

2012 IEEE ²IMTC

International Instrumentation
and Measurement Technology
Conference

Congress Graz Graz, Austria May 13-16, 2012

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IEEE Catalog Number: CFP12IMT-CDR Technical Support:
ISBN: 978-1-4577-1771-0 Conference Catalysts, LLC
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Providing energy efficient mobility in TDMA-controlled wireless sensor networks

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Abstract—TDMA-based medium access protocols provide energy efficient and real-time solutions for various sensor networking applications. In this paper an extension is suggested for static TDMA networks, providing connection of mobile nodes to the autonomous TDMA network, with very low overhead. The solution is suitable for applications where mobility is occasionally required for a low number of nodes, e.g. supervising nodes in a security system, or command interface in an autonomous data collecting system. The implementation issues of the suggested solution are discussed, along with the performance properties.

Keywords - sensor networks; services; energy-efficient, mobility

I. INTRODUCTION

In sensor networks energy efficiency is usually a key design issue. To reach long network lifetime, various approaches are used, from the hardware layer (e.g. using low-power components, switching off unused components) through the middleware (e.g. efficient medium access protocols) to the application level (e.g. power-efficient algorithms). In medium access layer, one efficient solution is time division multiple access (TDMA).

TDMA is a well-known medium access control (MAC) protocol, widely utilized in sensor networks. In TDMA, all nodes have a unique timeslot for transmission, which allows collision-free communication and is also very power efficient: since nodes know the scheduled time intervals of communication, they need to be awake only when sending and receiving messages, and can be asleep in the rest of the time; there is no need for idle listening. The main drawbacks of TDMA channel access is that it requires (usually global) time synchronization, causing overhead, and since the number of participating nodes is fixed in the schedule, unused time slots are wasted and the number of nodes is not easily changed. There exist self-organizing and distributed scheduling algorithms which provide network reconfiguration by periodic renegotiations of the schedule, e.g. in [1], using on demand wake-up, e.g. in [2], or allowing nodes to compete for unused slots, e.g. in [3]. In many TDMA networks, however, the nature of the network traffic and the number of nodes rarely changes, but eventually extra nodes may need to access the network. A notable example of such requirement appears in autonomous security systems, where most of the time the operation is performed as scheduled, but occasionally personnel with mobile devices want to interact with the system (e.g. a guard goes into the building to see the reason of an

alarm, and at the point of alarm he or she acknowledges or cancels the alarm). The problem with TDMA-based solutions is that devices are available only in their scheduled communication time-slices, but in these time-slices they are usually busy with their scheduled communication and thus cannot be reached without possibly causing collisions. Simply reserving extra time-slices for the rare external communication would cause large extra overhead.

This paper suggest a practical solution for allowing the energy efficient temporal connection of mobile devices to TDMA networks, e.g. for maintenance, downloading logs, issuing commands, or other type of interaction.

The outline of the solution is the following: the mobile node synchronizes itself to the network by overhearing normal TDMA messages, and then sends a wake-up message to a target node in a short reserved time-slot. Nodes in the network wake-up for very short times in the global wake-up interval to check if wake-up is required. After the wake-up interval only the target node stays awake and communicates with the mobile node using a hand-shake protocol. Since the wake-up interval is very short, due to the precise time synchronization between the mobile and target nodes, the extra power consumption of nodes not participating in a mobile communication is very low.

The rest of this paper is organized as follows: In section II related work will be reviewed. The proposed solution will be introduced in section III, while in section IV its implementation details will be discussed. Section V concludes.

II. RELATED WORK

In sensor networks both contention-based (e.g. CSMA, RTS/CTS) and schedule-based (TDMA) medium-access protocols are widely used. The advantage of contention-based protocols is their flexibility, but they tend to be less power efficient and response time cannot be guaranteed. In TDMA protocols the communication is performed in predefined time slots, allowing the design of collision-free and real-time communication schemes. Efficient TDMA scheduling also avoids idle listening, providing very power-efficient communication. Among the disadvantages of the TDMA approach the most notable are the wasted and unused time-slots, allowing lower throughput, and the communication (and thus energy) overhead caused by the synchronization [4]. Also mixed contention and TDMA-based protocols are used, to exploit the advantages of both approaches, e.g. S-MAC [5].

Despite of its drawbacks, the unique advantageous properties of TDMA make it an appealing solution for applications where real-time properties, guaranteed response time, bounded message latency are to be guaranteed, and also where energy efficiency is a critical feature. In [6] a monitoring system for coral reefs was developed using a power-aware and scalable TDMA scheme, in [7] GWMAC, a power-efficient TDMA MAC protocol was designed for glacial sensor networks, and in [8] a long lifetime network was created for traffic monitoring on TDMA bases, just to mention a few notable applications. TDMA-based solution are also used in network reprogramming, e.g. in Infuse [9], Sprinkler [10], and TeleScribe [11].

To design a TDMA schedule one must allocate time slots to transmitting nodes, depending on the topology and the packet generation rates, in order to avoid collisions and also to minimize message latency. The design of optimal TDMA schedules (i.e. the shortest conflict-free assignment of slots during which the packets generated at each node reach their destination over the routing tree) is an NP-complete problem, but efficient heuristics were proposed, even for distributed solutions [12]. To alleviate the difficulties of TDMA, appearing in practical applications, adaptive [1] and self-organizing TDMA protocols [13] were also proposed.

TDMA-W [2] is self-organizing and power-efficient protocol, where nodes wake up in their pre-assigned time slots (s-slots) only if communication is needed. Nodes use other special time slots (w-slots) to send wakeup messages to the destination nodes. After the received wakeup message the destination node stays awake in the unique s-slot of the source node. The allocation of the timeslots is self organized in the initialization part of the algorithm. Thus every node takes one individual s-slot and one possibly shared w-slot. This protocol is suitable for sensor networks where most of the communication is triggered by external events and where the traffic is relatively low. The improvement of the self organization algorithm was done in TDMA-WSN [14].

The idea behind the handling of dynamic nodes in a static network in our proposed solution is similar to the wakeup mechanism (w-slots) of TDMA-W, but in an even more efficient way. Our solution can be applied to any TDMA mechanism by reserving a time interval, where the mobile communication (wake-up and manage transmission) can take place. Our solution also allows more extensive communication between the target and the mobile device, compared to the regular TDMA messages.

III. MOBILITY IN TDMA NETWORKS

A. The TDMA operation

In Fig. 1 the schedule of a network containing four nodes can be seen. Note the same timing of the message transmissions (T) and receptions (R) of neighboring nodes, guaranteeing communication without idle listening and with no collisions. For right alignment of transmissions and receptions precise pair-wise time synchronization is required thus the messages contain time stamping information which can be used for synchronization purposes, as described in [15].

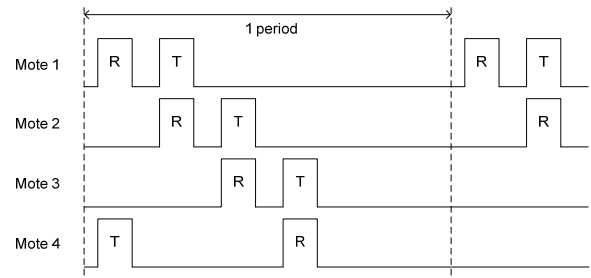


Figure 1. Communication in a TDMA networks

B. Mobile services

To allow the energy efficient temporal connection of mobile devices (e.g. laptop or PDA) to a TDMA network, the mobile node connects to a particular node in the network, and through this node performs the required actions (e.g. sends commands, downloads data), as shown in Fig. 2.

To allow TDMA communication with the mobile node, a service time interval is reserved in the TDMA schedule as shown in Fig. 3 (SRQ + SERVICE). In order to provide power-efficient services, nodes wake up for only a very short wakeup interval where the mobile node can send a service request message (SRQ) to a selected node. Upon reception of the SRQ the selected node stays awake for further communication with the mobile node. This communication is limited to a maximum length, determined by the schedule. During this period the mobile node can send and receive data.

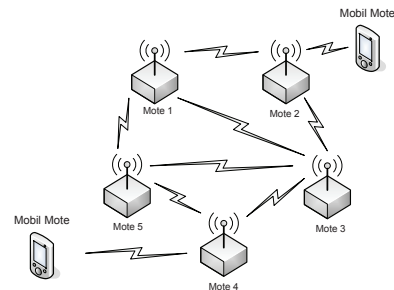


Figure 2. Connecting a mobile device to a TDMA network

Note that SRQ is a short message but nodes in the network do not need to stay awake for the whole length of the SRQ: if no transmission is detected by the receiving radio, the node can go back to sleep early. Thus when no mobile node is present in the network the overhead is very low. When the mobile node sends an SRQ, all receiving nodes stay awake till the end of the message, but except for the selected node, all nodes can go to sleep after.

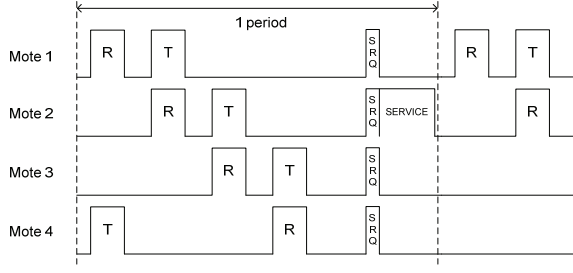


Figure 3. Mobile services in a TDMA

The first part of the service period is reserved for downloading data from the mobile node to the network (typically commands and parameters) as shown in Fig. 4. The rest of the service interval is used for uploading data to the mobile node, which is possibly done in multiple packets as illustrated in Fig. 4. The communication between the selected node and the mobile node lasts until the end of the service period and if necessary, can be continued in the next service interval. Note that when a communication session is interrupted at the end of the service period, there is no need to send SRQ in the next service period; the communication is fully transparent for the upper software layers. In Fig. 4 *SRV_REQ_WINDOW* is the length of the SRQ message, *SRV_TIMEOUT* is the maximum length of the service period and *SRV_START_DELAY* shows the time reserved for the download. Note that the proposed solution is master-slave based; the communication is always initiated by the mobile node, by sending SRQ.

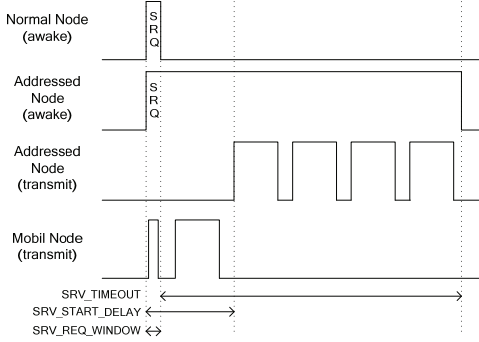


Figure 4. Operation in the service interval

IV. IMPLEMENTATION FOR SENSOR NETWORKS

A. Interface of the TDMA node

In this section we will describe the details of the software solution discussed in section III.B. The implementation was made under TinyOS in NesC [15].

```

interface ServiceProvider
{
  command void serviceReceived(uint8_t* buffer);
  command void serviceGetData(uint8_t* buffer);
  command uint8_t serviceStatus();
  command void serviceSendDone(bool success);
}

```

Figure 5. The interface of the service provider at the TDMA nodes

The proposed service requires the implementations of the interface shown in Fig. 5. After receiving a service message from the mobile node, the *serviceReceived(buffer)* command is called, where buffer contains the received parameters, related to the given service. Based on the parameter the service provider decides on the necessary action. The actual state of the service provider is polled with the *serviceStatus()* function, with the following possible return values:

- *SRV_NO_DATA*: the service provider has no data to send
- *SRV_DATA_AVAILABLE*: the service provider is ready to answer
- *SRV_DATA_LATER*: the service provider is not yet ready, but has data to send later

If the service provider is ready, then the *serviceGetData(buffer)* command is called and the service provider copies the data to be send to the buffer, which is then sent to the mobile node. After the completion of the communication the *serviceSendDone()* command informs the service provider on the success of the operation.

Notes:

- The calls *serviceGetData()* and *serviceStatus()* are time critical, thus here only copying of the data and the return of the status are allowed.
- Before sending the polling of the status can be performed multiple times.
- The completion of the send is signaled by the *serviceSendDone()* command, thus in this function the next packet can be prepared.

A simple example is shown in Fig. 6. The service provider has data right after the request (*SRV_DATA_AVAILABLE*), but the second packet will be ready after some processing (*SRV_DATA_LATER*). Thus the system waits for a time period of *SRV_DELAY* when the next packet is available (*SRV_DATA_AVAILABLE*). After sending the packet the process continues until the state *SRV_NO_DATA* is reached. (Note that the sending process is paused at the end of the service period and restarted in the next one.)

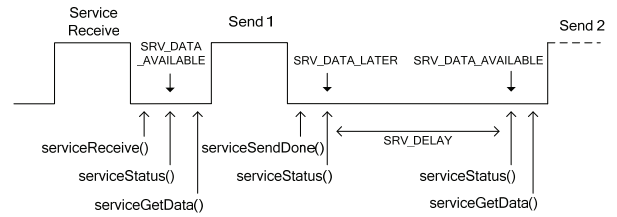


Figure 6. The operation of the mobile service

B. Software architecture of the TDMA node

The service-related state machine of the TDMA node can be seen in the Fig. 7.

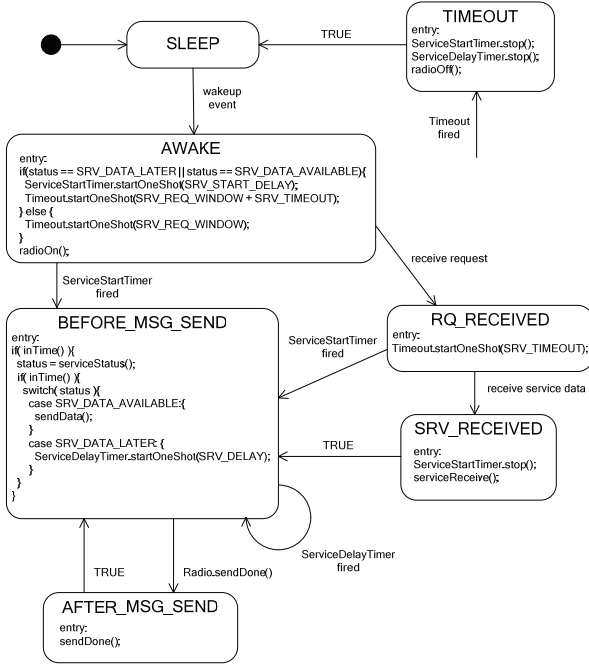


Figure 7. State machine of mobile service

For the meaning of *SRV_REQ_WINDOW* and *SRV_TIMEOUT* see Fig. 4. The *inTime()* function in the state machine decides whether it is possible to send one full packet in the remaining time of the service period, thus guarantees that the send does not overlap the next cycle.

C. Interface of the mobile node

The interface the mobile node can be seen in Fig. 8. The *serviceSend()* command sends the requested service parameters to, while the *serviceReply()* event receives data from the selected TDMA node with node ID contained in parameter *node_id*.

```

interface Service
{
    command void serviceSend(uint16_t node_id,
        uint8_t* buffer);
    event void serviceReply(uint16_t node_id,
        uint8_t* buffer);
}
  
```

Figure 8. The interface of the mobile service

D. Software architecture of the mobile node

In the *serviceSend()* command first the mobile node tries to synchronize itself to the selected TDMA node. This is done by overhearing messages in the network. Since messages contain time stamps for TDMA synchronization, the synchronization of the mobile node can be done by a method described in [16]. After synchronization the mobile node determines the exact time for sending the service request message.

In *serviceReply()* event the mobile mote simply forwards the received data to the application.

E. Evaluation

The proposed mobile service was implemented in a TDMA based wireless security system [17]. In the system the TDMA period was two seconds and in each period one service interval was scheduled with maximum length of 60ms. The schedule was based on a 62.5kHz timer, this using a precise time stamping method the accuracy of the wakeup was around 16μs. The timeslot for SRQ reception was set to 2ms. Fig. 9 shows the activities measured by a digital oscilloscope. Line 1 shows a non-selected node which wakes up for the SRQ reception only and then returns to sleep state. The selected node also wakes up at the same time, but stays awake for the whole length of the communication with the mobile node (line 2). The figure shows the download of one packet (line 3) and the upload of three packets (line 4), each of size 96 bytes. Line 3 shows the transmission activities of the mobile node (SRQ and one packet of downloaded data), while line 4 shows the transmission activities of the selected node (three packets were downloaded). The figure does not show the reception activities of nodes. When no mobile communication is required, the implemented service increases the duty cycle by less than 0.1%. During the service the radio is switched on only when packet exchange is necessary thus the power consumption is minimized.

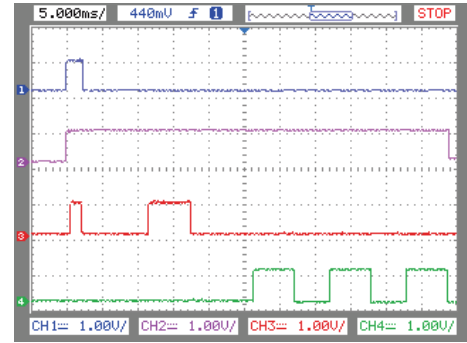


Figure 9. Node activities during the service period. (1) non-selected node wakes up for SRQ reception, (2) wakeup of selected node for SRQ reception and mobile communication, (3) mobile-node sends SRQ and downloads a command packet, (4) the selected node uploads three packets

V. CONCLUSION

In this paper a practical solution was suggested, which allows the energy efficient temporal connection of mobile devices to standalone TDMA networks. The proposed solution can be used e.g. for maintenance purposes, downloading logs or sending commands to the network. The mobile service requires minimal extra communication bandwidth and power consumption. As measurement results show, the overhead of the service is very low, in the test it was below 0.1%.

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