Decentralized Time-Synchronized Channel Swapping for Wireless Sensor Networks

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POSTER ABSTRACT: DECENTRALIZED TIME-SYNCHRONIZED CHANNEL SWAPPING FOR WIRELESS SENSOR NETWORKS

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ABSTRACT

We are working on a new concept for decentralized medium access control (MAC) coordination, termed as *decentralized time-synchronized channel swapping* (DT-SCS). Under the proposed DT-SCS and its associated MAC-layer protocol, wireless nodes converge to synchronous beacon packet transmissions across all IEEE802.15.4 channels with balanced number of nodes in each channel. This is achieved by the proposed reactive listening mechanisms, based on pulse coupled oscillator techniques. Peer-to-peer *channel swapping* can then take place via swap requests and acknowledgments made by concurrent transmitters in neighboring channels. Comparisons of DT-SCS against time-synchronized channel hopping (TSCH) reveal that our proposal comprises an excellent candidate for completely decentralized MAC-layer coordination in WSNs by providing for quick convergence to steady state, high bandwidth utilization, high connectivity and robustness to interference and hidden nodes.

1. INTRODUCTION

The concept of channel hopping has gained acceptance as a good solution according to high-bandwidth, energy-efficient, wireless sensor networks (WSNs), with time synchronized channel hopping (TSCH) [1] now being part of the IEEE802.15.4e-2012 standard. Via the advertising mechanism of TSCH, each node reserves timeslots within the slotframe interval and within the 16 channels of IEEE802.15.4. As the slotframe interval repeats periodically, all nodes transmit and listen in different channels, thus avoiding concentrated interference. However, the TSCH slotframe has a rigid (pre-defined) structure and filling up the available slots follows a rather complex advertising request and acknowledgment (RQ/ACK) process on a coordination channel. This channel is prone to interference and occasional self-inflicted collisions when the nodes are set to advertise slot reservations very aggressively. Conversely, if slot advertising is not aggressive and nodes leave the network, their slots may remain unoccupied for long periods until another advertisement RQ/ACK process reassigns them to other nodes. This limits the bandwidth usage per channel.

Our work addresses these issues based on the concept of *pulse coupled oscillators* (PCOs) [2, 3]. Specifically, we propose a novel *decentralized time-synchronized channel swapping* (DT-SCS) framework, in which nodes randomly join a channel and achieve PCO-based coordination via the periodic transmission of *beacon* packets at the MAC layer. For channels with equal number of nodes, DT-SCS converges to synchronized beacon packet transmission at the MAC in a completely uncoordinated manner. Furthermore, it allows for arbitrary pairwise swaps between nodes in neighboring channels with limited effort and without disrupting the WSN operation. Finally, due to the inherent adaptation of PCO mechanisms to the effects of nodes joining and leaving the process, our proposal is robust to interference as well as node churn during WSN reconfiguration.

2. PCO-BASED SYNC/DESYNC FOR DT-SCS

Consider a WSN consisting of W nodes randomly distributed in C channels, with each node transmitting short *beacon* packets periodically every T seconds. In the proposed DT-SCS mechanism, the nodes in each channel perform PCO-based desynchronization (i.e., they are "DESYNC" nodes) and elect a single "SYNC" node to provide for cross-channel synchronization. Within each period, the SYNC node of each channel listens for the SYNC beacon message in the next channel (with cyclic behavior between channels 1 and 16) and adjusts the transmission time of its own beacon packet in its own channel using PCO-based synchronization [3]. SYNC nodes will also move to the next channel if they detect that less nodes are present there. In this way, the WSN can converge to the steady state with $W_c = \frac{W}{C}$ nodes per channel (when W is not divisible by C, the case the scheme balances to $W_c \in \left\{\left\lfloor\frac{W}{C}\right\rfloor, \left\lceil\frac{W}{C}\right\rceil\right\}$ nodes per channel). The beacon packet transmission flow between DT-SCS nodes is schematically illustrated in Fig. 2 for the case of $C = 3$ channels with $W_c = 4$ nodes per channel (i.e., $W = 12$).

Once the system reaches the steady state, SYNC or DESYNC nodes in adjacent channels can swap channels and timeslots in pairs using a simple RQ/ACK scheme within a short predefined guard time before and after the expected

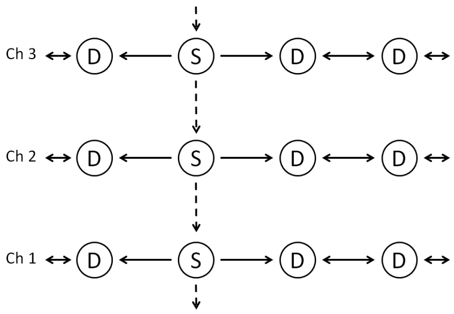

Fig. 1. DT-SCS within 3 channels, showing the intra-channel desynchronization (solid lines) and inter-channel synchronization (dotted lines) between Desync (D) and Sync (S) nodes, respectively. Arrows indicate the intended recipient of each beacon packet transmission.

beacon transmission. If nodes join or leave the network, all remaining nodes adjust their beacon packet timings spontaneously, in order to converge to a new steady state.

Once convergence to steady state is achieved, the only overhead in the proposed DT-SCS protocol stems from handling swap requests as well as beacon packet broadcasts. Both, however, are very short packets (less than ten bytes), which makes the overhead minimal compared to the payload packet transmission and reception.

The loss of beacon packets and timing errors due to interference cause node beacon times to *waver*, i.e., nodes send beacon messages at incorrect times. As such, all nodes receiving these messages are similarly affected. To combat this, we consider the notion of *coupling* between nodes, introduced by PCOs [3]: instead of a Desync node jumping directly to the midpoint of its beacon neighbors, the node *slides* towards the mid point with coupling factor α $(0 < \alpha < 1)$; similarly, a Sync node gradually adjusts its beaconing time by coupling factor β $(0 < \beta < 1)$ to align with the beacon of the Sync node in the next channel. Using PCOs with appropriate coupling factors ensures that any noise and instability in beacon timings is attenuated and does not propagate uncontrollably throughout all nodes and channels of DT-SCS.

3. INDICATIVE EXPERIMENTS WITH TELOSB MOTES

We implemented DT-SCS as an application in the Contiki 2.6 operating system running on TelosB motes. By utilizing the NullMAC and NullRDC netstack options of Contiki, we control all node interactions at the MAC layer via our application code. We consider a WSN deployment with 64 nodes in 16 channels, which leads to $W_c = 4$ nodes per channel in the steady state. We set the beacon period to $T = 228$ ms.

To measure the energy consumption of DT-SCS per node, we placed a TelosB sensor running DT-SCS in series with a high-tolerance 1-Ohm resistor and utilized a high-frequency oscilloscope to capture the current flow through the resistor in real time. Average results collected over 10 minutes of operation are reported. The average power consumption without transmitting or receiving payload was measured to be 13.57 mW. This is mainly due to maintaining beacon transmission and reception. Importantly, once convergence is achieved, the power overhead can be reduced by listening for beacon packets less frequently. For instance, setting the nodes to listen for beacons every eight periods brings the power consumption down to 1.58 mW. To set an illustrative comparison, the power consumption of a node operating TSCH under minimal payload (i.e., 128 bytes per four seconds) is 1.64 mW [4].

Under the aforementioned conditions, the convergence of the WSN using the proposed DT-SCS protocol was achieved within 3.73 s on average. On the other hand, TSCH convergences within 14.00 s on average (under the 6tisch simulator [4]). In addition, we measured the maximum achievable network throughput (i.e. transmission rate by all nodes in the WSN when they utilize their entire slot) to be 94.02 kbps. This is significantly higher than the corresponding maximum achievable network throughput of TSCH, which, under the default 6tisch setup [4], was measured to be 57.50 kbps.

4. CONCLUSION

The unique aspect of our approach is the concurrent use of pulsed coupled oscillators that perform synchronization and desynchronization in multiple channels. This allows for rapid convergence to the steady state in a completely decentralized manner, that is, without requiring a node or channel coordinator, or time synchronization via a global clock. Experimentation via simulations and a real implementation shows that, in comparison to TSCH, the proposed DT-SCS leads to a significant reduction of the convergence time and substantially higher network utilization.

5. REFERENCES

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