Timeliness in Wireless Sensor Networks: Common Misconceptions

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Abstract

Existing real-time methods enable wireless sensor networks (WSN) to achieve –in principle– different levels of timeliness guarantees. However, the design and evaluation processes of these methods are often grounded on naive assumptions that constrain their usability in real-world deployments.

In this paper, we analyze from a timeliness perspective a number of implicit and explicit assumptions common in existing methods and discuss their impact in real deployments. We base our arguments on gained experience from simulations under realistic assumptions in WSN as well as well-known research literature. Based on these arguments, we provide a list of considerations to mitigate the effects of misleading assumptions and achieve timeliness solutions consistent with the particularities of WSN.

1. Introduction

The rapid expansion of wireless sensor networks (WSN) [1] in an increasing number of application domains contributes to a growing demand of network services with thorough performance requirements. With the support of a large theoretical and practical background, existing timeliness solutions [2] aim at enabling WSN to operate with real-time guarantees. However, the design and evaluation of these methods are often based on naive assumptions that constrain their applicability in real-world deployments.

The definition of ambitious goals –which cannot be satisfied unless severe assumptions are granted– is one of the major drawbacks of current real-time methods. This overestimation of capacity entails important simplifications during the evaluation process. Among others, common practices include the definition of misleading evaluative criteria and the loss of generality due to ad-hoc test-beds. Hence, the quality assessment from a timeliness perspective becomes unclear because the methods are evaluated against unrealistic models.

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In this paper, we analyze –from a timeliness perspective– three main aspects of existing real-time solutions for WSN. First, we overview the different goals of existing real-time methods to deem their suitability if applied to realistic WSN. Secondly, we evaluate the impact of a number of implicit and explicit assumptions taken in the design of these methods. In most cases, these assumptions have a significant impact on the real-time performance and constrain the applicability in real-world deployments. Lastly, we examine different evaluation criteria and identify common misconceptions of the evaluative process that can lead to misguided conclusions.

Based on this analysis, we infer a number elementary considerations, which allow mitigating the impact of unrealistic assumptions and facilitate meaningful evaluation tests that increase the confidence of these methods.

The reminder of this paper is organized as follows: section 2 overviews some of the most representative methods in the current state-of-the-art; the following sections present a discussion about common misconceptions and misleading assumptions about real-time objectives (section 3), networking protocols (section 4), and evaluation criteria (section 5); based on this analysis, section 6 presents a series of considerations with the aim of mitigating the inclusion of these misconceptions in future developments; finally, section 7 concludes the paper.

2. Overview of Real-Time in WSN

Applications of WSN can be divided into two main areas: monitoring and tracking [3]. The former includes examples such as monitoring of health parameters in a medical context, environmental control, and structural monitoring of buildings. The latter, includes object tracking in multiple contexts as well as intrusion surveillance of restricted areas. Both domains exhibit inherent demands for real-time guarantees that existing methods try to satisfy at different levels.

Real-time MAC protocols aim at bounded data link transmission times, which are necessary to guarantee forwarding delays in single hop scenarios. Common ways to achieve this include traffic regulation mechanisms [4], scheduling of message transmissions [5], as well as structured network topologies [6], [7], and prioritized schemes [8].

Routing techniques pursue bounded end-to-end delays for multi-hop scenarios in a broad number of possible ways [9]. Examples include geographic packet forwarding [10], multi-path routing [11], and prioritized queuing models [12]. Multi-layer approaches try to embed the functionalities of different layers into a complete real-time framework with delay guarantees [13].

The analysis of end-to-end latency [14], [15] aims at providing a better understanding of timeliness capacities of WSN. This information enables adaptive methods to adjust their behavior to the current network conditions. In addition, low latency [16], robustness [17] and specially low energy consumption [18], [19], are properties inherently present within the goals of most real-time solutions.

3. Misleading Real-Time Objectives

The solid background of real-time systems is in many aspects a source of inspirations to provide real-time support in new research areas. However, the inherent capacity of satisfying real-time constraints may be significantly different from one domain to another. Overseeing the fundamental incompatibilities between both domains develop in some of the most common misuses of real-time methods applied to WSN, which may lead to unfeasible goals and unrealistic scenarios.

Assumption 1. *The goal of a real-time method is to provide hard real-time guarantees for each transmitted message.*

The notion of hard real-time systems [20], in which each event is associated with a strict deadline, does not match with the general architecture of WSN. Messages are transmitted via hop-by-hop forwarding through unreliable links; the end-to-end delivery ratio is typically low; and the low-energy profile of most communication stacks increases the probability of expiring the maximum retransmission attempts without success. A consequence of these facts is that any individual transmission is susceptible to fail.

Guaranteeing strict deadlines requires excessive resources and complex algorithms for which WSN are not designed. A more elaborated notion of timeliness and the definition of adequate metrics to evaluate the quality of service (QoS), accommodate to a larger extend with the inherent properties of WSN. For example, in [21] the authors present a notion of timeliness which based on the current real-time performance of the network extracts the probability of messages being transmitted within bounded intervals.

Efficient real-time methods should encourage the analysis and exploitation of network trade-offs, adapting their timeliness performance according to the suitability of expending resources.

4. Common Protocols Assumptions

Existing protocols are not free of assumptions. In this section we enumerate a number of misleading assumptions in existing protocols and their implications in realistic scenarios.

Assumption 2. *Availability of resources.*

In a number of existing protocols, it is common practice to base the methods on the assumption of specific hardware resources. Although it is possible to conceive a plausible scenario to justify these assumptions, they are not valid for the general case. For example, GPS devices are mentioned by [22], [19], and [11]; [8] assumes multiple radio transceivers; and [23] and [24] provide solution based on unconstrained nodes acting as access points.

Assumptions on such equipment imply the loss of generality and restrain the applicability of these methods to particular cases. Mitigating the implications of such assumptions by alternative methods strengthens both the validity and applicability of the method. However, the consequences of such substitutions may introduce inaccuracies with respect to the dedicated hardware that must be taken into account.

4.1. Data Link Level

Precise models of radio transceivers and the propagation of waves through the air are inherently complex due to the interaction of a considerably large number of physical laws. However, their accuracy may determine the validity of real-time models built on top of them. The trade-offs between accuracy and simplicity are not straight forward, and lead to different levels of precision. The following aspects have a significant impact on the data link models.

Assumption 3. *Radio links are symmetric and stable over time. Transmission range follows a radial pattern equal to the interference range.*

This set of assumptions has been widely discussed and refuted. Radio transmissions are neither symmetric nor stable over time as shown in [25], [26]. Both studies conclude that the transmission range of omnidirectional antennas is not regular for all directions and varies over time even in static set-ups. In [27], the authors experiment with the vertical placement of nodes and conclude that nodes placed a distance above the ground achieve a significant larger transmission and reception range.

From a timeliness perspective, the implications of unrealistic radio models introduce a number of important drawbacks. In the first place, in real-world scenarios the delivery ratio drops due to radio anomalies [28]. Hence, the necessary mechanisms to ensure successful transmission within strict deadlines must be reenforced. Moreover, further nodes are typically preferred by message forwarders, as they offer a shorter hop distance till the sink. However, these nodes may be located within the boundaries of the effective transmission range, where links suffer from a high bit error rate (BER). In [29], the authors explore the use of different metrics other than the *distance-to-sink* in order to determine the quality of paths. Their study reveals that the elaboration of a path metric is not straightforward and may require the combination of different indicators.

Broadcast messages, which are often used to build network trees, also suffer from similar effects. For example, a node closer to the sink will broadcast "HELLO" messages to its neighboring nodes, which will then register the source as the forwarding preference for their traffic. However, some of these child nodes may not be able to send their messages back, either due to the non-symmetric range of the radio devices or because of temporal instability. In [30], the authors explore further this effect and propose a simple method to determine stable links based on the consecutive reception of enumerated broadcast messages.

Assumption 4. *A radio transceiver is either in transmitting or receiving mode, or turned off.*

The common assumption with respect to the radio transceiver is that at any time, it is either turned off or in one of two possible states: receiving (Rx) or transmitting (Tx). However, the transition between these two modes produces a third state in which the transceiver is neither listening nor sending out any signal. This, in general, is widely neglected in simulation models, despite accounting for a large number of collisions. In real-world scenarios, it introduces a large enough interval of time –$192\mu s$ in a TI CC2420 [31]– between sensing the channel and being able to start transmitting. During this gap of time, other nodes sensing the medium may also start transmitting, which may lead to collisions if both nodes are within their interference ranges.

From a timeliness perspective, the most relevant impact of this effect is again a notable decrease of the effective delivery ratio, which indirectly affects the performance figures of real-time protocols validated against simplistic models.

Assumption 5. *The received signal strength (RSSI) is proportional to the distance between sender and receiver.*

The relation between RSSI and the distance between the communicating parts is not as straight forward as often assumed. In [32], the authors analyze the signal strength measured at increasing distances and conclude that although *the average* signal strength shows a correlated trend with respect to the distance, this cannot be extrapolated to individual measurements. This conclusion is shared in [33], which additionally explores the correlation between signal strength and packet loss. They found out that typically, high signal strength produces low packet loss, although surprisingly, the opposite statement does not necessarily hold.

4.2. MAC Protocols

Real-time MAC protocols try to guarantee bounded transmission delays between neighbor hops. Their success depend in great measure on carefully defining their operational boundaries. Certain assumptions, as the following, may lead to unsatisfactory results.

Assumption 6. *If no other node in the network is trying to access the medium, the medium is free.*

The assumption of complete isolation with respect the the wireless medium is not safe. Some existing methods (e.g. [34], [35], [36]) and most TDMA scheduling policies (e.g. [37], [38]) are designed under the assumption of having a constant amount of network capacity at their disposal.

Nevertheless, communications may still suffer from external interferences and reduced connectivity due to weak link. As a consequence, messages may result corrupted or not transmitted, despite theoretical guarantee of conflict-free communications provided by the protocol.

Protocol designers must take into account that RF communications are prone to uncontrollable interferences that may enter in conflict with TDMA schedules as well contention-free intervals. The assumption of a a completely isolated environment could be a valid claim for testing purposes. However, the calculation of real-time delay bounds based on this principle is not accurate.

Assumption 7. *WSN can be organized in fixed topologies which remain stable for the entire network life-time.*

The restriction to a particular network topology is common in some real-time protocols (e.g. [7]). In spite of being a legitimate requisite for characteristic scenarios, the implications of such assumptions are questionable in real deployments. In fact, provided that factors such as the radio anomalies discussed in assumption 3 are taken into account, the relation between the physical placement of nodes and their connectivity over time with neighbor nodes is not constant.

4.3. Routing Protocols

Routing protocols are not exempt of misleading assumptions which cannot be always taken for granted.

Assumption 8. *Location-awareness.*

Equipping each sensor node with a GPS device is out of budget for most WSN deployments. Realistic assumptions should be made also with respect to the availability of resources. Nevertheless, multiple location algorithms are available and can be combined with real-time methods. However, it is important to consider the unavoidable error of these algorithms in finding the exact position of a node. For example, the performance of routing protocols based on geographic forwarding (e.g. [10]) may be directly affected or seriously jeopardized if these errors occur.

Assumption 9. *The maximum length of any routing path is bounded. Hop distance is proportional to physical distance.*

Assuming upper bounds on the number of hops necessary to reach the sink from a given source node (e.g. [18]) is a very practical but unrealistic restriction. The elaboration of routing protocols that define the trajectory of messages towards the sink following the "shortest path" may result in low throughput. In [29], the authors analyze this effect and provide a number of alternative metrics.

Establishing a realistic upper bound requires strong assumptions on the network dynamics which are often out of control. Nevertheless, the establishment of a bound for the"longest possible path" introduces an implicit constrain in the protocol scalability.

Assumption 10. *Messages that cannot satisfy their deadlines are dropped.*

This case may not be considered an assumption but rather a common behavior of real-time routing protocols as a consequence of aiming at strict deadlines (see assumption 1). In most WSN scenarios with timeliness requirements, there is an added value to the *freshness* of data. Following this principle, old messages are often discarded at intermediate hops if the algorithm estimates that their end-to-end deadline cannot be fulfilled.

However, guaranteeing end-to-end delays is not effective if the protocol itself contemplates the possibility of dropping unsuccessful messages based on estimates. In some cases, receiving old data may produce better results than receiving no data at all. Alternative approaches may consider adaptive methods with the ability of defining flexible deadlines.

5. Imprecise Evaluation Criteria

Choosing meaningful evaluation criteria has a great impact on the performance figures and the quality of the evaluation procedure. In this section, we discuss some important misconceptions affecting the generalization of evaluation analysis in realistic scenarios.

5.1. Misleading Theoretical Proofs

Assumption 11. *Everything can be turned into an analytical expression.*

With the use of properly validated models, meaningful bounds for the network latency or other performance metrics can be inferred. However, in many cases the necessary level of abstraction introduces serious simplifications of complex systems; for example: assumptions about traffic pattern distributions, service times, or the minimum network density.

Analysis of *average-case scenarios* provide theoretical bounds for the figures of interest. However, introducing all possible factors that could interfere in the *worst-case scenario* is practically unfeasible in analytical expressions.

Assumption 12. *The distribution of average (service time/transmission latency/queue size) is constant during the entire network life-time.*

This assumption is correlated with the previous and reflects the unfeasibility of analytical expressions to capture the dynamic behavior of a WSN.

5.2. Simplistic Simulations Models

Assumption 13. "*Our model reflects accurately the physical properties of ...*".

Due to the complexities of physic laws and the propagation of waves, a realistic radio model including all possible anomalies is practicably unfeasible. Channel access, environment, and interferences are as important to model as the method being evaluated. Simplistic models may hide design flaws or applicability limitations that appear in real-world deployments.

Experiments such as [33], [28], and [39] show that the deviation between simulation results and real test-beds are not negligible. However, the additional level of complexity involving a real test-bed is not always affordable.

Nevertheless, an appropriate validation process can lead to sufficient levels of accuracy for the most significant figures. For example, in [40], the authors profile the necessary steps to achieve accurate evaluations of timeliness protocols with properly tuned simulations.

6. Considerations

Designing and implementing timeliness methods for WSN without relying on misleading assumptions is a challenge that still needs further attention. The definition of appropriate objectives and a careful validation of models are crucial to achieve high quality methods.

The following list of considerations summarize the main problems of existing methods, and may help overcome a number of popular misconceptions constraining the quality of timeliness solutions:

- Hard real-time solutions require strict deterministic models that are not compatible with WSN. Adaptive methods and a proper definition of QoS trade-offs may reduce the number of necessary restrictive assumptions.
- Realistic radio models are difficult to achieve, yet crucial in the evaluation of timeliness models. The careful validation of data link models plays a significant role in the elaboration of satisfactory methods.
- RF communications in WSN are typically exposed to many sources of interferences. MAC protocols have to

be robust enough to deal with unstable channels and weak links.

- Effective routing protocols should be able to support timeliness without requiring restrictive resources. Scalability and adaptiveness are also important figures to evaluate.
- Validation criteria must be consistent with the scenarios for which the evaluated methods are designed. Simplistic models may lead to optimistic figures that do not match the real performance.

7. Conclusion

In this paper, we enumerated a number of misleading assumptions that are found in many existing real-time methods for wireless sensor networks. Our analysis is conducted from a timeliness perspective with the goal of identifying the source of common misconceptions with a negative impact on the real-time performance.

Based on existing literature and gained experience of simulations under realistic assumptions, we presented argumentation against misleading evaluation and validation criteria leading to imprecise conclusions.

We completed our analysis with a series of considerations that may help mitigate the effects of misleading assumptions.

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