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Robust distributed active power control technique for IEEE 802.15.4 wireless sensor networks — A quantitative feedback theory approach

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ABSTRACT

A novel, practically implementable robust Distributed Active Power Control (DAPC) technique is presented for IEEE 802.15.4 wireless sensor networks by using Quantitative Feedback Theory (QFT). The proposed DAPC framework is based on tracking a target Received Signal Strength Indicator (RSSI) where the effects of radio channel uncertainty and interference between sensor nodes are considered as an unknown output disturbance. The key features of this technique are summarized as follows: (1) quantifiable improvements are achieved in terms of outage probability and power consumption, (2) exact information in relation to the network operating conditions, e.g., radio channels gains and interference between users, is not required, and (3) the proposed graphical design environment simplifies the trade-off between system performance metrics. Experimental results are provided that highlight the effectiveness of the proposed approach when compared with some existing DAPC techniques.

1. Introduction

Recent advances in wireless sensor technology have enabled the development of Wireless Sensor Networks (WSNs) that facilitate collection, monitoring and control of designated data from remote locations. Smart and healthcare environments and Body Area Networks (BANs) are among the WSNs applications that have received much attentions in recent years (Akyildiz, Su, Sankarasubramaniam, & Cayirci, 2002; Jagannathan, 2007; Yang, 2006). A number of challenges must be addressed by the engineer when designing a WSN that is capable of deployment in such a demanding application space (Jagannathan, 2007):

- It is imperative that the transmitted signal exhibits a certain minimum signal-strength at the receiver. This will aid in the demodulation process thereby improving Bit-Error-Rate (BER) of the received signal.
- Connectivity, the key Quality of Service (QoS) metric considered in this paper, is a recurring theme in wireless communications. The engineer must make sure that transceiver nodes remain connected under a variety of different conditions. Outage probability is typically employed as a performance metric to assess the system connectivity under the binding assumption that the communication between any transceiver pair will be lost/disconnected if the received signal-strength falls below a minimum threshold value.
- It is highly desirable that WSNs be capable of deployment in remote or hazardous environments, where battery replacement is often not viable. Thus, the design of power aware WSNs with extended operational longevity is a significant problem.

Power Control (PC) is the most obvious means of addressing these challenging issues. The design of efficient PC is constrained by a variety of factors. For example, wireless radio channels are typically affected by exogenous, uncertain factors that have an adverse impact on the system performance. Path loss, shadowing and fading effects can severely degrade the QoS and when mobility is introduced, the problem becomes inevitably more difficult to solve. As a concluding remark, the power aware WSN must also be *robust* to the aforementioned uncertain and time-varying factors as well as the interactions that inherently exist between sensor nodes (Rappaport, 2002).

1.1. Literature survey on power control techniques

Existing PC mechanisms for WSNs may be classified into two main categories: Passive PC (PPC) and Active PC (APC) (Pantazis & Vergados, 2007). PPC seeks to save energy by switching the radio (transceiver) interface module off when not in use. APC adjusts the transmission power according to the network operating

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[1] A part of this work has been presented in Alavi, Walsh, and Hayes (2008).

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conditions by keeping the radio interface active. A brief review is presented in the following. For a more comprehensive survey, interested reader is directed to Pantazis and Vergados (2007).

1.1.1. PPC techniques

In Burd, Pering, Stratakos, and Brodersen (2000), Im, Kim, and Ha (2001), Pantazis, Vergados, Vergados, and Douligeris (2009) and Sinha and Chandrakasan (2001) it was shown that the application of PPC techniques can produce substantial energy savings by reducing the energy usage of the Central Processing Unit (CPU) in idle system states. In Kravets and Krishnam (2000), Singh and Raghavendra (1998), Srisathapornphat and Shen (2002) and Ye, Heidemann, and Estrin (2002) a number of heuristic algorithms is proposed for PPC to decide when to turn off the radio interface. However, since a large amount of power can be consumed in switching the transceiver back ON each time, this operation can sometimes prove inefficient. It has therefore been suggested that operation in a power saving mode can only be energy efficient if the time spent in the idle mode is greater than a certain predefined threshold (Akyildiz et al., 2002).

1.1.2. APC techniques

Power-aware routing protocol is a typical APC technique that has received much attentions in the literature. Here, data transmission paths are managed so that reductions in transmission power levels can be achieved (Das & Bharghavan, 1997; Gomez, Campbell, Naghshineh, & Bisdikian, 1999; Singh, Woo, & Raghavendra, 1998). However, in order to obtain a satisfactory level of system performance in terms of power consumption, exact information in relation to the wireless channel gain is required (Misra & Banerjee, 2002). Moreover, it has been shown in Karl and Willig (2005) that the use of intermediate hops to divide the distance between source (i.e., sensor node) and destination (i.e., hop or coordinator) into shorter segments will not guarantee minimal transmission power. It should be clear, even from this overview, that obtaining an easy-to-implement energy efficient routing protocol is still an open research theme (Gomes, Souto, Kelner, & Sadok, 2006; Vergados, Pantazis, & Vergados, 2008). An alternative APC technique is based on the use of handshake signaling to synthesize Multiple Access Collision Avoidance (MACA) protocol (Karn, 1990) and/or some type of modified variation such as MACA Wireless (MACAW) (Bharghavan, Demers, Shenkar, & Zhang, 2004), and Floor Acquisition Multiple Access (FAMA) (Fullmer & Aceves, 1995). When a sensor node receives RTS/CTS (Request to Send/Clear to Send) frames, it begins communications with other neighbor nodes with lower transmission power. Since centralized information of the neighbor sensor nodes is a prerequisite here, the APC based on the use of handshake signaling is often complicated and time consuming.

As a concluding remark, an APC technique that adjusts transmission power using only limited information is appealing from an engineering perspective. The APC scheme that relies only on the limited information in a reasonable time, while maintaining satisfactory levels of QoS, is so-called DAPC technique in the literature (Gunnarsson & Gustafsson, 2003). In contrast, the APC scheme that requires exact information in relation to system operating condition such as radio channel gains and interference between sensor nodes is so-called Centralized APC (CAPC) technique that is beyond the scope of this work (Gunnarsson & Gustafsson, 2003).

There have also been a number of DAPC techniques reported that utilize Signal-to-Interference plus Noise Ratio (SINR) or Packet-Error-Rate (PER) measurements. In Muqqattash and Krunz (2004), the SINR is fed back for transmission PC. The proposed approach relies on the assumption that the radio channel gains between transceivers are the same in both directions (i.e., up and downlink) which is unrealistic in practical sensor network deployments. The DAPC algorithms proposed in Zurita Ares, Fischione, Speranzon, and Johansson (2007) are based on PER estimation that leads to a quite expensive computational burden, in particular for fading environments where the variance of the wireless channel gain is quite high and/or time varying.

1.2. Contribution of this work

In this paper, a novel, practically implementable DAPC technique is presented for IEEE 802.15.4 WSNs using the Quantitative Feedback Theory (QFT) approach proposed by Horowitz (1963). The system structure is based on tracking the Received Signal Strength Indicator (RSSI). The radio channel uncertainty, interference between sensor nodes and quantization/measurement error are considered as an unknown output disturbance. Robust stability *and* performance constraints are shown to be equivalent to a set of exclusion regions for the system loop gain function plotted on the standard Nichols chart at any given frequency. The desired power controller is achieved through an iterative shaping of the system frequency response so that these exclusion regions are avoided. This paper demonstrates the features of the proposed technique summarized as follows: (1) quantifiable improvements are achieved in terms of outage probability and power consumption, (2) exact information in relation to the network operating conditions, e.g., radio channel gains, interference between users, is not required, and (3) the proposed graphical design environment simplifies the trade-off between outage probability and power consumption. The proposed strategy is extensively tested experimentally on a fully complaint 802.15.4 testbed where mobility is considered using autonomous robots. This testbed provides a good basis for a formal comparison of the new approach with a number of existing DAPC strategies.

It is also noted that although the QFT approach has been successfully applied before in a wide variety of application spaces (see Houpis, Rasmussen, & Garcia-Sanz, 2006, and examples therein), this is the first time that its effectiveness has been exhibited using a real 802.15.4 WSN benchmark problem.

1.3. Paper outline

The work is laid out as follows. In Section 3, the proposed DAPC structure is formulated. Section 4 deals with the design of the PC algorithm based on QFT principles. The design constraints, selection of robustness weighting functions, and finally the loop-function shaping method are discussed. In Section 5 a benchmark example of a WSN infrastructure constructed using Moteiv's[2] Tmote-Sky wireless modules is introduced. In particular this section presents several technical notes; how to practically establish a power aware WSN that exhibits jointly improved QoS and energy consumption characteristics. Finally, experimental results are reported and the performance of the new methodology is compared with a selection of existing DAPC algorithms.

2. Nomenclature

Throughout this paper,

- decibel value of a variable x is denoted by $\bar{x}$, namely, $\bar{x} = 10\log_{10} x$;

[2] Moteiv (which has recently been rebranded as Sentilla Inc.) provides and develops the wireless sensor networking and related software used in this study. http://www.sentilla.com