

## 1 Papers for Reading : Topic: Time Synchronization

Fan, Lynch. Gradient clock synchronization [FL04]

Attiya, Hay, Welch. Optimal Clock Synchronization Under Energy Constraints [AHW05]

## 2 Introduction

Recent research envisions wireless sensor networks as collections of tiny, autonomous devices with computation, sensing and communication capabilities. Various implementations of such so-called sensor motes exist and networks of different scales have been deployed. There has been active research both on theory and algorithms and on software architectures. Although many classical distributed research results are applicable for sensor networks, new challenges require new answers.

The function of a sensor network usually depends on the collaborative effort of many sensor nodes rather than on a single node. Coordinated actions are critical, and hence clock synchronization is an important service. For example, the correct evaluation of distributed sensor data may require knowledge about the chronology of the sensor observations : If two sensor nodes observe a moving object, the objects direction can be established by determining which node observed the object first. The objects approximate speed can be computed only if the time elapsed between the observations is known. Synchronized clocks can also extend the lifetime of the network: Energy is a scarce resource for battery-powered sensor nodes. Their lifetime can be drastically prolonged by synchronous power on and shutdown of the communication circuits of a senderreceiver pair.

The synchronization of all clocks in the network to a time supplied from outside the network is commonly referred to as external synchronization. Internal synchronization requires only consistency among the network nodes, without any reference to an external time. In sensor networks, internal synchronization is sufficient for the temporal ordering of events or for coordinated actions. External synchronization is needed for example for measuring physical quantities such as speed.

### 3 Brief Outline of the paper [FL04]

Gradient clock synchronization [FL04] can be seen as a special case of internal synchronization. The gradient property requires the difference between any two network node's clocks to be bounded from above by a non-decreasing function of their distance. The distance between two nodes can be defined for example as their Euclidean distance, as their hop distance in the network, or as the message delay uncertainty between them. For the successful completion of actions by groups of sensor nodes, the gradient property is both necessary and sufficient. To illustrate this with two examples:

- 1) For energy-efficient operation, the duty cycle of a sensor nodes communication circuits has to be synchronous to that of its communication partners, i.e. of the nodes in its one-hop neighborhood. These are the nodes with the smallest distance.
  
- 2) When deriving the speed of an object from two node's observations, the total error is proportional to the quotient of the synchronization error and the Euclidean distance between the nodes. For a given maximum total error, faraway nodes are allowed to be more loosely synchronized than nodes that are close to each other [FL04]. In [FL04], a lower bound on the error of gradient clock synchronization was given.

#### 3.1 System Model and assumptions

This paper assumes fixed set of nodes start executing at the same time. Perhaps they are making another strong assumption, a reliable communication between nodes. Let  $D$  be the diameter of the network. Also minimum distance between any node is 1. It also assume all the hardware clocks have bounded drift. That is, author assume that there exists a constant  $\rho$ , where  $0 \leq \rho \leq 1$ , such that for any execution the drift is introduced.

#### 3.2 Lower Bound for Skew

The main contribution of the paper is that they give a lower bound for the skew/error in time synchronization. Let  $A$  be any clock synchronization algorithm, which composed of deterministic and indistinguishability arguments. Using simplified version of network, i.e; a chain of nodes arranged one after another, authors proved that  $A$  satisfies the  $f$ -gradient property. In the simplified version, the sequence of nodes  $p_1, \dots, p_n$  having an edge  $(p_i, p_{i+1})$  connecting the subsequent neighbors, where each other nodes are separated by a distance of 1.

The paper initially shows that,  $f(d, N) = \Omega(d + \frac{\log D}{\log \log D})$ . Then they proves that  $f(1) = \Omega(\frac{\log n}{\log \log n})$ . This result shows that if any two nodes are separated by a distance of atmost 1, then the skew will be  $\Omega(\frac{\log n}{\log \log n})$ . This gives the lower bound of the skew, and also the

inference from this is that the skew is proportional to distance and also the size of the network.

The basic clock synchronization model explains as below. If  $p_i$  and  $p_{i+1}$  are two neighboring nodes, then by having the nodes send each other their logical clock values  $L_i$  and  $L_{i+1}$  respectively, and setting their clock value to the maximum of the received and its local clock value, easily clock synchronization can be achieved with at most skew of 1. Perhaps it becomes difficult to achieve such synchronization throughout the network at the same time. So there will be clocks that are separated between nodes are not close. However, the lower bound result helps us to understand that as the network size increases the time delay is closely proportional to the size of the network and should be taken into consideration, in order to avoid collision.

### 3.3 Summary

In this paper, author makes a case for the use of guaranteed intervals for time synchronization in mobile ad-hoc networks. In particular, authors look at wireless sensor networks (WSNs), a specific class of mobile ad-hoc networks. WSNs are envisioned to comprise a large number of small, inexpensive devices that operate on a very constrained energy budget. Time synchronization is an important service in WSNs. Approaches developed in the distributed-systems field typically cannot be applied directly because of the limiting characteristics of WSNs:

1. there is no guarantee of stable connectivity between nodes.
2. Energy is a very scarce resource. Communication, which is needed to achieve and maintain synchronization, is expensive in terms of energy and hence has to be kept short.
3. Communication bandwidth is limited.
4. There is no a-priori configuration or infrastructure.

In particular, there are few or even no reference clocks available. In this paper, they make a number of contributions to the state of the art in the field of time synchronization for mobile ad-hoc networks.

Main claim is that interval-based time synchronization is particularly suited for these networks. Specifically, contributions are the following: authors present a new system model for the analysis of interval-based time synchronization in mobile ad-hoc networks. Then they justify why abstractions are well chosen for this class of networks. Using this system model, they derive worst-case bounds on the quality of interval-based synchronization and show the worst-case-optimality of a very simple algorithm. The simple, worst-case-optimal algorithm is not optimal in the average case. They present few algorithms that are also worst-case-optimal but achieve better synchronization quality in the average case. They show that the algorithms achieve optimal synchronization, at the cost of high memory and communication overhead. The paper describes how limiting the amount of data that is stored and communicated affects the synchronization quality. It is also shown that interval-based synchronization does not need particular

communication patterns such as trees or clustered hierarchies. Hence, interval-based synchronization is resilient to mobility; the theoretical results show that mobility actually improves it. Finally, they derive a lower bound on the error of gradient clock synchronization in the system model.

In this paper, authors examine gradient clock synchronization in a system model that is typical for sensor networks: they assume message-delay uncertainties to be negligible, and communication to be infrequent. The gradient property requires the difference between any two network nodes' clocks to be bounded from above by a non-decreasing function of their distance. This means that every node has to be synchronized better to nearby nodes than to faraway nodes. They provide a lower bound for the achievable synchronization quality in our model and discuss its relation to an existing bound in a different model.

## 4 Brief Outline of [AHW05]

Time Synchronization is one of an important challenge in distributed systems. Requirement of relative time synchronization is one of an important requirement in such network. In wireless and ad hoc network Reference broadcast uses basic broadcast nature of itself to establish synchronization. Perhaps this limit to single hop network, and as the network scales up additional mechanism have to be employed. In the literature there are multi hop algorithms that have the capability to re-broadcast information across the network. Using such algorithm we can drastically reduce the energy requirement for obtaining time synchronization across the network.

As the energy consumed by broadcast is exponentially equivalent to the distance for broadcast, using multi hop broadcast retransmission the energy consumed by the operation is reduced. However, this methodology has a drawback from the perspective of quality or time synchronization. As the number of hops to rebroadcast increases, the time synchronization quality decreases. Since the time delay occurs, the exact synchronization deteriorates.

Both the above contradictory goals are important challenges. This paper tries to achieve efficient and optimal time synchronization utilizing both the techniques. This paper proposes a distributed algorithm achieving the energy goal using the multi hop broadcast in a shallow environment/infrastructure to obtain optimal time synchronization. Basic idea of the algorithm is by providing a methodology to obtain estimate of clock reading over one hop and extend the idea over several hops. Perhaps this algorithm considers the worst case accumulated uncertainty.

This paper can easily extend to support loosely synchronized sources. Even this paper can accommodate clock drift. Spanning forest construction with the root of the trees as the nodes with their times synchronized to the external clock is one of the major contribution of the paper. The paper provides ways to estimate the bounds of the optimal skew.

## 4.1 Summary

Energy consumption, number of hops, and accuracy are part of trade offs for achieving the time synchronization. Energy required to broadcast for a distance of  $d$  is directly proportional to the distance itself. However, the dimension of broadcast is a power factor i.e; distance-power gradient,  $\beta \geq 1$ .

As we have seen before, skew is the error difference between logical clock reading and real time. The uncertainty of the message delivery delay relates to the skew itself. The skew therefore increases as the number of hops to deliver message increases. So obtaining optimal skew for a given energy constraint is a challenge. The main goal of the paper is to obtain the relation between above two and guarantee clock synchronization

Constructing a BFS tree with energy limitation is the basic idea for achieving the goal. The minimum depth of a particular spanning forest rooted at the time sources, of the topology graph induced by the energy budgets give the optimal skew. Perhaps the paper also shows to construct the shallow forest of minimum depth which give an upper bound. Using the shifting techniques the lower bound is attained.