A Proposal for a Notion of Timeliness in Wireless Sensor Networks

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Abstract

The intrinsic properties of Wireless Sensor Networks (WSN) such as their ad-hoc infrastructure, energy constraints, and limited availability of resources, constitute an unfavorable environment for end-to-end timeliness guarantees. Many existing solutions are based on a timeliness notion borrowed from real-time systems, which can only express strict end-to-end deadlines for individual messages. However, it is practically unfeasible to impose these timeliness requirements in WSN without overestimating the network capacity.

In this paper, we present a generalized notion of timeliness suitable for the unpredictable environments of WSN. This notion allows to express a target time interval and the level of confidence of a sequence of messages arriving within the interval. The generalized notion provides means to capture the probability of the end-to-end transmission delays of a sequence of messages within this interval. This notion fits the general requirements of time-sensitive applications while at the same time allows to cope with the unpredictability of real WSN.

1. Introduction

The inherent properties of Wireless Sensor Networks [1] (WSN) constitute an unfavorable environment for timeliness guarantees [2]: ad-hoc infrastructure, strict energy constraints, and limited availability of resources, combined with the exposure to uncontrolled environments (e.g. nature) as well as external interferences (e.g. RF noise) increases the uncertainty of successful transmissions.

The communication mechanism of WSN is based on hop-to-hop message forwarding schemes in which intermediate hops direct messages to one, or several neighbors until the destination is reached. However, the accomplishment of this task is jeopardized by additional aspects such as mobility and lack of global network coordinators.

There is a growing interest in overcoming these restrictions to effectively provide end-to-end timeliness guarantees in WSN [3]. Unfortunately, it is practically unfeasible to determine strict end-to-end delivery delays without overestimating the network capacity.

One fundamental problem is that the adopted notion of timeliness is directly borrowed from classic real-time literature [4]. Hence, the problem to be solved is reduced to providing deadlines to each individual message and a set of additional mechanisms which try to enforce them.

However, the uncertainties of wireless networks, and particularly of WSN, are such that individual messages are always subject to unbounded transmission delays [5]. Satisfying individual deadlines is not feasible a priori, unless additional presumptions about the network are taken [6].

Many of the existing methods introduce implicit assumptions on the underlying models which are required to ensure feasibility. These assumptions are typically related to static and regular topologies [7], symmetry of the radio propagation patterns [8] or absence of environmental interferences. However, by doing so these methods restrict their applicability to specific scenarios which may not be representative of real deployments.

In this paper, we propose a generalized timeliness notion which provides enough flexibility to suit the characteristics of WSN without restrictive assumptions. Instead of aiming at strict deadlines for individual messages, the generalized notion focuses on the timeliness capacity of a sequence of messages. The notion allows to express the end-to-end timeliness requirements by means of a target time interval and a confidence level. Hence, it is possible to relax the requirements imposed by methods based on strict deadlines while still providing valid means to evaluate timeliness performance.

The generalized notion of timeliness is more suitable to the principles of WSN. Unlike the classic notion from real-time, it allows to capture the timeliness performance of a sequence of messages rather than individuals which diminishes the effects of unbounded end-to-end delay transmissions. Note that it is a generalization of the classic notion of timeliness as it also allows to express the same level of strictness.

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The rest of the paper is organized as follows: Section 2 explores the related work in this field. Section 3 introduces the generalized notion of timeliness with more detail, followed by Section 4 which provides an example to illustrate its applicability. Finally, Section 5 concludes the paper.

2. Related work

Ongoing research to introduce real-time guarantees in WSN is carried out at many different levels. In [3] a survey of the current state-of-the-art is presented. Additionally, an overview of the problems in combined soft and hard real-time solutions covering the whole network stack as well as open challenges are discussed.

At the routing level, work in [9] and [10] assign velocities to messages which must be kept in order to fulfill their timeliness requirements. However, both assume static networks and nodes equipped with localization capabilities. In [11], delay guarantees are provided by means of a TDMA scheme at the expense of limiting the length of routing paths.

Traffic regulation mechanisms are also explored as means to provide end-to-end guarantees using queuing models. In [12], the combination of queuing models and message scheduler, turns into a traffic regulation mechanism that drops messages when they loose their expectations to meet predefined end-to-end deadlines. Additionally, an example is given to approximate the delay distribution of each hop in the event of instability by means of a Gaussian distribution. Other probabilistic methods to achieve QoS have been approached by different authors. For CPU scheduling, the notion of probabilistic deadlines and execution time distribution is explored in [13]. In [14], different levels of quality of service are considered with respect to timeliness and reliability providing probabilistic multi-path forwarding to ensure end-to-end delays. Note that despite these methods apply probabilistic techniques to their algorithms, they all aim at satisfying strict deadlines for individual messages.

In [15], the authors introduce an analysis of the impact of mobility in achieving timeliness guarantees. Additionally, a prioritized event transmission protocol based on a proactive routing protocol and resource reservation is foreseen, although the authors take the assumption of a predictable medium access protocol.

A common notion of timeliness, based on the assignment of strict end-to-end deadlines to each individual message is applied in the work referred. Not surprisingly, they all present a number of assumptions with respect to the network which restring their deployment.

With respect to the MAC level, much of the existing research is based on TDMA scheduling of neighbor nodes (e.g. [16]), hence constructing a schedule of transmissions with contention free periods. However, although valid results are obtained in controlled environments, the common restriction of these methods is the assumption of error-free communications. Moreover, the complexity of such strategies, specially in mobile networks, forces the addition of global network coordinators, which discourages their use. Alternative approaches exist, such as [17] which achieves hard real-time guarantees given an hexagonal topology of static nodes. This requirement is later relaxed in [18] although it still relies on static nodes. Besides, both methods are built on the assumptions of bounded network density and optimum communication conditions.

Analytical solutions have also been studied. In this direction, [19] approaches a sufficient schedulability condition to guarantee end-to-end delays in multi-hop WSN. Nevertheless, it is based on specific assumptions on the message transmission times and channel transmission speeds, as well as network density and path lengths. Moreover, it is practically unfeasible to produce analytical models capable to capture the dynamics of a real WSN. Assumptions, again, are necessary in order to adjust reality to the models.

3. Notions of timeliness

The concept of timeliness currently exploited in WSN is greatly influenced by the one originated in real-time networks. In particular, attention is centered around temporal guarantees of individual messages by means of fulfilling deadlines. Each message receives an end-to-end deadline which delimits the time to reach the destination. If the message has not been delivered after this instant, it is likely to be dropped at one of the intermediate hops, depending on the routing policy. Certain routing strategies will drop messages before the expiration of the deadline if they estimate that the deadline cannot be met.

3.1. Meaningful notion of timeliness

We explore a different approach to achieve a better alignment between the network capabilities and the desired timeliness requirements. Instead of constraining the methods to fulfill idealized timeliness properties, we propose to relax the concept of timeliness, to suit the particularities of WSN. We considered the following requirements:

1) The way in which timeliness requirements are expressed should not encourage applications to demand unfeasible degrees of performance that the network cannot provide. Hence, given the unfeasibility of WSN to guarantee single deadlines, applications should express their demands at a higher level than individual messages.
2) A notion of timeliness expressing only success or failure, i.e., deadline met or not, is of only limited value to WSN. Rather, a continuous function to embody the

level of conformance with respect to the timeliness performance is more suitable to the properties of WSN.

3) The capability of WSN to enforce strict end-to-end timeliness requirements is reduced and variable at run-time. Hence, a meaningful notion of timeliness should allow applications to express a level of confidence for the aimed timeliness performance.

The generalization of the notion of timeliness that we propose supports these requirements and is composed of the following parts:

1) Our notion expresses timeliness properties of a sequence of messages, which makes it possible to cope with the undeterminism individual delivery delays in WSN and still provide meaningful values. Note that a sequence of message can be any series of messages as long as they follow the same route inside the network.
2) A time interval (t_i, t_j) with $t_j > t_i \geq 0$, which sets the acceptable end-to-end delay bounds for a sequence of messages.
3) The level of confidence for the required end-to-end interval, expressed by means of a probability $0 < p < 1$ of successful arrivals within the interval.
4) The end-to-end delay distribution function, used as a timeliness indicator, which allows to capture the probability density of the sequence of messages arriving within the interval. The function, which can be obtained at run-time, provides sufficient information to determine the probability of sequences of messages arriving within the specified interval.
5) The selection of the probability level and the length of the interval allows the specification of strict timeliness yet providing additional levels of flexibility which suits the particularities of WSN. Thus, our notion is a generalization of the classic timeliness notion.

By considering a sequence instead of individual messages, it is possible to work around the indeterminism of WSN and still provide meaningful values. Furthermore, the selection of the probability level and the length of the interval allows the specification of strict timeliness yet providing additional levels of flexibility which adapt to the peculiarities of WSN. Moreover, this notion is adequate to evaluate the end-to-end timeliness performance as well as to express requirements in a way that does not demand excessive levels of precision that the network cannot achieve.

Figure 1 shows the probability density function (PDF) obtained by simulation of a routing path of length 5 hops as depicted in Figure 2. Each intermediate hop of this path had two neighbors and each hop on the network (including those forming the path) generated traffic with a time between messages following an exponential distribution with parameter $\lambda = 15s$.

The artificial load was set to simulate the effects of cross-traffic on a segment of a big network. Additional messages were generated periodically every $30s$ at the source of the path and its end-to-end delay captured at the sink.

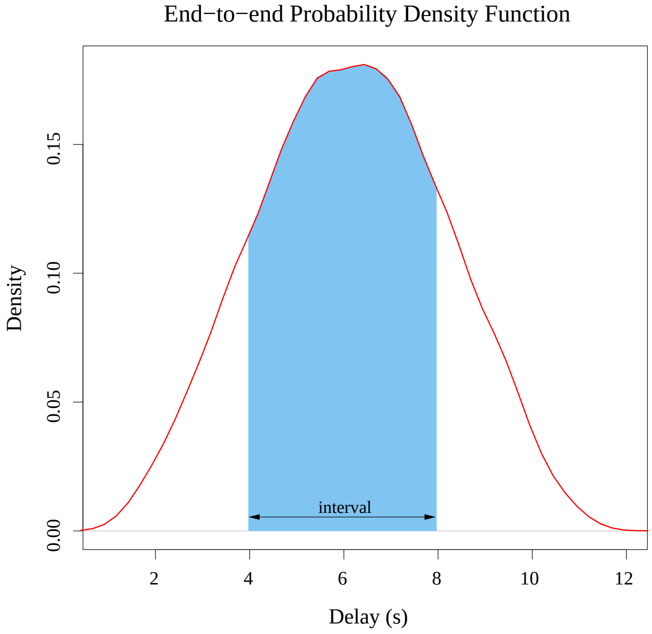

Figure 1. Expressing timeliness by means of the end-to-end distribution (PDF)

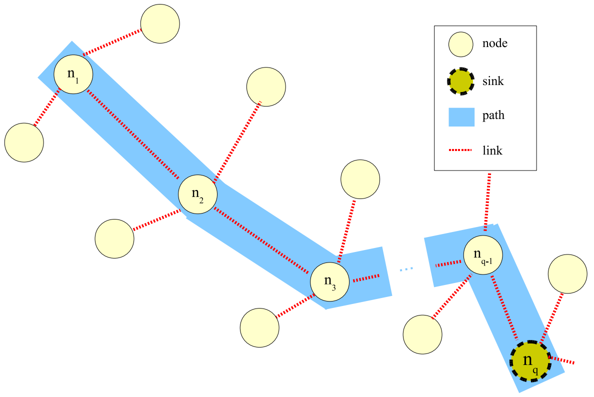

Figure 2. Simulation scenario

This scenario was simulated by means of the network simulator Omnet++ [20] [21] and Mobility Framework [22]. The routing path was manually fixed for this experiment and all messages on the network were directed to the sink. The chosen MAC protocol was Wisemac [23].

In this example, the timeliness requirements correspond to the interval $(4s, 8s)$. Hence, the area bellow the pdf curve represents the probability of end-to-end delays to fall within the interval. At run-time, it is possible to analyze the percentage of messages from a sequence which fulfill this timeliness requirement.

Figure 3 depicts the estimated cumulative distribution func-

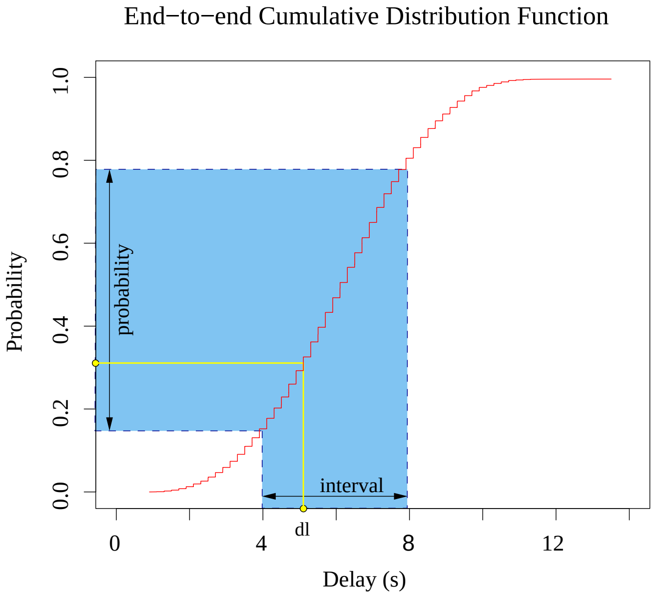

Figure 3. Expressing timeliness by means of the end-to-end distribution (CDF)

tion of the same experiment with an additional line illustrating the classic strict timeliness notion (dl). The probability of fulfilling the timeliness requirements is highlighted and represents approximately 60%.

Both figures, illustrate the relation between the bounds of the time interval and the achieved probability. Notice that both factors are directly dependent of each other.

3.2. Run-time considerations

Existing protocols and methods can be adapted to capture the end-to-end delay distribution used in the timeliness notion presented in this paper. However, there are a number of considerations to take into account to obtain satisfactory results.

- The end-to-end distribution of message delivery delays is not constant over time, thus estimations on the end-to-end delay distribution must continuosly adjusted. Methods to dynamically estimate end-to-end distributions at run-time adapting to dynamic changes of the network must be explored.
- Sensor nodes are equipped with limited resources. Thus, computations must be of low complexity and limited memory usage.
- Sharing global knowledge is expensive in terms of broadcasting messages. The estimation of end-to-end distribution should not generate additional traffic on the network and make use of local information to perform the calculations.

4. Applicability examples

To illustrate the applicability of the proposed notion of timeliness, we derive a sample scenario from a general Elderly Care use-case [24]. The goal of the application is providing automatized monitoring of elderly people in a care house. Sensor nodes are attached to the patients to monitor their general health and well being, with special interest in aspects related to mobility and temperature.

4.1. Scenario

The description of the scenario is as follows:

- Approximately 20 patients living in the same home (20 rooms in four floors).
- Two sensor nodes per patient: one equipped with a 3D accelerometer and a one with a temperature sensor.
- Two operation modes: normal and special.

The data transmission rate depends on the operational mode. In normal mode, nodes process their data after acquisition and transmit messages at a low frequency with respect to the sampling rate (e.g. average temperature), whereas in the special mode data is sent without processing for every sample.

Lets look at a patient recovering from a major fall. In this case, the information from the accelerometer is constantly transmitted to monitor the patient's mobility. The locomotion analysis processes the accelerometer data at a frequency ranging between 20 and 50Hz. The sensor nodes of other patients, which do not require such special monitoring, process their data by means of a local algorithm which generates an output at a much lower frequency (e.g. 1Hz).

Several time constraints appear due to the nature of the measurements. In the normal operation mode, some latency is well tolerated by the system. However, the special mode requires the data to be delivered within a few seconds to allow detailed locomotion monitoring.

4.2. Classic timeliness notion

The classic notion sets end-to-end deadline to each transmitted message. Lets assume that these are set to 15 seconds for normal mode and 2 seconds for the special.

Note that these values are chosen off-line, hence without any concrete knowledge of the network status. Therefore, either if a patient is close to the base station with direct connectivity or it is several hops distant, these deadlines are to be met. Furthermore, the timeliness requirements are expressed in a strict manner, without taking into account whether it is one single patient which requires special monitoring or many of them. However, the bandwidth availability and response time could greatly differ in both situations.

Most existing routing protocols would try to enforce the fulfillment of deadlines. However, it is expected that at a given time, either because the patient moves away from the base station, or due to the additional traffic generated by other nodes, some deadlines will be missed. In such a case, the common procedure is to drop messages without expectations to achieve the destination and save some bandwidth for other messages that still can make it. Alternatively, the message might be transmitted in spite of missing its deadline. However, in both cases the transmission will be accounted as a failure.

4.3. Generalized timeliness notion

Following the notion presented in this paper, the procedure changes the perception of timeliness requirements both at the application as well as at the network level. In a first instance, the application does not express strict end-to-end deadlines for individual messages but rather acceptable intervals for sequences of messages. In the example, this can be expressed in the way of requesting messages in the special mode to be delivered within the interval $(1s, 3s)$ with a probability of 80%. This way, a desired end-to-end delay distribution is expressed.

The difference with respect to the classic notion is that the effects of the unpredictability of WSN are taken into account. Hence, individual messages missing their deadlines are accepted as long as the end-to-end distribution satisfies the constraint. Only when the distribution of the sequence of message exceeds the expected distribution actions are to be taken.

The generalized notion of timeliness provides hooks to apply mechanisms enhancing the network behavior. For instance, by exploring trade-offs to increase the timeliness performance of intermediate hops at the expenses of higher energy consumption (e.g. discover new routes, increase duty cycle of intermediate hops, re-adjust the radio transmission power, etc). If the network stack (e.g. routing protocol) determines that the requested timeliness performance is not feasible, it is of no sense to continue accepting messages from the application layer without the proper adaptations to the current network status. Hence, the adequate feedback channel must be established with the application. For instance, the network stack may inform the application that only 60% of the messages arrive within the required time interval $(1s, 3s)$ while 80% of them do it within $(2s, 4.5s)$. The decision whether to relax the interval bounds or accept the lower probability is left to the application.

This procedure contradicts the classic notion in which the requirements are expressed in an unilateral way, and the network stack has no option but to deal with them. Possible actions are to adjust the sampling rate, perform local processing on the data or accepting that the sequence of messages will be delivered with a worse timeliness performance than it was originally desired.

5. Conclusion

In this paper we proposed a new notion of timeliness suitable to cope with the inherent properties of WSN. We argue that the classic approach is not appropriate as it forces existing solutions to introduce restrictive assumptions in order to achieve otherwise unfeasible performance levels.

The generalized notion, permits a better expressiveness of time requirements and reflects more precisely the timeliness performance of a WSN. Moreover, it facilitates the exploitation of trade-offs and introduces enough flexibility to cope with the uncertainties of WSN.

Further work in this area is currently carried out to develop new protocols based on this concept, as well as to exploit possible timeliness trade-offs. A routing protocol to exploit at run-time the timeliness notion presented in this paper is under development.

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