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Improved time synchronization in ML-MAC for WSN using relay nodes

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ABSTRACT

Time synchronization among nodes is an essential requirement in many wireless sensor network (WSN) applications. In unsynchronized network the local time in the subnet varies due to clock drift resulting in skew in the network that causes more energy consumption, packet loss and message delay. For synchronization of network we have deployed relay nodes (RNs) in a set of candidate locations in the network to satisfy specific requirements, such as connectivity, coverage.

We validate the effectiveness of our relay nodes placement strategy through numerical results to show that the RNs placed by our algorithms harvest more energy on average than those placed by the algorithms unaware of energy harvesting. Simulation results show that improved time synchronized multi-layer MAC (ML-MAC) using relay nodes outperforms the existing unsynchronized as well as ML-MAC scheme for network lifetime, packets dropped, reduced message delay and improving the synchronization accuracy at individual nodes.

1. Introduction

Wireless sensor networks are widely used in cosmic ray protection [1], volcano monitoring [2], seismic exploration [3] and other fields, where plenty of sensors are deployed in a vast geographical area. Due to cabling complexity, wired systems are expensive and require great effort for deployment and maintenance [4]. In many of WSN applications it is essential that nodes act in a coordinated and synchronized fashion necessitating global synchronization [5].

Sensing nodes in wireless sensor networks are set up with an inexpensive hardware clock that produces drift due to their low-end quartz crystals. Since this drift can vary with each sensing node, the hardware clocks of the nodes may not always remain synchronized. Lack of synchronization will lead to inaccurate and inefficient operation of many applications and protocols in WSNs [6,7]. Hence we need improved time synchronized protocol to minimize their synchronization error i.e. clock skew.

In real applications unintended events such as battery depletion and environmental impairment may cause these wireless devices to fail, divide the network into different zones and disrupt normal network functions. Therefore, fault tolerance becomes a crucial factor for successful deployment of wireless sensor networks. One way to acquire fault tolerance in wireless sensor networks is to deploy a small number of additional relay nodes between every pair of functioning devices (including sensor devices, coordinators, and other wireless devices) so that the network can survive failure of fewer nodes. This problem is known as relay node placement [8]. To apply time synchronization to ML-MAC [9] relay nodes, four practical aspects should be taken into account: minimizing energy consumption, reducing packets dropped, minimize delay and improving accuracy of synchronization.

As we will discuss in Section 2, some progress has been made in recent years. However, accurate time synchronization for relay node ML-MAC is still a challenging task.

In this paper, we propose an improved time synchronized relay node based ML-MAC protocol for WSN. The rest of the paper is structured as follows. After discussing related work covering the above four mentioned aspects in the next section, certain parameters are described, and then algorithm is elaborated in Section 3. Section 4 presents the simulation setup followed by simulation results and its analysis. Finally Section 5 concludes the paper.

2. Related work

Manish Kumar Jha et al. [9] proposed a multi-layer MAC (ML-MAC) protocol with 100 nodes in 200 s using ns2 simulator and MATLAB. A multi-layer MAC (ML-MAC) protocol is a technique to reduce node power consumption. Multi-layer MAC divides nodes into several groups called layers. All the nodes in the network except PAN coordinator are randomly assigned to these layers in such a way that whole geographic region of interest is in range of nodes of each layer. It is a distributed contention-based or

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random access MAC protocol where nodes discover their neighbors based on their radio signal level. Sensor nodes in ML-MAC have a very short listening time which reduces the energy required to communicate with other nodes. Also, the number of collisions in cases where two or more nodes try to send data or packets at the same time is minimized in ML-MAC. This saves the energy wasted in sending the corrupted packets again. Simulation results show much better performance of the energy consumption compared with the existing MAC protocols like S-MAC or IEEE 802.15.4.

Ranjana Thalore et al. [10] proposed a multi-layer MAC (ML-MAC) protocol with dense population with 1000 nodes in 1500 s which is a technique to increase network lifetime for IEEE 802.15.4 i.e. low rate wireless personal area networks (LR-WPANs). The simulation was done using QualNet version 5.2 software. The network lifetime improved by 47.38% compared to IEEE 802.15.4. ML-MAC concept is a promising protocol-design that may be utilized for significant enhancement of WSN lifetime. While simulation of the ML-MAC, collisions are observed probably due to synchronization drift between nodes.

2.1. Minimize energy consumption

Improved synchronization using relay nodes can also be used for power saving scheduling scheme to increase network lifetime by arranging nodes as in ML-MAC [9]. Sensor nodes are very far from their base stations so relay nodes will pass information to PAN Coordinator. Because sensor nodes are battery powered and it is also impossible to replace or recharge batteries so ultimately we have to minimize our energy consumption.

2.2. Reducing the packets dropped

In WSNs whenever data is transferred from one node to another, there may be packet loss which can be caused by congestion due to heavy traffic, collisions etc. ML-MAC [9] protocol reduces collisions as a reason for packet drop assuming perfect time-synchronization between nodes. However, ideal synchronization conditions do not exist in practical implementations.

2.3. Minimize delay

In ML-MAC [9], each node wakes up independently of neighboring nodes in order to save energy. However, due to the independence of the wake-up processes, additional delays are subjected on each node along the path to the sink because each node needs to wait for its next-hop node to wake up before it can transmit the packet [11]. This delay could be unacceptable for delay-sensitive applications, such as smoke detection or a catastrophic event such as tsunami alarm, which necessitates the event reporting delay to be small.

2.4. Improving the accuracy of synchronization

Time synchronization is an important aspect in wireless sensor network. Mostly time synchronization protocols aims at reducing the clock skew [12] between randomly deployed sensor nodes regardless of the distance between them. This necessitates work on improved time synchronization in ML-MAC using relay nodes.

Medium access control (MAC) is another category of approaches that may have a great impact on the performance of WSNs [13]. Very limited resources, dense deployment, dispersed applications and volatile communication links of WSNs need unique medium access techniques.

Synchronous MAC protocols guarantees that the receiver is ready to receive when a sender wakes up and has a packet to send, and hence it improves the communication efficiency but these

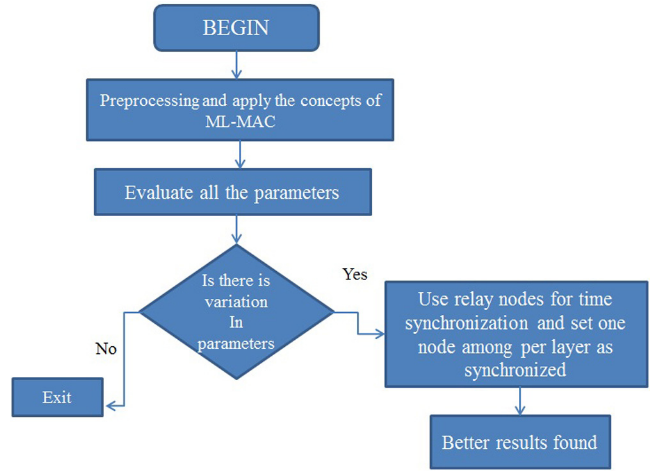

Fig. 1. Algorithm of improved ML-MAC using relay nodes.

WSNs are difficult to implement especially with limited energy source. Examples of synchronous MAC protocols include S-MAC [14] and T-MAC [15]. On the other hand, some of the MAC protocols are asynchronous. Asynchronous MAC protocols also put sensors to sleep periodically. However every node has an arbitrary offset to start its sleep wake-up cycles. In this case, the synchronization overhead is removed, but a sensor with a packet to send may have to delay the transmission until the receiver wakes up. Asynchronous MAC protocols include X-MAC [16] and Spec-MAC [17].

Mohammad Fathi et al. [18] proposed a synchronized energy-aware MAC protocol, i.e., RN-OSS (relay node operational state scheduling) in WSNs. They considered a two-tiered network with $N = 10$ RNs located at the same distance from the sink node.

3. Protocol design

3.1. Basic idea

Fig. 1 shows the algorithm for improved time synchronization in ML-MAC for WSN using relay nodes. We are deploying varying number of nodes while maintaining same node density. Initially we set the parameters w.r.t. ML-MAC and evaluate all the parameters. But due to drift some parameters get affected. We have applied the concept of relay nodes because long distance transmission by sensor nodes is not energy efficient since energy consumption is a super-linear function of the transmission distance. Our approach is to prolong the network lifetime while preserving network connectivity by deploying a small number of powerful relay nodes whose main task is to communicate with other sensor or relay nodes. Then we have compared the performance.

3.2. Caveat on the proposed protocol

Let G_1, G_2, G_n be groups with $S_1, S_2, \ldots, S_m$ number of nodes respectively in those groups. When we are considering the ML-MAC then parameter variation will take place as shown in Table 1. τ_1, τ_2, τ_3 are device starting and stopping time. Sensor nodes are

Table 1
Parameters variation in ML-MAC.

	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9
G_1	τ_1	τ_1	τ_1	–	–	–	–	–	–
G_2	–	–	–	τ_2	τ_2	τ_2	–	–	–
G_3	–	–	–	–	–	–	τ_3	τ_3	τ_3

Table 2
Parameters variation in case of drift.

	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9
G_1	τ_4	τ_5	τ_6	–	–	–	–	–	–
G_2	–	–	–	τ_7	τ_8	τ_9	–	–	–
G_3	–	–	–	–	–	–	τ_{10}	τ_{11}	τ_{12}

divided into different groups and each group is having the varying ON/OFF time as shown in Eq. (1):

$$\sum_{i}^{i+2} S_i = \tau_1 \quad \text{where } i = 1 \tag{1a}$$

$$\sum_{j}^{j+2} S_j = \tau_2 \quad \text{where } j = i + 3 \tag{1b}$$

$$\sum_{k}^{k+2} S_k = \tau_3 \quad \text{where } k = j + 3 \tag{1c}$$

τ_{sim} is the total simulation time of the network, T_1, T_2 and T_3 are the simulation time assigned to each layer defined by Eq. (2):

$$\underset{0}{\overset{T_1}{\tau_1}} + \underset{T_1+1}{\overset{T_2}{\tau_2}} + \underset{T_2+1}{\overset{T_3}{\tau_3}} = \tau_{\text{sim}} \tag{2}$$

When we observe in our network that there is some drift then parameter variation will take place as shown in Table 2. Drift is different for various nodes. For example 1st group 1st layer is having the different drift of 3, 4 and 5 s. $\Delta\tau_t$ is the small variation in time slots. Due to drift group and layer timings get affected by $\Delta\tau_t$ time. The active time for group i layer j (G_{ij}) is defined by Eq. (3):

$$\sum_{i,j=1}^{3} G_{ij} = \tau_1 \pm \Delta\tau_t \tag{3}$$

where $\Delta\tau_t = 3, 4, 5\ \forall\, i, j$.

We apply Set Cover Approximation Algorithm [19] to check the effects of clock drift in network. Given a set of areas for node placement, traffic-gen applications to be placed, $\Omega_R \geq 1$ (set of relay nodes) place relay nodes at the appropriate areas so that our objective that minimizes the cost and maximizes the N_L (network lifetime) as shown in Eqs. (4) and (5). We have a set U of η elements $e_1, e_2, \ldots, e_\eta$ and a set s of ω subsets $s_1, s_2, \ldots, s_\omega$ from U. A set cover is a collection of subsets from S satisfied that every elements in U belongs to one of the subsets. In our case we are also taking the 3 nodes from the 3 respective layers and one from the center i.e. PAN coordinator that's why we are taking the value 4.

$$\text{Number of relay nodes} = \sum \min \Omega_R \tag{4}$$

$$\text{obj} = \max \sum_{L=1}^{n} N_L \tag{5}$$

We verified the objective function by simulation. Now choose one node from Ω_{L1} (Layer 1), same as from Ω_{L2} (Layer 2) and Ω_{L3} (Layer 3), then set sensing relay nodes from different layers S_{R1}, S_{R2} and S_{R3} timings respectively as shown in Eq. (6):

$$s_{Rr} = \tau_l \quad \text{where } l, r = 1, 2, 3 \tag{6}$$

Our concept behind the energy savings of wireless communication between any two points is that there is a coordination between transmitter and receiver i.e. relay nodes are listening during the transmission otherwise packets are lost and information need to be resent.

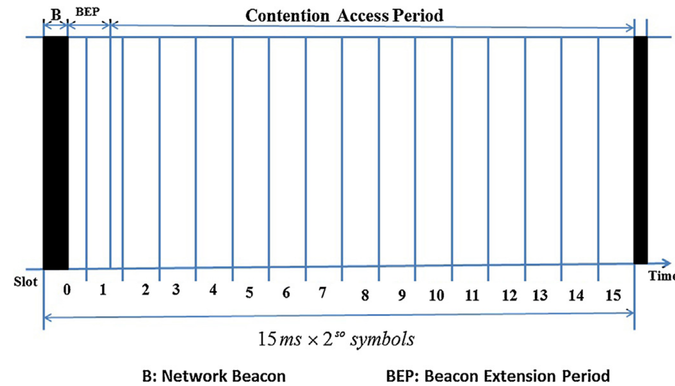

Fig. 2. Super-frame structure.

A common clock could assist the necessary coordination by assuring that the intermediate relay nodes "wake-up" or "go to sleep" at the correct time intervals in ways that the information is relayed and energy savings are realized. The IEEE 802.15.4 MAC standard defines an optional super frame structure [20]. It is initiated by the PAN coordinator. Its format is decided by the coordinator. As Fig. 2 shows, the super frame is bounded by network beacons and divided it into 16 equally sized slots. The first time slot of each super frame is used to transmit the beacon. The main purpose of the beacon is to synchronize the attached devices, identify the PAN, and describe the super-frame structure.

Our goal for improved time synchronization algorithm is based on local communication between neighboring nodes and time synchronicity emerges as a global network attribute even when sensing nodes that are not in range (but are connected through the network).

4. Simulation analysis

The main objective of this simulation is to evaluate performance of improved time synchronized relay node ML-MAC protocol in network to minimize energy consumption. The simulations have been done using QualNet version 6.1 [21] simulator that facilitates scalable simulations of a WSN.

In ML-MAC nodes are divided into different layers and each layer is having different ON/OFF time. But in unsynchronized ML-MAC we are assigning time frame i.e. 3–503 s for group 1 layer 1, then 504–1004 s for group 2 layer 1, and 1005–1505 s for group 3 layer 1. In this way we are repeating the timings for each layer in these intervals. But one layer is active at a time while rest are in sleep mode.

The simulations with time unsynchronized as well as time synchronized ML-MAC is done with large node density in network which is desirable in many applications. In all parts of simulations, we refer to a network scenario with 100, 900, 1600 and 2500 nodes deployed randomly by keeping the same node density. The nodes in the network are divided into 1, 9, 16 and 25 wireless sub-networks (subnets) with 100 nodes in each subnet.

4.1. Simulation set

QualNet supports only 254 nodes in a subnet so nodes are divided in various subnets in order to have a network with large number of nodes uniformly distributed in the area of interest. Each subnet has one FFD (Full Function Device) as PAN coordinator placed at center, rest are RFDs (Reduced Function Device) which can either communicate to PAN coordinator or other FFD device (if any). TRAF-GEN application is used for generation of data packets.

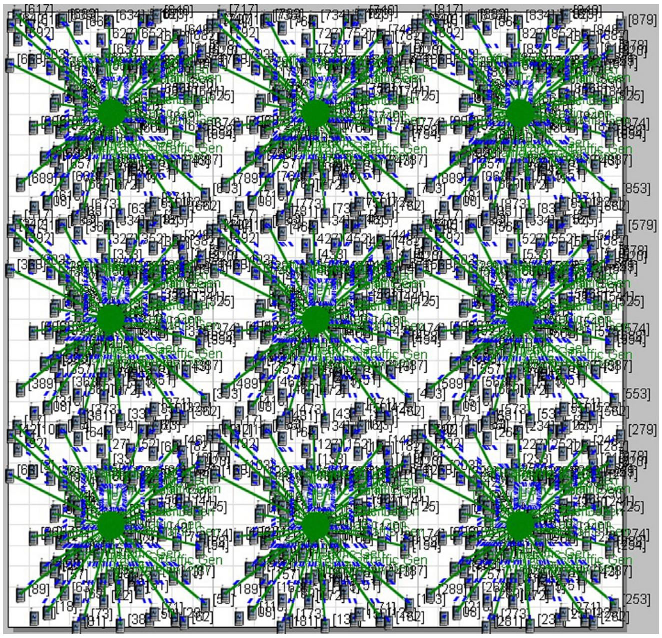

Fig. 3. Simulation scenario in QualNet 6.1.

Table 3
Simulation parameters.

Parameter	Value	Parameter	Value
Terrain	100 m × 100 m (100 nodes) 300 m × 300 m (900 nodes) 400 m × 400 m (1600 nodes) 500 m × 500 m (2500 nodes)	Transmission range	10 m
Simulation time	1505 s	Energy model	Generic
Number of nodes	100, 900, 1600, 2500	Transmit circuitry power consumption	24.75 mW
Layer drift timings	3–503, 504–1004, 1005–1505	Receive circuitry power consumption	13.5 mW
Message rate	1 packet/s	Idle circuitry power consumption	13.5 mW
Message size	38 bytes	Sleep circuitry power consumption	0.005 mW

Each node in the network generates a fixed number of data packets (or messages) per message inter-arrival time. In many data monitoring applications, data (temperature, pressure, vibration, etc.) is sensed and reported periodically to the PAN coordinators (sink) through relay nodes or coordinators. Fig. 3 shows scenario in QualNet 6.1 and Table 3 shows list of simulation parameters considered during simulations.

In this section further we represent simulation results of various performance metrics in QualNet 6.1 for evaluation of time unsynchronized as well as time synchronized based ML-MAC protocol.

Fig. 4 shows the network lifetime (in Days) with ML-MAC, drift, and relay solution. The calculation of network lifetime is done using the value of residual battery capacity obtained from simulations after running the scenario to a battery capacity of 500 mA h to the respective simulation time. The results show that with relay solution we observe more network lifetime as compared to other scenarios even though battery capacity of relay nodes are excluded from evaluation of network lifetime.

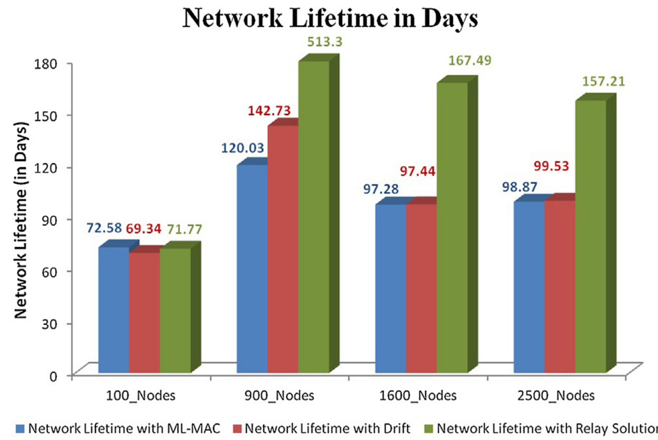

Fig. 4. Network lifetime.

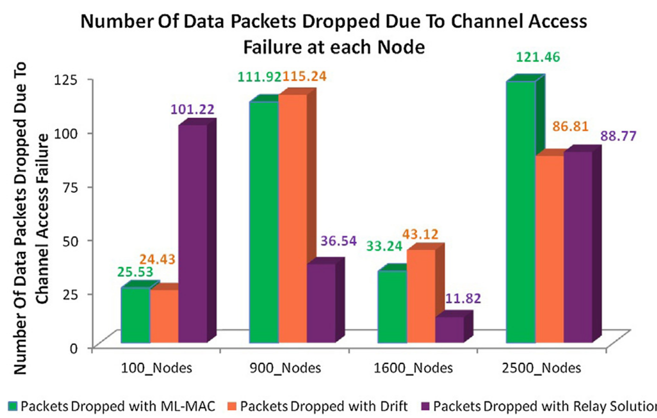

Fig. 5. Number of data packets dropped due to channel access failure.

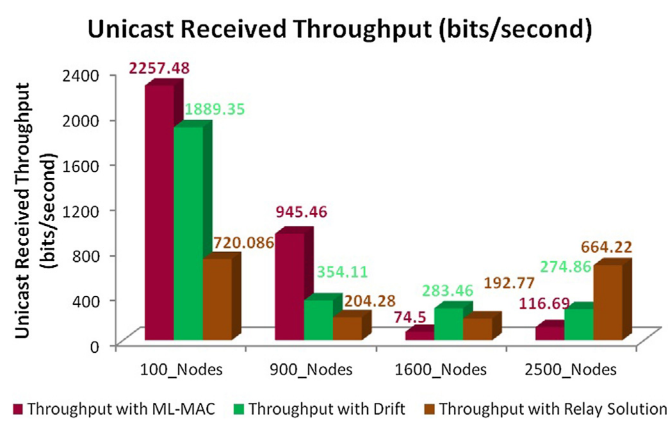

Fig. 6. Unicast received throughput.

Fig. 5 shows the number of data packets dropped due to channel access failure. It is the number of packets dropped when the channel is proceeding to failure point. The results show that as our network get synchronized with relay nodes and along with the increasing number of nodes, reduction in packets dropped is observed.

Fig. 6 shows the unicast received throughput at each PAN coordinator. Throughput of a network is judged by average rate of successful message delivery over a communication channel. With relay nodes througput is not so less as compared to with ML-MAC and drift. Due to the variation in trasnmission range and increased number of hops the throughput may have got affected in case of relay nodes.

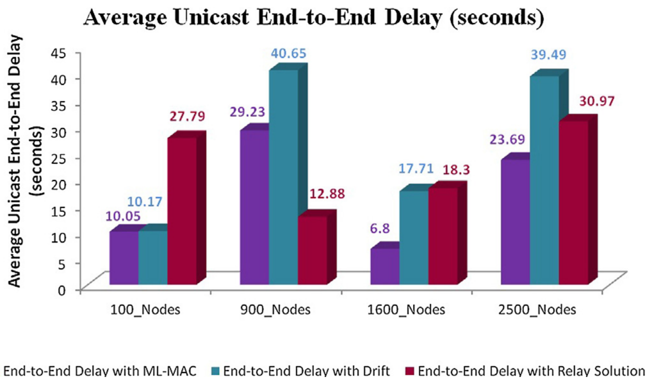

Fig. 7. Average unicast end-to-end delay.

Fig. 7 shows the average unicast end-to-end delay at each PAN coordinator. The average end-to-end delay of a packet depends on delays at each hop comprising of queuing, channel access and transmission delays, the number of hops, route discovery latency. Results show that with synchronization delay decreases except at one point.

Analyzing all simulations results, network with relay nodes performs better with respect to increased network lifetime, improves the accuracy of synchronization, reduced packets dropped and delay.

5. Conclusions

In this paper we propose improved time synchronized energy efficient WSN using relay nodes, and then using the proposed protocol analyze various parameters like network lifetime i.e. energy consumption, packets dropped, throughput and delay with respect to ML-MAC. Our improved time synchronized relay node together with the performance analysis can well estimate the network lifetime as compared to other networks. Packets dropped also get reduced with improved time synchronized relay nodes network. Hence, it can be used not only for ML-MAC but can be tested for other existing or new MAC protocols. Simulation results validate our protocol under various network conditions and application requirements.

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