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Review

A survey of protocols for Intermittently Connected Delay-Tolerant Wireless Sensor Networks

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ABSTRACT

Intermittently Connected Delay-Tolerant Wireless Sensor Networks (ICDT-WSNs), a branch of Wireless Sensor Networks (WSNs), have features of WSNs and the intermittent connectivity of Delay-Tolerant Networks (DTNs). The applications of ICDT-WSNs are increasing in recent years, however, the communication protocols suitable for this category of networks often fall short. Most of the existing communication protocols are designed for either WSNs or DTNs and tend to be inadequate for direct use in ICDT-WSNs. This survey summarizes characteristics of ICDT-WSNs and their communication protocol requirements, and examines the communication protocols designed for WSNs and DTNs in recent years from the perspective of ICDT-WSNs. Opportunities for future research in ICDT-WSNs are also outlined.

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1. Introduction

Intermittently Connected Delay-Tolerant Wireless Sensor Networks (ICDT-WSNs) are a new branch of Wireless Sensor Networks (WSNs), which have characteristics of WSNs and Delay-Tolerant Networks (DTNs). These characteristics include the limited energy, low computation capability, small storage, narrow bandwidth, short communication range (Akyildiz et al., 2002) and the intermittent connectivity that end-to-end paths do not always exist in networks (Dipankar Raychaudhuri, 2011). These difficulties make the design of communication protocols for ICDT-WSNs a challenging task, although ICDT-WSNs have been commonly used in areas whose development environments are unsafe or even impossible for human to access. Examples of use include wildlife tracking (Juang et al., 2002), assisting submarine location estimation (Zhou and Willett, 2007), solar-powered autonomous underwater vehicle (SAUV) platform for underwater networks (Bartos et al., 2008), coal mine structure surveillance (Li and Liu, 2007) and sandstorm forecast (Wang et al., 2011).

Most of the existing protocols cannot be directly employed in ICDT-WSNs, since they are either designed for WSNs or DTNs that

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do not take all limitations of ICDT-WSNs into consideration. Without reliable, robust and efficient communication protocols, the performance of ICDT-WSNs is degraded resulting in shortened network life time, decreased propagation speed and increased packet loss rate. As a consequence, the development of ICDT-WSN applications is constrained.

In this paper we list the attributes of ICDT-WSNs and the requirements for communication protocols of this category of networks, outline several communication protocols that have been designed in recent years, and evaluate them from the perspective of ICDT-WSNs for improvement opportunities in communication protocols. Some open problems in ICDT-WSNs and possible directions to address these problems are also discussed in this paper.

The rest of this paper is organized as follows: Section 2 gives brief introductions to WSNs and DTNs to provide sufficient background for ICDT-WSNs, and introduces ICDT-WSNs in detail. Transport, network, and link layer communication protocol outlines and evaluations are provided in Section 3. Section 4 gives out open problems in ICDT-WSNs and provides possible solutions. Conclusions are drawn in Section 5.

2. Background

2.1. Wireless Sensor Networks

Wireless Sensor Networks (WSNs) have been extensively studied and widely used in the recent decade. A WSN can consist of one to several types of sensor nodes such as visual, thermal, acoustic, infrared, radar, low sampling rate magnetic, and seismic (Akyildiz et al., 2002). WSNs are mission-oriented: all sensor nodes of a WSN cooperate together to accomplish the mission of the network, such as collecting environmental data from a designated area and tracking an object. According to the environment the WSNs are developed for, WSNs can be categorized into terrestrial, underwater or underground:

- *Terrestrial* WSNs are developed above ground, and are usually composed of hundreds to thousands of low-cost sensor nodes (Yick et al., 2008). The terrestrial WSNs can be used for environment sensing and monitoring, industry monitoring (Gungor and Hancke, 2009) and surface exploration. Radio Frequency (RF) communication is widely used in terrestrial WSNs. Energy efficiency is very important for terrestrial WSNs, since the power of sensor nodes is very limited even with solar cells.
- *Underwater* WSNs consist of a variable number of sensors and vehicles that are sparsely deployed under water for oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, navigation assistance and tactical surveillance applications (Akyildiz et al., 2005). Instead of RF communication, acoustic communication is preferred in underwater WSNs, because of the high attenuation of RF in aquatic environments (Heidemann et al., 2006). Compared to the terrestrial WSNs, underwater WSNs suffer more severe challenges: longer propagation delay, less bandwidth, more severely impaired channels and non-rechargeable, limited power.
- *Underground* WSNs comprise a number of sensor nodes buried underground or placed in coal mines or caves, used to monitor a variety of underground conditions (Li and Liu, 2007; Akyildiz and Stuntebeck, 2006). RF communication can be used in underground WSNs (Li and Liu, 2007), but the underground environment causes high attenuation of electromagnetic waves. Akyildiz and Stuntebeck (2006) point out that Magnetic Induction (MI) and seismic waves might be better for communication in underground WSNs. In addition to the challenges of underwater WSNs, signal fade is unavoidable in underground WSNs.

With the development of micro-electro-mechanical systems (MEMS) technology, sensor nodes have become smaller, lighter, smarter and cheaper. In addition to the main categories of WSNs mentioned above, WSNs are now being used in airplane surveillance (Bur et al., 2010) and body sensor networks (Domingo, 2011; Quwaider et al., 2010).

The network infrastructures, sensor nodes and communication protocols can be different from one WSN to another. Because WSNs are mission oriented, the topology design and device selection for a WSN depends on the application for each WSN.

Generally, WSNs have little or no infrastructure. According to the manner of node deployment, WSNs can be divided into two groups: *ad hoc* WSNs and *pre-planned* WSNs. Ad hoc WSNs have no infrastructure, the sensor nodes are deployed into a field randomly, possibly scattered from an airplane and left unattended. In order to maintain connectivity and detect failures, the protocols and algorithms for ad hoc WSNs should be able to self-organize. The ad hoc nature makes this category of WSNs suitable for disaster relief and operations in inaccessible areas. Pre-planned WSNs, on the contrary, are more structured networks, and can be grouped into wireless mesh networks. Sensor nodes in pre-planned WSNs are placed at particular positions in a pre-planned manner, such that topologies are well designed beforehand. For several examples of typical pre-planned WSNs see underwater WSNs (Akyildiz et al., 2005; Heidemann et al., 2006) and underground WSNs (Akyildiz and Stuntebeck, 2006; Li and Liu, 2007).

According to the mobility of sensor nodes, WSNs can be categorized into *static* WSNs and *mobile* WSNs. WSNs that only consist of non-moving sensor nodes are static WSNs. WSNs containing self-propelled sensor nodes are mobile WSNs. Depending on the design of a network, the movement of sensor nodes in a network can be controllable and predictable. This property not only distinguishes mobile WSNs from MANETs, but also provides an advantage for communication protocol design.

The communication protocols for WSNs can be classified into connection-oriented and disconnection-oriented. The *connection-oriented* protocols assume that a complete path from a source to a destination in a network always exists. But the *disconnection-oriented* protocols assume that a complete path between a source and a destination in the network does not always exist, and can be highly unstable (Spyropoulos et al., 2008a). The disconnection-oriented protocols also need to be tolerant to the long propagation delay caused by disconnection. Disconnection-oriented protocols are necessary for intermittently connected WSNs, which is discussed in Section 2.3.

2.2. Delay-Tolerant Networks

A *Delay-Tolerant Network* (DTN) is an overlay on top of regional networks,[1] and provides interoperability between these networks (Fall, 2003). DTNs are challenging networks, where the architectures and communication protocols used in traditional networks may operate poorly. The challenges associated with DTNs are intermittent connectivity, long or variable delay, asymmetric data rates, and high error rates.

The Delay-Tolerant Networking Research Group (DTNRG) (DTNRG, 2012) discusses the *bundle layer* as the overlay DTN architecture, which not only provides a transparent communication

[1] A regional network is a network in which the communication characteristics are homogeneous.