Probabilistic Timeliness Routing for Wireless Sensor Networks [*]

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Abstract

The nature of Wireless Sensor Networks and their deployments in real environments prevent the application of classic real-time methods to guarantee timeliness properties, which is further complicated by the pivotal importance of low energy consumption.

In this paper we present a method to estimate probabilities of meeting the end-to-end delivery deadlines and extend the concept of routing path, thus providing additional knowledge to the network hops.

1 Introduction

A Wireless sensor network (WSN) is typically formed by a set of resource constrained nodes communicating via hop-by-hop message forwarding and a small set of network sinks. This architecture, combined with the mobility of nodes, unreliability of their links, and exposure to external interferences represents a major challenge to provide any notion of quality of service (QoS). In addition, timeliness requirements [8] are affected by the mobility of nodes, the absence of stationary relays and reduced computational power.

Bounded end-to-end delays can be provided, when the network enforces deterministic behavior on each communication layer. This contradicts the basics of WSN as it either demands excessive resources or introduces over-constrained properties which cannot be achieved in real deployments (e.g. fixed or perfect network topology).

At the MAC layer, bounded delays might be achieved by means of periodic sensing of the medium and neighborhood synchronization which is often not affordable in terms of energy. At the routing level, global knowledge of the network topology (i.e. routing tables) does not fit in the limited memory capacity of a node. Hence, heuristics based on local knowledge have to be used.

In a good network strategy, the trade-off between resource utilization and performance should account for application requirements. For instance, timeliness requirements for a high importance message might justify the use of additional transmission power to ensure higher coverage and thus faster routing to the sink. However, this should not be enforced for the whole network as it would result in the overall network lifetime to abruptly decrease. Instead, the utilization of resources should be traded off with respect to relevant metrics.

Achieving this level of control despite the dynamics of WSN is not trivial. Many existing solutions rely on global network coordinators or non realistic assumptions and hence lose feasibility in real environments.
Ideally, hops should be able to collect the required information to take decisions by themselves. However, the amount of resources invested should be proportional to the performance demands and energy constraints.
For instance, sharing information with subsequent hops across the path to the sink is, at first sight, more appealing than doing it with hops outside that path. Indeed, exploiting a selective exchange of data among neighbors provides additional levels of knowledge that can lead to smarter networking decisions.

In this paper, we introduce a mechanism to provide probabilities of meeting end-to-end delays in WSN. We propose to exploit the concept of routing paths and provide hops the ability to maintain a status table of the following path segment. This is done by propagating local metrics among the routing path. In addition, we explore timeliness properties by means of a mechanism to extrapolate end-to-end delays based on the monitoring of one-hop link delays.
Ongoing research is carried out in this area: [4] and [5] assign velocities to messages which must be kept in order to fulfill their timeliness requirements. However, both assume static networks and nodes equipped

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with localization capabilities. In [7] delay guarantees are provided at the expense of limiting the length routing paths. [3] achieves hard real-time guarantees at the MAC layer given an hexagonal topology of nodes. This condition is relaxed in [9] although it still relies on static nodes, bounded network density and optimum communication conditions. Additionally, [1] approaches a sufficient schedulability condition to guarantee end-to-end delays in multi-hop WSN under specific restrictions.

1.1 Definitions and properties

A WSN can be represented as a graph $G(N, L)$ formed by a set of nodes N and a set of *single-hop links* L. Two nodes $n_i, n_j \in N$ are *directly connected* at a given time if there is a link $l \in L, l = (n_i, n_j)$ such that n_i and n_j can send and receive messages from each other. $S \subset N$ is the subset of sinks. Sinks might outperform nodes with respect to resources and energy availability.

A *(routing) path* rp_{n_1,n_q} is a sequence of links $(n_1, n_2)...(n_{q-1}, n_q)$ such that each intermediate node in the path is directly connected to the next one, thus providing a *multi-hop link* between the first node (source) and the final node (destination). A path s is contained in another path p if all the links belonging to s also belong to p. In that case, we define s as a *segment* of p. The length of a path is equal to the number of links belonging to it (hence, $|rp_{n_1,n_q}| = q$).

2 Routing path properties

Successive communications between the same nodes and sinks are a common scenario in WSN, e.g. in publish/subscribe schemes where the routing path is reused over time by both communication entities. We argue that the concept of path, however, is barely exploited. Typically, nodes have a preferred hop to whom they forward their messages and consecutive concatenations of this action form a path. Hops are, nevertheless, neither aware of belonging to that path nor of its inherited properties.

We propose a two step strategy. Firstly, assign properties to paths such that applications can express their demands and hops can adjust their behavior accordingly, e.g., desired end-to-end delay, "importance" of messages, or urgency.

Secondly, allow hops to obtain information about the remaining path by requesting metrics values to following hops. This way, nodes can anticipate their reactions to e.g. broken links or unsatisfying metrics values.

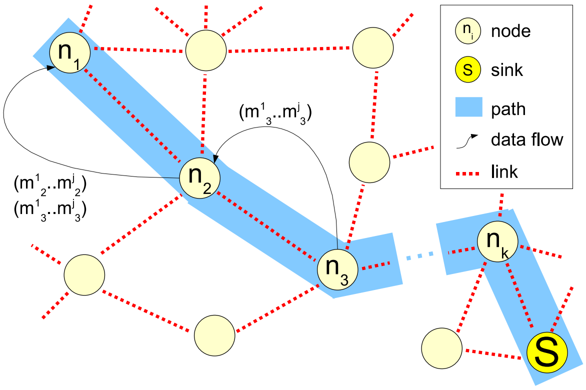

Figure 1: Network path and metric value propagation with $k = 2$

This acquired knowledge is stored in local memory as depicted in Table 1, where n_i is the actual hop, k the length of the segment to explore, and $(m^1..m^j)$ the fetched values of significant metrics.

Maintenance of such a table comes at the expense of local resources, namely: memory, computation time and additional network traffic. The latter increases proportionally to the propagation frequency of metrics values. Besides, energy consumption is indirectly affected by all of the above. Hence, a trade-off is needed between the resource utilization and the values of k and j.

Hop	Set of values
n_{i+1}	$(m_1^{i+1}, ..., m_j^{i+1})$
...	. . .
n_{i+k}	$(m_1^{i+k}, ..., m_j^{i+k})$

Table 1: Metric values of the next segment

Example. Consider the segment $s = (n_1, n_2, n_3)$ of Figure 1 and the metric of interest "measured *SNR* for the next one-hop link". Assume $k = 2$. Given that, n_3 monitors the link (n_3, n_2) and propagates changes of the measured values to n_2. Similarly, n_2 propagates this changes with the aggregation of its own. It is likely that the measured *SNR* for a link will vary continuously. However, we can expect that for a certain period of time it will remain close to previous measurements. Thus, the frequency at which this values should be propagated can be adjusted according to the measurement variability as well as the application requirements. In the example, n_2 should neglect small variations over time and only report to n_1 changes which exceed established bounds.

2.1 Probabilistic timeliness monitoring

Given a one-hop link $l = (n_i, n_j)$ we define D_l as the *random variable* (RV) which characterizes the one-hop transmission delay of link l and $p(D_l)$ as the *probability density function* (*pdf*) such that $p_l(\varepsilon) = P(D_l \leq \varepsilon)$, the probability that l introduces a delay of at most ε in the delivery of a message.

The end-to-end delay for a path rp is then a RV, D_{rp}, formed by the composition of the delays of its links:

$$D_{rp} = \sum_{\forall (i,j) \in rp} D_{(i,j)} \tag{1}$$

and,

$$p_{D_{rp}}(\tau) = P(D_{rp} \leq \tau) \tag{2}$$

Then, assuming that the *pdf*s of the RVs characterizing each of the links have the same distribution, non-negative and mutually independent, it is possible to apply the *Center Limit Theorem* (*CLT*) [10] to characterize the *pdf* of the path as a normally distributed RV[1] with parameters:

$$\begin{aligned} \mu_{D_{rp}} &= \sum_{\forall l \in rp} \mu_{D_l} \\ \sigma^2_{D_{rp}} &= \sum_{\forall l \in rp} \sigma^2_{D_l} \end{aligned} \tag{3}$$

The assumption of all RVs being mutually independent is taken as a premise at this point. One could argue that nearby links might be characterized by RV which are indeed dependent (i.e. $E[V_a, Vb] \neq E[V_a] \cdot E[V_b]]$). We expect that the spatial distribution of nodes and the typical low throughput of WSN will minimize by itself this possibility. Therefore, under this circumstances the probability introduced in Equation 2 converges to

$$\begin{aligned} p_{D_{rp}}(\tau) &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{d} e^{\frac{y^2}{2}} dy \\ \tau &= \frac{D_{rp} - \mu_{D_{rp}}}{\sigma_{D_{rp}}} \end{aligned} \tag{4}$$

In this case, the expected value for the end-to-end latency of rp is $E(D_{rp}) = \mu_{D_{rp}}$.

2.1.1 Run-time calculations

We consider the delay d_l experienced by a message over a link $l \in L$ as the sum of two terms:

$$d_l = d_l^{fw} + d_l^{tx} \tag{5}$$

being d_l^{fw} the time the message is being processed and queued in the node and d_l^{tx} the transmission time over the medium. Since $d_l^{fw} \gg d_l^{tx}$, the transmission time is considered negligible and only the processing and queuing delay d_l^{fw} is taken into account.

Hence, the sequence of delays experienced by consecutive messages is a RV. Its distribution is not important as long as we can generalize the same distribution for all nodes in the path. Indeed, this distribution should be approximately the same as it depends on the network protocols which are common to the entire network. Nevertheless, the specific parameters (i.e. expected value and variance) will vary for each link according to its performance. Thus, it is enough to estimate the average and variance of such distribution to apply the CLT.

We propose the *exponential weighted moving average* (*EWMA*) [2] as a mean to obtain this calculation with little memory utilization and low CPU overhead (Equation 6). A parameter α ($0 \leq \alpha \leq 1$) is set to weigh the actual measurements with respect to the past, hence smoothing the consequences of the past trends and possible aberrations.

$$\begin{aligned} \bar{x}^*_n &= \alpha x_t + (1-\alpha)\bar{x}^*_{n-1} \\ {s^*_n}^2 &= \frac{\alpha}{2-\alpha} s^2_n \end{aligned} \tag{6}$$

Equation 7 provides the sampling variance with low memory requirements.

$$s^2_n = \frac{n-1}{n} s^2_{n-1} + \frac{n-1}{n} (x - \bar{x}_n)^2 \tag{7}$$

Note $x = T_{out} - T_{in}$, the measured time between the reception time of a message T_{in} and the end of its transmission to the next hop T_{out}.

2.2 Routing strategy

It is unlikely that Equation 4 can be computed at run-time on a normal node. Nevertheless, we propose that this computation is performed at the sink during the establishment of the path, e.g. publish/subscribe negotiation. This way, the sink can provide an estimation of the probability of the average end-to-end delay. This

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[1] Although the CLT is commonly applied to large number of samples, an argumentation about good approximations for smaller sums of RVs is found in [6].

information can be used by the node's application to decide on appropriate strategies. Later on, dynamic adjustments might occur at run-time and thus updates on these values by the sink might also follow.

Our second proposal is that nodes make use of the metric propagation strategy to detect whether the following path segments are still suitable or not. E.g. if the values show an increasing delay, it is likely that one or some of the following links are being jeopardized and hence an alternative route to the sink might be needed.

The evaluation of the cost and benefits of such decisions is difficult to assess. We investigate possible trade-offs between the significant factors, namely: the length of the segment to explore k, the number of metrics j, the propagation frequency, and the effect of uncontrollable network dynamics.

With respect to the segment length, the maximization of cost/benefit fits between two extremes: $k = 1$ is the case where each node takes decisions based only on its local knowledge (neighborhood), while $k = |rp|$ implies full knowledge of the path. In the latter, it is presumable that smarter routing decisions can be taken, avoiding dead paths and congestion. Similarly, a higher number of metrics frequently updated allow the node to take decisions based on a more sophisticated algorithm. However, the three factors will have a strong impact on the overall amount of control messages along the path as well as the energy spent at each node to handle and process these messages.

On top of this, the trade-off among these factors is also influenced by the uncontrollable network dynamics. Hence the importance of adaptive re-adjustments of the controllable factors in order to achieve a reasonable utilization of resources (e.g. lower the propagation frequency when the tendency of previous values show stability).

3 Conclusions and ongoing work

In this paper we presented a method to estimate end-to-end deadlines based on a probabilistic approach. We explore timeliness properties across the routing path and a possible application in routing decisions. Moreover, the work presented in this paper exploits the concept of routing paths to extend the available knowledge at each hop, thus allowing smarter decisions at routing. The proposed method introduces the ability of maintaining a status table of the following path segment on each hop, being updated according to path requirements. Further ongoing work includes the analysis of cost and benefit factors, identification of additional metrics of interest and their interrelation as well as possible energy trade-offs.

References

[1] Tarek F. Abdelzaher, Shashi Prabh, and Raghu Kiran. On real-time capacity limits of multihop wireless sensor networks. In *Proceedings of the IEEE International Real-Time Symposium (RTSS)*, 2004.

[2] Lars Burgstahler and Martin Neubauer. New modification of the exponential moving average algorithm for bandwidth estimation.

[3] M. Caccamo, L.Y. Zhang, Lui Sha, and G. Buttazzo. An implicit prioritized access protocol for wireless sensor networks. *23rd IEEE Real-Time Systems Symposium (RTSS)*, 2002.

[4] O. Chipara, Zhimin He, Guoliang Xing, Qin Chen, Xiaorui Wang, Chenyang Lu, J. Stankovic, and T. Abdelzaher. Real-time power-aware routing in sensor networks. *14th IEEE International Workshop on Quality of Service (IWQoS).*, June 2006.

[5] T. He, J.A. Stankovic, C. Lu, and T.F. Abdelzaher. Speed: A stateless protocol for real-time communication in sensor networks. In *Proceedings of ICDCS'03*, May 2003.

[6] Turgay Korkmaz and Marwan Krunz. Bandwidth-delay constrained path selection under inaccurate state information. *IEEE/ACM Transactions on Networking*, June 2003.

[7] A. Sahoo and P. Baronia. An energy efficient mac in wireless sensor networks to provide delay guarantee. *15th IEEE Workshop on Local and Metropolitan Area Networks. LANMAN*, June 2007.

[8] J. Stankovic, T. Abdelzaher, C. Lu, L. Sha, and J. Hou. Real-time communication and coordination in embedded sensor networks. In *Proceedings of the IEEE , 91(7)*, July 2003.

[9] Thomas Watteyne and Isabelle Auge-Blum. Proposition of a hard real-time mac protocol for wireless sensor networks. In *Proceedings of the 13th IEEE International Symposium on Modeling, Analysis, and Simulation of Computer and Telecommunication Systems (MASCOTS)*. IEEE Computer Society, 2005.

[10] Ying Xiao, Krishnaiyan Thulasiraman, and Guoliang Xue. Approximation and heuristic algorithms for delay constrained path selection under inaccurate state information. *International Conference on Quality of Service in Heterogeneous Wired/Wireless Netowrks (QSHINE)*, 2004.