Investigating Energy Efficiency and Timeliness for Linear Wireless Sensor Networks

Radosveta Sokullu*, Eren Demir

Ege University, Department of Electrical and Electronics Engineering, İzmir 35040, Turkey

Abstract

Wireless sensor networks (WSNs) keep attracting the attention of researchers due to the newly emerging areas of application fueled by the development of inexpensive sensors and advanced communication technologies. A large group of applications - monitoring of pipelines, roads and bridges, as well as recently evolving IoT applications - specifically require linear topology. Compared to traditional WSNs, these linear wireless sensor networks (LWSN) pose additional challenges in terms of overall delay and energy efficiency. Even though there are numerous and also very successful MAC protocols for WSN, very few of them take into consideration the specifics of linear topologies. Thus our aim is to address these challenges by proposing LINE-MAC, a MAC protocol tailored especially for LWSN. Our simulation results show that LINE-MAC achieves significant improvement in end-to-end delay, energy consumption and packet delivery ratio (PDR) compared to a general, energy and delay efficient MAC protocol for WSN.

Keywords: Wireless sensor networks; Linear topology; Energy efficiency; Latency; Castalia.

1. Introduction

In recent years with the proliferation of wireless sensor nodes hardware and software a number of new wireless sensor network (WSN) topology and traffic patterns have emerged. In many WSN applications the deployment imposes linear topology where the collection of data is done over a long string of nodes connected to a sink at one end. Examples include monitoring of highway, gas, oil and water pipelines [1]. Such structures are usually very long and the distance from one end point to another can vary from several hundred meters to tens of kilometers which would make them vulnerable to a large number of possible failures, unacceptable delays and high probability of

* Corresponding author, Lecturer, EEE Department, EU. Tel.: +90-232-388-4000.
E-mail address: radosveta.sokullu@ege.edu.tr
errors. The newly establish concept of the “Internet of Things” (IoT) also opens the road to many new scenarios that employ line topology. The “Smart Lighting” project is an example of IoT concept adopted in a real-life application, where the WSN provides diverse services such as luminosity control for street lightening, lamp monitoring, emergency and tracking of elder people [2]. The proposed system utilizes sensor nodes mounted on existing lamp posts, located densely in the streets and is a perfect example of a long line topology WSN. Another example of WSN with line topology is the PipeNet system that collects pressure and vibration data at high sampling rates to provide near-real-time data pipe monitoring [3]. Also related to pipe-monitoring is the water monitoring system, “Streamflood and Waterflood Tracking System” which is designed to detect, identify and locate important abnormalities such as obstruction or leakage in the pipeline without human intervention [4]. Railway, bridge and tunnel monitoring [5] as well as bridge monitoring [6] are other applications that employ line topology. In this paper we refer to these types of networks as linear wireless sensor networks (LWSNs).

LWSNs differ from other WSN in terms of the way communication is carried out. The long chained transmission, increased network delays, single neighbor transmissions and the well-known “relay burden problem” are additional challenges posed by line topology. Most of the research mentioned above is based on solving these challenges at the routing layer. However, it is well known that the operation of the MAC protocol in WSN provides significant possibilities to effectively regulating important network performance parameters as throughput, energy efficiency, latency and network lifetime. That is the reason why in this paper we focus on exploiting the tools and functions at the MAC layer to provide higher energy efficiency, latency and PDR for LWSNs.

The rest of paper is organized as follows. Section 2 provides a short overview of some of the latest WSN MAC protocols and their relation to linear topology. Section 3 presents the proposed system model and protocol operation. Section 4 presents simulation scenarios and results. The last section concludes the paper.

2. Related Work

LWSN pose two major challenges: ensuring successful end-to-end delivery and providing a reasonable packet delivery timeframe. The main reason for these is that linear topology limits the number of neighbors and thus the possible transmission routes, so data delivery is more exposed to failure than in traditional WSNs. Besides critical node failures and energy exhaustion, failures can also occur due to increased number of retransmissions which results in higher packet collision rate and traffic congestion. There are several MAC protocols which focus on minimizing packet loss in LWSN. In [1] the authors propose a “long-chain” MAC protocol where the forwarding nodes book in advance and forward packets to reduce end-to-end delay in “long sensor networks” without sacrificing energy efficiency. In [4], the authors describe SWATS (Stream-flood and Water-flood Tracking System) a multi-dimensional linear sensor network. For communication and energy efficiency a MAC protocol with low duty cycle is designed that allows idle listening avoidance. In [7], the authors study the impact of the choice of MAC protocol (TDMA or CDMA) on the behavior of LWSNs in terms of lifetime and congestion avoidance. They suggest cooperative communications of sensor nodes sharing their physical resources particularly their antennas to create virtual multiple transmission paths. In [10], the authors present DiS-MAC which reaches the considerable channel utilization of 1/2, but requires every node to direct the radiation beam of its antenna.

The protocols mentioned above improve the performance of the network but require increased node complexity and lack in energy efficiency. The AREA-MAC (Asynchronous, Real-time, Energy-efficient and Adaptive MAC) is a very recent MAC protocol that addresses both time critical and energy-efficient WSN applications [11, 12]. The nodes in AREA-MAC use low power listening (LPL) and wake up very shortly to check the channel activity without actually receiving any data. They go back to sleep if the channel is idle, otherwise receive the data. Different from previous protocols like [13], [14], and [15], nodes in AREA-MAC use short and adaptive preambles with destination address and acknowledgement combination. It solves many of the problems which arise with long preambles, such as energy consumption, overhearing at non-target receivers, and excess latency at each hop [16]. Neighboring nodes wake up for a small period of time and check the destination address. The target node acknowledges the source node immediately, which causes the source node to stop sending further preambles and to start transmitting data packets. All the other non-target nodes go back to sleep immediately. This minimizes the possibility of a collision, idle listening and overhearing. Over-emitting with AREA-MAC is also improved with adaptive duty cycling. While sending a data packet, a node that still has more data to send indicates this to the receiving node by enabling the
“more-to-follow” bit of the data packet. By default AREA-MAC supports transmitting of only two consecutive data packets via an adaptive duty cycling process in order not to block other neighbors from accessing the channel. This is based on the assumption that nodes do not generate too much data and a node sends (or forwards) a data packet as soon as it generated (or received).

AREA-MAC is a very promising and efficient MAC layer protocol. However, its operation is based on transmissions to several first level and second level neighbors, which makes it unsuitable for linear topologies. Furthermore, AREA-MAC provides good throughput only for quite small to medium size networks. When the number of nodes is increased above 64 the throughput drastically drops. Thus, in our study, first we investigate the reasons for this throughput decrease. Then we propose a new protocol, LINE-MAC which is specifically targeted for linear topologies and prove that it outperforms AREA-MAC in those cases. The optimization parameters considered are energy consumption, delay and PDR.

3. Design of The Proposed MAC Protocol

3.1. System Model & Assumptions

We consider a one-dimensional WSN consisting of N nodes indexed by 0, 1, 2, …., (N-1). The node indexed by 0 is always the sink node and we assume that the sink node does not have any energy limitations, whereas other nodes have limited and non-replicable energy resources. All nodes except the sink node can sense, transmit and receive, functioning both as sources and forwarding nodes. All nodes are fixed and know their locations as related to their ID number. All nodes in the network are equally spaced and the density of the nodes is high enough, so that a node can directly communicate with two neighbors on each side. The communication range for the nodes is fixed. A node may connect to the sink if it is within range or by multi-hop communication through other nodes.

The topology of the sensor network examined in this paper is based on a multi-hop linear network (Fig. 1). Data packets generated from the source nodes are transmitted to neighboring nodes through a single-hop or multi-hop communication in order to reach the sink. Node j is called up 1-hop-neighbor of node k if its ID number is one less than that of node k. Similarly, a up 2-hop-neighbour for j, is the one whose ID number is two less than the ID j. Similar numbering rule holds for down 1-hop and 2-hop neighbors in the direction away from the sink.

3.2. Investigation of AREA-MAC for Linear Topologies

AREA-MAC works very well with 16 nodes for grid and random topologies. When the number of nodes is increased the PDR drops to %75 (grid 6x6 - Fig. 2). With 64 nodes random positioning of the sink brings noticeable improvement (Fig. 2 right). However, despite its eminent advantages AREA-MAC does not scale well - when the number of nodes increases, the PDR noticeably drops and shifting the sink randomly is only a partial solution.

The major reason for this throughput decrease is the collision of preACK packets, sent at the same time by nodes that have received a broadcast preamble packet (N0 routing scheme - Fig.3). AREA-MAC does not include a mechanism to eliminate the preACK collision. This collision probability can be minimized by increasing the number
of neighbors that receive the broadcasted preamble. However, when nodes are located in a linear fashion, preACK collisions lead to a vicious loop which drastically decreases the throughput and may even lead to system breakdown.

Fig. 3. Vicious circle arising from preACK collision in broadcast N0 scenario.

AREA-MAC uses an adaptive duty cycling which helps achieve an acceptable PDR and delay with minimum energy consumption. It supports the transmission of two consecutive data packets because in a grid topology nodes generally have more than one neighbor to forward data packets. However, in a linear topology nodes are forwarding data to the sink in a chain fashion and thus have one (or two if a second level neighbor is considered) neighbors. So, especially nodes closer to sink node often have more than two packets in the queue. This is also known as “burden relay” problem for linear topology.

In LWSNs, the data flow direction is always towards the sink except for broadcast transmission of preambles. Therefore, when a node A has data to send, it transmits a burst of preambles during the check interval. If the 1-hop-neighbor (“first forwarding node”) of A, A1 receives the preamble which is destined to A1, it sends back a preACK to A for acknowledging that it is ready to receive the data packet. If a 2-hop-neighbor (i.e. “second forwarding node”) of A, A2 wakes up while A1 is sending a preACK to A or is receiving data from A, it will go back to sleep immediately because there is no packet destined to A2. After receiving the full data packet, A1 has to forward it towards the sink and in turn starts sending preambles to its next neighbor towards the sink. Because A2 is in sleep mode, A1 has to wait until its next scheduled wake-up time. During that time period it keeps sending preambles, which causes unnecessary energy consumption as shown in Fig. 4. This will also causes increased delay for the packets waiting in the queue.

AREA-MAC is a very effective sensor network protocol but despite its adaptivity and flexibility it gives rise to some very specific problems when applied to LWSN. Inspired by the advantages of AREA-MAC we propose solution to these problems and define a MAC layer protocol tailored for operation with linear topologies.

3.3. Proposed Protocol Algorithm and Operation

The proposed LINE-MAC protocol brings the following three major changes to the operation of AREA-MAC:

First: When neighboring nodes receive broadcasted preambles, they immediately send a preACK packet. Each node activates a timer and if it does not receive any data, instead of entering constant short sleep we propose it enters sleep mode for a random period of time. Thus preACK collision is avoided because one of the two nodes will wake up earlier and receive the next preamble packet first. (Fig.5) The second node, on wake up, finds the channel busy and enters long sleep.

Second: Nodes closer to sink end up forwarding more packets - “relay burden problem” - which causes higher energy consumption and longer delays. Transmitting only two consecutive data packets is not enough for the nodes closer to sink because the rest of the packets in the queue have to wait until the next wake up time. For LWSN this leads to extremely long delays. To reduce the delay we suggest adjusting the number of consecutive packets to be sent according to the traffic conditions by using the parameter “packetLimit” which can be dynamically changed.

Third: Overheard packets constitute a considerable portion of energy waste in WSNs. For AREA-MAC an overheard packet can be a preamble, an ACK or a data packet. If a node receives a preamble or a preACK, which is
not destined to it (overhearing) it immediately enters long sleep mode. However, in line topology, the information contained in the sender/receiver address portion of the preACK packet can be used by overhearing neighbors to determine whether they will be a next hop towards the sink. If an overhearing node is the next forwarding node for the current incoming data packets, it will only go to short sleep until the data transmission ends (Fig.6). When the data transmission of the previous node ends, it will wake up to receive the first preamble packet. Thus, overhearing preACK packets are used to reduce end-to-end delay and mitigate the transmission of unnecessary preambles.

Furthermore, each receiving node sends an acknowledgement to the sender node for each data packet it receives. As we want to adapt the schedule of the overhearing node as close as possible to the on-going neighboring data transmission process it is important that the overhearing node, which is a prospective forwarding node, knows how many data packets will be sent after the current preACK packet. This information does not require very strict synchronization but helps the node decide with good approximation how long the data transmissions will last. Without this information, it can wake up too early or too late. Therefore, similar to the 4-way handshaking, we suggest that each preACK packet indicates the number of remaining data packets. The value is determined according to the number of data packets waiting in the queue and the packetLimit. So, as seen in Fig. 7, neighboring nodes can adjust their wake-up schedule. This leads to more stable, adaptive and reliable communication in LWSN.

The algorithm of the whole transmission process using the proposed LINE-MAC protocol is sketched in Fig. 8. It improves the timeliness and energy efficiency by using overheard ACK packets and by adding information about the number of consecutive data packets to be sent into the preamble packets. Especially for the nodes closer to the sink, the number of consecutive data packets is quite high. Additionally, the suggested randomized back-off for preACK packets helps prevent preACK collisions for broadcast-style communication of preamble packets.
4. Performance Evaluation

The proposed protocol is implemented on Castalia. Table I shows the key parameters we used in our simulations. We evaluate three major parameters related to network performance, energy consumption and delay. First we consider PDR using a data generation interval of 75 sec. for grid deployment. Each node generates approximately 25-30 packets. Fig. 9 (a) shows the PDR of AREA-MAC, which due to the increased number of forwarded packets, drops drastically for network size above 64. Fig. 9 (b) shows the PDR comparison between AREA-MAC and our proposed protocol LINE-MAC. Nodes are equally spaced and deployed in a linear fashion. N0 denotes
unrestricted broadcast, N1 refers to the case when packets are sent/forwarded only to 1-hop-neighbours, N1&N2 – to 1-hop and 2-hop-neighbours. The PDR for the proposed LINE-MAC remains above %95, while for all the other cases it linearly drops with the increase in the number of nodes. The number of packets to be sent consecutively is selected adaptively according to the traffic of the network which turns to be a decisive parameter in linear topologies.

Second, we evaluate the energy efficiency of the proposed protocol. Fig. 10 shows the average energy consumption for each node. For AREA-MAC the energy consumption increases for nodes closer to the sink, which is due to the “relay burden problem. With LINE-MAC, each node consumes nearly the same amount of energy regardless of its proximity to the sink. Taking advantage of overhead preACK packets makes our protocol more efficient in terms of energy consumption.

The third important parameter we evaluate is the end-to-end delay of a successful packet transmission. If a packet is received successfully but arrives with an unacceptable delay it might be useless. Fig. 11 shows the histograms of the end-to-end delay distribution for both AREA-MAC and LINE-MAC where each bucket corresponds to 300ms.

In LINE-MAC we adaptively increase the number of consecutive data packets according to the traffic conditions which greatly reduces the overall delay. Also, overhead preACK packets allow the node to wake-up in accordance with the transmission of the previous neighbor. Finally, the preamble carries information about the number of data packets to be sent which is broadcasted with the preACK packet. This helps overcome the early sleeping problem. Together the result is reduced delay and overall better performance of the proposed protocol for linear topologies.
5. Conclusion

In this paper we investigate methods for reducing the energy consumption and delivery latency for linear WSN. We propose and evaluate by simulation a new MAC protocol, called LINE-MAC, which is especially suitable for time-sensitive WSN applications requiring linear topology. We compare its performance with AREA-MAC using three major performance metrics: packet delivery ratio, average end-to-end delay and energy consumption. The results show that our proposed protocol performs much better than AREA-MAC under linear topology. In the future, we plan to implement our protocol on real nodes and compare results with simulation.

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