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Analysis of Adaptive Multi-hop Time Synchronization in Large Wireless Sensor Networks

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***Abstract*—Time synchronization in wireless sensor networks is important for sensing services that require clock accuracy but use sensors without accurate hardware clocks. Pairwise synchronization is a common technique for two nodes to synchronize their clocks; a leading protocol that extends it across a larger network is AMTS. The challenge with AMTS and other protocols is that synchronization may incur significant communication overhead and more importantly reduce battery lifetime. Although AMTS has been analyzed with small networks, in this paper we analyze its performance in chain, grid and tree topology networks, identifying the trade off between synchronization period and energy consumption.**

***Index Terms*—Time Synchronization, Wireless Sensor Networks, Adaptive Multi-hop Time Synchronization, Energy Consumption Model.**

I. Introduction

Wireless sensor networks (WSNs) consist of resource-constrained nodes that collectively sense the environment and report back to central nodes or servers. The nodes have limited hardware capabilities, therefore specialize communication protocols are designed to give optimal performance given the constraints. One limitation is on-board clocks: nodes may not have a separate hardware clock, with the clock only implemented as a counter in software. The result is that clocks on sensor nodes may be inaccurate; manufacturing tolerance, aging, temperature, pressure and other factors may lead to different clock rates on different sensors [1]. Hence researchers have developed time synchronization protocols for WSNs.

A. Key Research on Time Syncrhonization

A key component of WSN time synchronizatio protocols is pairwise synchronization [8], where a sender and receiver node exchange protocol messages such that one can calculate the clock drift and adjust its clock accordingly so that it is synchronized with the other node. Different protocols [2] have been designed for WSNs that extend pairwise synchronization so that all nodes in the network can synchronize their clocks. A popular protocol for WSNs is Timing-sync Protocol for Sensor Networks (TSPN) [4]. It starts with a level discovery phase performed when the network is formed. A simple flooding scheme is used starting from a root node (the reference clock and in practice often a gateway or sink node in the WSN) that sees levels assigned to each node in the network based on the number of hops from the root. For example, root node is level 0, 1-hop neighbors are level 1, 2-hop neighbors are level 2, and so on. Then a synchronization phase is used, where pairwise synchronization is applied from a node to a node in a lower level, such that eventually all nodes are synchronised to the root node. The synchronization phase is repeated at regular intervals, depending on the clock drift.

A design challenge of TSPN is determining the synchronization period such that the accuracy of clocks in the network is high, while minimizing energy consumption. Synchronizing too often can lead to significant energy consumption, reducing the lifetime of the network. Adaptive Multi-hop Time Synchronization (AMTS) [10] extends TSPN with the aim of reducing energy consumption. It uses the level discovery and synchronization phases, but modifies synchronization to estimate both clock offset and clock skew (TSPN only estimates clock offset; knowing the skew can allow for fewer synchronizations). In addition AMTS introduces a network evaluation phase where nodes examine the traffic required from the previous synchronization phase to decide whether the next synchronization should use one of two modes: the normal always-on (AO) mode which delivers high accuracy but at expense of large overhead, or the sensor initiated (SI) mode when network resources need to be saved (e.g. low battery life remaining, or scenarios where clock drift mainly occurs when sensing events take place). AMTS defines an algorithm for automatically switching between the two modes [5] [6].

B. Aims of Our Research

A key design trade off for time synchronization protocols is that of clock accuracy versus network traffic and energy consumption. Keeping the clocks of all nodes synchronized with a reference node can require significant network traffic, which in turn requires energy consumption especially for packet transmission and reception. Although for small, simple network topologies (e.g. a chain) the overhead can be tolerable, as networks grow, the overhead may be too much

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for most applications. This is due to two main reasons:

1) With large networks and different topologies (compared to a chain), the number of neighbors may vary significantly. This impacts on the number of transmissions and receptions, an in turn energy consumption.

2) With large networks significant radio interference between nodes can arise (and interference from other transmitters not in the WSN is more likely). This can lead to varying transmission delays (due to packet collisions and retransmissions) decreasing the accuracy of the pairwise synchronization.

AMTS has been analyzed for a chain topology as well as variations, such as branches. TSPN has been analyzed for a chain topology as well as preliminary results for a network of 50 nodes. Neither analyses have considered the impact of different topologies or interference on performance. The aim of our research is to identify the limitations of AMTS in the present of these more realistic conditions. This paper specifically aims to compare AMTS performance for different topologies and synchronization periods. Future work will also introduce interference from nodes outside of the WSN.

II. An Overview of AMTS

AMTS is a time synchronization protocol that uses pairwise synchronization between pairs of nodes at neighboring levels. It consists of three phases as described in the following subsections and summarized in Figure 1 [10].

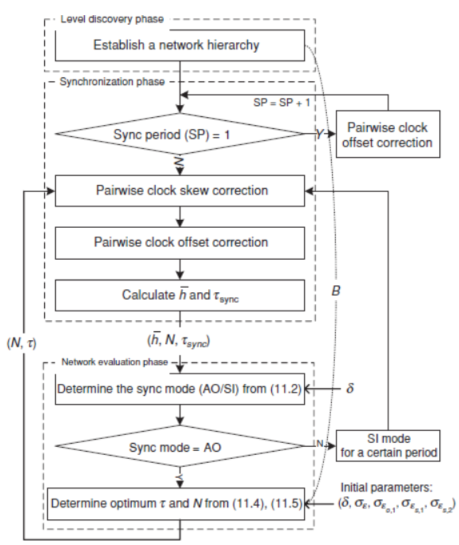

Fig. 1: Flow Chart of AMTS Algorithm

A. Level Discovery Phase

The level discovery phase is performed at the start of the network operation to assign levels to each node. The idea is that the root/reference node is level 0, its 1-hop neighbors are level 1, its 2-hop neighbors are level 2, and so on. The steps are:

1) Select a root node using an appropriate leader election algorithm and assign a zero level to the root node.
2) Broadcast a level discovery packet (LDP) containing the identity and the level of packet.
3) Assign a level that is one greater than that of the received packet to every node that receives an LDP which sends a new LDP attaching its own level. consists of pairwise synchronizations between adjacent nodes until every node in the network is synchronized to the reference.
4) Repeat this process until every node in the network is successfully assigned a level.

B. Synchronization Phase

This phase consists of pairwise synchronizations between adjacent nodes until every node in the network is synchronized to the reference. In this phase, AMTS estimates not only the current clock offset but also the clock frequency (skew) to guarantee long-term reliability of synchronization. Hence, AMTS requires far less frequent resynchronizations.

C. Network Evaluation Phase

In this phase the reference node investigates the current status of network traffic in order to optimize the resynchronization period and the number of beacons in terms of energy efficiency. Moreover, it selects the synchronization mode to be either always on (AO) (always maintain network-wide synchronization) or sensor initiated (SI) (synchronize only when it needs to) based on the network status.

D. Parameters

Key parameters in AMTS are:

- B: number of branches in a spanning tree of the network.
- τ: re-synchronization period.
- $\bar{h}$: average number of hops per unit time.
- δ: latency factor reflecting the amount of allowed delay in data transmission [9].
- N: number of beacons per pairwise synchronization.

III. Analysis Methodology

In this paper we analyze the performance of AMTS via simulation.

A. Metrics

To analyse the performance of AMTS we consider the following metrics:

Clock accuracy [seconds]: The perceived time at a node is compared with the actual time at the reference clock (root node). The network-wide clock accuracy is the average of time difference between each node and the reference node. Lower time difference means higher clock accuracy.

Overhead [bits per second]: There is communication overhead in synchronizing clocks. Specifically with AMTS nodes need to discover levels and then periodically perform pairwise syncrhonization. The overhead is reported as the average number of bits per second sent per node.

Energy consumption [Watts]: While the processing required for AMTS is quite low, significant energy may be consumed by both transmitting packets and receiving packets. We use the following model to determine the energy consumption, E, at in (1) each node:

$$E = t_{idle} \times e_{idle} + t_{sleep} \times e_{sleep} + t_{Tx} \times e_{Tx} + t_{Rx} \times e_{Rx} \quad (1)$$

where t is the time the node spends on one of four states (idle, sleep, transmitting, receiving) and e is the energy consumed in each state [12].

B. Network Topology

The arrangement of nodes in the WSN may impact on the performance of AMTS. With large number of nodes, and more neigbor nodes, interference may increase leading to less accurate time synchronization. To consider the impact of topology on AMTS we have analyzed the following topologies as illustrated in Figure 2.

- Chain (linear) topology, consisting of N nodes. The first node is the reference (root) node.
- (Square) Grid topology, consisting of $N \times N$ nodes with equal horizontal and vertical separation. The top left node is the reference node.
- Tree topology, consisting of 1 root node and below it an $N \times N$ grid.

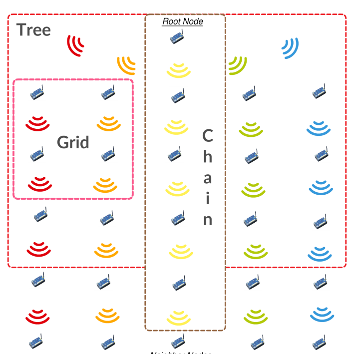

Fig. 2: Chain, Grid and Tree topologies

The distance between nodes in all topologies is set such that a node is only within wireless range of the next node in the chain or horizontal and vertical neighbors (for grid and tree).

C. System Parameters

The key parameters we change in the analysis are:

- Topology: chain, grid or tree topologies with N between 2 and 5.
- Synchronization protocol: We consider only two cases: no synchronization (as a reference) and AMTS. Subsequent parameters only apply for AMTS.
- Synchronization period: The time between performing synchronisations with AMTS. Typically in the order of 10's of minutes.
- AMTS mode: AMTS supports two modes, AO and SI, and we collect results for each mode.

Other parameters which are fixed in our analysis are:

TABLE I: Network Parameters

Parameter	Value	Units (SI)
Area size (X,Y)	(1000, 1200)	m
Simulation duration	1440	minutes
Max. Tx power	1.1	mW
Min. Radio Power (Sensitivity)	-100	dBm
Carrier Frequency	2.4	GHz
Network Type	Flood	-
E_{max}	0.01	mW
E_o	0.05	mW
E_s	0.00475	mW
T_{max}	0.01	mW
Packet sizes (NW.and APP.Layer)	88	bytes
e_{sleep}	0.06	mW
e_{idle}	0.138	mW
e_{Rx}	9.6	mW
e_{Tx}	1.1	mW
$e_{CPU(Active)}$	7.6	mW
$e_{CPU(Inactive)}$	0.237	mW

TABLE II: AMTS Parameters

Parameter	Value	Units
B	1 to 5	branch
N	125	Mbps
SP	1, 2, 3, ...	periods
$\hbar$	1 to 5	hops
Synchronization Mode	AO and SI	modes
τ_{max}	2.094	msec
τ_{sync}	0.729094	msec
τ	10, 20, 30, 50, 60	minutes
Latency Factor (δ)	0 to 1	-
σ_{ε}	3.33	msec
$\sigma_{\varepsilon_{o,1}}$	16.67	usec
$\sigma_{\varepsilon_{s,1}}$	1.58	usec
$\sigma_{\varepsilon_{s,2}}$	1.72	usec

D. Simulation Implementation

We use OmNet++ 4.6.0 network simulator to simulate the 3 topologies and configurable parameter into farm area environment by MiXim-2.3 and iNet frameworks to analyze AMTS. We have implemented the core features of AMTS in ZigBee nodes within OmNet++, i.e. network level discovery, synchronization and network evaluation phases. In general, based on crystal oscillators which provide a local time for each network node. Consider the physical clock synchronization of machines in a distributed system to UTC. At any point of time, if the time at UTC is t, the time in the clock of machine p is C_p(t). In a perfect world, C_p(t) = t for all p and all t. This means dC/dt = 1. However, due to the clock inaccuracy discussed above, a timer (clock) is said to be working within its specification if [7] [11]:

$$1 - p <= \frac{dC(t)}{dt} <= 1 + p$$

where constant p is the maximum skew rate specified by the manufacturer.

IV. Result

Fig. 3, 6, 9 and 12) show the clock accuracy obtained with and without AMTS protocol for increasing synchronization period. It shows that increasing the period reduce the accuracy. the reason for this is after adding the protocol, it can reduce clock error better than without AMTS.

Fig. 4, 7, 10 and 13) show the overhead obtained with AMTS protocol for increasing synchronization period. it shows that by increasing synchronization period, the overhead decrease. the reason for this is after add the protocol, it can generate long term in accuracy and low energy by the AMTS protocol.

Fig. 5, 8, 11 and 14) show the energy consumption between 2 mode (SI/AO) obtained with AMTS protocol for increasing synchronization period. It shows that increasing the period reduce the energy. the reason for after add 99.3 bits per seconds(12 bytes per seconds) can reduce clock error at 66.87 percent and use the energy about 25.23 milliwatts per a day (if use AA Ni-NH 1.2V: 3.36 Watts $\times$ 2 Units = 266 Days).

Fig. 12 to 17) show accuracy, overhad and energy with 3 topologies trand to re-sync periods and comparison between SI and AO modes in the AMTS protocol, After change to AO mode can reduce overhead 70 percents of SI mode, and impove accuracy 2 times of no AMTS, but still tread off by use the energy consumption about 16 times and 4 times in SI and AO mode respectively in not add the protocol.

V. Conclusion

Our analysis of AMTS in 3 different network topologies highlights the key tradeoffs between synchronization period and energy consumption in WSNs, especially for larger networks. Future work will consider larger networks as well as the role of interference from other nodes on the pairwise syncrhnization.

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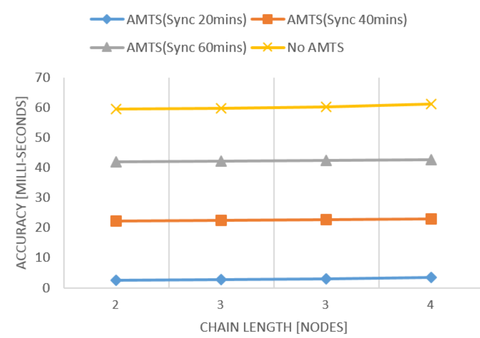

Fig. 3: Chain Topology: Clock Accuracy

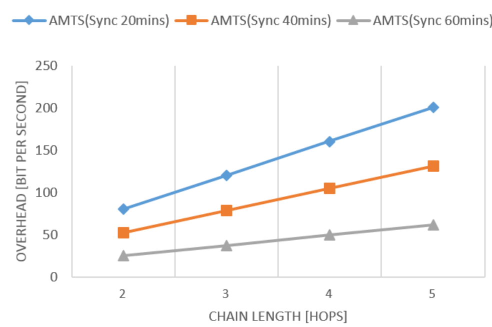

Fig. 4: Chain Topology: Overhead Protocol

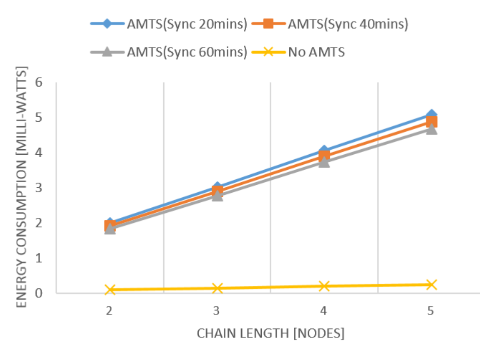

Fig. 5: Chain Topology: Energy Consumption

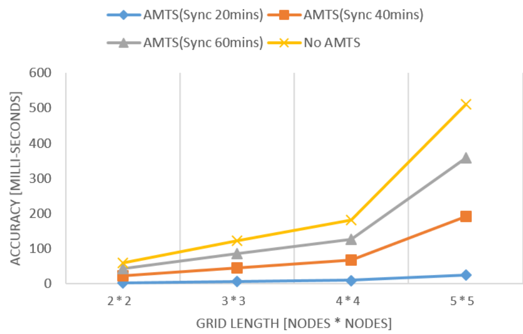

Fig. 6: Grid Topology: Clock Accuracy

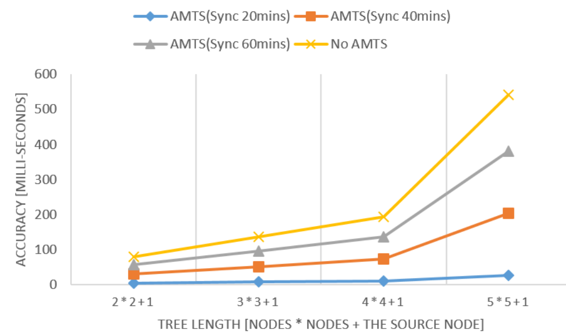

Fig. 9: Tree Topology: Clock Accuracy

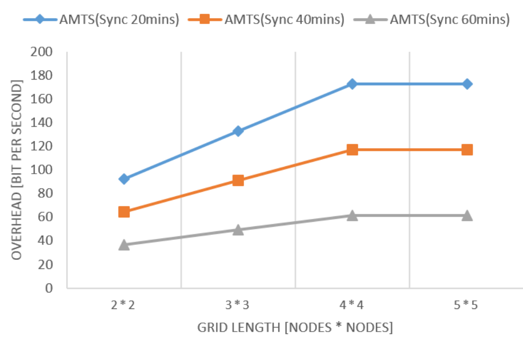

Fig. 7: Grid Topology: Overhead Protocol

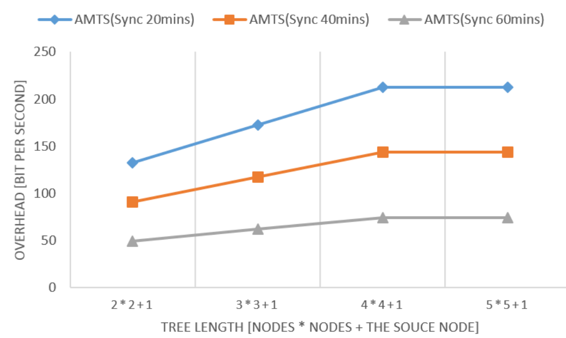

Fig. 10: Tree Topology: Overhead Protocol

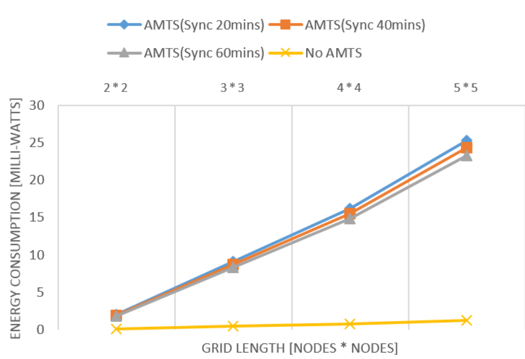

Fig. 8: Grid Topology: Energy Consumption

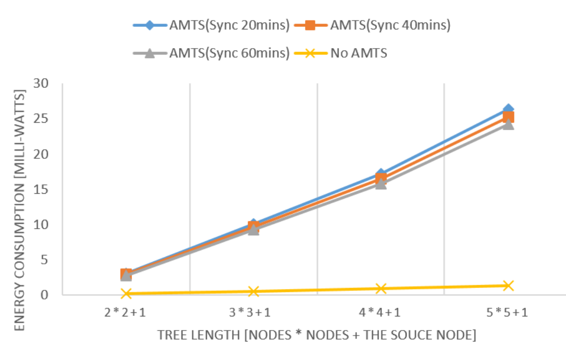

Fig. 11: Tree Topology: Energy Consumption

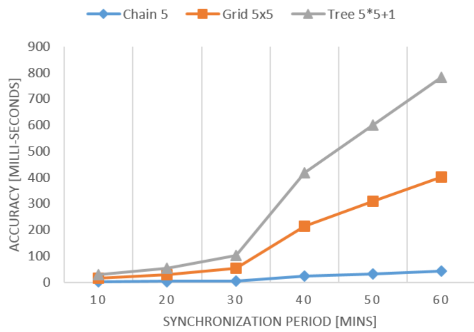

Fig. 12: Sync Period: Clock Accuracy

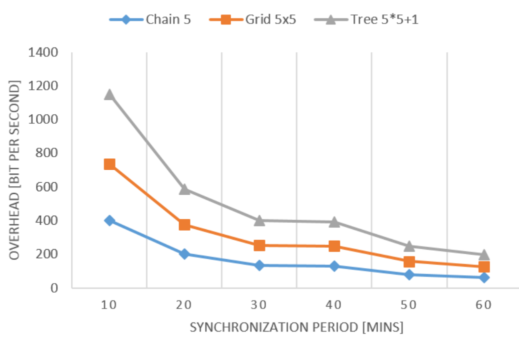

Fig. 13: Sync Period: Overhead Protocol

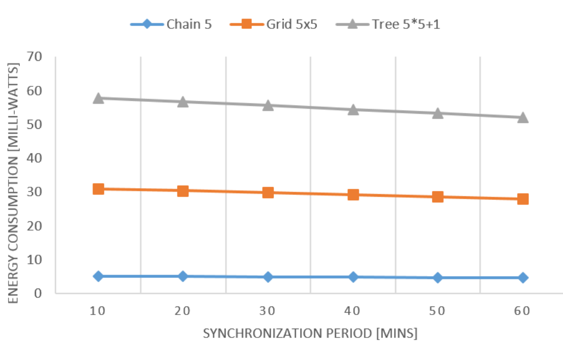

Fig. 14: Sync Period: Energy Consumption

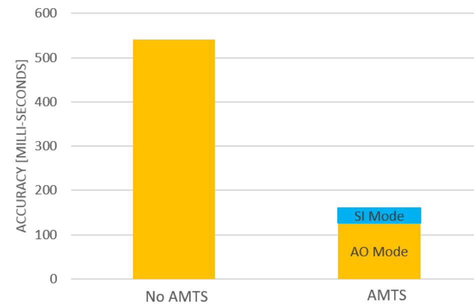

Fig. 15: Protocol Mode: Clock Accuracy

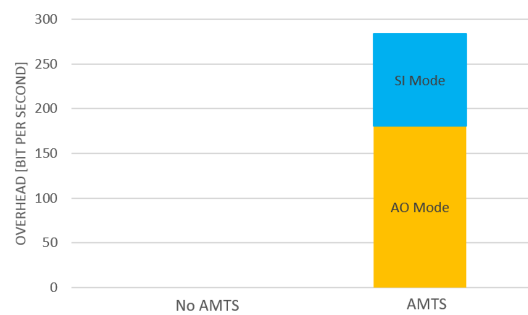

Fig. 16: Protocol Mode: Overhead Protocol

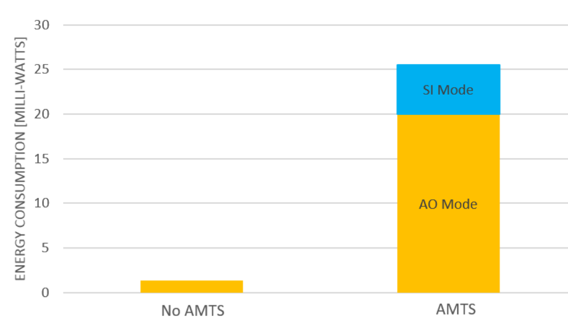

Fig. 17: Protocol Mode: Energy Consumption