

Time synchronization algorithms for digital sensor networks used in structural health monitoring systems

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ABSTRACT

Recently, much attention is paid on structural health monitoring technology for maintaining the healthiness of buildings. As for the technique called Sensor Grid which is used for a digital sensor network, related studies are applied in various research organizations. A lot of sensor units consisting of sensors, CPUs and network interfaces are used for the Sensor Grid. In the Sensor Grid, since data are processed and integrated in a network by sensor elements, infrastructure for a network can be reduced significantly. As a basic technology for digital sensor network, in this paper, Time Synchronization is discussed. Two simple techniques on Time Synchronization were examined and related experiments were conducted. At the same kind of nodes, we obtained performances of Time Synchronization as good as $8.50 \pm 7.22 \mu\text{sec}$. However, with different models or different network interfaces, the performance varies. With Broadcast Delivery type for Time Stamps, we obtained stable synchronous performance in all trials. Under the same network topology and using the same network interface, the performance was stable. It was about $20.8 \pm 6.37 \mu\text{sec}$. Broadcast Delivery type for Time Stamps was inferior to Network Delay Measurement Type in performance of the synchronization. However its performance stability was better. And it shows a peculiar performance by environment (a network, topology, hardware and others) of a node. By considering all of these facts, a good and feasible time synchronization system may be established.

INTRODUCTION

Recently, much attention is paid on structural health monitoring technology for maintaining the healthiness of buildings. For example, it is reported that for the structural health monitoring system of Tsing Ma Bridge completed in 1997 in Hong Kong, each

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sensor channel costs more than US\$27,000. Cost of cables and the deployment will be very high if a structural health monitoring system which consists of large number of sensors is wired and centralized. Also it is difficult to process and transmit the numerous data.

For this reason, the distributed digital sensor network instead of the conventional centralized among sensor system becomes much more popular. The distributed sensor nodes consist of sensor elements for catching an event, processing units (CPUs) for processing the measured data, and the network devices. In distributed sensor network, each sensor node is independent. In a distributed digital sensor network, data is collected by sensor nodes automatically and cooperatively. Therefore, various techniques such as Sensor Localization, Time Synchronization, and sensor calibration are needed. In this paper, time synchronization among sensor nodes will be studied. A feasible time synchronization algorithm is proposed.

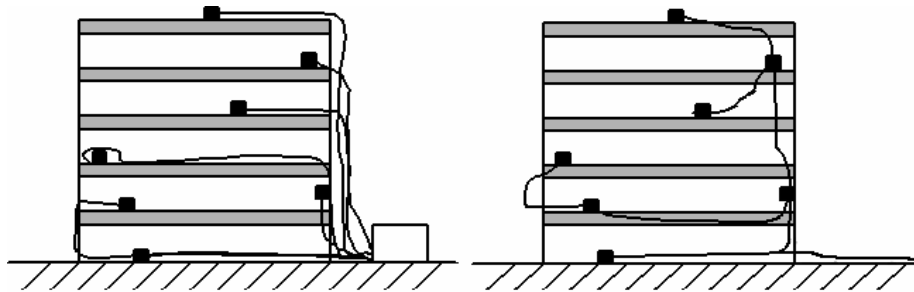


Figure 1: A centralized system model (left), and a distributed system (right)



Figure 2: Many cables (A vibration destruction experiment at E-Defense)

SENSOR GRID

In recent years, digital sensor networks attract many researchers and engineers.

In E-Defense operated in Miki-City, Hyogo, a Sensor Grid based project, "ED-grid project", is launched and promoted mainly by NIED (National Research Institute for Earth Science and Disaster Prevention). Sensor Grid is different from a conventional centralized network in which information obtained at every sensor is transmitted to a server. In every

sensor, CPU is implemented so that the acquired data can be pre-processed before being delivered to the server. Also, communications among any sensors can be realized.

In Sensor Grid, every sensor can be regarded as a tiny computer, and is a digital sensor unit having a capability of grid computing.

TIME SYNCHRONIZATION FOR A DIGITAL SENSOR NETWORK

As mentioned before, CPU is deployed in a sensor unit in Sensor grid and works as a brain in a sensor unit. Sensor grid is a digital sensor network, measured data are converted digitally, extra information such as position of sensors and time of events is required. Such information should be added to the original data and together be transmitted through a network.

When time information is attached to the data, all sensors have to maintain a common time. For example, an interval is 1 millisecond in time between every two samplings when a sensor of a sampling rate of 1 kHz is used. However, Time Synchronization on a scale of microsecond is required to add equal time information to measurement data from all sensors. Even if Time Synchronization with resolution of ten microseconds is performed when a sensor of sampling rate of 1 kHz is used, an error of 1% occurs for measured data. Therefore, in a digital sensor network, time synchronization for sensors is an important issue.

However, in sensor grid, networks are mainly used for transferring sensed data other than performing Time Synchronization. Yet Time Synchronization has to be performed frequently and regularly, and it can not be done during the data transmission. This means that a complicated algorithm which requires much time for performing Time Synchronization cannot be used.

For Time Synchronization, a simpler algorithm with which only short time is needed should be studied.

TIME SYNCHRONIZATION ALGORITHMS

As mentioned in previous section, Network infrastructure for data transmission should be used without installing new signal cable for Time Synchronization. Therefore, the occupation of a network for Time Synchronization among sensor nodes is limited. Meanwhile it is necessary for Digital Sensor Network to do Time Synchronization regularly and frequently.

Based on these facts, Time Synchronization algorithms are proposed. We assume:

- When a process of Time Synchronization runs, there is no other traffic on a network
- A power supply is available
- No additional infrastructure for is needed
- Sensor nodes stand still without moving

In algorithm indicated in the next section: Algorithm1, a node measures a delay of a network and evaluates a gap of the time between nodes (Network Delay Measurement Type).

In algorithm showed in the next section: Algorithm2, all nodes set time stamps with a broadcast of the packet by UDP. With these time stamps being compared, a gap of the time can be determined (Broadcast Delivery type for Time Stamp).

Algorithm 1 : Network Delay Measurement Type

This is an algorithm to evaluate a time gap between nodes by measuring a network delay between transmission and reception of a packet between Root node and Sensor node. This is the Time Synchronization technique which applied a principle of SNTP simplified NTP used for Time Synchronization on conventional Internet to.

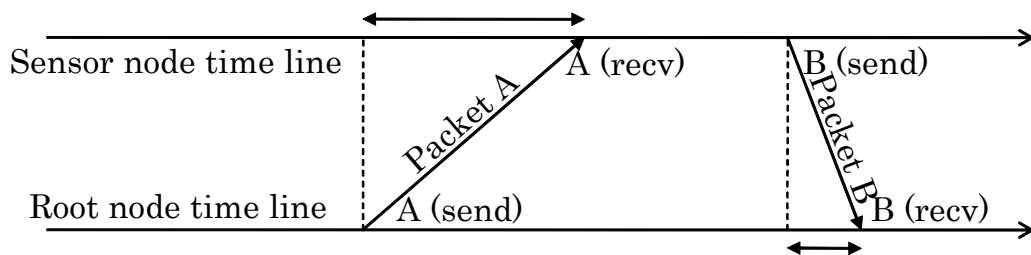


Figure 3: A principle of NTP

$$A(recv) - A(send) = network\ delay + \Delta t \quad (1)$$

$$B(recv) - B(send) = network\ delay - \Delta t \quad (2)$$

Where Δt is A gap of clock time between 2 nodes

Since the network delay can be regarded as the same, Δt can be obtained as:

$$\Delta t = ((A(recv) - A(send)) - ((B(recv) - B(send))) \quad (3)$$

The time needed for a packet transmission from a node to another node is equal to half of turnaround time of a packet transmission between the nodes. Therefore the transmission of a message time in clock of Root node is attached to a synchronization packet when Root node transmits this packet to a Sensor node. Sensor node calculates its correct synchronized time according to that information from a received packet and also the time for packet transfer.

Algorithm 2 : Broadcast Delivery type for Time Stamps

This algorithm uses a broadcast by UDP to remove a message transmission overhead of the packet. All nodes set time stamps when they received a broadcasted packet. A difference of time stamp between nodes is a time gap, assuming that the broadcast will be received approximately simultaneously. Sensor node performs Time Synchronization by setting its own time according to this time gap. Therefore, other than Root node and Sensor node, another node to broadcast packets is necessary. This node is called “Sub-root node”.

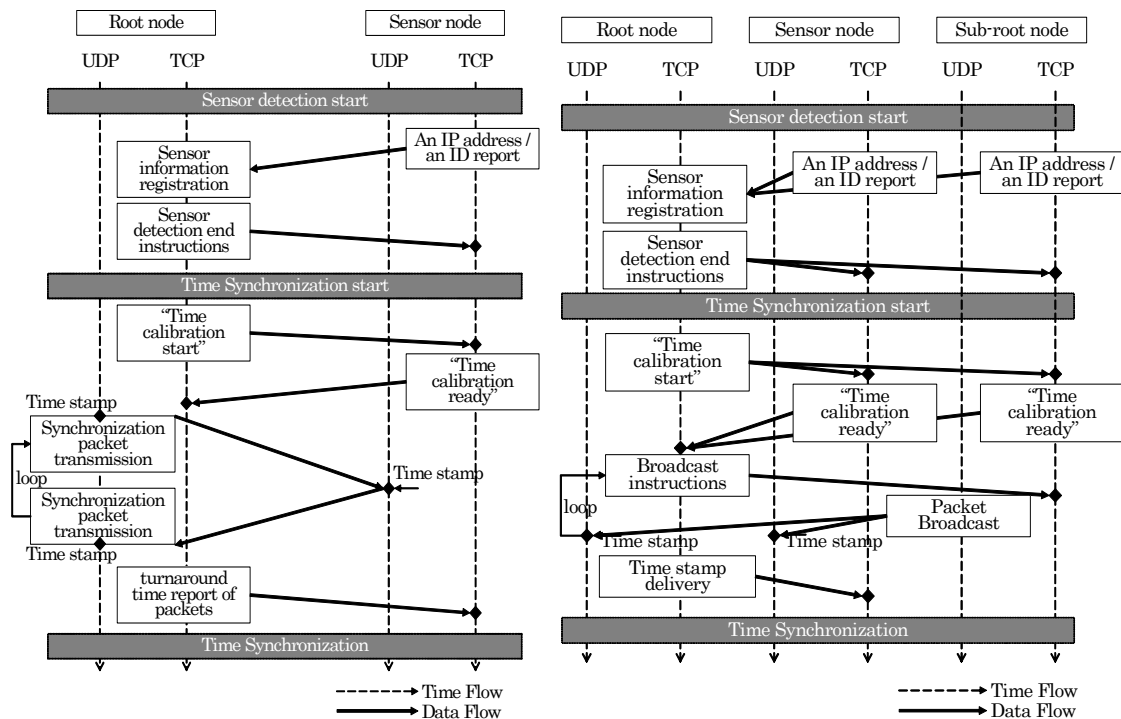


Figure4. Network Flow (Left : Network Delay Measurement, Right : Type Broadcast Delivery type for Time Stamps)

TIME SYNCHRONIZATION PROTOCOL IMPLEMENTATION EXPERIMENT

8 PCs are connected via a switching hub. Among eight nodes, MACHINE01 is the Root node. In Broadcast Delivery type for Time Stamps, MACHINE08 is the Sub-root node to broadcast a packet. The remaining six nodes are Sensor nodes. These six sensor nodes are synchronized with Root node.

In order to study the influence under different conditions, nodes' environment is changed purposely as showed below:

- To observe influence by a difference of CPU and memory, we changed a model of a PC of MACHINE01 to 03 and MACHINE04 to 08.
- To observe influence by a difference of network interface, we changed a network interface card (NIC) of MACHINE05 and MACHINE07.
- To observe influence by a difference of a hierarchy of network topology, we let two switching hubs go by way of MACHINE03 and MACHINE06 in addition.

For each of these two algorithms, experiments are executed eight times. The results are shown in Figure10. Figure10 shows clock gaps between a Root node and sensor nodes just after they are synchronized.

With Function generator, sine wave is inputted into all Sensor nodes and Root node simultaneously. Wave pattern is observed in each node and a time gap can be evaluated by observing the phase difference between two wave patterns.

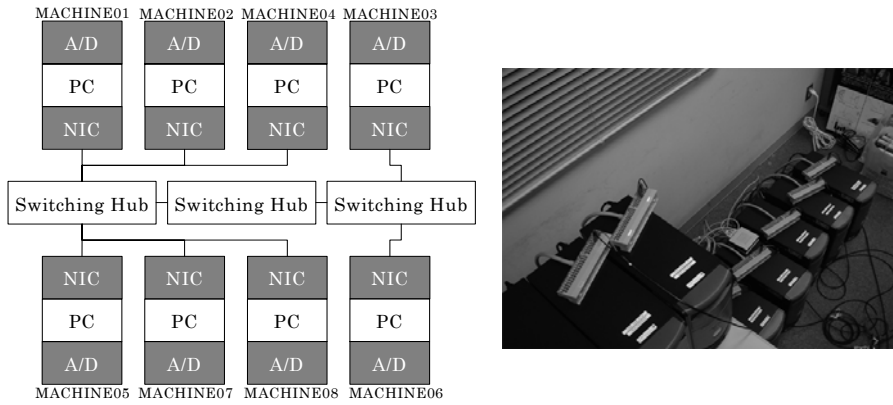


Figure5. Figure of network constitution and Experimental devices

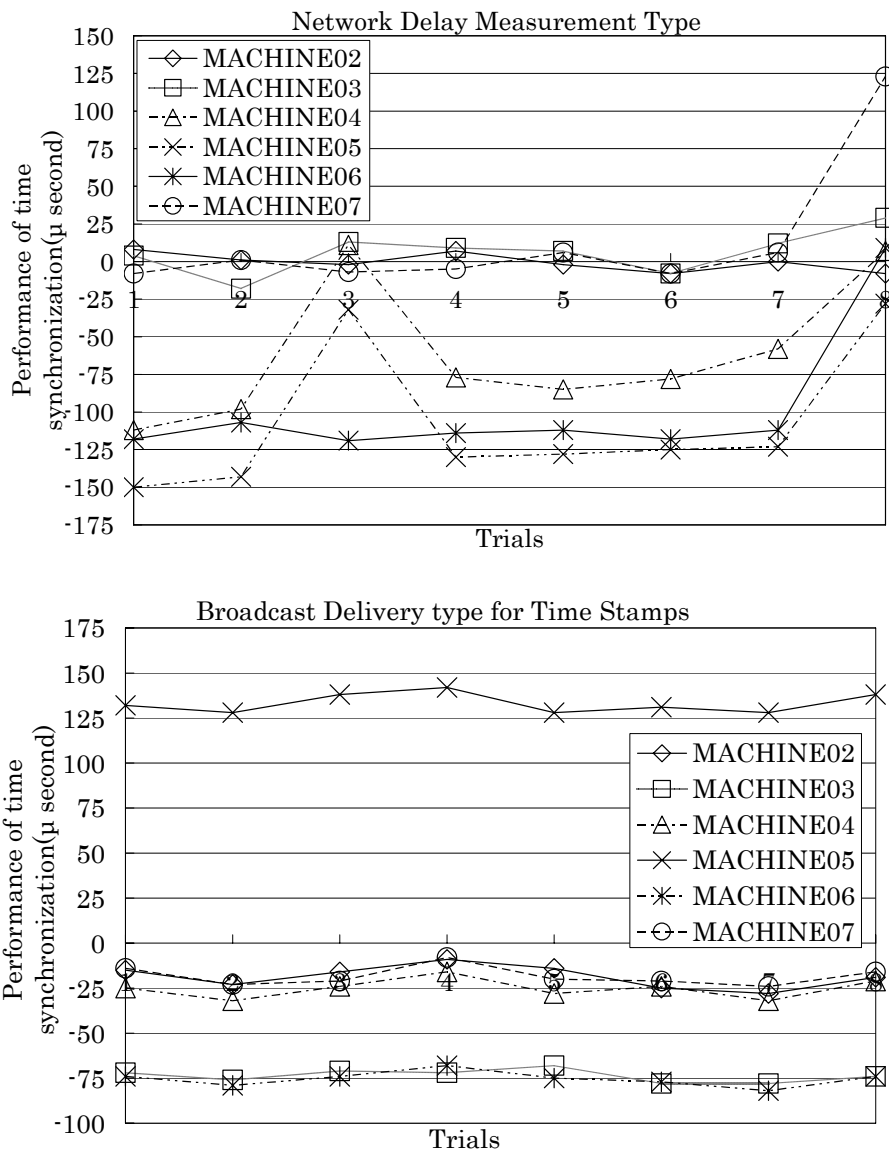


Figure6. Results of performance evaluation experiments of Time Synchronization (Top: Network Delay Measurement Type, Bottom: Broadcast Delivery Type)

DISCUSSION

Time Synchronization is a basic technology for the Sensor Grid which is used for structural health monitoring.

We examined two simple algorithms under the conditions mentioned in section 4. Based on implementation experiments, we are considering what kind of synchronization technique is feasible for implementing a Time Synchronization system.

For proposing these very simple protocols, we used two communication protocols, TCP and UDP. In these protocols, nodes achieve time synchronization by transmitting and receiving a packet.

At first the Network Delay Measurement Type is studied. The network delay caused by transferring packet from a node to the other was measured. With Root node delivering its own time, time synchronization can be achieved considering the measured network delay.

Then, the Broadcast Delivery type for Time Stamps method was also studied. Nodes set time stamps when they hear the broadcasted packets and use the reception time to evaluate gaps of the time between nodes. Thus time synchronization can also be achieved.

In Network Delay Measurement Type, even if network topology was different, for node whose environment is the same as that of the Root node (MACHINE02, MACHINE03), accuracy of $8.50 \pm 7.22\mu$ sec can be achieved. The experiment results varied little so that stable time synchronization can be achieved. However, instability was seen in performance for a node that has a different environment. In Network Delay Measurement Type, it was confirmed that performance was not affected by network environment such as network topology or difference of NIC.

In Broadcast Delivery type for Time Stamps, stable performance was shown for every trial. Under the same network topology, accuracies for all nodes except MACHINE05 were stable, within $20.8 \pm 6.37\mu$ sec. As for MACHINE05, performance showed a stable result in $133 \pm 5.49\mu$ sec. The reason is that NIC of MACHINE05 was changed to a thing with an FIFO buffering function. In addition, performance of MACHINE03 and MACHINE06 whose hierarchy of network topology was different from other nodes was $74.5 \pm 3.83\mu$ sec. From this, we are able to know that performance is not so good for a different hierarchy of network topology in Broadcast Delivery type for Time Stamps. However, there was little change of performance for every trial under a certain topology environment and thus showed a stable performance.

The best performance is found in Network Delay Measurement Type, but this technique has a poor stability. However, Broadcast Delivery type for Time Stamps was inferior to Network Delay Measurement Type in performance of the time synchronization, but was able to have good stability. Performance stability is very important. However, Broadcast Delivery type for Time Stamps shows a peculiar performance under particular environments (a network, topology, hardware and others) of a node.

By considering all of these facts, a better and feasible time synchronization system may be established.

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