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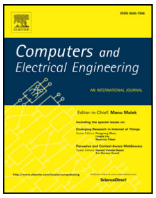

Lifetime balanced data aggregation for the internet of things

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ABSTRACT

This paper proposes LBA, a lifetime balanced data aggregation scheme for the Internet of Things (IoT) under an application-specified end-to-end delay requirement. In contrast to existing aggregation schemes, LBA aims to prolong the IoT network lifetime under network heterogeneity and dynamics, while ensuring the required data delivery delay. To achieve this goal in a distributed manner, LBA adaptively adjusts the aggregation delays of neighboring devices to balance the lifetime between them. As such balancing takes place in all neighborhoods, the minimal device lifetime in the network is increased gradually, thus prolonging the lifetime of the entire network. The effectiveness of LBA is demonstrated via extensive experiments on a testbed. Generally, when the network presents a higher degree of heterogeneity and dynamics, LBA's performance gain over a state-of-the-art non-adaptive data aggregation scheme becomes more significant, and the gap between LBA's performance and its theoretical upper bound gets smaller.

1. Introduction

In the Internet of Things (IoT), tiny IoT devices are usually powered by small batteries with limited energy supplies. When deploying these devices for long-term applications such as continuous environmental monitoring, it is critical to prolong the IoT network lifetime.

Data aggregation [1,2] has been widely recognized and applied as an effective technique to reduce the communication cost and extend the operational lifetime of devices. With data aggregation, a device is allowed to hold data received from neighboring devices or data generated by itself for a period of time (referred to as *aggregation delay*), aggregate them together, and send out the aggregated result. This way, redundancy is eliminated from raw data and the communication cost is reduced. In this paper, we present a unique data aggregation scheme, called LBA (Lifetime Balanced Aggregation), to prolong the IoT network lifetime while satisfying the application-specified end-to-end data delivery delay requirement.

1.1. Motivation and contributions

In a data aggregation scheme, the extent to which data volume can be suppressed depends highly on the aggregation delay. With a larger aggregation delay, more data may be suppressed and less energy may be consumed on data transmissions; hence, the communication efficiency may be increased. However, more delay would be added to the end-to-end data delivery. Therefore, there is a tradeoff between communication efficiency and end-to-end delay. As the first contribution of

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Table 1
Comparison with selected existing schemes.

Schemes	Bounded Delay	Asynchronous	Distributed	Handle Network Dynamics
[12,13]	No	Yes	Yes	No
[14]	Yes	No	No	No
[15]	Yes	No	Yes	No
[16]	Yes	No	Yes	Yes
[17]	Yes	Yes	Yes	No
LBA	Yes	Yes	Yes	Yes

the paper, we study the generic (ρ, Θ) *end-to-end delay requirement*, which requires that each sensory data shall reach the sink within Θ time after its generation with a probability of at least ρ. Here, ρ and Θ are application-specified parameters. We conduct a comprehensive study on the relation between data traffic, aggregation delay, (ρ, Θ) end-to-end delay requirement, and device lifetime, which provides a theoretical foundation to the proposed LBA scheme.

In practice, devices may have different lifetime due to various reasons. For example, the following devices may have a shorter lifetime than their peers: (i) devices with a battery of poorer quality; (ii) bottleneck devices on a data collection tree; (iii) solar-powered devices [3,4] but deployed at shady locales; or (iv) wireless-chargeable devices [5–8] but deployed far away from the charger. Moreover, the IoT network conditions are heterogeneous and dynamic by nature. Data traffic, link quality, and network topology often vary over time. Thus, device lifetimes may change over time, and in general, it is difficult to identify or predict which devices have a shorter lifetime. As energy depletion in a single device may cause network disconnection or create coverage holes, which could render the entire network nonfunctional, many IoT network applications [9–11] have defined the *network lifetime* as the minimal device lifetime among all devices in the network, which is also the focus of our study in this paper. Based on the above observations, the second contribution of the paper is the design and implementation of the LBA scheme to prolong the IoT network lifetime under the end-to-end delay constraint.

It has the following features:

- LBA adjusts the aggregation delays of neighboring devices (along the source-to-sink path) together in a collaborative manner, so that the lifetime between them may be balanced without increasing the end-to-end delay. This way, the end-to-end delay requirement is satisfied while, as neighboring devices keep balancing their lifetime, the minimal device lifetime in the network is increased and thus the IoT network lifetime is extended.
- LBA is a distributed and scalable scheme as the adjustment of aggregation delays only occurs locally between neighbors.
- LBA is able to deal with network heterogeneity and dynamics in a timely manner, as the adjustment of aggregation delays is triggered as soon as the lifetime between neighboring devices becomes unbalanced due to network changes.
- LBA is able to adjust aggregation behaviors dynamically to the network changes such as route switching, packet loss, etc., and, therefore, is applicable in practical scenarios.
- LBA is a generic data aggregation scheme, which is applicable to heterogeneous networks that experience performance tradeoff between system lifetime and end-to-end delay. These networks include both IoT and traditional sensor networks.

We have implemented and evaluated LBA on a testbed of 32 TelosB nodes, and demonstrated its effectiveness with extensive experiment results under various network configurations.

1.2. Comparison with existing schemes

Many data aggregation schemes have been proposed in the past, which we will discuss in detail in Section 7. While most of these schemes focus on traffic suppression and communication efficiency, a few of them consider the tradeoff between communication efficiency and end-to-end delivery delay. In Table 1, we compare LBA with these schemes in terms of whether an end-to-end delay bound can be guaranteed, whether time synchronization is required between devices, whether a scheme is a distributed and localized solution, and whether a scheme is able to handle network heterogeneity and dynamics.

Among these schemes, [12] simply degrades the packet utility as the delivery delay increases while [13] conducts data aggregation on the shortest path tree to reduce the delivery delay; but, none of them is able to provide a delay bound guarantee on the end-to-end data delivery. Hariharan and Shro [14], Solis and Obraczka [15], Xiang et al. [16] minimize the network-wide energy consumption based, however, on an important assumption that time is synchronized between devices. Becchetti et al. [17] proposes an asynchronous and distributed data aggregation scheme. It allocates the end-to-end delay bound equally at each device along the source-to-sink path. Unfortunately, it cannot deal with network heterogeneity or dynamics, which are critical and practical factors that affect the network lifetime.

In comparison, the proposed LBA scheme is a distributed solution without requiring time synchronization between devices. It extends the network lifetime under the end-to-end delay constraint, even under various network dynamics such as packet losses, channel contention, and routing changes.

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