Optimizing TDMA Design for Real-Time Applications in Wireless Sensor Networks

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ABSTRACT

Many wireless sensor networks (WSNs) are used to collect and aggregate data from potentially hostile environments. Catering to this, early application scenarios did not put tight constraints on performance properties like delay, but rather focused on ruggedness and energy conservation. Yet, there is a growing number of scenarios like e.g. production monitoring, intrusion detection, or health care systems which depend on the sensor network to provide performance guarantees in order to be able to act upon the phenomena being sensed in a timely fashion. Nevertheless, these applications still face the traditional issue of energy-efficiency. In this paper, we present means to find energy-efficient medium assignments in time-slotted multi-hop networks that satisfy given real-time constraints. Specifically, we present a way to find the optimal length of time slots and periods in TDMA schemes. We also present a software to compute those values for typical sink-tree WSNs.

General Terms

Wireless Sensor Networks, Energy-Efficiency, Real-time guarantees, Optimal TDMA, Network calculus

1. INTRODUCTION

Wireless sensor networks have requirements and characteristics that are considerably different from those of common computer networks. Issues include low energy reserves, limited processing power, uncontrolled environments and other adverse factors. The main attention has been put on meeting these restrictions, so there has been much research on minimizing energy usage by introducing sleep times, reducing the amount of transmitted data, etc. While those topics remain important, other aspects have been neglected. With long sleep times come long delays, which can grow rapidly with the size of the network, depending on its topology.

Traffic flows as well as scheduling regimes have so far often been considered fluid, neglecting aspects like packetizing or TDMA and describing them only by their sustained maximum or average rate and modifiers like a burst for incoming traffic or latencies for services, which is a good approximation for fast and relatively fine-grained data streams. When looking at very slow data streams however, that model loses precision. With slow medium data rates and processing, data sent over such a network loses its fluid characteristics. This becomes a concern in TDMA systems, where participants only receive intermittent service during their assigned time slots, and need to be quiet outside those slots. Modeling such a system with fluid models fails to take this into consideration.

We present the optimization problem of finding the most energy-preserving frame length in a TDMA system while still meeting worst-case delay constraints, and we show an analytical approach to compute that value in generic sink-trees. We also present an implementation using the existing DISCO Network Calculator framework [7], allowing us to analyze the impact of discrete models on worst-case delay bounds. This provides us with a means to compute bounds for TDMA parameters in sink-tree sensor networks.

The problem we address is different from other approaches that try to find optimally fast solutions, like e.g. [4], in that we find the *minimum* medium allocation that still allows the WSN to work within the given limits. Other related work covers aspects of TDMA networks, like time synchronization [9] or resource allocation and reuse in spatially spread out networks [1 5]. The general tenor is to maximize performance of a network, whereas we aim for the minimum performance at which quality of service requirements, in this case delay, are still fulfilled. thus achieving energy-efficiency.

This work is founded on the basic network calculus as described in [2]. Furthermore, it draws upon the extensions towards sensor networks which were introduced in [6] and further elaborated in [8]. Based on that, the DISCO network calculator has been created which has been extended for the numerical part of this paper.

2. OPTIMAL TDMA DESIGN

When designing a TDMA system, a choice has to be made for how long the repetitive TDMA frame as well as the individual slot sizes of each participating node are. Since the advantage of TDMA systems against concurrent medium access lies in the fact that each participant obtains exclusive use of the medium, it has to be ensured that each participant gets assigned enough time to perform its tasks. For some network nodes, that just requires a short slot in which they can send collected data, and perhaps receive an acknowledgment from an upstream node. However, in multi-hop systems, some nodes act as routers, and have higher bandwidth requirements for forwarding other nodes' data, while perhaps collecting and sending data themselves. Aside from avoiding contention, using TDMA also reduces energy consumption by making it possible for nodes to power down in periods without relevant traffic.

Since in wireless sensor networks, two main concerns are minimizing power consumption and meeting delay bounds, while transmission bandwidth requirements tend to be low, we want to maximize the frame length, giving the sensor nodes the opportunity to disable their radio transceivers or even go into deep sleep modes.

2.1 General TDMA Design Problem

From those requirements, we formulate the TDMA design problem as an optimization problem for a tree network with n nodes where from each node a flow is originating:

$$\begin{array}{lll} \text{max.} & Z = \min_{1 \le i \le n} \{f - s_i\} & \\ \text{s.t.} & \sum_{i=1}^{n} s_i \le f & \text{(TDMA integrity)} \\ & \forall i: \ d_i(f, \vec{s}|r, b, C) \le D & \text{(Delay)} \\ & \forall i: \ \frac{s_i}{f} \cdot C \ge F_i r & \text{(Rate)} \\ & \forall i: s_i \ge 0, \ f \ge 0 & \text{(Non-negativity)} \end{array}$$

Here, f is the length of the repetitive TDMA frame, s_i is the amount of time devoted to node i for sending (slot size of node i). These constitute the decision variables. For the parameters of the problem we further have, D as the maximum permissible delay that may be incurred by any flow in the sensor field, $d_i(f, \vec{s}|r, b, C) = h(\gamma_{r,b}, \beta^i_{eff})$ as the actual maximum delay incurred by flow i (which is computed based on the effective service curve β^i_{eff} computed by a PMOO analysis [8] of the network), F_i as the number flows carried by node i (including the flow originating at node i), C as the medium rate ("capacity"), and r as the (maximum) sustained rate for any flow as well as b as the maximum burst of a flow. Note that we assume the sensors to have identical arrival curves $\gamma_{r,b}$ as well as an identical delay requirement D, which for most practical situation will be no restriction and makes the further analysis more tractable.

The objective function reflects the fact that the minimum sleeping period over all nodes in the field should be maximized, thus achieving a maximum lifetime of the network. The TDMA integrity constraint captures the fact that all slot sizes together must fit into the TDMA frame. Obviously the delay constraints should be met for all flows, which is captured by the delay constraints, as well as all the rate constraints must be met in order not to obtain infinite delay bounds for the flows. Of course, we also have non-negativity constraints for the decision variables. As a remark, in the objective function there is a hidden assumption on the relative energy costs for switching between different states like transmission, reception, and idle. It is assumed that those state transitions have roughly the same cost, as it is the case for many transceiver architectures (see e.g. [10]), such that by minimizing the sleep period of a node with respect to sending will in fact coincide with minimizing the amount of energy consumed for transmission *and* reception by maximally batching data before forwarding them (within the delay constraints).

Unfortunately, this general modeling of the TDMA design problem results in a very hard to solve non-linear programming problem with $n + 1$ decision variables and $3n + 2$ constraints. The non-linearity is exhibited in the objective function as well as in the delay constraints. Hence, the only viable approach is to simplify the problem structure if a solution shall be found for larger instances of the TDMA design problem. There are two intuitive approaches towards relaxing the problem:

1. *Equal Slot Sizing (ESS):* the assignment may be made such that inside a fixed time slot length, each node can transmit enough data to fulfill all requirements.
2. *Traffic-Proportional Slot Sizing* (TPSS): slots may be assigned such that each node only claims the resources necessary to fulfill its own duties, depending on the input bandwidth and forwarded data streams.

While the second relaxation approach may appear more efficient, it is also harder to set up. The first approach requires rather little information – the number of nodes and the bandwidth requirements of the node serving the highest number of flows –, the second method requires good knowledge of the topology, which may not always be at hand.

In both cases two variables need to be controlled: The overall frame length f and the individual slot length s, where however for ESS this slot length is for each node, while for TPSS each node obtains a multiple of that slot length depending on the number of flows it has to carry. Obviously in both cases, with an increasing frame length, a node may sleep longer between transmission or reception phases, but delay is increased at the same time. For a given f in a network with n nodes, s is limited to values between an upper bound $\frac{f}{n}$ and a lower bound that is given by the minimum bandwidth requirements.

Interestingly, despite the more intuitively more appealing nature of the TPSS relaxation, the ESS relaxation achieves better results with respect to maximizing the minimum sleep period in the field. As it is also the easier one to solve we further on focus on the ESS relaxation for solving the TDMA design problem:

$$\begin{array}{ll} \text{max.} & Z = f - s \\ \text{s.t.} & s \le \frac{f}{n} \\ & d(f, s|r, b, C) = \max_{1 \le i \le n} d_i(f, s|r, b, C) \le D \\ & \frac{s}{f} \cdot C \ge F_{max} r \\ & f \ge 0 \end{array}$$

Fig. 1 shows a simple network and the resulting graphical representation of the optimization problem for $C = 10$, $r = 1$, $b = 1$, $D = 1$. It can be seen that the optimum must be taken on at the lower border of the feasible region. In fact, we can derive a closed form of the the border constituted by the delay constraint because the delay constraint is a quadratic form in s and f which can be solved for s with two real solutions of which we take the larger one as it results in a more binding constraint. A moment's consideration exhibits that, with g as the solution of the delay constraint for s, $\forall f: \frac{\partial g}{\partial f} < 1$ since otherwise an increase in frame size would result in a larger increase of the slot size, which obviously cannot be the case. On the other hand the partial derivative of the objective function after f is 1, which means that the optimum must be taken on at the corner point of the feasible region where delay constraint and TDMA integrity constraint intersect. In other words, the *TDMA design problem under ESS* can be reduced to *matching the delay with the TDMA integrity constraint.*

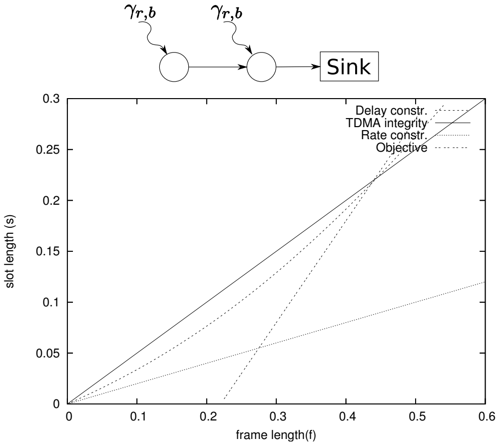

Figure 1: A two-node sample network and the graphical illustration of the resulting optimization problem for ESS. The feasible region is above the delay constraint and below the TDMA integrity constraint. The rate constraint does not affect the feasible region in this example.

2.2 Analytical Solution for ESS in General Sink Trees

What remains to do in general sink trees compared to the two-hop network in the previous setting is to show that the delay constraint again takes on a quadratic form. This then allows to easily express the slot size as a function of the frame size and the same arguments as in the two hop case will lead to the conclusion that the optimum solution is given at the point where delay and TDMA integrity constraint are matched. Hence let us discuss the delay constraint in a general sink tree network:

We assume a general sink tree network with each node offering a service curve $\beta_{\frac{s}{f}C,f-s}$ and flows starting from each node constrained by arrival curve $\gamma_{r,b}$. Looking at a particular flow we have a situation as depicted in Fig. 2. Applying the PMOO analysis results in the following effective service curve for the flow of interest:

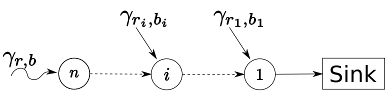

Figure 2: Flow in a general sink tree

$$\begin{aligned}\beta^n_{eff} &= \left[[\beta_{R,T} - \gamma_{r_1,b_1}]^+ \otimes \beta_{R,T} - \gamma_{r_2,b_2}\right]^+ \otimes \dots \\ &= \beta_{R-\sum_{i=1}^{n-1} r_i,\ \frac{T\left(nR-\sum_{i=0}^{n-1}\sum_{j=1}^{i} r_j\right)+\sum_{i=1}^{n-1} b_i}{R-\sum_{i=1}^{n-1} r_i}}\end{aligned}$$

with $R = \frac{s}{f}C$ and $T = f - s$ and $r_i = a_i r$ and $b_i = c_i b + d_i r T$. For the latter expressions the parameters $a_i, c_i, d_i \in \mathcal{N}$ are depending on the topology. The delay constraint for flow n (i.e the one originating at node n) can thus be expressed as a quadratic form in f and s which can be recast to s where we can ignore the smaller right hand side version as the larger one is the physically meaningful. Hence, we can again reason that the optimal solution must be taken on at the cornerpoint of the feasible region where TDMA integrity and delay constraint are matched.

3. NUMERICAL APPROACH IN THE DISCRETE SETTING

For the numerical approach, we extended the DISCO Network Calculator [7] to handle affine curves as described in [3], which allows us to model discrete service and arrival curves and perform network analysis with such. We specifically model the service curves like β shown in Figure 3. The arrival curve is modeled as a simple token bucket, mostly to reduce computing time. It also resembles the behavior of a sensor that is constantly doing measurements, like a low-bandwidth audio stream or some other task that requires frequent sampling.

The TDMA design problem, based on the insight from the previous section that TDMA integrity and delay constraint have to be matched, ultimately boils down to a root-finding problem: a black-box function $d(f, s|r, b, C, D)$ returns the delay incurred for the parameters. Since we have seen that the optimum is found at $s = \frac{f}{n}$, this is a function with one variable $d(f|r, b, C, D)$. Since we want to maximize the frame length f, we seek a solution f' for which $d(f'|.) = D$, which is a root for $d(f|.) - D = 0$. We further know that $\forall 0 < f < f': d(f|.) - D < 0$ and $\forall f > f': d(f|.) - D > 0$. Thus, we can use interval bisection to find the root. We are specifically using an algorithm that approaches the root from below, making sure that the calculated value is smaller than f', ensuring it is inside the feasible region.

3.1 Numerical Examples

Using that procedure, we set up a number of sample networks, among them the one from the previous section and fully populated binary trees of depth 3 and 5 and analyzed those in the enhanced DISCO Network Calculator. The results presented in Table 1 show that a discrete analysis has an advantage over an analysis in the fluid domain. The magnitude of that advantage depends on the scenario. The

Figure 3 explains the improvement. The latency bound is computed as the maximum horizontal distance between the arrival curve α and the service curve. In the fluid setting, the service curve models the average medium rate $\frac{s}{f}C$ available to a node, as shown by the curve β'; in the discrete setting, a node periodically gets the full rate C, which makes the discrete service curve β "jump" above β'. Because of this, it holds that $\forall \alpha \in \mathcal{F}: h(\alpha, \beta) \leq h(\alpha, \beta')$.

Setting	C	r	b	D	fluid f	discrete f
2 nodes	10	1	1	1	0.4444	0.7368
Binary tree, 3 deep	5000	1	1	10	3.5356	3.5859
Binary tree, 5 deep	5000	1	1	10	1.2811	1.4435

Table 1: Comparison of numerical results in fluid and discrete settings

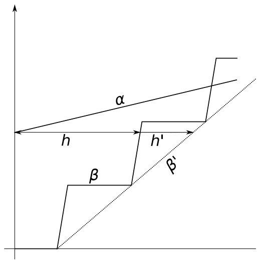

Figure 3: Illustration of the improvement

It is apparent from the numerical results that for larger networks, the relative advantage of a discrete analysis becomes smaller. The same holds for service curves with a lower step height. This is because, due to the nature of the effective end-to-end service curve, the step size remains the same, but the latency grows with each hop and interfering flow. When referring to Figure 3, h grows faster than $h' - h$.

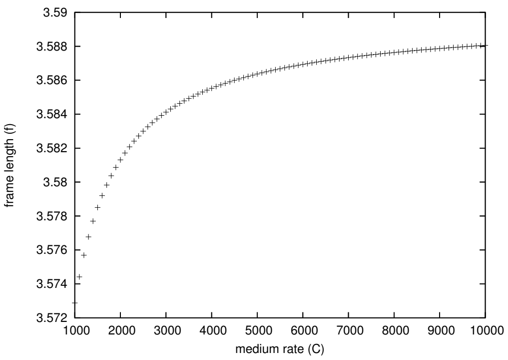

Figure 4: Frame lengths for varying medium speed

It is also notable that in our test-cases, the optimal value for f scaled linearly with D, so for a given network with all other parameters fixed, the frame length can be easily extrapolated from a few computed values. The behavior with changing C is potentially more interesting, since a modified service curve is accompanied with it. However, when looking at a sample data set in Figure 4, which was created by varying C from 1000 to 10000 in steps of 100 with $r = 1$, $b = 1$ and $D = 10$, one notices that the gains in the possible frame lengths are minimal and even diminishing for larger rates. Such small gains in frame length are likely outweighed by the rising energy requirements imposed by the hardware necessary to achieve a faster transmission speed.

4. REFERENCES

[1] Patrik Björklund, Peter Värbrand, and Di Yuan. Resource Optimization of Spatial TDMA in Ad Hoc Radio Networks: A Column Generation Approach.

[2] Jean-Yves Le Boudec and Patrick Thiran. *Network calculus: a theory of deterministic queuing systems for the internet.* Springer-Verlag New York, Inc., New York, NY, USA, 2001.

[3] Anne Bouillard and Éric Thierry. An algorithmic toolbox for network calculus. Technical report, Unité de recherche INRIA Rennes, 2007.

[4] Shuguang Cui, A. Madan, R.and Goldsmith, and S. Lall. Energy-delay tradeoffs for data collection in TDMA-based sensor networks. In *ICC 2005 Vol. 5.* IEEE, May 2005.

[5] S.C. Ergen and P. Varaiya. TDMA scheduling algorithms for sensor networks. Technical report, University of California, Berkley, 2005.

[6] Jens Schmitt and Utz Roedig. Sensor Network Calculus - A Framework for Worst Case Analysis. In *Proceedings of IEEE/ACM International Conference on Distributed Computing in Sensor Systems (DCOSS'05), Marina del Rey, USA*, pages 141–154. Springer, LNCS 3560, June 2005. ISBN 3-540-26422-1.

[7] Jens B. Schmitt and Frank A. Zdarsky. The DISCO Network Calculator - A Toolbox for Worst Case Analysis. In *Proceedings of the First International Conference on Performance Evaluation Methodologies and Tools (VALUETOOLS'06), Pisa, Italy.* ACM, November 2006.

[8] Jens B. Schmitt, Frank A. Zdarsky, and Ivan Martinovic. Performance Bounds in Feed-Forward Networks under Blind Multiplexing. Technical Report 349/06, University of Kaiserslautern, Germany, April 2006.

[9] M. Sichitiu and C. Veerarittiphan. Simple, accurate time synchronization for wireless sensor networks. In *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC) 2003.* IEEE, 2003.

[10] A.Y. Wang and C.G. Sodini. A simple energy model for wireless microsensor transceivers. In *Global Telecommunications Conference 2004.* IEEE, IEEE, November 2004.