Poster Abstract: A Quantitative Error Analysis of Synchronized Sampling on Wireless Sensor Networks for Earthquake Monitoring

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1. INTRODUCTION

Wireless sensor network technology enables low-cost and high-density earthquake monitoring. The earthquake monitoring measures structural vibrations caused by earthquakes. The earthquake monitoring contributes the progress of earthquake engineering and earthquake resistant technology. If we acquire high quality vibration data, we can precisely estimate structural damage.

However, the high quality sensing is difficult because of the distribution manner of wireless sensor networks. In [3], we described overview of our earthquake monitoring. In this paper, we focus on a synchronized sampling mechanism in the earthquake monitoring: especially, its design and evaluation. Section 2 discusses what kind of factors cause sensing error in wireless sensor networks, Section 3 propose a synchronized low-jitter sampling mechanism, which minimize sensing error, and Section 4 evaluates the synchronized low-jitter sampling using a shaking table. Finally, Section 5 concludes this work.

2. ERROR FACTORS ON WIRELESS SENSOR NETWORKS

Earthquake monitoring requires high accuracy sensing, because inaccurate sensor data cannot be used for structural or earthquake analysis. In this section, we discuss what kind of factors affect sensing accuracy on wireless sensor networks.

There are three factors in sensing error in wireless sensor networks: sampling error, sensor noise, and quantization error. Sampling error is caused by sampling jitter as shown in Figure 1. Sampling jitters are caused by timing differences between an ideal timing and an actual timing, and the sampling error depends on sampling jitter and frequency components of measured signals. The sensor noise is caused by Gaussian white noise, which the sensor has. The quantization error is caused by the resolution of an AD converter and sensitivity of the sensor.

In these factors, the sampling error is the most important factor in wireless sensor networks. Ideal sampling for earthquake monitoring is as follows: all sensor nodes synchronously sample sensor data, and the sampling intervals are constant at any time. The synchronous sampling is required to estimate correlation among the all sensor nodes. If we acquire the correlation among nodes, we can estimate story drift of the structure, and the story drift is a key indicator of structural safety. The constant intervals are required to restore a precise original waveform.

The wireless sensor networks cannot achieve the ideal sampling because of two characteristics. First, sampling tasks on sensor nodes are scheduled with software while existing wired sensing is designed with hardware. The software based task-scheduling makes difficulty for time-sensitive applications. For example, in case of using TinyOS, a sampling task is invoked after indeterministic delay. Therefore, TinyOS cannot sample acceleration in the ideal timings [1].

Second, wireless sensor networks are a distributed system: each node has an individual clock, and the clocks have inherent errors. The inherent errors make sampling jitter, and the jitter becomes larger when the measurement time becomes longer because of the accumulation of sampling interval difference even if we use time-synchronization protocol like FTSP [2]. On the other hand, since existing wired sensing systems are centralized systems, the wired sensing does not have jitter on the sampling points.

There are some works, which focus on vibration monitoring with wireless sensor networks [1][4]. However, the works did not consider sampling jitter. Although [1] achieved low-jitter sampling, the work lacks quantitative evaluation of the sampling error.

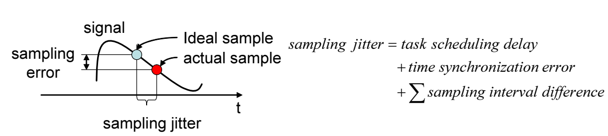

Figure 1: Sampling Error

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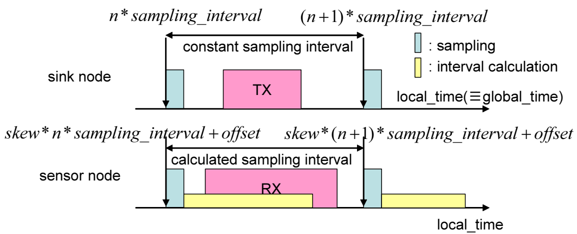

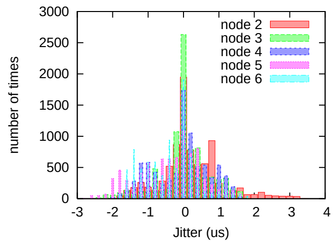

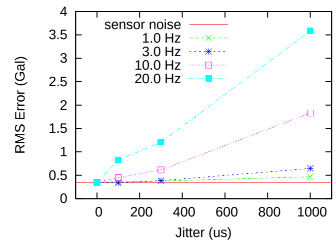

Figure 2: Synchronized Low-Jitter Sampling **Figure 3: Jitter Histogram** **Figure 5: Error Evaluation**

3. SYNCHRONIZED LOW-JITTER SAMPLING

We designed and implemented a synchronized low-jitter sampling mechanism based on the discussion in Section 2. The mechanism allows each node to synchronously sample sensor data among all nodes by adjusting every sampling interval, and distributes the sampling jitter to each sample.

Brief overview of the synchronized low-jitter sampling mechanism is as follows. The sink node samples acceleration with constant interval and broadcasts synchronization packets periodically. Each sensor node synchronizes itself to the sink node, like FTSP, with MAC-Layer time-stamping and linear regression. Sensor nodes calculate adequate sampling interval per sample based on synchronization information such as skew and offset as shown in Figure 2, and the calculated interval is set to a CPU timer compare register.

In the synchronized low-jitter sampling mechanism, a sampling task is deterministically invoked. We implemented the mechanism on a compact hard real-time operating system for sensor nodes, called as PAVENET OS [3]. PAVENET OS provides three task priorities: high-priority, low-priority, and best-effort. Higher priority tasks can preempt tasks which have lower priorities. In this implementation, high priority tasks are a wireless communication task and a sampling task, and the other tasks are low-priority or best-effort tasks. To eliminate the indeterministic delay by wireless communication, we developed a sampling synchronized MAC protocol: the wireless media is turned on 1 ms after sampling and is turned off 1 ms before next sampling.

4. EVALUATION

First, we evaluated the synchronization accuracy using a logic analyzer. The results shows that all nodes synchronously sample acceleration within 3.4 us maximum jitter and 0.7 us average jitter, as shown in Figure 3: single-hop, sync interval=20.48 s, and linear regression points = 4.

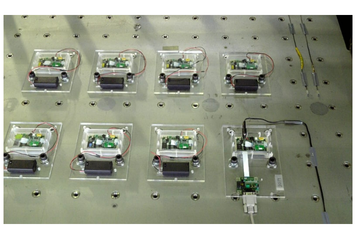

Figure 4: Shaking Table Test

Second, we evaluated the synchronized low-jitter sampling mechanism using a shaking table as shown in Figure 4. A shaking table is an instrument for earthquake engineering, and can experimentally shake the table with an arbitrary input signal. Because the shaking table is rigid body, the table gives same acceleration to all nodes. We compared the output from nodes, and evaluated the measurement error.

Our sensor node has an acceleration sensor, which has 50 uG/$\sqrt{Hz}$ noise level (1 G=981 Gal), Vdd/5G sensitivity, a 50 Hz cut-off low-pass-filter, and a 16-bit resolution AD converter. Therefore, the sensor nodes have 0.347 Gal RMS Gaussian error and 0.0763 Gal identically-distributed error. We used sine waves as input, their frequencies are 20 Hz, 10 Hz, 3 Hz, and 1 Hz, and their amplitudes are about 60 Gal. The waves assume frequency characteristics of earthquake waves. To evaluate sampling error by sampling jitter, we used 6 nodes, including a sink node, three jitter injected nodes (the delay is 1 ms, 300 us, or 100 us), and two jitter-less sensor node.

The result is shown in Figure 5. The 1 ms jitter injected node shows 3.59 Gal RMS error at the 20 Hz sine wave. It means that inaccurate time-synchronization or task-scheduling delay affects sensing quality. On the other hand, jitter-less sensor nodes show 0.357 Gal RMS error at the 20 Hz sin wave. This value means that the mechanism reduces sampling error to 2.8% of entire error.

5. CONCLUSION

We have proposed a synchronized low-jitter sampling mechanism, and the mechanism reduces the sampling error to 2.8% of entire error. The wireless sensor networks with the mechanism achieve almost the same accuracy as existing wired sensing systems. Currently, we are studying a limitation of measurement accuracy and the relation between accuracy and power consumption on the wireless sensor networks.

6. REFERENCES

[1] S. Kim, S. Pakzad, D. Culler, J. Demmel, G. Fenves, S. Glaser, and M. Turon. Health monitoring of civil infrastructures using wireless sensor networks. In *Proc. of IPSN*, pages 254–263, April 2007.

[2] M. Maroti, B. Kusy, G. Simon, and A. Ledeczi. The flooding time synchronization protocol. In *Proc. of SenSys*, pages 39–49, November 2004.

[3] M. Suzuki, N. Kurata, S. Saruwatari, and H. Morikawa. Demo abstract: A high-density earthquake monitoring system using wireless sensor networks. In *Proc. of SenSys*, pages 373–374, November 2007.

[4] G. Werner-Allen, K. Lorincz, J. Johnson, J. Lees, and M. Welsh. Fidelity and yield in a volcano monitoring sensor network. In *Proc. of OSDI*, pages 381–396, November 2006.