Practical Implementation Aspects of the Data Timed Sending (DTS) Protocol Using Wake-up Radio (WuR)

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Abstract. The energy efficient Data Timed Sending (DTS) protocol enables information transfer from sensor nodes to sink host by choosing the appropriate transmission time of a short packet without data payload. Wake-up Radio (WuR) devices allow asynchronous communication of Wireless Sensor Networks (WSNs) putting the sensor nodes' main radio modules in continuous sleep state thus increasing energy efficiency. A common characteristic for the DTS protocol and WuR is that they are designed for applications where sensors take sparse measurements, typically one measurement every few minutes. This paper investigates the combination of the DTS protocol with WuR into a single integrated solution. The analytical analysis shows that the DTS protocol significantly reduces the energy consumption when coupled with WuR making this solution suitable for applications with battery powered WSN (e.g. body area WSN).

Keywords: DTS · WuR · WSN · Energy efficiency

1 Introduction

Wireless Sensor Networks (WSNs) consist of a number of sensor nodes that wirelessly transfer some measured information to a so-called sink node for further processing. A development bottleneck of WSNs and associated applications is the limited battery power supply of the sensor nodes. The battery lifetime can be prolonged with energy efficient communication protocols and with low-power hardware.

Communication protocols save energy by efficient routing, packet formatting, data processing or other algorithmic solutions. The *Data Timed Sending* (DTS) communication protocol [1–3] achieves energy savings of 25–30% in the sensor nodes, compared with traditional WSN protocols (e.g. ZigBee, LoWPAN etc.), by reducing the packets' size so that the TX radio module spends minimal time in on-state. The very short information to be transferred is coded into the *time* when it is sent rather than in a

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classical data payload. This allows reduction of the DTS packets to minimal values (no payload needed) at the expense of introducing additional delays in the network.

Traditional WSNs require wake up in regular time intervals (duty-cycling) to listen to the channel. The energy waste caused by continuous channel listening can be significantly lowered using the *Wake-up Radio* (WuR) concept [4–6]. In WuR systems, the sensor node is in continuous sleep-state and an additional always-on ultra low-power receiver, called *Wake-up Radio receiver* (WuRx), is added. The WuRx serves only to detect *Wake-up Call* (WuC), transmitted by the sink node's *Wake-up Transmitter* (WuTx), and to wake up the node after that, whereas the data messages are exchanged through the nodes' main radios in traditional fashion (Bluetooth, ZigBee, etc.). The WuC consists of only a few bytes and contains the destination address that enables selective awakening. WuR system saves energy at sensor nodes.

This paper proposes implementation of the DTS protocol combined with WuR hardware in order to improve the energy efficiency of the WSN communication. Section 2 gives the related work to the DTS operational principle and to WuR. Section 3 presents the integration of the DTS protocol with WuR into a single solution called DTS-WuR that is then compared to the case when no DTS is used. Section 4 gives the results for the energy saving achieved by the DTS-WuR, and, finally, Sect. 5 summarizes the conclusions.

2 Related Work on DTS and WuR

The DTS protocol [1–3] formats the time into frames divided into slots and each slot is additionally divided into subslots. Each slot in the frame corresponds to certain sensor node and each subslot corresponds to certain value of the measured phenomenon. The sensor nodes are synchronized with the sink node and the information about the measured value is transferred from the sensor node to the sink node by choosing appropriate time slot and subslot in which the DTS packet will be sent. Due to the communication delay, this protocol is feasible for applications with low measurement rates.

At the hardware level, all components strive to achieve lower energy consumption by ability to work in high and low power modes. The energy saving element in WuR systems is the ultra-low power WuRx that has current consumption in the order of μA or even nA [4]. There are several types of WuR systems [5] such as *in-band* WuRs, *out-of-band* WuRs etc. [7].

Unlike previous works, this paper discusses the implementation aspects of the DTS protocol combined with WuR systems into a single solution. To showcase the benefits of the DTS and WuR combination, the paper additionally performs a comparative energy consumption and energy savings analysis between:

- The combined **DTS-WuR solution**, where the data from the sensor nodes is coded into the exact time when it is sent (inherently introducing additional communication delay in the WSN) and the packets are extremely short with no need for data payload and

- The **no-DTS-WuR solution**, where the data from the sensor nodes is sent immediately upon reception of a WuC with no additional delays, but with a need for packets with long data payloads.

The rationale behind is that the WuR systems introduce asynchronous WSN operation, thus comparisons are sound only for cases with and without DTS.

3 Practical Implementation of DTS Using WuR

DTS protocol and WuR systems are both suitable for applications with low measurement rates. Their main difference is that the DTS protocol needs synchronization, whereas the WuR is designed to enable an asynchronous communication. To allow the integration of the DTS protocol with WuR, the classical DTS protocol [1] undergoes two modifications:

- Substitution of the continuous nodes' synchronization with temporary synchronization that lasts only during the measurement process and
- Transmission of the DTS packet by the sensor node's WuTx instead of the main radio transceiver. Since the DTS packet does not contain any data payload, its length and format are the same as those of WuC and this packet is called Wake-up Information Message (WuIM). The only difference between the WuIM and WuC is the content of their destination field.

Figure 1 shows the Message Sequence Chart (MSC) for comparison of the DTS-WuR system with the no-DTS-WuR system. In the DTS-WuR system, when the sink node decides to retrieve measurement from a certain sensor node, it wakes up both its main Micro-Controller Unit (MCU) and WuTx and sends WuC with address code corresponding to that sensor node. Then, its WuTx goes back into sleep-state. Simultaneously with the WuC transmission, sink's WuRx starts its stopwatch and the main MCU goes back into sleep-state. When the response (WuIM) from the sensor node arrives, sink's WuRx stops the stopwatch, wakes up the main MCU and forwards the value of time elapsed. Finally, according to the value of time elapsed, the main MCU calculates the value of the measured phenomenon, stores that value in memory and goes into sleep-state again.

At DTS-WuR system, before the measurement startup, the sensor node's main MCU is in sleep-state. When the sensor node's WuRx (which is in on-state all the time) receives a WuC, it makes address check up and, if the address matches, it wakes up the main MCU. The main MCU captures the sensor's reading, calculates the waiting time (delay) and goes back into sleep-state. After the expiration of the waiting time, the main MCU and WuTx wake up, WuTx sends WuIM with address code corresponding to the sink node, and then both main MCU and WuTx go back into sleep-state again.

Since the sink's WuRx in the DTS-WuR system spends much less energy than the sink's RX in the no-DTS-WuR, the DTS-WuR system achieves better energy efficiency on the sink's side.

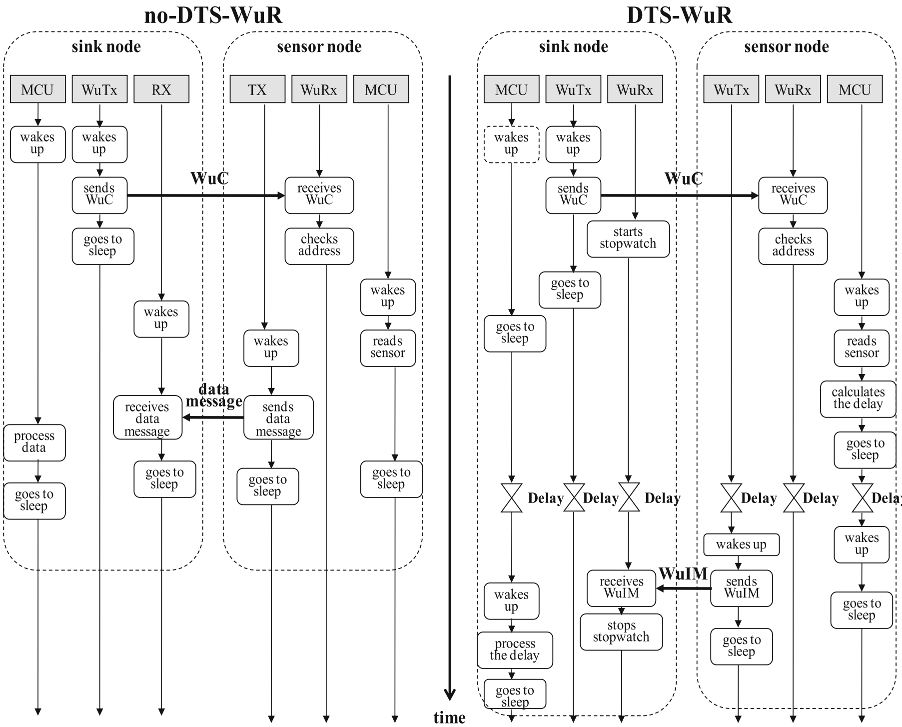


Fig. 1. Message Sequence Chart (MSC) for one measurement cycle for the no-DTS-WuR system and for the DTS-WuR system

4 Energy Consumption Analysis and Results

The energy consumption comparison between the DTS-WuR and the no-DTS-WuR solution relies on the WuR board presented in [5]. The main energy consumption entities of this 3 V battery powered board are the CC1101 868 MHz transceiver (RX, TX, WuTx) and the MSP430F2350 chip (node's main MCU).

The energy consumption analysis is conducted by calculating the amount of energy the RX, TX, WuRx, WuTx and main MCU (the elements in Fig. 1 plus the sensor) cumulatively spend during one measurement cycle. The power consumption of hardware components, durations of messages, durations of power-mode states, and application parameters are given in Tables 1, 2 and 3.

Table 1. Energy consumption parameters for the no-DTS-WuR solution only

Parameter	Value
Main radio power consumption in RX/TX/sleep states	56.4 mW/52.2 mW/0.6 μW
Data message duration	3.2 ms

Table 2. Energy consumption parameters for the DTS-WuR only

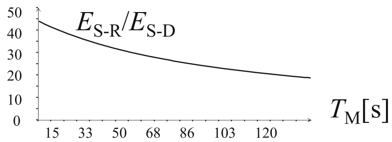
Parameter	Value
WuIM duration	12.2 ms

Table 3. Energy consumption parameters for both no-DTS-WuR and DTS-WuR solutions

Parameter	Value
Main MCU power consumption in wake-up/sleep states	900 μW/0.3 μW
WuTx power consumption in transmitting/sleep states	43.2 mW/0.6 μW
WuRx power consumption in receiving/idle states	26.4 μW/7.8 μW
WuRx power consumption when transfers data to main MCU	26.4 μW
WuC duration	12.2 ms
WuRx to main MCU data transfer duration	≈0 s
Time needed main MCU to process data	≈31.25 μs
Sensor's power consumption/reading duration	60 mW/0.5 s
Measurement interval	15 to 120 s

The sensor power consumption and sensor reading time are set to 60 mW and 0.5 s, respectively, which are common values for WSN sensors. Furthermore, the measurement time interval T_M (time between two successive measurements) is simulated to be in the range of 15 to 120 s. For example, in the body area networks, parameters which can be measured at such rates are body temperature, pulse rate etc.

Figure 2 shows the resulting sink's energy consumption ratio between the no-DTS-WuR ($E_{S\text{-}R}$) and the DTS-WuR ($E_{S\text{-}D}$). It is evident that the DTS-WuR provides significant energy savings that are higher for smaller measurement intervals.



(a)

Fig. 2. Sink node energy consumption ratio between no-DTS-WuR and DTS-WuR ($E_{S\text{-}R}/E_{S\text{-}D}$) for different measurement intervals T_M

The comparison of the energy consumption between the traditional TX and the WuTx must take into account both the packet sizes and bit rates. The packet size of the WuIM is considerably lower than the size of the data message, but the WuTx has considerably lower bit rate than the TX as well [5] (due to the lower sensitivity of the WuRx). The power consumptions and durations in the on-state of the TX and the WuTx are such that there is no significant energy saving on the sensor nodes' side. However, there are significant energy savings in the sink.

Typical application scenario where combination of WuR and DTS can show their energy-efficiency would be a body area network where the sink node is battery powered and it retrieves measurements from the remote sensors each 120 s. In this scenario, the WuR hardware alone achieves significant energy savings in the sensor nodes compared to the classical WSNs. But this paper shows that DTS protocol enables the WuR hardware to achieve significant energy savings (20 times) in the sink node too, compared to the classical WSNs.

5 Conclusion

This paper combines the DTS protocol with WuR to achieve asynchronous DTS that increases the energy efficiency in WSNs. The DTS protocol codes data into time inherently introducing communication delays. But, the introduction of the DTS protocol allows communication with very short packets significantly increasing the energy efficiency in the WSN. Due to the fact that WuRx consumes much less energy than RX, the energy savings occur at sink nodes making the DTS-WuR suitable for applications with battery powered WSNs.

Future work will comprise experimentation with different parameters and different scenarios (e.g. multiple sensor nodes competing for the medium etc.).

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