Comparison Between Centralized And Distributed Coordination For TDMA Operation In Wireless Sensor Networks

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Abstract: We compare centralized and distributed approaches for the coordination of transmission slots of wireless sensors for collision-free time division multiple access (TDMA) operation. For the centralized coordination, we focus on the guaranteed time slot (GTS) mechanism of the IEEE802.15.4 standard. For the distributed coordination, we present results with the DESYNC algorithm and its recent time-frequency extension. The results are derived via measurements with real TinyOS wireless sensor nodes using the CC2420 transceiver and reveal that both approaches obtain comparable throughput per node, with the GTS mechanism obtaining higher throughput only for the smaller permissible superframe duration. Moreover, distributed coordination is by nature more robust and scalable as it does not have a single point of failure and it can be scaled to multi-channel operation; however, it requires higher startup delay in order to converge to the steady state of operation.

Index Terms: distributed vs centralized coordination, TDMA, wireless sensor networks

I. Introduction

Synchronization in wireless sensor networks (WSN) is essential for uninterrupted time division multiple access (TDMA) operation [1]-[3]. Beyond the well-known coordinator-based approaches for synchronization that are standardized within the IEEE802.15.4 [3], new approaches have appeared that achieve synchronization based on the principle of reactive listening: wireless sensors autonomously schedule their transmission times by reacting to beacon or "fire" messages broadcasted by each node without requiring a central coordinator node [1][2]. Furthermore, for centralized and distributed TDMA, multi-channel MAC protocols have appeared [4]-[7], which aim for load balancing via time-frequency division multiple access. From these proposals, in this paper we focus on [6] in particular, which, unlike other proposals [4][5][7] presents a truly distributed time-frequency division multiple access (DTFDMA) protocol that has been practically deployed and tested in wireless sensor networks based on the IEEE802.15.4 standard. The DTFDMA scheme has very low complexity and allows for self-organization of an arbitrary number of sensors regardless of the initial synchronization status and distribution of nodes amongst the available channels.

This paper's contribution is in the practical comparison of the achievable bandwidth of the distributed TFDMA of [6] against the centralized GTS scheme of IEEE802.15.4 [3]. We first review the DTFDMA mechanism and the centralized GTS coordination in Section II. The experimental results for both schemes and concluding remarked are provided in Section III and IV respectively.

II. Related Work

The core functionalities of IEEE 802.15.4 medium access control (MAC) are the CSMA/CA mechanism and the guaranteed time slot (GTS) allocation. In this paper, we focus on the later, which is reviewed in the following section. Moreover, Section B reviews the DTFDMA scheme that is suitable for environments where a coordinator may not be present.

A. Centralized GTS

The IEEE 802.15.4 MAC protocol is responsible for supporting the personal area network (PAN) association and disassociation, generating and synchronizing beacon transmission and employing the CSMA/CA mechanism for channel access. There are two operational modes based on the determination of PAN coordinator: the *non beacon-enabled mode*, in which the MAC is controlled by non-slotted CSMA-CA, and the *beacon-enabled mode*, in which periodic beacon packets transmitted from the PAN coordinator are used for centralized synchronization amongst the nodes in the network.

The latter mode is useful to allocate and deallocate time slots in a superframe, which are termed as the guaranteed time slots. The IEEE802.15.4 standard provides the *contention-free period* (CFP) for GTS allocation as illustrated in the Figure 1.

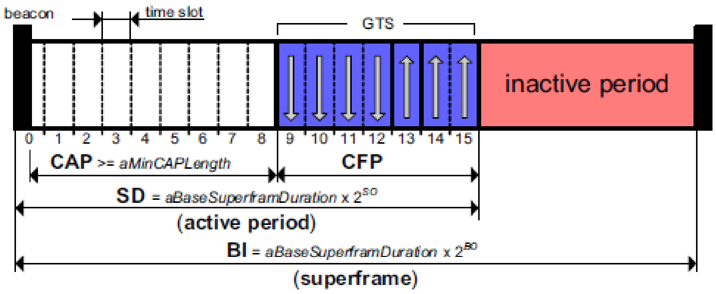

Figure 1. The superframe structure in IEEE802.15.4 with beacon enabled [9].

The beacon interval (BI) is identified by the time between two consecutive beacons. It consists of the active and inactive period. The active period called superframe duration (SD) is composed of the contention access period (CAP) and the optional CFP. The lengths of BI and SD are calculated from the beacon order (BO) and the superframe order (SO) and are given by:

$$\mathrm{BI} = \mathrm{aBaseSuperframeDuration} \times 2^{\mathrm{BO}} \tag{1}$$

$$\mathrm{SD} = \mathrm{aBaseSuperframeDuration} \times 2^{\mathrm{SO}} \tag{2}$$

where $0 \leq \mathrm{SO} \leq \mathrm{BO} \leq 14$ and $\mathrm{aBaseSuperframeDuration}$ defines the minimum length of the superframe, corresponding to $\mathrm{SO} = \mathrm{BO} = 0$. The default setting is $\mathrm{aBaseSuperframeDuration} = 15.36\mathrm{ms}$ for the data rate of 250kbps that is achieved nominally at 2.4GHz [3].

Nodes compete for the medium access using slotted CSMA/CA within the CAP. The IEEE802.15.4 protocol provides the optional CFP. If the PAN coordinator has sufficient resources, it will allocate the requested time slots for each node. Therefore, high bandwidth utilization can be obtained from the allocation management of the GTS mode. If $\mathrm{BO} = \mathrm{SO}$, the maximum throughput will be obtained in the system, since a duty cycle equal to unity is obtained.

B. Distributed TFDMA

Within a fully-connected wireless sensor network, each sensor node can receive a message broadcasted from any other node (such broadcasted messages are called "fire" messages in the context of distributed synchronization [1]). If all wireless sensor nodes broadcast such fire messages, this is used in the DESYNC protocol [1] in order to make each node adapt its next fire message broadcast time to be in the middle between the fire times of its predecessor and its successor. As shown in the Figure 2, the adaptation of the fire message phase uses the previous and next node's fire message broadcast phase within the periodic time measurement (from 0 to Ts) in-between successive firings of the same node. For the kth periodic iteration, each node n_i, $1 \leq i \leq W_{\mathrm{tot}}$ (with W_{tot} the total number of nodes), adapts its phase φ_i by [1]:

$$\varphi_i^{(k)} = (1-\alpha)\varphi_i^{(k-1)} + \alpha \frac{\varphi_{i-1}^{(k-1)} + \varphi_{i+1}^{(k-1)}}{2} \tag{3}$$

at the moment the next node fires (i.e. when $\varphi_{i+1}^{(k-1)} = 0$), with $\alpha \in (0,1)$ a parameter that scales how far n_i moves from its current fire phase ($\varphi_i^{(k-1)}$) toward the desired midpoint between the previous and the next node's phase [1].

Previous work [1] showed that the reactive listening primitive of (3) leads to near-optimal TDMA behavior in the steady state, i.e. after k_{ss} periods, where all fire messages are periodic with:

$$\left|\varphi_i^{(k_{\mathrm{ss}})} - \varphi_i^{(k_{\mathrm{ss}}-1)}\right| < q_{\mathrm{ss}} \tag{4}$$

with q_{ss} a preset threshold, e.g. $q_{\mathrm{ss}} \in (0.01, 0.05)$. In steady state, each node transmits data packets for T/W_{tot}s immediately following its fire-message broadcast.

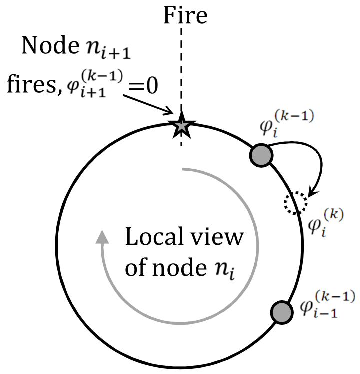

Figure 2. The cycle indicates the node's own counting of one period (from 0 to $\boldsymbol{T}$s). When the node reaches the top, it fires and resets the counter to zero. The fire message adaptation of node $\boldsymbol{n_i}$ happens when node $\boldsymbol{n_{i+1}}$ (next node) fires in DESYNC [1] following (3).

The IEEE802.15.4 MAC provides multiple channel selection at 2.4 GHz with the minimal interference of the adjacent channels. Distributed TFDMA attempts to split the number of nodes in order to balance them into all channels and apply DESYNC within each channel [6]. For example, for $C = 2$ channels and $W_{\mathrm{tot}} = 8$ nodes, the goal would be separate into two distinct sets: $W_1 = W_2 = 4$, i.e. 4 nodes in each channel. The following summarizes TFDMA operation; full details are included in [6].

At the beginning, each node chooses a channel $\mathrm{Ch}\{c\}$ $(1 \le c \le C)$ randomly and utilizes the DESYNC algorithm. After it is the steady state of the TDMA behaviour, the channel switching will be started to the previous and next channel i.e. from $\mathrm{Ch}\{c\}$ to $\mathrm{Ch}\{c + s_c\}$ $(1 \le c \le C$, with the switch direction $s_c \in \{\pm 1, \dots, \pm \lfloor C/2 \rfloor\}$ and cyclic extension: $\mathrm{Ch}\{C + |s_c|\} \equiv \mathrm{Ch}\{|s_c|\}$, $\mathrm{Ch}\{1 - |s_c|\} \equiv \mathrm{Ch}\{C + 1 - |s_c|\})$, by broadcasting a "switch" message in $\mathrm{Ch}\{c\}$. A node attempting to switch is allowed to listen to the broadcasted fire messages of others to check the number of nodes in the new channel. After that it decides to stay the new channel if there are fewer nodes present than in the old channel. If not, the node will switch back to the old channel, broadcast a "return" message and then rejoin desynchronization and data transmission in $\mathrm{Ch}\{c\}$. An important parameter controlling the channel switching is the switching probability of each node, which is tuned to decrease to zero to allow for convergence to steady state [6].

III. Experiments

We used TinyOS wireless sensors with the 2.4GHz CC2420 Chipcon wireless transceiver. All messages use the TinyOS standard while the data messages contain 96-byte payloads. For the Distributed TFDMA experiments, we use 8 nodes and up to two channels. The backoff time was reduced to 1.2ms since no collisions are expected once the system has converged to steady state. The maximum data rate with single transmitter and receiver setup was found to be 137.4kbps.

The results with DTFDMA under this setup are given in Table 1. The normalized throughput defines the ratio between the total throughput and the maximum measured throughput. The highest and lowest throughput per individual node are represented by the "max" and "min" rows in Table 1, respectively. Finally, the message loss is the ratio between the total data payloads lost and the total payloads received successfully.

For the (centralized) GTS experiments, we examine the effect of the beacon and superframe order on the throughput. GTS allows for (up to) 7 stations to join, which creates a total of 8 nodes including the coordinator. Under the utilized GTS implementation [3], when $(\mathrm{BO}, \mathrm{SO}) < 5$, devices (stations) are not able to send the ACK message to the coordinator after receiving slot allocation. On the other hand, when $(\mathrm{BO}, \mathrm{SO}) > 7$, the PAN coordinator cannot receive any data from a device after allocating the GTS slot. Therefore the parameter settings for our experiments with GTS were $5 \le (\mathrm{BO} = \mathrm{SO}) \le 7$.

The results of Table 2 show the total throughput measured from the 7 slots available for GTS allocation, as well as the average throughput per slot. The message loss was measured directly from the experiments.

Total Channels	2	1
Tot. throughput (kbps)	271.9	133.4
Normalized, %	194.1	92.4
Max per node (kbps)	34.1	16.7
Min per node (kbps)	33.7	16.5
Message loss (%)	0.01	0.01

Table 1. Results under the distributed TFDMA.

Beacon Order	5	6	7
Tot. throughput (Kbps)	177.0	89.6	43.5
Average per slot (Kbps)	25.3	12.8	6.2
Message loss (%)	0.00	0.00	0.00

Table 2. Results under the centralized GTS.

IV. Concluding Remarks

We compared the distributed TFDMA and the centralized GTS of IEEE802.15.4. DTFDMA's throughput can be significantly higher in comparison to the GTS scheme because of the use of multiple channels. For single channel transmission it achieves somewhat lower throughput due to overheads from fire messages. However, no centralized coordinator is required. Our experiments demonstrated that the setup delay for GTS is equal to one superframe duration, while DTFDMA may require a few seconds to converge to the steady state. Both methods allow for near zero packet loss under normal operating conditions and without any reconfiguration taking place.

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