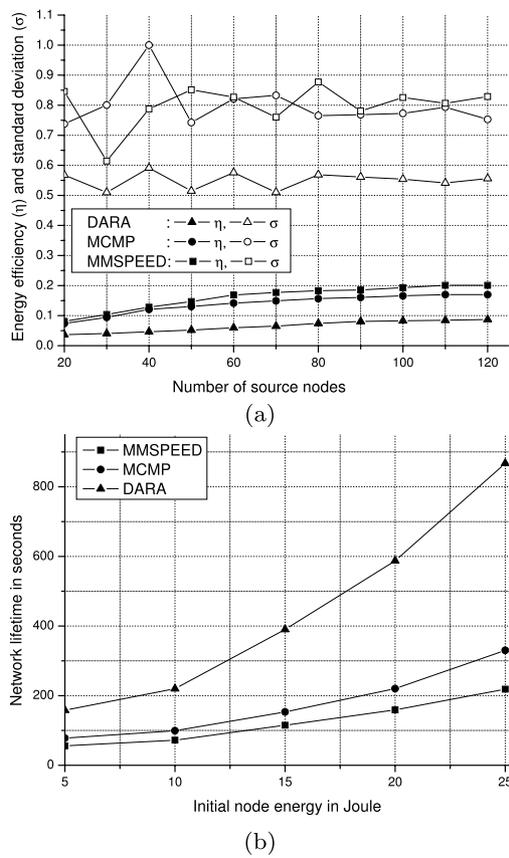
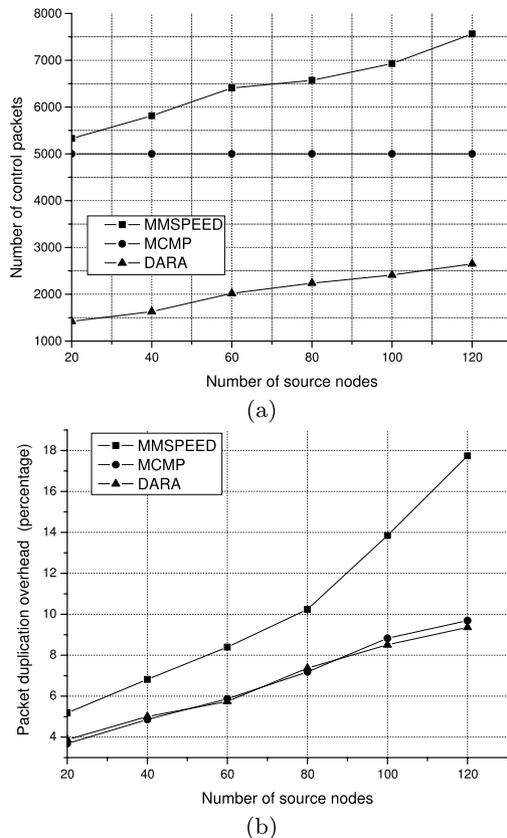


Fig. 8 (a) Energy cost and standard deviation of residual energy and (b) Network lifetime.

loaded node. However, MMSPEED and MCMP continue to retransmit a packet on repeated failure even if the receiving node gets blocked, which causes unsuccessful transmission and worse utilization of network resources. Figure 7(b) also shows that, in all cases, the reliability increases as delay requirement relaxes and this is obvious.

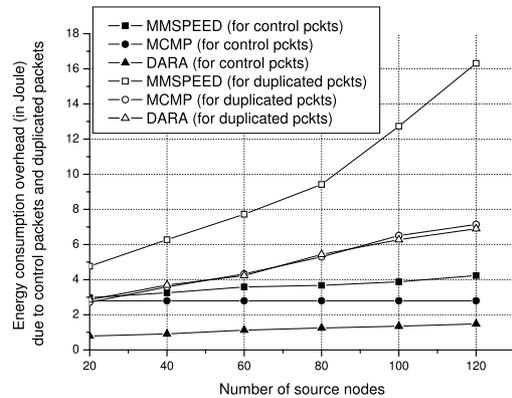
As shown in Fig. 8(a), DARA is energy efficient as compared to others. This is due to the use of power controlled transmissions and reduced number of retransmissions. Furthermore, DARA reduces the standard deviation of energy consumption by (i) using residual energy of target node as routing metric and (ii) distributing the total traffic load over spatially separated nodes, which in turn increases the network lifetime. Measuring lifetime of a sensor network (in timescale) in a simulation environment is a tedious task, because it typically ranges from several months to 1 or 2 years. It greatly depends on the initial energy of nodes, the amount of traffic and the MAC and routing protocols employed in the network. Therefore, in order to show the comparative performances of the algorithms, we have executed simulation runs for varying initial node energies. The simulation is run for 1000 seconds. The traffic settings and other parameters are kept as before. The graphs of Fig. 8(b) show that DARA can increase the network lifetime by 2.5 times on an average than that of MCMP. This result is achieved by DARA because of its spatial distribution of total traffic load



**Fig. 9** Workload overhead versus number of source nodes. (a) Control packet overhead and (b) Packet duplication overhead.

towards multiple sinks and minimized control packet overhead. In contrast, MMSPEED suffers from reduced network lifetime even in comparison with MCMP as it has higher overheads due to control packets and duplicate packets.

Here we discuss on various overheads. Every routing algorithm in wireless environment has its overhead of exchanging control packets like ROUTE REQ/REPLY messages or HELLO packets or BEACON messages etc. These additional messages do not carry any useful information rather they are required to make optimal routing paths or routing decisions. Even though, these control packets are very small in size, the corresponding workloads and energy consumptions are increased with the increased number of such packets in the network. Overheads are also incurred by packet duplication in MCQoS aware routing algorithms. Therefore, reducing all these additional packets is an important performance metric for energy-constrained sensor network. Figure 9 compares the workload overhead of different algorithms. The graphs of Fig. 9(a) demonstrate that the control packet overhead of DARA is surprisingly less than other algorithms. The reason behind this can be explained as follows. All nodes in MMSPEED and MCMP periodically broadcast location update packets and NINFO packets, respectively, after fixed time interval<sup>†</sup>. Unlike these protocols, nodes in DARA algorithm dynamically decide (see Appendix A) when to broadcast a BEACON message. There-



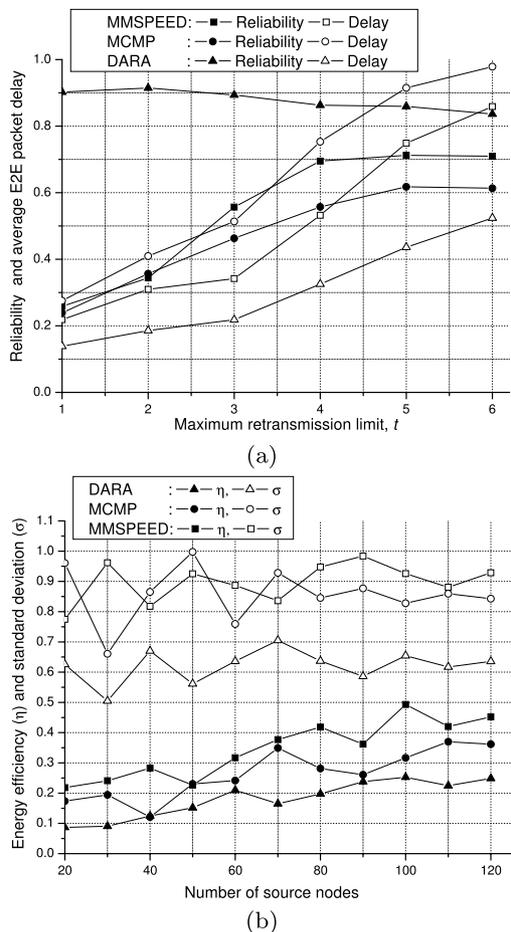
**Fig. 10** Energy consumption overhead.

fore, the nodes that neither sense any event nor forward any data packet broadcast BEACON message only one time, at the start of simulation; they don't send BEACON messages afterwards. After the initialization period, BEACON messages are broadcasted by the sensing and forwarder nodes only. The graphs also show that the number of control packets increases both in MMSPEED and DARA with increased number of source nodes, but that in MCMP remains constant. The reason is that MCMP uses only NINFO packets that are broadcasted at fixed time intervals, whereas MMSPEED needs to transmit back-pressure packets [3] (in addition to periodic location update packets) that are increased with the number of source nodes. Similarly, as the number of source nodes increases the number of broadcasted BEACON messages is also increased linearly in DARA, since it increases the number of active nodes as well as the traffic load of the network.

The graphs of Fig. 9(b) show that the packet duplication overheads of MCMP and DARA algorithms are very less ( $< 10\%$ ) and almost same for all values of the number of source nodes, because both send duplicate packets from the source nodes only by solving optimization problems. Also, both the algorithms use the same estimated link reliability. On the other hand, MMSPEED has higher overhead (as much as 17.8%) in comparison with MCMP and DARA since it duplicates packets both at the source and forwarder nodes. Also, MMSPEED duplicates packets based on E2E reaching probability, which is multiplicative and a small variation in each link reliability would change the E2E reaching probability remarkably.

The total energy consumption overhead, during the whole simulation period, due to control packets and duplicate packets, separately, are plotted in Fig. 10. As expected theoretically, in all algorithms, the energy consumed by duplicate packets are higher than that for control packets, and obviously the gaps are increased with the number of source nodes. Also notice that the graphs in Fig. 10 resemble the trends of those in Figs. 9(a) and 9(b) for control packets and duplicate packets, respectively. This is because of the linear

<sup>†</sup>In our experiments, we set this time interval 60 seconds, which is reasonable for a total simulation period of 300 seconds.



**Fig. 11** In this case, sensor nodes and sinks are mobile. (a) Reliability and average E2E packet delay for different retry counts. (b) Energy cost and standard deviation of residual energy.

relationship between the number of packets and the amount of energy conservation. MMSPEED suffers from higher energy overheads both for control packets and duplicate packets. Even though DARA’s energy overhead for duplicate packets is almost same as MCMP, its energy overhead due to control packets is much less. The reasons are already stated in descriptions of Figs. 9(a) and 9(b). Therefore, the proposed multi-constrained QoS routing scheme offers reduced overall overhead.

Our last simulation studies performance evaluation of the routing algorithms in a dynamic environment where nodes and sinks are allowed to move. In this experiment, the mobility speed of each individual node is randomly chosen from the range 10 km/hour to 30 km/hour. The traffic and other parameter settings are same as before. Figure 11(a) shows that the reliability decreases and the average E2E packet delay increases while the sensor nodes and sinks are mobile. The reasons behind this result are two folds: (i) the use of older neighbor information (routing metrics) decreases the routing efficiency and (ii) the quality of transmission and reception decreases due to mobility. Similarly, in case of mobile sensor nodes, both the energy consumption

and the standard deviation of residual energy are increased by a small amount, as shown in Fig. 11(b). This happens because of increased number of retransmissions and control packet overheads.

## 6. Conclusions

The integrated employment of aggregate routing, packet duplication, SGF, DDPS and MAC layer functionality makes the proposed MCQoS provisioning model efficient. The proposed routing mechanism is proactive; therefore network nodes would not be overshooted with high traffic as well as the network lifetime would be longer. It optimizes the trade-offs between the reliability and the delay guarantee while improving the spatial balance of energy burdens.

How to modify the *aggregate routing function* of DARA algorithm in the case of heterogeneous node deployment (i.e., individual nodes have different transmission range, energy, memory and computation power), is our next problem to address. We also want to extend the proposed routing scheme so that it can handle routing hole problem efficiently.

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## References

- [1] P.V. Mieghem and F.A. Kuipers, “On the complexity of QoS routing,” *Comput. Commun.*, vol.26, no.4, pp.376–387, March 2003.
- [2] A. Mahapatra, K. Anand, and D.P. Agrawal, “QoS and energy aware routing for real-time traffic in wireless sensor networks,” *Comput. Commun.*, vol.29, no.4, pp.437–445, 2006.
- [3] E. Felemban, C.G. Lee, E. Ekici, R. Boder, and S. Vural, “MMSPEED: Multipath multi-speed protocol for QoS of reliability and timeliness in wireless sensor networks,” *IEEE Trans. Mobile Comput.*, vol.5, no.6, pp.738–754, 2006.
- [4] X. Huang and Y. Fang, “Multi-constrained QoS multipath routing in wireless sensor networks,” *ACM Wireless Networks*, 2007.
- [5] S. Lee, B. Bhattacharjee, and S. Banerjee, “Efficient geographic routing in multihop wireless networks,” *Proc. ACM Intl. Symp. on Mobile Ad Hoc Networking and Computing (MobiHoc)*, USA, 2005.
- [6] K. Zeng, K. Ren, W. Lou, and P.J. Moran, “Energy-aware geographic routing in lossy wireless sensor networks with environmental energy supply,” *Proc. 3rd Intl. Conf. on QoS in Heterogeneous Wired/Wireless Networks*, 2006.
- [7] Y.B. Kou and N. Vaidya, “Location-aided routing (LAR) in mobile ad hoc networks,” *Proc. ACM/IEEE Intl. Conf. on Mobile Computing and Networking*, Dallas, 1998.
- [8] S. Basagni, I. Chlamtac, and V. Syrotiuk, “A distance routing effect algorithm for mobility (DREAM),” *Proc. ACM/IEEE Intl. Conf. on Mobile Computing and Networking (MobiCom)*, Dallas, 1998.

- [9] T. He, C. Huang, B. Blum, J. Stankovic, and T. Abdelzaher, "Range-free localization schemes for large scale sensor networks," Proc. MobiCom, 2003.
- [10] L. Koen and R. Niels, "Distributed localization in wireless sensor networks: A quantitative comparison," Comput. Netw., vol.43, no.4, pp.499–518, Nov. 2003.
- [11] S. Tang and W. Li, "QoS supporting and optimal energy allocation for a cluster based wireless sensor network," Comput. Commun., vol.29, no.13, pp.2569–2577, March 2006.
- [12] O.B. Akan and I.F. Akyildiz, "Event-to-sink reliable transport in wireless sensor networks," IEEE/ACM Trans. Netw., vol.13, no.5, pp.1003–1016, Oct. 2005.
- [13] Q. Gao, K. Blow, D. Holding, I. Marshall, and X. Peng, "Radio range adjustment for energy efficient wireless sensor networks," J. Ad Hoc Networks, 2004.
- [14] W.J. Cook, W.H. Cunningham, W.R. Pulleyblank, and A. Schrijver, Combinatorial Optimization, John Wiley & Sons, 1st ed. (Nov. 12, 1997), ISBN:0-471-55894-X.
- [15] T. He, J. Stankovic, C. Lu, and T. Abdelzaher, "SPEED: A stateless protocol for real-time communication in sensor networks," Proc. IEEE Intl. Conf. Distributed Computing Systems, pp.46–55, 2003.
- [16] M. Demirbas and M. Hussain, "A MAC layer protocol for priority-based reliable multicast in wireless ad hoc networks," Proc. IEEE Intl. Symp. on a World of Wireless, Mobile and Multimedia Networks, 2006.
- [17] The Network Simulator — ns-2.30, <http://www.isi.edu/nsnam/ns/ns-build.html>

## Appendix A: Interval of BEACON Messages

Setting the optimized value of  $d_{beac}$  is very important for resource constraint sensor networks. If  $d_{beac}$  is very low then the neighbor nodes would be able to take routing decisions based on most updated neighbor information. But, doing so is inefficient in terms of energy utilization and network throughput. On the other hand, if  $d_{beac}$  is kept very high then the routing decisions might be inappropriate due to the use of older neighbor information, which in turn breaches both the reliability constraint and delay guarantee. Therefore, rather than broadcasting the BEACON messages periodically after a constant period of time, we argue that  $d_{beac}$  should be driven by the metrics that it carries. For instance, if the nodes are static, the value of  $d_{beac}$  could be very high as because we allow any forwarding node to receive data packets as far as the following two conditions are true:

(i) The estimated sojourn time  $E[\delta]$  of a packet lies between the lower and upper threshold values,  $\delta_{ThLow} \leq E[\delta] \leq \delta_{ThUp}$ . Where,  $E[\delta] < \delta_{ThLow}$  indicates that the node is very lightly loaded, while the condition  $E[\delta] > \delta_{ThUp}$  describes that the node is heavily loaded. Appendix B discusses on the typical values of  $\delta_{ThLow}$  and  $\delta_{ThUp}$ .

(ii) The residual energy of the node,  $E_{residual}$ , is not decreased below its threshold value.

Violation of any one of the above two conditions will initiate a BEACON message. To avoid oscillations in routing, the minimum duration between the two consecutive BEACON messages is kept as 10 seconds in our implementation. Whereas, in the case of node mobility, in lieu of considering the above conditions, BEACON messages are broadcasted periodically and  $d_{beac}$  is dynamically increased

or decreased with node mobility speed.

## Appendix B: Parameter Estimation

Let  $\bar{\delta}_i$  be the average sojourn time predicted from the model and  $\hat{\delta}_i$  be the average sojourn time estimated from the measurements when the arrival intensity is  $(1 + n_i)g_i\tau A$ ,  $i=1,2,\dots,q$ . Since the estimated sojourn time  $\hat{\delta}_i$  is the mean of samples, it is approximately a normal distributed random variable with mean  $\delta_i$  and variance  $\sigma_i^2\delta_i/n_i$ , when the number of samples  $n$  is very large. Hence, the model parameter ( $\bar{\delta}_i$ ) can be estimated by maximizing the log-likelihood function.

$$\log \prod_{i=1}^q \frac{1}{\sqrt{2\pi\sigma_i^2/n_i}} \exp \left\{ -\frac{(\hat{\delta}_i - \bar{\delta}_i)^2}{2\sigma_i^2/n_i} \right\}$$

Maximizing the log-likelihood function above is equivalent to minimizing the weighted sum of square errors as follows

$$\sum_{i=1}^q \frac{(\hat{\delta}_i - \bar{\delta}_i)^2}{\sigma_i^2/n_i}$$

As an approximation, the estimated variance of sojourn time,  $\hat{\sigma}_i^2$ , can be used instead of  $\sigma_i^2$ . Now, the problem of parameter estimation becomes a question of optimization,

$$(\hat{\delta}_i) = \arg \min_{\bar{\delta}_i} \sum_{i=1}^q \frac{(\hat{\delta}_i - \bar{\delta}_i)^2}{\hat{\sigma}_i^2/n_i}$$

This optimization problem can be solved in various ways [14]. We set  $\delta_{ThLow} = 20\%$  of  $\max(\hat{\delta})$  and  $\delta_{ThUp} = 80\%$  of  $\max(\hat{\delta})$ .



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