Computer Networks 136 (2018) 155–170

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Achieving adaptive broadcasting performance tradeoff for energy-critical sensor networks: A bottom-up approach

Lijie Xu[a,b,c,*], Geng Yang[a,b], Jia Xu[a,b], Lei Wang[a,b], Haipeng Dai[c]

[a] School of Computer Science, Nanjing University of Posts and Telecommunications, Nanjing, Jiangsu 210023, PR China
[b] Jiangsu Key Laboratory of Big Data Security & Intelligent Processing, Nanjing, Jiangsu 210023, PR China
[c] State Key Laboratory for Novel Software Technology, Nanjing University, Nanjing, Jiangsu 210023, PR China

ARTICLE INFO

Article history:
Received 15 September 2017
Revised 26 January 2018
Accepted 12 March 2018
Available online 13 March 2018

Keywords:
Wireless sensor networks
Low-duty-cycle
Broadcasting schedule
Bottom-up solution
Adaptive broadcasting performance tradeoff

ABSTRACT

Low-duty-cycle mode is widely adopted in energy-critical wireless sensor networks (WSNs). Such mode greatly reduces the energy waste caused by idle listening. However, it brings many new challenges for broadcasting. This paper mainly focuses on the minimum cost broadcast problem for low-duty-cycle WSNs. We propose a novel opportunistic broadcasting transmission model, which makes full use of the broadcast nature of wireless media to reduce the total energy consumption for broadcasting. The key idea is to allow nodes to defer their wake-up slots to opportunistically overhear the broadcasting messages sent by their neighbors, which could reduce the total energy consumption for broadcasting but increase the average end-to-end broadcasting delay. In this paper, we define a generalized broadcasting cost function, which can make a flexible tradeoff between average end-to-end broadcasting delay and total energy consumption for broadcasting, to adaptively meet various broadcasting performance requirements. Our target is to utilize the opportunistic broadcasting transmission model to design an efficient broadcasting schedule for low-duty-cycle WSNs, so that the broadcasting cost function is minimized. First, we define the Receiver-Constrained Minimum Cost Single-hop Broadcast Problem (RC-MCSB) and propose an optimal solution with a polynomial running time. Next, we extend the solution of RC-MCSB problem to our target problem and present a novel and efficient bottom-up solution. The simulation results have verified the significant performance advantage of our proposed bottom-up solution over the existing top-down solutions and the other solutions.

1. Introduction

As the key technique of Internet of Things [1,2], wireless sensor networks (WSNs) [3] have received lots of attentions in the past decades and made great progress in both academic and industrial communities. Many typical WSNs applications [4–6] often require nodes should be deployed in tough environments where the sensor nodes are difficult to replace or recharge their batteries, and also require the network system should run for a long enough period. Therefore, how to efficiently prolong the network lifetime becomes a very important problem. To this end, many energy efficient solutions have been proposed for energy-critical WSNs [7–10]. Most of these existing works assume the network is operated at low-duty-cycle mode, where each sensor node has its own working-sleeping schedule to wake up periodically. Low-duty-cycle operation can significantly reduce the energy consumption caused by idle listening, which has been verified as the main source of energy waste for WSNs with low traffic characteristic [11]. However, such mode still brings many new challenges, especially for broadcasting applications [12], which are the often-used fundamental functions for WSNs.

First, low-duty-cycle mode will have an effect on delay performance for broadcasting. Specifically, each sender cannot forward the broadcasting message until the receiver wakes up, it will result in a notable increase on communication delay between any neighboring nodes, which is called sleep latency [13]. More importantly, the energy performance for broadcasting could also be significantly degraded. For the traditional always-awake WSNs, the implementation of any local single-hop broadcast just requires one transmission from the sender, due to the inherent broadcast nature of wireless media. However, low-duty-cycle mode will make the neighboring nodes have totally different working-sleeping schedules such that wireless media could lose its inherent advantage

* Corresponding author at: School of Computer Science, Nanjing University of Posts and Telecommunications, 9 Wenyuan Road, Qixia District, Nanjing, 210023, PR China

E-mail addresses: ljxu@njupt.edu.cn (L. Xu), yangg@njupt.edu.cn (G. Yang), xujia@njupt.edu.cn (J. Xu), leiwang@njupt.edu.cn (L. Wang), dhpphd2003@gmail.com (H. Dai).

https://doi.org/10.1016/j.comnet.2018.03.007
1389-1286/

for broadcasting, which implies any local single-hop broadcast will be inefficiently implemented by multiple unicasts. For broadcasting applications with large messages, such as code update, the degradation on energy performance for broadcasting will be more significant. Thus, how to design a broadcast scheme with high performance for low-duty-cycle WSNs is an important and challenging issue.

For real broadcasting applications, delay and energy are usually both the important performance metrics. Many existing works have investigated the energy optimization problem for broadcasting under delay constraints. However, it is usually unnecessary to require the broadcasting should have a strict delay constraint for many real applications. More broadcasting applications focus on the tradeoff between delay performance and energy performance. In practice, broadcasting performance requirements are usually application-specific. For example, the broadcasting applications with small and urgent messages, such as *configuration dissemination*, will pay more attention on delay performance than energy performance, in order to satisfy the new updated system requirement as soon as possible and reduce the chance of false positive or false negative. The broadcasting applications with large and non-urgent messages, such as *code update*, will pay more attention on energy performance than delay performance, since the updated code image normally consists of multiple packets, which will further deteriorate the energy efficiency of broadcasting. For broadcast problem in low-duty-cycle WSNs, thus, we tend to define the optimization objective as the generalized broadcasting performance, which can make an adaptive tradeoff between delay performance and energy performance. On the other hand, most of the existing works assume the traditional transmission model for broadcasting, in which every node will receive the broadcasting message at its scheduled wake-up time. Such model will lead to a low energy efficiency for broadcasting, since it totally ignores the inherent broadcast nature of wireless media and any local single-hop broadcast will be realized by a number of unicasts. Actually, we find that even for low-duty-cycle WSNs, the inherent broadcast nature of wireless media can still be fully exploited to improve the energy efficiency for broadcasting, by adopting a novel opportunistic broadcasting transmission model. The key idea is to allow any node to defer its wake-up time to opportunistically overhear the broadcasting message from the nearby forwarder. By such way, we can find the total energy consumption for broadcasting could be reduced, however, at the cost of the increase of average broadcasting delay. In other words, the opportunistic broadcasting transmission model can essentially provide a flexible control on the tradeoff between delay performance and energy performance.

Similar to the literature [39], we employ broadcasting cost, which is defined as the function weights delay and energy, to characterize the generalized broadcasting performance in this paper. Note that, we can adaptively adjust the tradeoff factor parameter in the broadcasting cost function to characterize various broadcasting performance requirements. This paper aims to utilize the opportunistic broadcasting transmission model to design an efficient broadcasting schedule for low-duty-cycle WSNs, so that the broadcasting cost function is minimized.

The main contributions of our work are summarized as follows:

- Compared with most of the existing works, the optimization objective of this paper is more practical. We define a generalized broadcasting cost function, which can provide a flexible control on the tradeoff between average end-to-end broadcasting delay and total energy consumption for broadcasting. By adaptively adjusting the tradeoff factor in objective function, our proposed solution can be universally applicable for the applications with various broadcasting performance requirements.
- We adopt the novel opportunistic broadcasting transmission model. By allowing nodes to postpone their wale-up time to opportunistically overhear the message, such model provides a flexible control on the tradeoff between delay performance and energy performance, which can offer a much more fine-grained design for the optimal broadcasting schedule to the target problem.
- Different from our previous work [14], in this paper, we come up with a novel bottom-up approach to address our target problem. Specifically, we first define a Receiver-Constrained Minimum Cost Single-hop Broadcast Problem (RC-MCSB), and propose an efficient dynamic programming algorithm with a polynomial running time. Then, we extend the solution of RC-MCSB to our target problem, *i.e.*, the Minimum Cost Broadcast Problem (MCB) for multihop networks, and devise a novel and efficient bottom-up algorithm. Further, we discuss how to extend our proposed algorithm to the generalized case where a few neighboring nodes could have the identical working-sleeping schedule.
- Extensive simulation results show that our proposed bottom-up algorithm has a much better performance than the existing top-down solutions and the other solutions.

The rest of the paper is organized as follows: Section 2 summarizes the related work. Section 3 illustrates the network model and states the problem. Detailed description and analysis of our proposed algorithm are presented in Section 4. Followed by the discussion and the simulation results in Section 5 and Section 6. Finally, Section 7 concludes our findings.

2. Related work

As an important and challenging issue, the broadcast problem for low-duty-cycle WSNs has been well-investigated by the researchers in the past years [12,15–38]. The existing works always regard delay and energy efficiency as the main broadcasting performance metrics.

Guo et al. [15] designed an opportunistic flooding algorithm for low-duty-cycle WSNs with unreliable links. By letting senders make probabilistic forwarding decisions based on the delay distribution of next-hop nodes, the opportunistic flooding algorithm greatly improves the broadcasting delay. Lu and Whitehouse [16] utilized the capture effect in physical layer to propose an efficient broadcasting protocol for low-duty-cycle WSNs, the solution allows the concurrent transmissions between multiple nodes and thus greatly reduces the broadcasting delay. In [19], the authors proposed a completely contention-free data dissemination protocol, *i.e.*, Pando, which can continuously disseminate rateless encoded packets over the parallel pipelines by integrating Fountain codes with constructive interference and pipelining. The experimental results reveal that Pando can provide 100% reliability and significantly reduce the dissemination delay. Zhang et al. [20] considered the broadcast problem for multi-channel asymmetric duty-cycled sensor networks, and proposed a multi-channel based efficient broadcast protocol, which can achieve low delay and high delivery rate. In [21], the authors proposed a novel collision-tolerant broadcast scheduling strategy for duty-cycled sensor networks, this strategy provides the chance to further reduce broadcasting delay by allowing collisions at non-critical nodes to speed up the broadcast process for critical ones. In [22], the authors proposed an energy-efficient broadcast redundancy minimization scheduling scheme for low-duty-cycle sensor networks. It first finds a set of forwarders that minimizes the number of broadcast transmissions, then constructs a forest of sub-trees based on the relationship between each forwarders and its corresponding receivers, a broadcast tree is ultimately constructed by connecting all sub-trees