Computer Networks 104 (2016) 79–93

Contents lists available at ScienceDirect

Computer Networks

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

TRM-MAC: A TDMA-based reliable multicast MAC protocol for WSNs with flexibility to trade-off between latency and reliability

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ARTICLE INFO

Article history:
Received 21 June 2015
Revised 7 April 2016
Accepted 21 April 2016
Available online 10 May 2016

Keywords:
Wireless sensor networks
Media access control
Reliable multicast

ABSTRACT

Multicast in wireless sensor networks (WSNs) is an efficient way to deliver the same data to multiple sensor nodes. Reliable multicast in WSNs is desirable for critical tasks like code updation and query based data collection. The erroneous nature of the wireless medium coupled with limited resources of sensor nodes, makes the design of reliable multicast protocol a challenging task. In this paper, we propose a framework for reliable multicast transmission in WSNs using TDMA-based channel access which works on top of a Multicast Spanning Tree (MST) rooted at the base station. The existing TDMA-based MAC protocols do not provide any mechanism to handle the collision and explosion of feedback messages, and therefore, they cannot be used in the proposed framework to support reliable multicast. To handle this issue, we propose a TDMA-based reliable multicast MAC (TRM-MAC) protocol for WSNs. The TRM-MAC protocol is parametric in the sense that it can be used to trade-off between reliability and delay performance, as per the requirement of the underlying applications. We have analyzed the TRM-MAC protocol to evaluate its delay and reliability performance at different packet loss rates, and have also compared its performance with those of others using simulation study. Both simulation and analytical results show that the TRM-MAC protocol considerably improves the performance of multicast communication in WSNs.

1. Introduction

A WSN consists of a number of sensor nodes, which have limited energy, CPU power, and memory. The sensor nodes may run different applications for different tasks such as event detection, localization, tracking, and monitoring. Such applications should be updated and configured multiple times during the lifetime of the network. An update by transmitting the contents one by one to individual sensor node would be very inefficient and would consume a lot of resources such as bandwidth and energy. In this situation, multicasting can provide an efficient mechanism for updating and configuring the applications running over sensor nodes by reducing the number of transmitted packets. The diffusive nature of the radio medium, also known as the Wireless Multicast Advantage (WMA), makes the multicast operation more effective in WSNs. Another example of multicast communication in WSNs is on-demand data collection, where the base station (sink node) sends a data query to a pre-specified group of sensor nodes asking them to send their sensory data. Moreover, the group of sensor nodes may not be known to the sink node beforehand. An example of such a query is “which sensor nodes have measured the temperature above θ degree?”. A detailed discussion on multicast communication in WSNs can be found in [26].

A WSN is usually multi-hop in nature, and therefore, direct transmission of multicast message from the sink to the sensor nodes is not possible. A straightforward solution to this problem is to let the sensor nodes work as routers. In such a case, every node will relay the received multicast packet to its one-hop neighbors. However, this approach can lead to a large number of redundant transmissions (*network flooding*), and defeat the purpose of using multicast communication. Additionally, forwarding of the same packet in a proximity by multiple nodes, not only causes wastage of energy but also increases the chance of packet collision, and therefore, affects the reliability of multicast transmission. This *network flooding* problem in WSNs is essentially handled by restricting the set of forwarding nodes as much as possible, while still ensuring that all the group members receive the data. To achieve this, a source-rooted multicast spanning tree (MST) is constructed, that contains all destinations (multicast group members) along with a few additional internal nodes (routers). Out of the many possible multicast trees, the tree to be selected, depends upon the optimization goal, viz., minimizing delay, minimizing energy consumption of the nodes or maximizing the bandwidth utilization. The issue of constructing MST with minimal cost is

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http://dx.doi.org/10.1016/j.comnet.2016.04.018

known as the Steiner-tree problem and it is known to be NP-complete [8].

Although having such a multicast tree drastically reduces redundant transmissions, it does not eliminate the possibility of packet collisions among the routers. Moreover, the routers in a proximity would simultaneously start forwarding the received multicast messages and cause a high degree of message collision. This situation of simultaneous data transmission is also known as *correlated-contention* [6].

The above discussion suggests that, in order to achieve reliable multicast in WSNs, the underlying media access control (MAC) protocol, should effectively handle the collisions due to *correlated-contention*. In the literature, time division multiple access (TDMA) and carrier sensing multiple access (CSMA) are the two major approaches for media access in WSNs. Of these two approaches, CSMA does not use any topology or clock information and resolves the contention for every data transmission. Thus, it is highly robust to any change in the network. But, as CSMA is based on the principle of “listen before talk“ (LBT), it does not specifically avoid simultaneous transmission or *correlated-contention*. On the other hand, due to its collision-free and energy-efficient properties, TDMA is more suitable as a MAC protocol in WSNs, particularly, in case of *correlated-contention*, where CSMA and its variations are not able to meet the requirements of the applications. There is always a reluctance to use TDMA as a choice for MAC protocol for WSNs due to its synchronization requirement. However, the recent advancement in the design of high-precision and low-cost crystal oscillators, together with large volume of research work to provide efficient protocols for achieving high precision clock synchronization among the nodes in WSNs, has attracted researchers to reconsider TDMA-based solutions for WSNs. Additionally, the clock synchronization is an essential feature of many sensor applications.

Channel errors can occur in a WSN due to background noise and varying properties of communication links. Therefore, merely having an MST to avoid *network flooding* and an efficient MAC protocol to handle collisions due to *correlated-contention*, are not sufficient to ensure reliable multicasting. Any reliable multicast protocol should also provide some mechanism to deal with packet losses. In general, the reliable delivery in multi-hop wireless networks, is handled at either transport layer or MAC layer or at both the layers. One of the first question is, whether to rely entirely on end-to-end acknowledgement at transport layer or to additionally use MAC layer acknowledgements and retransmissions. Due to higher packet loss rate (PLR) in wireless networks, handling packet losses only at transport layer can lead to higher delays and poor bandwidth utilization. Additionally, for high packet loss rate , MAC layer acknowledgements can keep the energy cost within reasonable bounds, whereas the cost for the case with pure end-to-end acknowledgement explodes [14]. Therefore, it becomes necessary to deal with packet loss at MAC layer also in WSNs, and have a balance of end-to-end vs. hop-by-hop reliability.

Most of the wireless MAC protocols use Automatic Repeat reQuest (ARQ) to provide error control for unicast data transmission because of its effectiveness and simplicity. Unfortunately, these ARQ mechanisms cannot be used to ensure multicast transmission reliability, because of following reasons.

- There is no efficient mechanism to resolve the contention between feedback messages sent by the receivers of a multicast packet.
- In case, every receiver sends feedback on receipt of multicast data, the delay incurred to receive the feedback would be very high.

These issues become crucial when the size of multicast group is fairly large. The existing MAC layer protocols for reliable multicasting can be categorized under two major classes based on feedback mechanisms used, viz. positive acknowledgement based (ACK-based) and negative acknowledgement based (NACK-based) approaches. In ACK-based protocols, each time a receiver correctly receives a packet, it returns a positive acknowledgment. Timeouts are used by the sender to detect the loss of packets. In NACK-based protocols, the sender considers packet transmission as successful until it receives a negative acknowledgement (NACK) from a receiver. If the sender receives at least one NACK, it retransmits the packet. The receiver does not send anything on successful reception of the packet. In this approach, the receiver has to check for the lost packets.

In this paper, we propose a TDMA-based Energy Aware MAC (TRM-MAC) protocol for reliable multicasting in WSNs. The protocol is based on a preexisting MST along with a TDMA slot-schedule, specifying the slots at which the nodes can make their transmissions. The TDMA eliminates collisions, overhearing and idle listening, which are the main sources of reliability degradation and energy consumption. To ensure the reliability of a particular transmission at MAC layer, we have used a combination of ACK-based and NACK-based approaches together with TDMA and prioritized-CSMA channel access mechanisms. Furthermore, the proposed protocol is parametric in the sense that it can be used to trade-off reliability with energy and delay as per the requirement of the underlying applications and also to balance the task of reliable multicasting between transport and MAC layers. Note that, in WSNs, all nodes cooperate for a single task, and only one application run at any given time. The TRM-MAC protocol is designed for multicast (sink to sensors) applications, whereas for convergecast applications any MAC protocol available in the literature can be used.

A detailed survey of MAC protocols for WSNs can be found in [12]. Proposed TRM-MAC protocol can be seen as one of the operational mode of a MAC protocol for sensor nodes, that is used only in case of multicast applications. However, the proposed protocol can be integrated with the existing TDMA based MAC protocols, such as IEEE 802.15.4 MAC in beacon mode, to facilitate multicast and convergecast transmissions in WSNs simultaneously.

In summary, the major contribution of this paper is to achieve reliable multicast at link layer which currently is not present in existing TDMA-based MAC protocols. For example, TDMA options present in 802.15.4-2006 MAC and its later revision, do not provide any mechanism to support reliable multicast, i.e., how to handle the acknowledgement message explosion problem and the resulting collision among ACK messages. Additionally, we have proposed a framework for reliable multicast transmission in WSNs based on proposed TRM-MAC which runs on top of an existing MST rooted at the base station.

This paper extends our earlier work proposed in [5], and makes the following core contributions.

- A method to select nodes that use ACK-based approach to improve the reliability performance of the proposed scheme.
- An algorithm to avoid the collision between NACK messages by appropriately deciding the local ordering of nodes that use NACK-based approach. This further improves the reliability of the multicast data dissemination in WSNs.
- Mathematical analysis of the proposed TRM-MAC protocol to evaluate its performance in terms of delay and reliability.
- Simulation of the proposed MAC protocol to evaluate its performance after applying the above mentioned optimization schemes.

The rest of the paper is organized as follows. In Section 3, we discuss the reliability requirement of multicast communication in WSNs. In Section 4, we discuss the proposed framework for reliable multicast in WSNs. The detailed description of TRM-MAC protocol is covered in Section 5. Section 6 analyses the perfor-