Impact of Time Slot Adjustment on a Multi-hop and Multi-channel Solution for Dynamic WSN Topologies

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Abstract: Ensure data delivery and extend the network lifetime are challenges that must be addressed when it comes to deploy a WSN in outdoor harsh environment where it operates over unstable links. The instability of radio links may induce a connectivity that is time-varying even when nodes are not moving. For these dynamic topologies, resources allocated to the nodes must be adjusted to the local traffic conditions. Amongst the proposed solutions, schedule-based protocols achieve an energy efficiency as they allow nodes to sleep during their inactive periods. As the channel conditions are time-varying, and paths followed by the packets are changing, inducing an instability in the distribution of the traffic load over the network. This paper is dealing with the mastering of the size of the reception time slot of the next hop node. Our solution dynamically takes in consideration the local traffic load to resize the time slots. This adaptive solution is compared with the fixed-length window scheme, it obviously improves the performance of the WSN in terms of cycle length, idle listening and collision reduction, and achieves suitable data delivery ratio.

1 INTRODUCTION

Wireless sensor network (WSN) stands as a powerful solution for wide area environmental monitoring. Sensor nodes equipped with data sensing device autonomously organize themselves to deliver sampled data to a particular node, the sink. As sensor nodes have limited battery power, the transmission range and the data rate have to be optimized according to the deployment conditions. These characteristics impose many challenges, especially for WSNs with fluctuating conditions of signal propagation. In this paper, we focus on convergecast traffic in WSNs having dynamic topologies. It is the case for WSNs deployed in harsh outdoor environment such as over freshwater areas (lakes for example). For the WSNs we are dealing with, the positions of nodes remain fairly stable over time, but radio links may be volatile.

Our solution consists in a scheduling-based MAC protocol where each node is assigned both time slots and radio frequency for reception. In this protocol, each node selects periodically its next-hop node among the neighbors according to the radio links characteristics in order to route the traffic. Since we deal with dynamic topologies, neighborhood of each node is periodically updated. Instability of links has an impact on the amount of traffic a particular node has to route. In the paper we propose and evaluate a mechanism to adjust the size of the receiving time slots. We show that, coupled with a multi-channel solution, it has a great impact on the time needed for gathering data over such a WSN.

2 RELATED WORK

In this section, we investigate meanly the solutions that have been proposed for dynamic topologies on one hand and for TDMA-based MAC Protocols for WSNs on the other hand.

When wireless links are intermittent, routing of packets may become uncertain and/or induces large end-to-end delays. WSN nodes are usually densely deployed in order to ensure the global connectivity and the coverage of the monitored area. Connectivity may be lost when some radio links on the path of packets are temporarily disrupted. This variability of

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the topology has a negative impact on the multi-hop forwarding process and induces unpredictable end-to-end delays. If this variability of topology happens when some nodes are moving, the concept of data mule can be used (Tseng et al., 2013). The goal of the studies in (Nour Brinis, 2012) is to determine the optimal number of data mules required to extend the covered network lifetime while meeting a given packet delivery delay deadline.

In our contribution the hypothesis of having several moving nodes is not necessary. Received or locally produced packets are stored in the node buffer used with FIFO policy. When the radio link of the next-hop is temporary broken, packets have to wait for better propagation conditions or another next-hop has to be chosen. The amount of traffic reaching at a given node is depending on (i) the offered load submitted by the source nodes, (ii) the instantaneous shape of the WSN topology. Using a static capacity of packet reception for nodes may lead to congestion areas and to FIFO overflow. This particular point leads us to specify a dynamic capacity of reception. Our objective is to adapt the size of the time slot dedicated to reception of frames, to the local instantaneous load. The scheduling-based MAC protocol we chose has to be fitted in order to take into account the impact of the dynamicity of the WSN topology. The use of a unique or several frequencies has no significant impact on this challenge. The question we are dealing with here is: how to right-size the length of the reception period without adversely impacting the traffic flow through the network.

The problem of Time Slot Scheduling has been deeply investigated for ad-Hoc Wireless Network. In the WSN domain when TDMA is used, the *convergecast* strategy requires both adequate coordination among the nodes and proper sizing of time slots to avoid high packet collision rates or frequent FIFO overflows near the sink node. Slot assignment and slot adjustment are the two approaches usually explored (Pal and Chatterjee, 2014).

In (Cui et al., 2004), a variable length Time Division Multiple Access scheme is proposed for improving total energy consumption. In (Cui et al., 2005), delay and energy are taken into account to propose an algorithm for variable length TDMA schedules. Most of the time, the available contributions are driven by energy and delay considerations, for WSN topologies supposed to be rather stable. Slot assignment becomes very complex when the topology is really time-varying. The scheme allocation as presented in (Ergen and Varaiya, 2010) seems to be proposed for topologies having bidirectional and stable radio links. These hypotheses are usually retained for slot assignment using a coloring process (Mahfoudh et al., 2010). Radio link quality measurements we done for transmission over freshwater (Bizagwira et al., 2014) justify another approach.

3 PROTOCOL DESCRIPTION AND PROBLEM FORMULATION

The protocol stack we propose has to be energetically efficient for WSNs having an unstable topology. This objective leads us (i) to retain a cross layering approach for Network layer and MAC Layer, (ii) and to use periodical sleeping periods to spare energy. The physical layer is inspired from the spectrum allocation and channel specifications proposed in the 433 MHz frequency band by DASH7 Alliance (Tuset-Peiró et al., 2014; Mode, 2013). This choice allows us to have 8 non-overlapping channels for transmission.

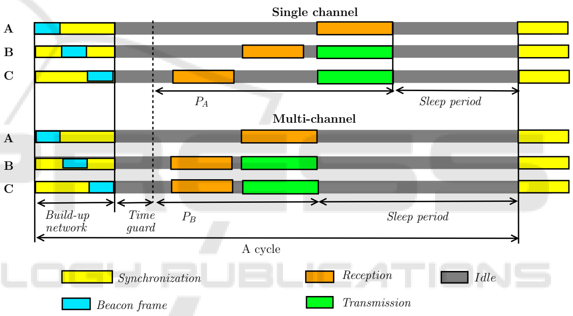


Figure 1: Mapping of time slot allocation within a cycle for both single and multiple channel use.

3.1 Global Segmentation of Time

The operating cycle of the low layers of our protocol stack is divided into four periods as shown in Figure 1:

- Synchronization and Build up Period : For multi-hop deterministic synchronization of nodes using beacons.
- Time guard period: Time guard allowing our solution to be adaptive.
- Data gathering period: For multi-hop forwarding of data frames to the sink.
- Sleeping Period: All the nodes sleep periodically for energy saving.

Synchronization, neighborhood discovery and routing strategy used to join the sink are done at the beginning of each cycle using a beacon cascading. Synchronization is initiated by the sink that broadcasts a beacon including the reference clock, the length of current cycle and other information related to the reception schedule.

3.2 Main Characteristics of MAC Protocol

The data gathering period is governed by a TDMA schedule-based MAC protocol. It is a synchronous and receiver-based protocol that applies the scheduling decided from information obtained during the last synchronization and build-up period. The neighborhood has to be discovered again at the beginning of each cycle. The results (as the quality of the radio link) is used to choose the best next-hop to reach the sink. The 8 frequency channels defined by DASH7 provides a multi-channel capability for data transmission.

The choice of channel scheduling is done during the beacon cascading. When a node receives a beacon, it reads the sender schedule and updates its neighborhood knowledge table. Then, it selects its next hop for data transmission before sending, in turn, its own beacon. The neighborhood knowledge table allows each node to choose a reception frequency and time slot, taking into account the local use of the radio spectrum. As shown in Figure 1, the beginning of the receiving Time Slot is deliberately chosen to accelerate the *convergecast* traffic. The quality of the path towards the sink is the main factor impacting the choice of the next hop.

4 ADJUSTMENT OF THE TIME SLOT DURATION FOR DYNAMIC TOPOLOGIES

For WSNs using *convergecast*, the nodes near the sink have more traffic to store and forward than other nodes in the network, and nodes located at the periphery of such networks have no forwarding activity. Moreover, when a WSN operates using unstable links, the traffic load of a given node is also time-varying. In this section, we state the problem of dynamic resizing of reception time slots of nodes in accordance with the traffic of their potential child-nodes. The global objective is to adjust dynamically the time slot size of each node, to the instantaneous local load. As this length is adapted to the traffic, (i) the wasted energy due to the idle listening will be reduced, (ii) the risk of FIFO overflow will be minimized and (iii) the length of the sleeping period can be maximized.

4.1 Global Presentation of the Master Process of the Time Slot Duration

Dynamic topologies using unreliable radio links induce a kind of packet routing instability and a variable risk of packet retransmission. This drawback is mitigated by the part played by the FIFO of the nodes. In a given area the cumulative number of packets stored in the local FIFOs is a local load indicator. This is the parameter we retained as the main variable to master the size of the time slot of nodes. In the closed loop control system that we propose for the adjustment of the time slot duration of the node i, our objective is to empty the FIFOs of its child nodes for each cycle.

4.2 Specification of the Algorithm Used for Resizing the Reception Period Length

Let us consider node N_i a generic node of our WSN. The Process Variable (PV) is the number of packets remaining in the FIFO of the neighboring nodes that have chosen N_i as the next hop. The Set Point (SP) is corresponding to the state we want to reach for the content of these FIFOs at the end of the receiving time slot of N_i. SP stands for the number of packets having to wait for another cycle to be transmitted.

$$e(t) = PV - SP \tag{1}$$

represents the error we want to minimize by a mastering process. S_{max} is used to reduce the impact of proportional component of the mastering process when the local congestion is growing too fast.

In the Algorithm 1, $SP = 1$ packet. PV is used to accumulate the remaining packets in the FIFOs of nodes having N_i as their next-hop. This accumulation is bounded by the threshold S_{max}. Let Trx_i be the length of current reception period of N_i. It is resized according to: $Trx_0 \longleftarrow Trx_0 + K_p * e(t)$. 5 and 5 packets are empirically chosen, respectively for K_p and S_{max}. The value of Trx_i is constraint within the interval $[Trx_{iMin}\ Trx_{iMax}]$: interval bounded by the initial value for the time slot, and a maximum value allowing us to estimate the length of PA or PB of figure 1. Let ID_{sender} be the address of the node having chosen N_i as next hop, $N_{pkt(x)}$, and $L_{senders}$ be respectively the number of packets remaining in the FIFO of node x and the list of packet sender nodes for the current cycle.

```
begin
    while reception period not expired do
        if data packet received then
            records ID_sender and N_pkt;
            if ID_sender already exist in L_senders
              then
                update the N_pkt(ID_sender) for
                  ID_sender node;
            else
                append (ID_sender, N_pkt) to
                  L_senders;
            end
        end
    end
    PV ⟵ 0
    foreach neighbor node j in L_senders do
        PV ⟵ PV + N_j
    end
    if PV > S_max then
        PV ⟵ S_max
    end
    e(t) ⟵ PV − 1
    Trx_i ⟵ Trx_i + K_p * e(t)
end
```

Algorithm 1: The algorithm that is used for resizing the reception period length.

5 RESULTS

We use NS-3 to simulate our proposal scheme and incorporate protocol in several scenarios. In this section, we discuss our WSN protocol stack implementation and give the detail settings. In practice, this WSN has been implemented on a TI CC430 based component to be deployed on the surface of water, i.e., over the lac for monitoring the aquatic environment. All the MAC layer and routing algorithms presented above have been implemented in our NS-3 model. We chose to use the Log-Distance Shadowing model experimental measurement (Bizagwira et al., 2014) as our propagation model. The choice of parameter values of the model is justified by (Tuset-Peiró et al., 2014; Tuset et al., 2013).

In this section, we evaluate the performance of the proposed dynamic reception window resizing scheme and its consequences on the network throughput as well as energy efficiency of the sensor nodes. We conduct two different simulation scenarios and compare the performance based on three metrics: packet delivery ratio, average energy consumption, and average latency. In the first scenario, we set a fixed interval for reception period - as is done in SMAC (*Sensor MAC*) protocol (Chang et al., 2013), for all nodes in the network. Each node schedules its transmission time according to the chosen next hop, and fixes the duration of the reception period. In the second scenario, we apply our dynamic resizing scheme for both small and large size reception period. Table 1 shows the parameters used in our simulation. The network topology consists of 26 nodes, which are spread randomly through the network field of 300 m x 300 m as shown in figure 2. Each node generates 1 data packet per cycle except for the sink node (green colored) that collects the traffic. The cycle duration is 4 seconds.

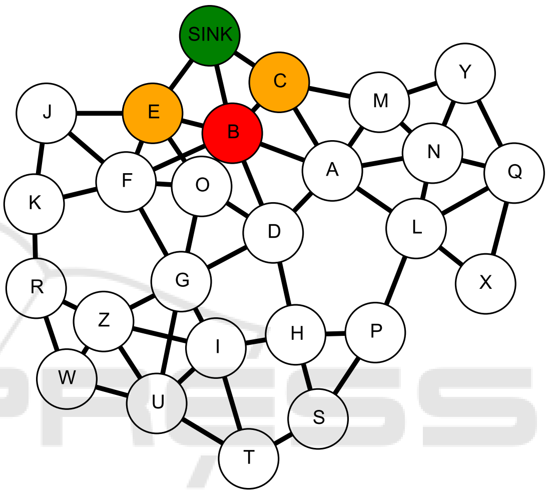


Figure 2: Network topology.

Table 1: Simulation parameters.

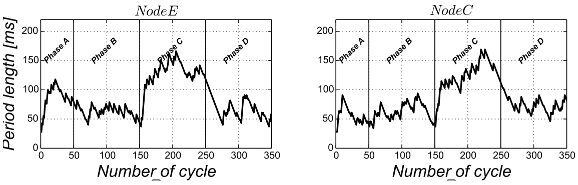
Parameters	*Value*
Prop. model	Log-Distance Shadowing
Number of nodes	26
Topology	Random
Size	300 m x 300 m
Channel	Single, multiple (8 non-overlapping frequencies)
Cycle duration	4 seconds
Simulation duration	600 seconds
Buffer length	45 packets
Data rate	1 data packet per node and per cycle

5.1 Fixed-length Reception Period

As we explained before, the sink node triggers the network activity by sending a new beacon as the start signal of the beginning of a cycle. For this scenario, the sink includes in the beacon the fixed duration of reception period. The beacon cascading process broadcasts this value to all others nodes of the WSN.

5.2 Adaptive Length Reception Period

All the nodes are initialized with a same reception period length of 27 ms. The figure 3 is an example showing how the window size adjustment is carried out over time. Our test utopology is given in the figure 2.



(a) (b)

Figure 3: The adjustment over time of the reception periods for the sink neighbor nodes.

The test scenario consists in turning off node *B* during a given amount of time (between 150^{th} and 250^{th} cycles). We are looking its impact on the window size of nodes *C* and *E*.

5.3 Discussions

As introduced earlier, we analyze the performance of our MAC protocol scheme in terms of (i) *Packet delivery ratio* (PDR), and (ii) activity duration as defined in figure 1 (length of the cycle - sleeping period PD).

It is important to emphasize that - in order to compare both cases, fixed-length and adaptive reception periods, on the same basis, we set the length value for the first as the maximum allowed value for the second.

Packet Delivery Ratio. The ratio of packets that are successfully delivered to the sink compared to the number of packets that have been sent out by the source nodes.

The results for single channel and multi-channel are quite similar. For small values (35 and 70 ms), the window size is not sufficient to allow all traffic, especially around the sink where there is a bottleneck. This induces a large number of packets dropped due to lack of space in node FIFOs. Concerning the window size for our adaptive method, we also observe that for nodes closer to the sink, the max-size is quickly reached and the size of the reception period never diminishes.

For large window values, as it is illustrated in the figure 4, the major part of the traffic is delivered to the sink. A 100% delivery of packets is never reached because some nodes in the network periphery are too far apart to have a permanent connectivity. So the packet delivery rate for these nodes is relatively low. There are also always collisions in congestion areas and packets never reach the destination despite retransmissions.

On the other hand, the results are quite similar because (i) the mechanism for choosing the start dates of the reception period ensures that nearby nodes windows can be temporally disjointed, (ii) the CSMA/CA mechanism is sufficiently effective to transmit frames within the set time, (iii) the topology is sufficiently sparse to have only few collisions.

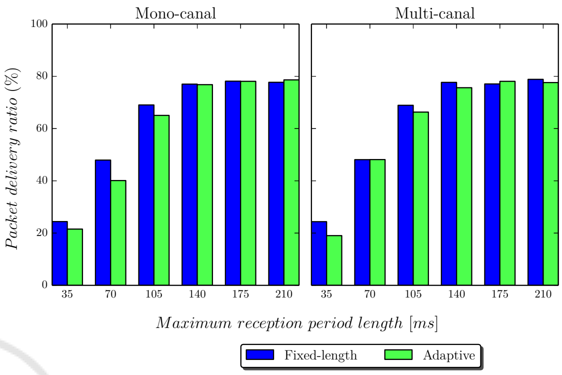


Figure 4: Packet delivery ratio.

We note also that the delivery rate in the case of a fixed window size can sometimes be slightly higher: this is due to the transient phase at the beginning of the simulation process. For the adaptive method, simulation process starts with nodes having a small reception period (27 ms) which does not allow flowing as much traffic as in the situation where the sizes of the windows are fixed and larger. This also explains the small difference that we have, for larger size windows.

The period adjustment process has a transient period during which the adaptive algorithm increments the length of the reception period before reaching the convenient value. During this time, nodes would accumulate packets, some are later dropped when a FIFO overflow.

Activity Duration. The activity duration is the time between the date of the wake up of the first node and the date of the switching to the sleeping mode of the last node of our topology. As it is illustrated in the figure 5, the average activity duration is lower with the adaptive mechanism than with the fixed-length scheme. In the first case, nodes spend around 50% of their time in sleeping mode. This is an important feature, as it would enable reducing the duty-cycle and makes the protocol more reactive to the topology changes. We note that the adaptive mechanism of the window size associated with multi-channel scheme is highly effective from an energy saving point of view.

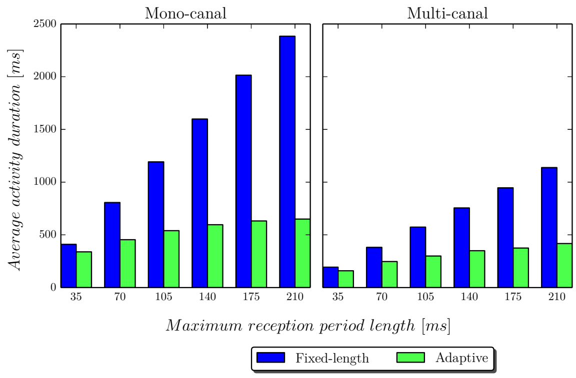


Figure 5: Average activity duration within working cycle.

Despite the transitional phase of setting up the network that induces FIFO overflows and slightly longer end-to-end delays, the data delivery ratios at the sink are equivalent and sometimes better.

6 CONCLUSION

In this paper, we proposed an adaptive approach based on a schedule-based MAC protocol, to efficiently utilize the resources of WSNs, especially deployed in harsh environment and having an unstable topology. Most of protocols proposed to deal with dynamic topologies argue on the efficiency of the schedule-based MAC protocol. They ensure an adequate delivery ratio while optimizing energy consumption is still a challenging task. Idle listening, overhearing and collision are the main sources of energy wasting in WSNs. The presented approach uses the traffic information to right-size the reception period and therefore to minimize the idle listening. Moreover, it employs multi-channel scheme to enable parallel transmission within the network and consequently, it reduces both collision and overhearing.

The results clearly show that it significantly improves the performance in terms of average activity duration while providing, at the same time, a good packet delivery ratio. It also reduces by a half the latency compared to traditional schemes. This meets the requirements for our target application where the nodes will communicate over intermittent radio links. The global solution we are dealing with is able to withstand the effect of unstable topologies in an interesting energy-saving manner.

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