LOCALMOR: LOCALized Multi-Objective Routing for Wireless Sensor Networks

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Abstract

This paper proposes a multi-objective quality of service (QoS) routing protocol for wireless sensor networks (WSN). The protocol takes into account the traffic diversity typical for many applications and provides a differentiation in routing using QoS metrics. It ensures several QoS metrics for different traffic categories, and attempts for each packet to fulfill the required metrics in a power-aware and localized way. It employs memory and computation efficient estimators in a distributed manner and uses a multi-sink single-path approach to increase reliability. The main contribution of this paper is data traffic based QoS with regard to all the considered QoS metrics. As far as we know, this protocol is the first that makes use of the diversity in the data traffic while considering latency, reliability, residual energy in the sensor nodes, and transmission power between nodes and casts QoS metrics as a multi-objective problem. The proposed algorithm can operate with any MAC protocol, provided that it employs an ACK mechanism. Simulation results show the proposed protocol outperforms all compared state-of-the-art QoS and localized routing protocols.

I. Introduction

Quality of service (QoS) routing using geographical information for WSN has been lately considered by the research community, where some new protocols have been proposed, such as SPEED [1], MMSPEED [2], GREES [3], RPAR [4], and EAGFS [5]. Still, none of these protocols makes a clear differentiation between traffic in route selection with respect to QoS requirements. They define either the same combined metric (of all the considered QoS metrics) [1], [5], [3], or several services but with respect to only one metric [4], [2]. This may not be enough for some applications, such as vehicular and biomedical WSN, where different traffics may have different QoS requirements. Our main contribution is the design of a localized routing protocol, which enables to provide different QoS services according to the traffic type, while simultaneously considering latency, reliability, residual energy, and transmission power. To our best knowledge, the proposed protocol is the first that makes such differentiation and considers all the above mentioned QoS metrics at the same time.

We consider a general scenario where sensors collect different kinds of data and transmit them towards fixed sinks via other sensors in a multi-hop, ad hoc paradigm. We define two kinds of sinks; primary sink and secondary sink, to which a separate copy of each message that requires high reliability is sent. The two sinks must be placed in separate area to avoid traffic congestion. We consider in this paper three different requirements, i) energy efficiency, ii) reliability, and iii) latency. Giving these requirements we classify data traffic into: i) regular traffic, ii) reliability-sensitive traffic, which should be delivered without loss, but can tolerate reasonable delay, e.g file transfer iii) delay-sensitive traffic, that should be delivered within a deadline, but may tolerate reasonable packet loss, e.g video streaming, and finally iv) critical traffic of high importance, requiring the highest reliability and delivery within a deadline. Following this classification the proposed protocol is designed using a modular approach, aiming to ensure exactly the required QoS for each packet.

The remaining of the paper is organized as follows: Section II gives the network model, assumptions, and notations used in the paper. Section III describes the proposed protocol, whose performance evaluation is illustrated in Section IV through a comparative simulation study. Finally, Section V concludes the paper.

II. Assumptions and Notations

In the following the network is represented by a set V of nodes. We note $dist_{v_i,v_j}$ as the linear distance between two nodes $v_i, v_j \in V$. Each node should be aware of its own coordinates, which be obtained using some distributed localization service. This position serves as the network (global) address. In addition, the node should be aware of its current battery state B_{v_i} (also termed *residual energy*). We assume that nodes have the same and spherical transmission power range P_{range}, and that each node can control its transmission power [4]. The set of nodes in v_i's vicinity denoted by N_{v_i} is called v_i's neighboring nodes, defined by: $N_{v_i} = \{v_j : dist_{v_i,v_j} \leq P_{range}\}$. In addition to, N_{v_i}, we define the set of neighboring nodes providing positive advance for node, v_i, towards a final destination, v_d, denoted by $N^{advc}_{v_i,v_d}$, as the set of neighboring nodes that are closer to the destination than v_i. It is given by: $N^{advc}_{v_i,v_d} = \{v_j \in N_{v_i} : dist_{v_j,v_d} \leq dist_{v_i,v_d}\}$. Like all geographic routing protocols, each node needs to know about the positions of its neighboring nodes as well as the destination. A HELLO protocol is executed between neighboring nodes allowing mutual update of the neighboring nodes' list, their positions, and several parameters, as in [2], [3]. For localized routing to be effective, nodes are supposed to be stationary or with low mobility. Node density is supposed to be high enough to prevent void situation, in which a router cannot find a closer node to the destination amongst its neighboring nodes.

A typical energy-efficient model is used in this paper [6]. This model relies on the usage of adaptive and dynamic power according to the distance separating the transmitter and the receiver, which is power-efficient and appropriate since localization information is available. To transmit one bit from a source to a destination over a distance, d, the consumed energy is given as:

$$E = 2E_{elec} + \beta d^{\alpha}, \quad (1)$$

where E_{elec} is the energy utilized by transceiver electronic, which is independent of distance. βd^{α} accounts for the radiated power necessary to transmit over d, where α is the path loss ($2 \leq \alpha \leq 5$) and β is a constant given in $Joule/(bits \times m^{\alpha})$.

III. Protocol Description

A. Energy Module

Regular packets are directly routed by this module, while the other modules are used for the QoS-sensitive packets to find out the candidates ensuring the imposed constraints before being routed by this module. Both power transmission costs and residual energy of routers should be considered to achieve power efficiency. To cope with this trade-off we use a non-aggregated min-max approach. The problem for regular packets is to select at node, v_i, the most power-efficient node for destination, v_d, from the set of neighboring nodes offering positive advance, $N^{advc}_{v_i,v_d}$, provided by the neighbor manager (described latter). Considering Eq. 1, the cost that can be managed when routing is only the radiated power for transmission (the second part of the sum). That is, for a candidate node, v_j, the required energy related to routing is given by $\beta(dist_{v_i,v_j})^{\alpha}$ - called hereafter the transmission energy link cost. The other criterion is the battery state (B_{v_j}) of the candidate node. Obviously, the best choice with respect to the first criterion is the node that has the minimum transmission power cost, while the best with respect to the second criterion is the one having the highest amount of energy in its battery. Let us denote the first criterion's optimum, v_T, and the second v_R. For every candidate, v_j, its relative deviation for each metric's optimum is calculated as:

$$Z_T(v_j) = \max\Big(\frac{|\beta(dist_{v_i,v_j})^{\alpha}| - |\beta(dist_{v_i,v_T})^{\alpha}|}{|\beta(dist_{v_i,v_T})^{\alpha}|}, \frac{|\beta(dist_{v_i,v_j})^{\alpha}| - |\beta(dist_{v_i,v_T})^{\alpha}|}{|\beta(dist_{v_i,v_j})^{\alpha}|}\Big) \quad (2)$$

$$Z_B(v_j) = \max\Big(\frac{|B_{v_j}| - |B_{v_R}|}{|B_{v_R}|}, \frac{|B_{v_j}| - |B_{v_R}|}{|B_{v_j}|}\Big) \quad (3)$$

The min-max optimum is obtained as follows: the set, S_0, of nodes minimizing the maximum deviation with respect to both criteria, is calculated,

$$S_0 = \{x : \max_{m \in \{T,B\}} \{Z_m(x)\} = \min_{j \in N^{advc}_{v_i,v_d}} \max_{k \in \{T,B\}} \{Z_k(v_j)\}\} \quad (4)$$

If $|S_0| = 1$, then S_0's element is the selected optimum. Also, if the metric for which the value of $\{Z_k(v_j)\}$ reaches the maximum is not unique for all S_0's elements, i.e., some nodes in S_0 (having min max value) have maximum deviation in Z_T and others in Z_B, then the node offering the best advance from S_0 will be selected. However, if $|S_0| > 1$ and the metric, say l, for which the value of $\{Z_k(v_j)\}$ reaches the maximum is unique for all S_0's elements then the final solution, S, is calculated from S_0 as the set of nodes from S_0 that minimizes the deviation for the metric other than l, i.e.

$$S = \{x : Z_k(v_x) = \min_{j \in S_0} \{Z_k(v_j)\}, k = \{T,B\} - l\}. \quad (5)$$

B. Reliability-sensitive Module

This module deals with packets requiring high reliability, which is addressed by sending a copy to both primary and secondary sinks, increasing thus the chances of delivery. This multi-sink single-path approach is selected instead of the single-sink multi-path approach used in [2], which results in data packets convergence near or at the sink, and consequently increases traffic contention and collisions. For each copy, the reliability module selects from

$N^{advc}_{v_i,v_d}$ the node providing the highest packet reception ratio (prr), i.e.,

$$\max_{j \in N^{advc}_{v_i,v_d}} prr_j. \qquad (6)$$

prr_j is estimated for each neighbor node. It indicates the probability of successful delivery to a neighbor node. If more than one node provide the maximum value, then the most energy efficient is selected by using the power-efficiency module. Each node estimates prr_j for every neighboring node. MAC ACKs are used as indication of recpetion/loss of packets at the next hop, and the estimation is updated with Exponential Weighted Moving Average (EWMA) at each time window, using the number of packets received/lost during the current time window and the past value of the estimation [7]. Estimated values are maintained and broadcasted in HELLO packets by the number manager. EWMA estimation was chosen as it has smaller memory footprint and simpler computational process than the other variant-based estimation methods such as flip-flop estimator, Kalman filter, and linear regression [7]. This simplicity makes it more suitable for WSN.

C. Delay-sensitive Module

This module uses the packet velocity approach given in [4] that has the advantage of not requiring any synchronization between nodes. The main difference from [4], however, is the use of a simple but memory and time-efficient estimation method (EWMA) instead of Jacobson's algorithm, and particularly the consideration of waiting time at the next hop's queue. Assume delay-sensitive packet has a delivery deadline, dd, specified by the upper layers and indicating the time the packet should be delivered to the sink node. We define two velocities to be used; required velocity (speed), s_{req}, and offered (actual) velocity, s_{v_j}, for every node v_j in $N^{advc}_{v_i,v_d}$.

Upon receiving a packet the recipient node stamps the corresponding reception event locally. To account for all the possible delays in the node, i.e., queuing, contention, retransmission, etc., it updates the deadline *prior to each transmission* in the MAC layer to account for the delay from receiving the packet until it reaches its final transmission. If the reception time is denoted, t_{rec}, the time of last transmission, t_{tr}, the bandwidth, bw, and the packet size, $size$, then the time remaining to the deadline, rt, is updated at node, v_i, as

$$rt = rt_{req} - (t_{tr} - t_{rec} + size/bw), \qquad (7)$$

where rt_{req} is the value of, rt, at time of reception, and $t_{tr} - t_{rec} + size/bw$ gives the entire delay from the reception of the packet at v_i until the transmission of the last bit. It includes both queueing delay $(t_{rec} - t_{tr})$ and data transfer delay $(size/bw)$. Propagation delay can smoothly be added but it is omitted since it can be negligible. Upon reception of the packet at v_i, the required speed is calculated using both the remaining time to the deadline (stamped in the packet either by the previous node or the upper layer) and the remaining distance to the destination as given

$$s_{req} = \frac{dist_{v_i,v_d}}{rt}. \qquad (8)$$

This way we propose a solution to handling the end-to-end deadline as local problem of satisfying the required velocity at each hop. Furthermore, no global time stamping is used but only relative time, which does not require clock synchronization.

To achieve the required velocity, the delay-sensitive module at node, v_i, calculates the velocity offered by every candidate, using EWMA-based estimations provided by the neighbor. These estimations include waiting time at the queue of node v_i, say w_{v_i}, transmission time to the next node, dtr_{v_j}, and waiting time at the queue of the latter, w_{v_j}. None of the previous solutions in the literature considers the waiting time at next node's queue. Note that delay due to transmission, dtr_{v_j}, includes estimation of the time interval from the packet becomes head of v_i's transmission queue until its reception at v_j. This includes all delays due to contention (channel sensing, RTS/CTS if any, slots, etc. depending on the used MAC protocol) and data transfer delay. It is updated after each packet transmission with EWMA, using its delay ω as a sample, given by: $\omega = t_{ACK} - size(ACK)/bw - t_0$. Where t_0 denotes the time the packet is ready for transmission (becoming the head of transmission queue), t_{ACK} the time of ACK reception, bw the bandwidth and $size(ACK)$ the size of the ACK packet. The estimated velocity for node, v_j, is given by:

$$s_{v_j} = \frac{dits_{v_i,v_d} - dist_{v_j,v_d}}{w_{v_i} + dtr_{v_j} + w_{v_j}}. \qquad (9)$$

After computing velocities of all candidate nodes, the delay-sensitive module calculates the set of nodes supposed to meet the required deadline, $N^{s_{req}}_{v_i,v_d}$, as,

$$N^{s_{req}}_{v_i,v_d} = \{v_j \in N^{adv}_{v_i,v_d} : s_{v_j} \geq s_{req}\}. \qquad (10)$$

This set is then transferred to the power-efficiency module to extract the most power-efficient node.

Critical packets are first routed by this module. In contrary to delay-sensitive packets, $N^{s_{req}}_{v_i,v_d}$ is passed to reliability-sensitive module that selects the most reliable candidate instead of most energy efficient.

D. Neighbor Manager

The neighbor manager runs the HELLO protocol, manages neighbor table, and implements EWMA-based estimations described before. This enables it to provide the other modules with the required information according to the packet type. Neighbor table assigns an entry for each neighbor node, which includes all information related to the node such as position, residual energy, estimated waiting time, estimated transmission delay, required transmission energy towards it, and estimated packet reception ratio. The HELLO protocol consists in periodical broadcast of HELLO packets. These packets are used to update existing entries, add new entries when new nodes move within the node's vicinity, and delete entries when neighboring nodes move away or break down, which can be detected in case of not receiving HELLO packets after a defined period of time (timeout). Neighbor manager is the first module that receives the packet from the higher layers. It executes the appropriate module depending on the packet type and provides the module with all information it needs such as the set of nodes ensuring positive advance N^{advc} and current values of the required parameters of each of them.

IV. Simulation Study

An extended version of GloMoSim was used, on which we implemented the proposed protocol, LOCALMOR, as well as several state-of-the-art localized and QoS routing protocols, namely SPEED [1], MMSPEED [2], EAGFS [5], and the basic greedy forwarding protocol (GFW). We performed a comparative simulation study among these protocols including different scenarios of traffic type diversity. The simulation setup consists of 400 nodes located in a 1200 m^2 area in a grid topology, and $1000s$ of simulation time. Two sinks that act as a primary and secondary sinks were used, and put in the edges of the simulation area, i.e. at positions $(0,0)$ and $(1200,1200)$ respectively, while a source node was placed in the center of the area. This positioning enables long and equal distance routes creation towards the two sinks. CBR traffic was generated with a load of $1kbytes/sec$ in all scenarios. Critical packets and regular packets were used in the traffic. These two classes allow to test all the modules since both delay-sensitive and reliability-sensitive modules are involved when routing critical packets. Each CBR packet has been stochastically tagged with a packet type according to tunable rates. Critical packet rate was varied from 0.1 to 1, and the remaining rate to 1 in each setting was allocated to regular packets, i.e. the overall traffic load is fixed for all scenarios. The performance metrics we used are; the end-to-end delay, the end-to-end packet reception ratio (prr), and the rate of packets arriving within the deadline. The deadline was fixed in this simulation to $0.2s$ for all critical packets. The simulation results, depicted in Figures 1, 2, and 3, show that LOCALMOR outperforms all state-of-the-art schemes with respect to all metrics. LOCALMOR has the highest packet reception ratio and the lowest delay. Furthermore, while the other protocols performance with respect to latency and prr are relatively stable, LOCALMOR linearly increases its performance as a function of critical packet rate. This can be explained when the number of critical packets increases, they are routed through faster and more reliable routers, unlike the other protocols that do not make such a differentiation, except MMSPEED. MMSPEED makes a certain differentiation with respect to delay requirement, but LOCALMOR considers the estimation of queueing delay at the next hop, in addition to traffic differentiation. This consideration is the reason that LOCALMOR performs better than MMSPEED regarding the end-to-end delay. The qual distance towards the two sinks and the uniform distribution of nodes justify the low latency was achieved thanks to proper route selection, and not influenced by the positioning of the secondary sink, i.e. close position of the secondary sink may give unfair advantage to LOCALMOR regarding this metric. To achieve reliability, MMSPEED uses a multipath single-sink strategy (for all packets without making any distinction), which results in packet congestion either at the final sink or intermediate nodes. Whereas, our protocol differentiates packets' with reliability-sensitive from reliability-unsensitive packets, and for the former it uses the efficient duplication technique towards geographically divergent sinks and through single path. Unlike in the previous metrics, the percentage of packets delivered by the deadline of the protocols that do not make any differentiation among packets is dramatically affected by the rise of rate of the critical packets. MMSPEED is relatively less affected but its performance is less than LOCALMOR, whose performance even increases linearly with the critical packets' rate, and thus exhibit a tremendous improvement.

V. Conclusion

A new localized multi-objective routing protocol has been proposed in this paper. Its main contribution is the consideration of the traffic diversity in terms ofquality of service (QoS) requirement, typical for many applications as well as the differentiation in routing for different QoS metrics. The data traffic is classified into several categories according to the required QoS metrics, where different routing metrics and techniques are suggested for each category. For each packet, the protocol ensures the required QoS metrics in a power-aware way, by locally selecting the best candidate. It employs memory and computation

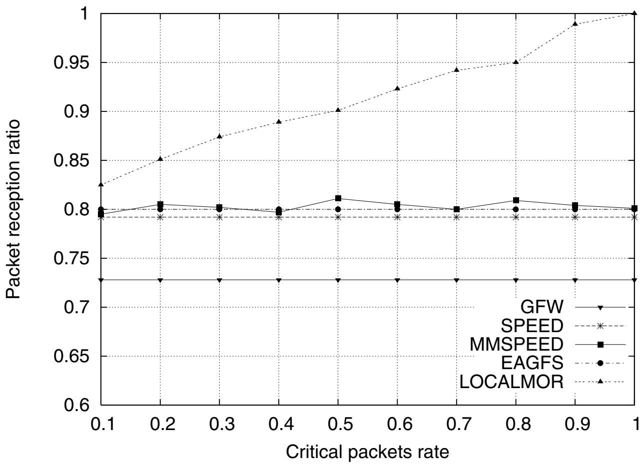

Fig. 1. Packet Reception Ratio

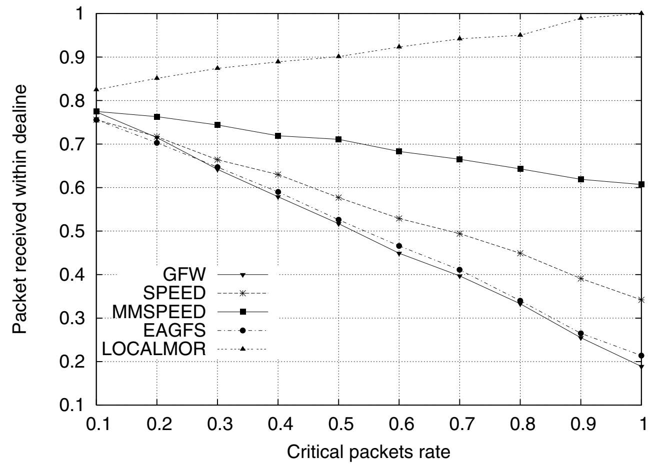

Fig. 3. Packets Arriving Within Deadline

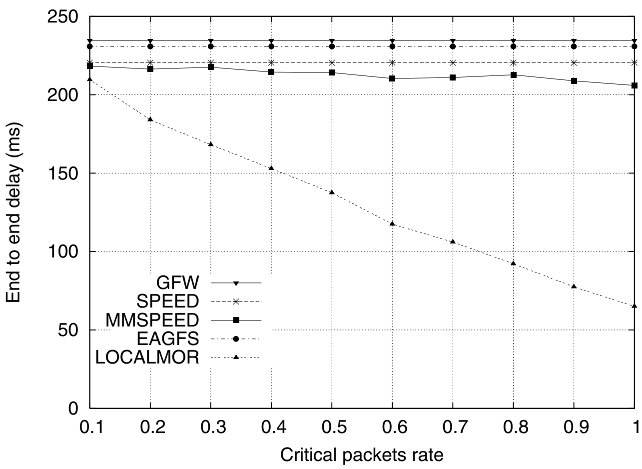

Fig. 2. End-to-End Delay

efficient estimators and uses a multi-sink single-path approach to increase the reliability. Energy was considered by always selecting the most power-efficient candidate offering the required data-related QoS (delay and/or reliability). Taking into consideration and differentiating both delay and reliability requirements, along with transmission power and residual energy for energy efficiency, attributes the essential features of the proposed protocol, which distinguish it from all protocols published in the literature. Simulation results show that the proposed protocol outperforms all compared state-of-the-art routing protocols. As a future work, we plan to investigate the scalability of the proposed protocol using configurations including a high number of nodes, to measure more metrics such as energy consumption, and to consider implementation in a real sensor network using motes.

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