ENERGY/LATENCY TRADE-OFFS IN GEOGRAPHIC ROUTING FOR ULTRAWIDEBAND WIRELESS SENSOR NETWORKS

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Abstract: Wireless Sensor Networks (WSNs) may exploit accurate localization capabilities of ultrawideband (UWB) transceivers to improve performance of high layer protocols. We analyze power consumption of a WSN accommodating both communication and positioning into the same UWB transceiver and implementing a geographic routing algorithm, either the Greedy Perimeter Stateless Routing (GPSR) or its energy aware version, the *e*-GPSR. Power consumption depends on beacon rate for positions' updates, the number of hops to reach the destination and the number of neighbors per node. On the other hand, the beacon rate impacts the reliability of the neighbor lists; the number of hops impacts on the end-to-end latency; the number of neighbors, i.e. the network connectivity, impacts on routing performance. The presented analysis assesses, by means of both theoretical investigations and simulation results, the main trade-offs between power consumption and latency that can be applied to obtain the best achievable performance.

1 INTRODUCTION

WSNs have attracted great interest in both research and commercial communities for their wide application range and versatility. Typical applications require nodes with average power consumption substantially lower than for other wireless networks. In recent years the research focused on how to overcome the power issue by introducing *energy-aware* functionalities in WSNs design, even though a common criteria for all applications cannot be established.

UWB technology enables low power transmissions, thanks to the efficient use of spectrum and low duty-cycle signals, and the easy integration of localization functionality. The use of power-awareness and location aided algorithms at network (NWK) layer appears as the best choice. Performance of such algorithms is strictly related to the knowledge of neighbors information (Stojmenovic, 2002).

In this paper we consider the Greedy Perimeter Stateless Routing (GPSR) algorithm (Karp and Kung, 2000) and the energy-aware version, namely the *e*-GPSR, we recently proposed in (Persia and Cassioli, 2007). Our analysis shows the trade-offs that should be applied when designing this type of networks, because the main factors impacting energy consumption also impact latency and routing performance. We show that the *e*-GPSR guarantees low power consumption and latency, thanks to its intrinsic forwarding criteria.

2 PROBLEM STATEMENT

Basic requirements of WSNs are low power consumption (uniformly distributed among network nodes) and low latency (especially for mission-critical applications). For low data rate location/tracking (LDR-L/T) UWB WSNs exploiting geographic routing, a further requirement is given by low beacon traffic, aiming to the best balance between positioning and communication tasks and to the optimal beacon update rate to maintain good performance of geographic forwarding. The power consumption of each node depends on its own activities, while the latency depends on node's connectivity and the reliability of geographic routing depends on the beacon rate and nodes' mobility. In the following, we formulate the problem statement through theoretical investigations, showing the interrelations between power consumption, latency and neighbor lists updating.

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The total energy consumed by a WSN of N nodes to transmit M packets can be expressed as (Sozer et al., 2000; Wang et al., 2006):

$$E_{tot} = \sum_{j=1}^{M} \sum_{i=1}^{N} n_i E_{0_{i,j}} A(r_i) \tag{1}$$

where n_i is the number of hops needed by the $i-$th source node to reach the destination, $E_{0_{i,j}}$ is the minimum energy necessary for the packet j transmitted by the $i-$source to be received by the next hop, r_i its coverage range and $A(r_i) \propto r_i^{\alpha_{loss}}$ is the path loss attenuation with $3 \leq \alpha_{loss} \leq 4$ for harsh environments. Let's assume for sake of simplicity that the farthest node from the destination, i.e. at a distance d, needs N hops to transmit one packet and that the coverage range is $r_i = r = d/N$ for all nodes, thus $E_{0_{i,j}} = E_0$. Its total consumed energy is:

$$E_{hop} = E_0 A(\frac{d}{N}) + E_0 A(\frac{d}{N})2 \ldots + E_0 A(\frac{d}{N})N$$
$$= E_0 A(\frac{d}{N})\frac{N(N+1)}{2} \tag{2}$$

For a number of hops $N' < N$, we have $A(\frac{d}{N}) << A(\frac{d}{N'})$ and

$$E_0 A\left(\frac{d}{N}\right)\frac{N(N+1)}{2} < E_0 A\left(\frac{d}{N'}\right)\frac{N'(N'+1)}{2}, \tag{3}$$

thus paths with a large number of hops consume less energy than paths involving a small number of hops. On the other hand, large numbers of involved hops imply increased latency.

The latency in a network is commonly measured in terms of number of hops required to relay a packet from the source (S) to the destination (D) located at a distance d. With reference to Fig. 1, applying the analysis in (Cheng and Robertazzi, 1989), the expected value of the *vacant* distance r_{e_i} for single-hop distance is:

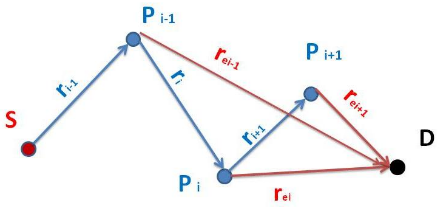

Figure 1: Forwarding mechanism.

$$E[r_{e_i}] = \frac{1 - e^{-\mu(d - r_{e_i})}(1 + \mu(d - r_{e_{i-1}}))}{\mu(1 - e^{-\mu(d - r_{ei-1})})} \tag{4}$$

where r_i and r_{e_i} are depicted in Fig. 1, with $r_i + r_{e_i} = d$ and μ is the density of nodes in the area. The expected value of the r_i is $E[r_i] = d - E[r_{e_i}]$ and the average number of hops l needed to transmit a packet from S to D is:

$$E[l] = \lceil \frac{E[r_i]}{r} \rceil \tag{5}$$

where $\lceil \cdot \rceil$ is the ceiling operator and r is the nodes' coverage radius. Evaluating (5) for different coverage radii in a WSN of $N = 40$ nodes and d =10 m, in a sensing area of 25×25 m^2, we obtain that the average number of hops is around 2 for r =6 m, whereas it drastically increases for a small coverage radius. Hence, large nodes' coverage range is needed to achieve low latency, with a consequent increase of power consumption. Accurate analysis of power consumption in LDR-L/T UWB sensor networks, which usually produce low data traffic, cannot leave out the energy fraction spent for the positioning beacon transmissions, exploited at the NWK layer by location aided routing. Frequent beacon transmissions provide up-to-date positioning in mobile scenarios that guarantees the highest level of delivery success rate of geographic routing algorithms. The drawback is that frequent beacon transmissions in a uncoordinated access scheme (aloha) increase the collision probability, with consequent packet loss.

Performance analyses of geographic routing that assume a *perfect knowledge* of neighbors positions available at any time without control traffic are valid for static scenarios, but are not realistic for mobile scenarios. Our analysis uses this ideal case as a benchmark of achievable performance (CASE: *Ideal*), whereas two other realistic scenarios are defined to investigate the two effects of the beacon traffic: an increase of the overall traffic load, which is managed flatly by the aloha MAC, and a potential loss of position updates. The first scenario models the beacon traffic load as a traffic source that adds up to the data traffic, but the perfect knowledge of exact neighbors position at any time is still assumed. The aim of this test case (CASE: *Beacon*) is to find the maximum beacon repetition rate tolerable by the WSN such that packet collisions do not cause the collapse of the WSN. An even more realistic scenario (CASE: *POS+Beacon*), where each node periodically broadcasts beacons and periodically acquires neighbors information at each beacon interval T, is used to evaluate the impact of loss of position updates.

3 PERFORMANCE ANALYSIS

We consider a UWB sensor network of M nodes located in random positions in an area of 25 m × 25 m. Anchor nodes are static, the others mobile. All nodes within the communication range r of a node are considered as its neighbors for the GPSR, whereas a subset is selected for the e-GPSR according to its selection criteria explained in the following.

The sink node (SN) is assumed to have a communication range R able to cover the entire area, such that downlink communications are direct and without errors. The SN queries to the network the position of a randomly chosen node. Every node receiving the query verifies whether it is the right destination: if not, it discards the packet. Otherwise, it sends back to the SN the reply packet through a multi-hop path, reactively created by means of one of the two versions of the geographic algorithm under test.

The physical layer is modeled by the cascade of a SNR Evaluator and a Decider. The SNR Evaluator computes the signal-to-noise ratio (SNR) associated to the received packets and the Decider compares its output with a threshold SNR_{th}, discarding the packets whose SNR is below.

The MAC layer implements a pure aloha scheme.

At the NWK layer we adopt a routing scheme based on the GPSR (Karp and Kung, 2000). Two versions of the GPSR are compared, the traditional and the energy-aware version in (Persia and Cassioli, 2007). The difference between these two versions stays in the selection criteria of the next hop in the *Greedy mode*, whereas there is no difference in the *Perimeter mode*, which is the recovery strategy in case of failure of the Greedy approach. During the *Greedy mode* the traditional GPSR selects the next hop according to the MFR (Most Forward within Radius) approach, i.e. the neighbor geographically closest to the packet destination is selected. The e-GPSR adds to the MFR two other criteria in the *Greedy mode* which take into account both energy and latency constraints. For each node j, the possible candidates for the next hop constitute a subset, $N_{\Theta}^{(j)} \cap \tilde{N}^{(j)}$, of the $N^{(j)}$ neighbors of the present hop node j, such that the following conditions are verified:

$$N_{\Theta}^{(j)} \subseteq N^{(j)} \mid \forall i \in N_{\Theta}^{(j)},\ \alpha_i \leq \Theta^{(j)} \tag{6}$$

$$\tilde{N}^{(j)} \subseteq N^{(j)} \mid \forall k \in \tilde{N}^{(j)},\ E_k \geq E_{TH}^{(j)} \tag{7}$$

where $N_{\Theta}^{(j)}$ and $\tilde{N}^{(j)}$ are the subsets of nodes that verify (6) and (7), respectively, α_i is the angle between the line that joins the node j with the i-th node and the line that joins the node j with the destination (the SN for our cases), and E_k is the residual charge of the k-th neighbor node. The condition (6) can be seen as a *latency constraint*, whereas (7) is the *power constraint*.

Each forwarding node j adaptively sets the angle $\Theta^{(j)}$ as $\Theta^{(j)} = \alpha^{(j)} + x_{\Theta} \cdot (90 - \alpha^{(j)})$ and the threshold $E_{TH}^{(j)}$ as $E_{TH}^{(j)} = (1 - x_C) \cdot E_{charge}^{(j)}$, where $\alpha^{(j)}$ is the minimum angle obtained by considering, among all neighbors of the node j, the nearest node to the $\overline{j-D}$ line, $E_{charge}^{(j)}$ is the maximum residual charge among the residual charges E_k of its neighbors, and $x_C \in [0,1]$ and $x_{\Theta} \in [0,1]$ are routing design parameters (Persia and Cassioli, 2007), which modulate the number of neighbors of each node that varies not only due to the coverage range.

Table 1: Simulations' setup.

RANDOM WAY POINT MOBILITY MODEL	Speed: 0.5 m/s Pause time: 0.1 s
DATA RATE	$R_b = 1$ Mb/s
TRAFFIC MODEL	CBR at 1 packet/s 84 bits per packet
BATTERY CHARGE	Initial: $E_I = 10$ mAh

Performance analysis has been carried out by dynamic system simulations in Omnet++. The simulation assumptions and parameters are listed in Table 1. For each case under study, we average the statistics over a set of 5 independent stochastic discrete-event simulations, each having a duration of 100 s. Fig. 2 shows the average and standard deviation (STD) of residual charge for all nodes. In the presence of beacon traffic for the GPSR, the average level of residual charge increases with increasing beacon intervals, whereas the STD decreases for large beacon intervals, indicating a not uniform discharge throughout the WSN. For the e-GPSR, the average residual charge slightly decreases in the presence of beacon traffic, and its dependence on the beacon interval is negligible. The STD is constant with respect to the beacon interval and slightly greater than the ideal case. Hence, nodes discharge quite uniformly over the whole network, increasing the network lifetime and the reliability of links and positioning. Nevertheless, the above analysis does not take

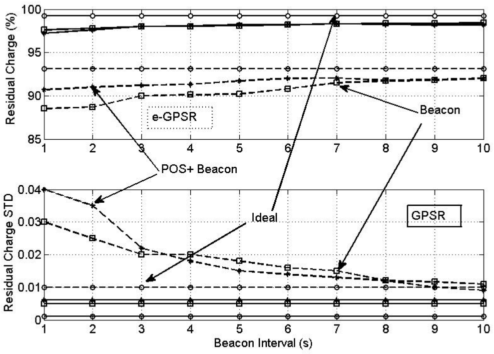

Figure 2: Average (upper plot) and standard deviation (lower plot) of the residual charge of network nodes.

into account the success delivery rate of the considered routing algorithms. Not all data packets are correctly received at the destination, because some packets are discarded somewhere, due to packet collisions, thus their relaying does not consume the expected energy level. Since the GPSR sends more control packets than the *e*-GPSR, because its neighbor list includes more nodes, the GPSR's energy consumption shown above is sligthly lower than it would be if a larger number of packets reached the destination. We may formulate this issue in terms of *average energy efficiency* of all nodes, defined as:

$$\overline{E}_S = \frac{1}{N}\sum_{j=1}^{N}\frac{(1-x_R(j))E_I}{M_D(j)} \tag{8}$$

where E_I is the initial energy, $x_R(j)$ is the residual fraction of E_I of the j node at the end of simulation, $M_D(j)$ is the number of correctly delivered packets.

Fig. 3 depicts the average energy efficiency versus the beacon interval, assuming an initial energy $E_I = 15$ dBm (compliant to UWB regulation) and a S-D distance $d \simeq 10$ m. Although the theoretical model (2) predicts an energy consumption below 15 dBm only when 40 hops are used, the GPSR consumes $\simeq 30$ dBm and the *e*-GPSR $\simeq 5$ dBm for a beacon interval of 3 s with a maximum of 6 hops, as shown in Fig. 4. There, the bar plot of the *latency factor*, i.e. the average number of hops necessary to deliver data packets from S to D, is depicted. The *e*-GPSR exhibits a comparable behavior for the two coverage radii. Hence, a suitable trade-off between power and latency can be found. The GPSR shows a non uniform distribution of latency factor. This attitude becomes remarkable in the realistic scenario, where packets are delivered towards the destination only when the actual route is discovered; otherwise packets are forwarded among useless hops, due to the non perfect knowledge of nodes' positions.

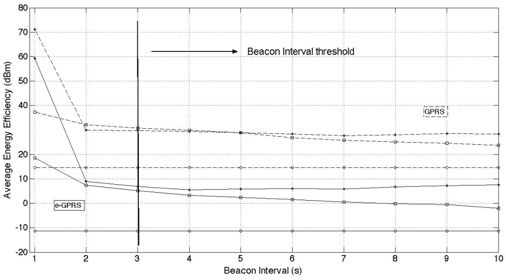

Figure 3: Average energy efficiency needed to transmit a packet from the farthest node to the sink node.

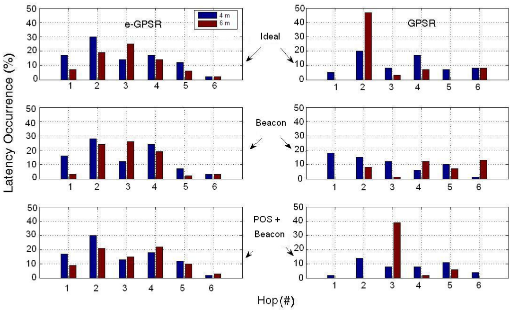

Figure 4: Latency factor for coverage radii of 4m and 6m, assuming a beacon interval of 3s.

4 CONCLUSIONS

Power consumption and latency of GPSR and *e*-GPSR for a UWB WSN have been evaluated and compared, based on theoretical models at first, then through dynamic system simulations. In realistic conditions, i.e. in the presence of control and data traffic in the network, the *e*-GPSR is able to provide a low power consumption and latency. The simultaneous satisfaction of both constraints enable the use of UWB WSNs for *time-driven* applications such as industrial chain monitoring or security/alarm scenarios.

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