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Cross-layer link adaptation design for UWB-based sensor networks ☆

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ABSTRACT

A routing protocol is essential for the success of wireless sensor networks (WSNs). Its task is to ensure a reliable communication between neighbouring nodes, and to transmit data (via an intermediate node) form any node to the central node. However, unlike traditional ad hoc networks, WSN are energy constrained since nodes operate with limited battery capacity. Thus, the routing protocols for WSN must be designed with a focus on the energy efficiency criterion. This paper presents a cross-layer link adaptation scheme for an energy efficient routing protocol for ultra-wideband (UWB)-based sensor networks. We use a joint consideration of physical and multiple access layer in order to minimize the energy consumption of the network, and hence increasing its lifetime. Multiple accesses are assumed to have a UWB time-hopping signalling structure. Our goal is to define the link adaptation as a numerical optimization in which the energy consumption of a multihop route is taken into account.

1. Introduction

Wireless sensor networks are special ad hoc networks with large number of nodes collaborating to accomplish common tasks such as data environment collection, security monitoring and positioning. Wireless sensor networks (WSNs) are energy constrained, while all nodes operate with limited battery capacity; their coverage is usually limited to a few meters.

The interest in low energy consumption is growing steadily. In fact, the energy efficiency is the key issue for wireless sensor networks, which mainly rely on limited batter power. In these types of networks the focus is more on minimizing energy consumption than maximizing rate.

Ultra-wideband (UWB) is an emerging technology for short-range wireless communications. UWB technology has several advantages over more conventional technologies. It seems to be a viable candidate to offer ideal solutions for sensor networks applications [1]. In fact, UWB based systems have potentially low complexity and low cost, use noise-like signal, very high time-domain allowing for location application and are robust to multipath fading and jamming. For the energy consumption, UWB has the potential of efficient operation, since UWB has the lowest consumed energy per bit among other RF technologies according to the measurement and simulation results [2].

Energy efficiency in UWB sensor networks depends mainly on the time a node has to listen, receiving or idle listening requires a lot more energy than sending or active-off states [3]. Therefore, an efficient management of the limited power supply is the key element for achieving acceptable network lifetimes.

Routing problems are usually considered to be the core of wireless sensor network design. However, in most application scenarios, WSN nodes are powered by small batteries, which are often in practice non-rechargeable. Therefore, software solution, which combines cross-layer and energy aware system design to increase energy efficiency, is a promising way worth exploring.

Many routing algorithms have been proposed in prior researches. The shortest path is the typical and fundamental consideration for network flow routing problems [4]. Bhardwaj and Chandrakasan [5] have provided upper bounds on the lifetime of sensor networks where sensor node locations are given. In [6], the authors propose a transmission range distribution optimization scheme to maximize the network lifetime given fixed node locations. However, many of these routing protocols separate the different layers (physical layer, medium access and routing). This may lead to largely suboptimal network designs.

In this paper, we investigate a route optimization problem (via link adaptation) for UWB-based sensor networks. Our goal is to adapt all routes to transmit the data from any node to the central node with the best energy performance according to certain quality of service (QoS) to provide an energy-efficiency routing strategy. The optimization formulation assumes that an existing route has already been found between node and sink. It allows QoS

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requirements in terms of end-to-end bit error rate. Both transmissions and circuit energy consumption are taken into consideration.

The analysis given here takes into account the mutual interactions between the physical and multiple accesses layer. In fact, the cross-layer analysis is still a complex problem [7]. Hence, some assumptions must be considered to give a useful analysis.

The reminder of the paper is organized as follows: the next section summarizes existing routing protocols designed for WSNs. Since in this paper we are interested in cross-layer link adaptation design, we describe in Section 3 a related work on this topic. Section 4 describes the system model. The mathematical problem formulation is given in Section 5. Results and discussions are given in Section 6. Finally, a conclusion is given in Section 7.

2. Routing in ad hoc wireless sensor networks

Despite the innumerable applications of WSNs, these networks have several restrictions, e.g., limited energy supply, limited computing power, and limited bandwidth of the wireless links connecting sensor nodes. However, the most important factor of WSNs design is to carry out data communication while trying to prolong the lifetime of the network.

Routing in a wireless sensor network is the procedure of finding a path from one node to another. Usually, this will be a multihop route, involving intermediate relay nodes.

WSNs differing from one to another, several algorithms have been investigated for the routing problem. These routing mechanisms have considered the characteristics of sensor nodes along with the application and architecture requirements. Almost all of the routing protocols can be classified according to the network structure as flat, hierarchical or location-based. Furthermore, these protocols can be classified into multipath-based, query-based, negotiation-based, and QoS-based, depending on the protocol operation [8]. Akkaya and Younis [9] explored the WSN routing protocols based on network architecture developed in recent years in their survey on routing protocols for wireless sensor networks.

It should be noted that the sensor nodes are often deployed densely in the area either close to or inside the physical phenomenon. Since they are densely deployed, neighbour nodes may be very close to each other. As a result, multihop transmission is expected to consume less power than one hop transmission.

As mentioned earlier, the most important factor to take into consideration when developing a WSN is energy efficiency. In fact, the nodes select the energy efficient route to transmit the data. Fig. 1 is used to describe each of these approaches, and node "T" is the source node that senses the phenomena. In the following, we summarize some of the routing in WSNs [10]:

- *Maximum available power (PA) route*: the route that has maximum total available power is preferred (red[1] route).
- *Minimum energy (ME) route*: the route that consumes minimum energy to transmit the data packets between the sink and the sensor node is the ME route (blue[1] route).
- *Minimum hop (MH) route*: the route that makes the minimum hop to the sink in preferred (green[1] route).

3. Cross-layer design of UWB ad hoc sensor networks

Ad hoc networks have the advantage of low cost deployment and they can be easily tailored for specific applications. They are suitable for a several applications such as data networks, home networks [11], device networks (such as Bluetooth [12]), sensor networks [13], etc.

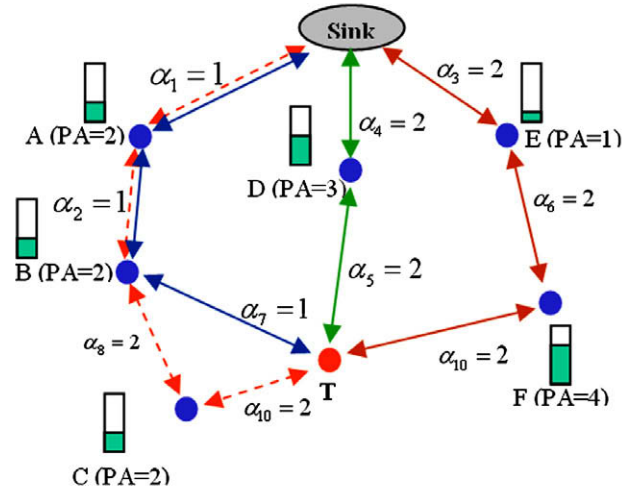

Fig. 1. Energy efficiency of the route.

A large range of application-dependent network requirements must be met regardless of the network topology, the link quality at each local node and the node traffic. Moreover, the nodes usually have stringent energy constraints as well. Significant research has been directed towards implementing application-dependent QoS requirements in variable network conditions.

To optimize the performances of the network, traditional techniques analyze each layer of the OSI's model separately. This approach may lead to inefficient designs. In fact, there are underlying features, particularly the energy consumption, which span across several layers.

Since few years, the cross-layer design optimization of resource management algorithms has been proposed for various network scenarios and considering various performance measures. Although most of this research has concentrated on the layered protocol approach and has proposed adaptive for the particularly considered layer. The most important analysis is specifically addressed power control, adaptive techniques and coding, at the link layer, scheduling at the MAC (medium access control) layer and energy constrained routing at the network layer.

Several works show that significant performance improvement can be achieved by considering cross-layer design in ad hoc networks. For example, a cross-layer design for joint physical/transport is described in [14], and MAC/transport [15] has also been reported.

The authors in [14] present a distributed power control algorithm that couples with the existing TCP congestion control algorithms to increase end-to-end throughput and energy efficiency of multihop transmissions in wireless multihop networks.

Yung and Shakkottai [15] develop a fair hop-by-hop congestion control algorithm with the MAC constraint being imposed in the form of a channel access time constraint, using an optimization based framework.

The issue of cross-layer design in the context of power control interactions with radio link and transport layer data retransmission protocols using a hierarchical control theoretic approach for modeling has been considered in [16]. For ad hoc networks, energy efficient routing implies tight interdependencies among all layers of the protocol stack [17]. The authors in [18] study the problem of joint routing, link scheduling and power control to support high data rates for broadband wireless multihop networks.

Most paper analyzing UWB networks are interested in the data rate utility problem [19–22]. The authors in [19] formulated the

[1] For interpretation of the references to color in Fig. 1, the reader is referred to the web version of this paper.