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A Review Of:

TDMH-MAC: Real-time and Multi-hop in the Same Wireless MAC

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Intro

Real-time systems depend not only on the logical result of the system's computations, but also the time at which the system produces the results. There are a number of commercial MAC protocols that have been developed for Wireless Sensor Networks(WSN), such as ZigBee, however, few have been targeted for real-time applications. This paper introduces the Time Deterministic Multi-Hop(TDMH)-MAC protocol, based on a mesh topology and designed for real-time communications over low data rate WSNs.

The Problem

The support of real-time communications over Wireless Sensor Networks has shown to be challenging; timeliness and reliability demands of real-time systems make common channel access schemes, such as CSMA/CA, unsuitable due to their non-deterministic properties and opportunities for packet collisions.

There are additional challenges that come with developing real-time communications on WSNs, such as the level of energy consumption of wireless nodes on the network. Generally, WSN protocols attempt to conserve nodes' energy consumption by having the node's 'sleep' in between activities. Asynchronous protocols do not schedule nodes' sleep/wake cycles, resulting in aloha-like protocols with high latency and poor determinism. Synchronous protocols group nodes in clusters with a common sleep/wake schedule to enhance throughput and reduce delay at the cluster level, but require increased management and oversight.

Existing wireless MAC protocols can be divided between those which guarantee tight latency bounds, but are constrained to star topologies; and protocols which support multi-hop networks, however rarely provide any type of latency bounds.

The TDMH-MAC Protocol

The TDMH-MAC protocol, a centralized connection-oriented TDMA(Time Division Multiple Access) mesh protocol, is a new wireless MAC protocol capable of supporting real-time multi-hop communications based on the 802.15.4 IEEE physical layer standard(Terraneo et al., 2018).

The network consists of a number of nodes, and a single Master node , ultimately in control of the network's schedule & synchronization. The role of master node is generally assigned to the network gateway which connects the network to the Internet, or to a programmable Logic Controller(PLC) in an industrial control plant. These already exist as a single point of failure for their respective networks, therefore the centralized protocol does not add an additional mode of failure. The master node keeps track of active streams, and current network topology, rescheduling the network's data transmissions whenever either of the two changes. The nodes on the network periodically send their knowledge of the network topology to the master node, which in turn continuously performs what is referred to as 'topology collection' to maintain a full graph of the network. This knowledge is used by the master node to globally schedule the network's real-time communication streams, resulting in collision-free data transmissions.

The parameters of all the remaining nodes that make up the network are identical to each other, with the exception of each node's unique ID. Only the nodes closest to the master node transmit directly to it. As mentioned previously, all nodes periodically send their knowledge of the network to the master node, therefore nodes forward topology information and stream requests from higher layers towards the master node.

The topology collection scheme used is named as one of the key innovations of the protocol. TDMH-MAC efficiently gathers information about the network topology during the uplink activity, and propagates it to the master node through a topology collection distributed algorithm which builds on the FLOPSYNC-2 synchronization scheme (Terraneo et al., 2014) and Glossy flooding scheme (Ferrari et al., 2011). TDMH-MAC extends FLOPSYNC-2 by including a 32 bit counter that is incremented at every synchronization period. Every node knows the synchronization period, therefore by multiplying it by the counter it is possible to know the global network time used to schedule all network activities. In Glossy, a flood initiator transmits a frame containing, at least, a hop counter which when received by a node is incremented, and then rebroadcast following a fixed small delay. TDMH-MAC uses Glossy to flood the FLOPSYNC-2 frames and takes advantage of the fact this provides each node with the number of hops that exist between it and the flood initiator, or, in this case, the master node.

Each node on the network periodically broadcasts it's topology information however only one node can broadcast during each control uplink slot. To avoid collisions, the node that transmits in each control uplink slot is selected using a 'Round 'Robin' scheme. The uplink slots are numbered, and the nodes in the network take turns; from node [(n-1):0]. When a node overhears a neighbour's control uplink frame, it updates its own local knowledge of the network topology, which will be forwarded when the node's next turn to broadcast occurs. To assure that at every retransmission the topology information is forwarded closer to the master node, TDMH-MAC exploits the hop information made available by Glossy, and nodes select a neighbour with a lower hop count than themselves to forward their topology information. This efficiently routes the data to the master node in the minimum number of transmissions. In an ideal network configuration, where lowest numbers have effectively been assigned to the nodes closest to the master node, this scheme is incredibly efficient at propagating the network topology information from the edges of the network in towards the master node.

TDMH-MAC is mainly targeted at real-time systems performing periodic tasks, one assumption here is that topology changes to the network are infrequent enough to allow detection and distribution of a new schedule with negligible downtown(not targeted at use cases requiring mobile nodes).

The TDMH-MAC protocol can be logically viewed as composed of 3 distinct activities; Control downlink, Control uplink, and Data transmission.

During control downlink the master node uses a constructive interference scheme(Glossy) to efficiently distribute network management information and updates to the schedule to the nodes on the network. Frames must be flooded across multiple hops, therefore control downlink activities consume more data slots to perform than uplink activities.

Control uplink slots are used to conduct on-line topology collection and initiate new streams between nodes. During these slots, each node in turn(Round Robin style) informs other nodes of its presence and provides knowledge of the current network topology forward towards the master node.

Data communication is accomplished through the use of logical point-to-point links between nodes, referred to as 'streams'. Streams can be opened dynamically between any two nodes in the network, have a dedicated bandwidth, and route application-level packets with bounded end-to-end latency. Individual application-level packets can be transmitted through multiple frames for redundancy, and, due to the network's mesh topology, may also be transmitted through multiple paths for increased reliability in the case of link or node failure.

During data transmission application data is transmitted in accordance with the global TDMA schedule, defined by the master node. Due to the operation of the MAC during a nodes 'data slots' being entirely schedule driven, all nodes know in advance when they are to transmit, receive, or sleep to conserve energy. Nodes can sleep for the entirety of their unused slots, enhancing energy efficiency, and resulting in energy consumption that scales linearly with the data rate traversing the node.

TDMH-MAC is able to compute both the control overhead and the power consumption of the network a-priori. All network transmissions have constant data slot lengths, therefore the master node, given the network configuration, is able to compute the control overhead and guarantee the amount of bandwidth available for data transmissions. Running TDMH-MAC on a WSN node has very predictable power consumption, and with knowledge of the network configuration, some topology information, and the current schedule the master node is able to estimate the average current consumption of each node on the network.

The Experiments

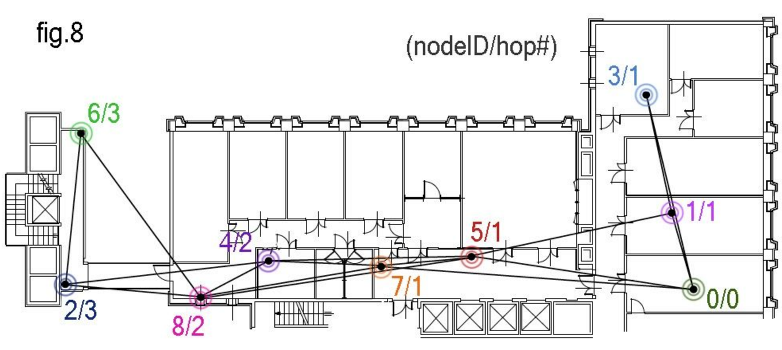
The results of a simulation exploration campaign of network configurations and 2 experiments, one testing the network's reliability, the other, the network's redundancy, were presented for the TDMH-MAC protocol.

The simulation campaign was performed with the network properties of; a hexagon-like network topology(a node has <= 6 neighbours); node IDs assigned in reverse order(the worst case scenario); single frame uplink slots(smallest possible); and a tile duration of 100 ms. Trials were performed with a network size of [2:128] nodes, configured for a max of number of [8:128] nodes. The network formation time was calculated as a function of number of nodes and network configuration, and the network convergence time after node failure was measured as a function of number of nodes & network configuration. The results showed that for networks under 32 nodes the formation time was under 100 seconds, and up to 304.8 seconds for 128 nodes. The convergence time for the node furthest away from the master node is comparable to the network formation time, although with a delay of (n-1) by the number of rounds the network is configured to wait without hearing from a node prior to assuming its failure.

Both of the physical experiments were set up with 9 Wandstem WSN nodes distributed in the first floor of building 21 of the Politecnico di Milano(fig.8) and were performed with the same network configuration of max 32 modes, max hops 6, and 100 ms tile duration and maximum allowable data frame size.

For the 'reliability' experiment, the network was started, and once topology reached a steady state, the topology was logged over the following 2 days. The reliability metric used was the percentage of time each link is listed in the topology, referred to as the 'link uptime'. The results of this experiment showed that the reliability of most nodes was >80%. Nodes far apart were seen to sporadically connect, resulting in a few low reliability links due to distance and/or external interference. The mesh topology network however allows the to compensate for link failures with spatial redundancy until a reschedule can occur.

fig.8



For the 'redundancy' experiment, 3 streams were scheduled; from node 3, 4, and 6 towards node 0. The network was also logged over the following 2 days, however, the first day without redundancy, and the second day, with double spatial redundancy(forces the duplicated frames across different paths). The reliability metric used was the % of application-level packets correctly received. The results showed the reliability of all 3 streams was above 95% on both days, and with double spatial redundancy, all 3 streams produced reliability scores of 99% or higher. Therefore, with or without redundancy, the TDMH-MAC is able to provide reliable data transmission, which is, however, improved further by the addition of redundancy.

Conclusions & Further Work

From the experimental results, it was concluded that the TDMH-MAC protocol could be easily scaled to networks of > 100 nodes and 10 hops.

The network efficiently collects and forwards the current network topology to the master node allowing for centralized resource allocation; eliminating collisions and enabling bounded latency periodic communications. In the face of network interference and link topology changes, network reliability can be provided through temporal and spatial redundancy due to the network's mesh topology. It is suggested that further scaling of the network would exacerbate the tradeoff between control overhead and topology convergence, as well as increase the schedule size and introduce lengthy dissemination times. The proposition of the use of a different physical layer than 802.15.4, with a higher data rate, would reduce topology convergence time and potentially enable support for mobile nodes.

Thoughts & Criticisms

There are a large number of network configuration factors that affect the convergence time and behavior of the network, therefore it is understandable that exhaustive simulations of all potential were not run. However, the simulations completed were all run with the worst case scenario network configuration properties. It would have been valuable to run them with a few other cases as well, or at least the best case scenario, to compare the difference in network behavior between the most and least optimal configurations. Considering this protocol is intended for WSNs compiled of primarily static nodes performing periodic tasks -suggesting the application of factory automation- it seems likely that optimal configurations could often be attained, or at least striven for. If a significant degradation occurs in functioning between worst and best case configurations it may give those setting up the network reason to optimize the physical setup of the network nodes when it may be costly or inconvenient to do so.

Bibliography

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