Efficient, Single Hop Time Synchronization Protocol for Randomly Connected WSNs

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***Abstract*—This letter develops a single-hop fast accurate and energy-efficient time synchronization protocol for wireless sensor networks. The protocol is designed to operate in harsh environments and is based on a resistive electrical network metaphor. It treats the nodes' times as the states of a discrete decentralized unconditionally stable dynamical system. The synchronizer monitors the evolution of these states during the transient phase to determine the instant at which the time encoded by a state is close to the master node time. The procedure can yield high quality time estimates with accuracies that are fractions of the communication cycle. The synchronization method is developed and its capabilities are demonstrated by simulation and physical experiments on the MICA-Z wireless sensor network.**

***Index Terms*—Wireless sensor networks, wireless application protocol, consensus protocols.**

I. Introduction

WIRELESS sensor networks (WSNs) consist of multiple devices called sensor nodes that are spread over a geographical area [1], [2]. Each of these sensor nodes consists of transducers or sensors, radio transceiver with wireless capabilities, low complexity processing units, and power supply. These systems are usually made of cheap components and deployed in harsh environments where communication is limited and the probability of node failure is high. Under such conditions, the nodes of the network can only communicate in an opportunistic manner making multi-hop communication and/or a fixed communication topology unattainable. The nodes have to reduce their message exchange rate to the minimum possible since communication can quickly drain the node battery. Despite the above and other difficulties, a WSN is expected to carry-out its function in a practical manner.

Making all the WSN nodes agree on a common time, which is most likely that of a gateway node (GWN), is one of the activities (e.g., routing, topology/geometry reconstruction, etc.) the network has to perform in order to function. While the literature abounds with techniques on synchronization [3]–[5], most of these methods do not suit operation in harsh environments. They assume a specific stationary network connectivity, a node labeling scheme or (and) multi-hop communication, among other assumptions.

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A promising approach to synchronize the nodes of a WSN in harsh environments is consensus control [6]. Synchronizing techniques utilizing this approach [7], [8] use the states of a decentralized dynamical system to create a virtual clock at each node. Nearest-neighbor communication is employed to control the evolution of the states in a manner that would make all of them register the same time reading of the GWN. There are serious issues that still need addressing before this approach becomes practical in harsh environments. One concern regarding techniques using this approach is their excessive use of communication; this can quickly deplete the nodes' batteries. In addition, the accuracy and convergence rate of existing consensus-based methods may not be practical. Also, stability of the virtual clock may depend on the type of topology of the network or on the stationarity of the topology during operation.

This letter suggests a decentralized dynamical system that can operate as a virtual clock individual nodes of a WSN may use to estimate the GWN time. The local system onboard a node uses as input the values of the local times communicated by its immediate neighbors. It produces as output an estimate of the GWN time. Once a node decides that its time estimate is close to that of the GWN, it seizes communication and uses the estimate to reset its physical clock. A node can terminate its local time update while in the transient phase by using a stopping criterion derived from the dynamical nature of the local time series estimate. Each node in the network is guaranteed to converge to a local time that is close to that of the GWN if a path exists from the GWN that spans all the nodes of the network.

II. The Synchronization Procedure

In this section, the electric circuit analogy used to develop the synchronizer is explained. Also, the components of the system are presented.

A. The Resistive Network Metaphor

To have a reasonable ability to function in a harsh environment, a node behavior should not be conditioned on the global properties the WSN must possess. A node function that assumes a certain network connectivity or a labeling system is highly unlikely to succeed if a node is damaged. This immediately excludes the possibility of using multi-hop communication.

It may appear difficult to find a node-level synchronization procedure that requires only a single hop communication, that is not strongly reliant on a connectivity arrangement but still provides guarantees on the network's ability to function. However, electrical networks prove otherwise [9]. If the voltage of any node in an electrical network is fixed to a certain value V, all the other non-isolated nodes (i.e., a path exists from a node to the fixed voltage node) will register the same voltage. The nodes of the electric network function in a manner that is indifferent to both labeling and connectivity if a path from the fixed voltage node exists that spans all the nodes of the network. Moreover, inserting new nodes into the network will not affect operation if the new nodes are part of a spanning path. In a similar way, deleting nodes will not affect network operation if the removed nodes do not render the set of spanning paths empty. As can be seen, a strong analogy exists between the local time of a WSN node and the voltage of a resistive electrical circuit.

B. Node Local Time Update

The electric analogy discussed above is used to build the discrete system of the WSN virtual clock. Let t_{N+1}, be the reference update time of the GWN at iteration n. This time is equal to the time of message exchange (ΔT) multiplied by the iteration value n ($t_{N+1}(n) = \Delta T \cdot n$). The updated time equation for each node i, t_i, is given by:

$$t_i(n+1) = \frac{1}{C_i} \sum_{j \in \chi_i} t_j(n) \quad j = 1, \ldots, N \tag{1}$$

where N is the number of nodes in the WSN, and χ_i is the set of neighbors to node i and C_i is the cardinality of χ_i . The nodes of the WSN can be expressed as the discrete time state space sysetm with a ramp input:

$$\begin{aligned} T(n+1) &= A \cdot T(n) + B \cdot t_{N+1}(n) \\ &= A \cdot T(n) + B \cdot (\Delta T \cdot n) \end{aligned} \tag{2}$$

where A is the network connectivity matrix, $T(n)$ represents the nodes' times ($T(n) = [t_1(n)t_2(n) \ldots .t_N(n)]^T$), B is a column vector with binary elements 0 or 1 ($B = [b_1 b_2 \ldots .b_N]^T$). If the i'th element of B is zero, it means that the i'th node is not connected to the gateway node. The matrix A contains nonnegative entries with row vectors (a_i),

$$A = \begin{bmatrix} a_1 & a_2 & .. & a_N \end{bmatrix}^T. \tag{3}$$

where the L-1 norm of a_i ($\|a_i\|_1$) satisfies the following:

$$\begin{cases} \|a_i\|_1 = 1 & if \quad b_i = 0 \\ \|a_i\|_1 < 1 & if \quad b_i = 1 \end{cases} \tag{4}$$

The error as a function of the discrete time is expressed as:

$$E(n+1) = A \cdot E(n) + \Delta\ T \cdot \widehat{1} \tag{5}$$

where $E(n) = \begin{bmatrix} \Delta T \cdot n - t_1(n) \\ \Delta T \cdot n - t_2(n) \\ \vdots \\ \Delta T \cdot n - t_N(n) \end{bmatrix}$, and $\widehat{1} = \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix}$.

The system in (2) is unconditionally marginally stable. It is simple to show that if the network contains a spanning path and if B is not all zeros (i.e., the gateway node is connected to at least one of the WSN nodes), the system in (2) is stable with steady state error:

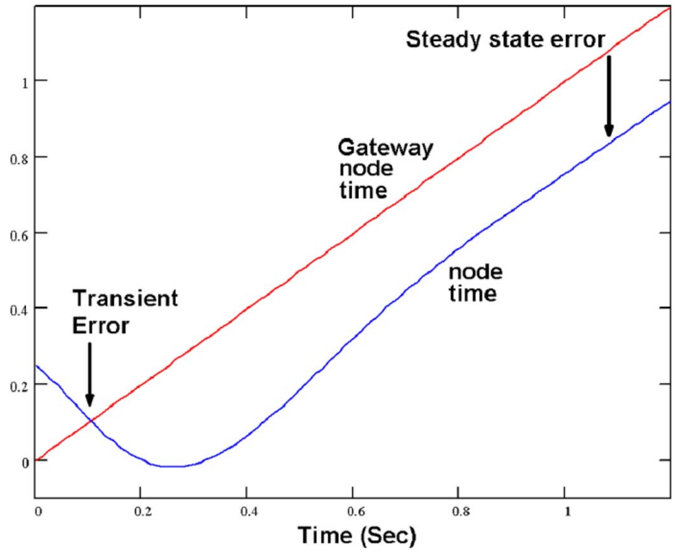

Fig. 1. Time absolute error dip in the transient phase.

$$Ess = \Delta T \cdot (I - A)^{-1} \cdot \widehat{1} \tag{6}$$

where $Ess = \lim_{n\to\infty} E(n)$.

C. The Stopping Criterion

Equation (6) states that the system in (2) can bring the local times of the WSN nodes arbitrarily close to that of the gateway node by reducing ΔT. This is not practical for a WSN since communication can quickly drain a node's battery. An alternative to increasing the synchronization accuracy without excessive high communciation rates may be obtained by examining the dynamical behavior of equations (2) and (5). It is noticed that all the nodes of the network experience a strong dip in the absolute value of the error prior to the steady state phase. This is caused by the evolving local time intersecting the time of the GWN as shown in Figure 1. Ideally, the error should drop to zero. However, for a finite message exachage rate, the absolute value of the error significantly drops for all the nodes to values well below ΔT. Currently, this observation is investigated using intensive simulation and physical experiments. The obeservation persisted even when stochastic link connectivity was used. For example, the connectivity of the nework in Figure 2 (t_1 is the gateway node) is chosen as a Bernoulli random variable:

$$\mathrm{f}(\mathrm{C}_{\mathrm{i,j}}) = \begin{bmatrix} p & \mathrm{C}_{\mathrm{i,j}} = 1 \\ 1-p & \mathrm{C}_{\mathrm{i,j}} = 0 \end{bmatrix} \tag{7}$$

Figure 3 shows the error profiles of node-3 of the network for two cases. The first case involves deterministic channels ($p = 1$). The other one is for maximum connectivity ambiguity ($p = 0.5$). As can be seen in both cases, the dip trend in the absolute value of the error persisted. Moreover, the times the dips occur for all the network nodes are very close.

A stopping criterion (SC) is needed to terminate the iterative process before the steady state is reached. This is carried-out by exploiting the dip behaviour which the protocol exhibits.

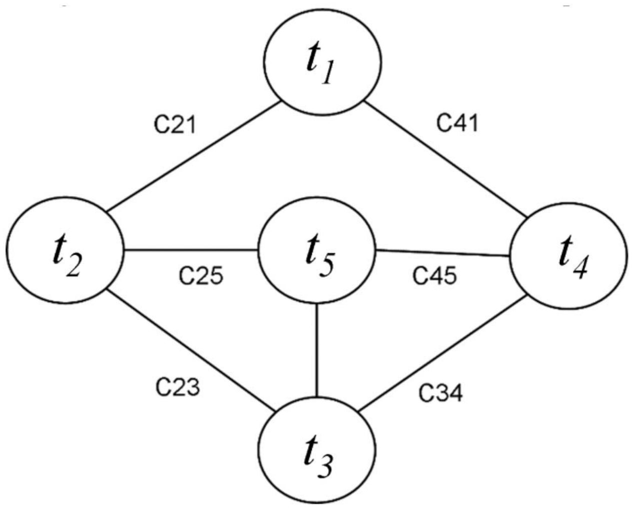

Fig. 2. Test nework with t_1 as the gateway node.

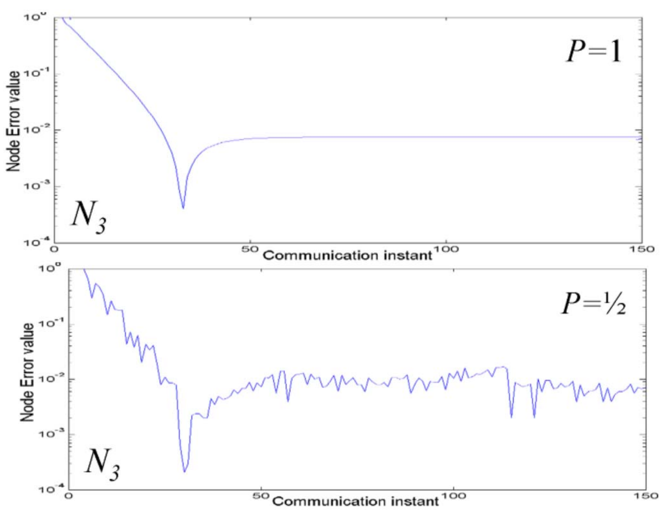

Fig. 3. Error profile of node-3 in Figure 2 with channels being on 100% of the time (p=1) and 50% of the time (p=0.5).

A detection filter that operates on the local time series has to be applied by each node to the evolving local time estimate. This filter generates the indicator signal that will be used in localizing the instant at which the evolving local time is close to the GWN time. A logical rule is then applied to pinpoint the local instant that will be selected as the global time. This instant is used to initialize the physical clock of the node. The rule is based on polarity change of the filter output provided that K communication cycles have elapsed. It is found that K=11 works for all the cases that were tested.

Optimmum design of the indcator filter is a mathematically involved task that requires formal investigation of the patterns the dynamics of equations (2) and (5) generate and will be left for future investigation. Here a heuristic finite impule response (FIR) filter is suggested to provide the needed indicator signal. The filter is jointly sensitive to change in slope and curvature of the evolving time trace. It is found through experimentation that the zero-crossings of the output of the filter correspond with high probability to the instant at which the dip in error happens. One such filter that can used is the difference

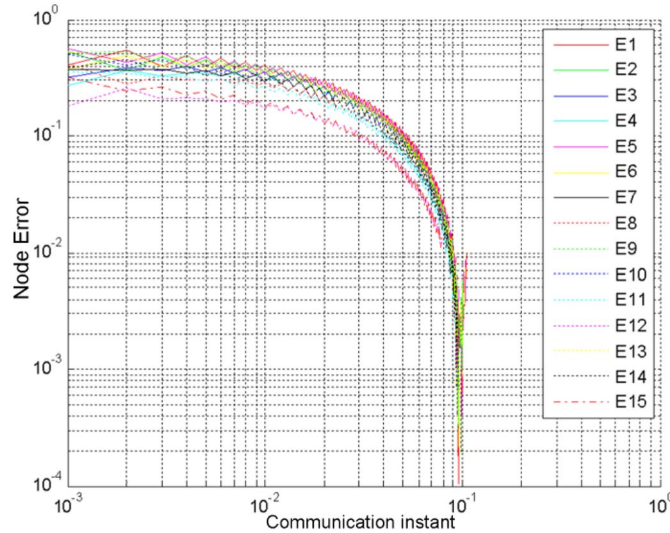

Fig. 4. Error of the nodes before procedure is terminated.

filter of length 5 with impulse response, $h(n)$, given by:

$$\mathrm{h}(n) = 0.2\cdot\delta_{n+3} + 0.5\cdot\delta_{n+2} + 0.2\cdot\delta_{n+1} - 0.2\cdot\delta_{n-1} - 0.5\cdot\delta_{n-2} - 0.2\cdot\delta_{n-3} \quad (8)$$

where δ is the Khronecker delta function.

III. Results

The experiments are carried-out using the MicaZ sensor network from MEMSIC. Experiments were performed on a variety of network topologies. However, the results for a 16-node network with grid connectivity is reported here. The communication frequency is approximately 1KHz and the Packet Size is 64bits. The soft clocks of the nodes were arbitrarily initialized. Figure 4 shows the evolution of the time error curves for all the nodes before the network is synchronized and node communication seized.

The data from the experiment is shown in Table I. As can be seen, the minimum error at the peak of the dip region is considerably less than the 1 millisecond communication cycle. It is worth noting that the minimum error for all nodes occurred around the same time. This is observed for all the cases that were tested. Despite the heuristic nature of the detection filter, it performed reasonably well yielding timing errors close to the minimum with number of communication cycles that is very close to the minimum. While in few cases (N12 and N15) the error is relatively higher than the minimum, it is still lower than the steady state error with significant saving in communication.

The synchronizing scheme will benefit from a better design of the detection filter since the physical implementation of the synchronizer introduces noise in the evolving time. Figure 5 shows the evolution of the error curve for a node in a four-node WSN along with the decision of when to stop the soft clock. The decision filter performed well when tested using simulation. However, the noise the physical implementation introduced adversely affected its performance.

Experiments with 4, 9 and 16 nodes WSNs revealed that the growth in the time the suggested procedure needs for synchronization versus the size of the network is almost linear in the

TABLE I
NODE ERROR RESULTS FOR THE 16-NODE GRID NETWORK

	Min Error		Steady State Error		Detected Error	
Nodes	Comm.. Instant	Value	Comm.. instant	Value	Comm.. Instant	Value
N1	96	0.0001029	447	0.0413387	106	0.0095701
N2	100	0.0003394	446	0.0403887	105	0.0086201
N3	96	0.0003152	444	0.0381499	103	0.0028916
N4	100	0.0001886	441	0.0358427	100	0.0001886
N5	100	0.0003394	446	0.0403887	105	0.0086201
N6	96	0.0002157	444	0.0388284	104	0.0076122
N7	100	0.0002003	441	0.0353678	100	0.0002003
N8	99	0.0004591	436	0.0316356	96	0.0006695
N9	96	0.0003152	444	0.0381499	103	0.0028916
N10	100	0.0002003	441	0.0353678	100	0.0002003
N11	99	0.0002846	433	0.0290566	92	0.0024287
N12	95	1.00546E-5	420	0.0208459	80	0.0140003
N13	100	0.0001886	441	0.0358427	100	0.0001886
N14	99	0.0004591	436	0.0316356	96	0.0006695
N15	95	1.00546E-5	420	0.0208458	80	0.0140003
Max	100	0.0004591	447	0.0413387	106	0.0140003
Min	95	1.00546E-5	420	0.0208458	80	0.0001886

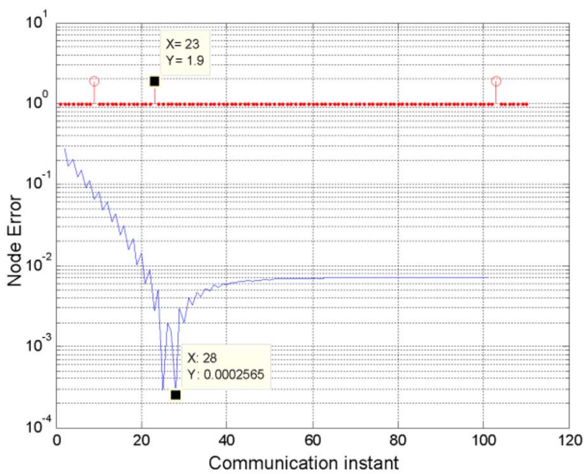

Fig. 5. Detection filter operating on both experimental data.

number of nodes. This indicates that the protocol is scalable for large-scale networks.

The suggested protocol is compared using a nine-node WSN to two synchronization protocols for WSN. The first is the Rated Flooding Time Synchronization Protocol (RFTSP) and Energy-Efficient Gradient Time Synchronization Protocol (EGTSP). RFTSP is a variant of the FTSP protocol [10] with a control over the rate of flooding each node is permitted. EGTSP [11] is a localized algorithm that achieves a global time consensus and gradient time property using effective drift compensation and incremental averaging estimation. Figure 6 shows the maximum error profile of the network for all the protocols concerned. As can be seen, the suggested protocol provides a clear indication of when to stop, hence synchronizing faster than the other two. The steady state phase of each of the other two protocols is a random process that consumes a considerable amount of communication cycles in order to be identified.

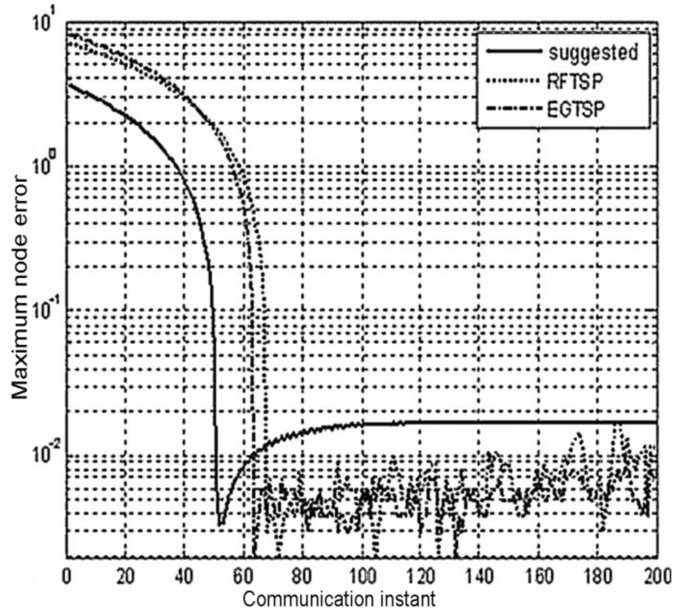

Fig. 6. Maximum error curve of different protocols with 9-Grid nodes.

IV. CONCLUSION

The letter suggests a synchronization procedure that addresses the needs of WSNs operating in harsh environments. The experimental and the simulation results clearly demonstrate the capabilities of the suggested synchronizer. Future work will focus on mathematical analysis of the synchronizer, better design of the detection filter, and the experimental investigation when connectivity is stochastic.

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