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An energy consumption analysis of the Wireless HART TDMA protocol

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ABSTRACT

In this paper we analyze in detail the energy consumption characteristics of the Wireless HART protocol when operated with a popular transceiver, the ChipCon CC2420. We analyze how much various factors contribute to the overall energy consumption over a longer period of 12 h. These factors include the amount of management traffic and the power levels required for various transceiver activities (transmit, receive, listen, sleep). It turns out that in light traffic scenarios and with only a minimum-complexity level of exploitation of the transceivers sleeping capabilities the energy spent in the sleep state over 12 h is quite substantial. We then proceed to analyze the energy consumption characteristics with a more complex usage of the transceivers sleeping capabilities in which each node individually selects its next sleep state according to its transmission/reception schedule. With this scheme the energy consumption in the sleep state (over 12 h) can be reduced substantially.

1. Introduction

In many application areas of embedded wireless networks, for instance in building automation or industrial control, source nodes send data frames periodically to a gateway or sink node across a set of forwarder nodes [32,33,9]. For cost-effective, quick and scalable deployment, sensor nodes often run on batteries and therefore have only a limited amount of energy. The sensed data should be transported reliably and in a timely fashion to the sink. At the same time the operation of the whole network and of individual nodes should be energy-efficient. Therefore, reporting the sensed data reliably while consuming the minimum amount of energy is of great concern. In many sensor node designs the radio chip is the largest consumer of energy. Since the medium access layer usually controls the states of the radio, it has a large impact on overall energy-consumption. Different media access methods result in different trade-offs between end-to-end delay and energy-efficiency. From among the large number of existing MAC protocols for wireless sensor networks (contention-based protocols include [6,27,38], contention-free protocols include [35,28], see [20] for a survey), a TDMA-based protocol has been chosen as a basis for the Wireless HART (WHART) standard [5]. A common view on TDMA-based protocols is that they offer good opportunities for energy-efficient operation of sensor nodes, as they allow nodes to enter a sleep state when they are not involved in any communications. Furthermore, TDMA is traditionally the method of choice for some of WHARTs major application areas like industrial and process automation, since it offers a level of determinism that is not achievable with other types of MAC protocols. WHART utilizes the physical layer of IEEE 802.15.4 and specifies a new MAC protocol. This new MAC protocol combines slow frequency hopping with a TDMA scheme. The TDMA slot allocation happens a priori at network configuration time. WHART supports multi-hop mesh topologies, and all devices must have routing capabilities.

The first contribution of this paper is a detailed, simulation-based analysis of the energy-consumption behavior of WHART when used with the popular IEEE 802.15.4-compliant ChipCon CC2420 radio transceiver [3] and 8 MHz Texas Instruments MSP430 microcontroller [23].

In doing this, we go beyond mere reporting of energy-consumption figures for certain deployment scenarios. Specifically, we apply the response surface methodology [24] to analyze how various factors influence the total energy consumption. Identifying the factors contributing most to the overall network energy-consumption allows to focus efforts to save energy to the most promising areas. It is worth noting that in our analysis we also include the various WHART protocol overheads, for example the impact of time synchronization and management slots. It is furthermore important to note that, while our analysis focuses on the CC2420, the methodology applies in the same way to other transceivers as well.

We perform this analysis in two stages. In the first stage we do consider sleeping, but we have not fully exploited the sleeping

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capabilities of the CC2420. Instead, we have chosen the lightest available sleep mode. This lightest sleep mode has the highest power consumption of all sleep modes and the shortest wakeup time, and a nodes transceiver enters it after each slot in which the node was active (i.e. transmitting or receiving). This approach has minimal implementation complexity and does not need to consider the nodes TMDA schedule at all – it allows a node to start its wakeup operation at the beginning of a time slot and be ready for transmission or reception within the same slot early enough. Our statistical analysis, which looks at various factors contributing to the energy consumption over 12 h, reveals that the energy consumed in this sleep state contributes to approximately 40% of the total variation observed.

In the second stage of our analysis we exploit that the transceiver offers several different sleep states of varying depth. The deeper sleep states require more energy and time to wake up from them. We analyze a method that individual nodes can apply to their TDMA schedule (as received from a central entity at network configuration time). By this method a node determines after each active slot the deepest sleep mode that would still allow it to be awake when its next active slot comes – it has a slightly higher implementation complexity and runtime costs as the method used in the first stage. This method takes into account how much time it takes to switch from one sleep state into another or into the active state. Our results show that with applying this simple method substantial energy savings for the sleep energy can be achieved.

To the best of our knowledge, this paper provides the first detailed analysis of the main factors contributing to the energy-consumption of WHART. It extends the conference paper [17] by considering all sleep modes of the CC2420 transceiver instead of only the lightest one, by considering management cost in addition to time synchronization cost, by using more complex network topologies and by considering the microcontroller power consumption,

The remainder of the paper is structured as follows. Section 2 presents an overview of the WHART standard. Subsequently, in Section 3 we describe the simulation-based performance evaluation approach used in this paper. The sensitivity analysis results are presented in Section 4. In this section we also present the analysis of the performance cost of time synchronization and management slots. In Section 5 we analyze the transceivers energy consumption when the sleeping capabilities are more fully exploited. Related work is discussed in Section 6 and finally, Section 7 concludes the paper with some possible ideas for future work. Additional details to this paper are available as technical report [16].

2. Overview of Wireless HART

Wireless HART [10,12,11,13] (abbreviated as WHART in the following) is one of the first wireless communication standards specifically designed for process automation applications. The standard has been finalized in 2007, and at the beginning of 2010 it has been ratified as an IEC standard. On the physical layer, WHART adopts radios that are compliant to the IEEE 802.15.4 standard [21]. It operates in the 2.4 GHz band and offers a data rate of 250 kbit/s. On top of the physical layer, WHART employs a TDMA-based MAC protocol and additionally performs slow frequency hopping (hopping on a per-slot basis). The frequency hopping-pattern is determined from a well-known pseudo-random sequence. The TDMA slot allocation is centrally controlled (by the *network manager*) and slots are assigned at network configuration time. Furthermore, the network manager can re-schedule the network dynamically, based on health reports issued by each node every 15 min. Such a health report includes a list of the neighbors of a node and hence a part of the network topology. The network manager re-schedules only upon topology changes, which we consider to be a relatively rare event.

2.1. Network architecture

The network architecture of a WHART network features three different types of components (compare Fig. 1).

The WHART *field devices* are used for collecting measurement data from the field and for forwarding this data to a gateway node. They typically integrate wireless communication, sensing, and computational facilities. A field device might be either a genuine WHART device or it might be a legacy (wired) HART device equipped with a HART-specific wired-to-wireless adapter. In this paper we assume that field devices are battery-driven, so we are especially interested in their energy-consumption.

A *gateway* forms the boundary between a WHART segment and other (often wired) parts of an automation network and is usually not energy-constrained. The gateway is the point where all sensor data provided by WHART field devices is collected and prepared for further processing. It enables communication between host applications and field devices. There is only one gateway per network and all the WHART devices are known to the gateway.

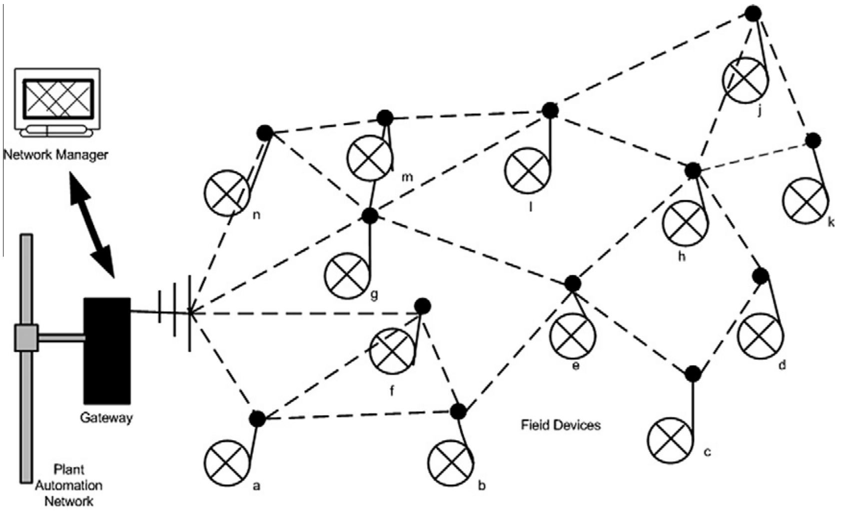

Fig. 1. WHART basic network components.