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Clock Skew Compensator for Wireless Wearable Computer Systems

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Abstract

Wearable computer systems can use the wireless universal serial bus (WUSB) that refers to USB technology that is merged with WiMedia PHY/MAC technical specifications. In this paper, we focus on an integrated system of the wireless USB over the IEEE 802.15.6 wireless body area networks (WBAN) for wireless wearable computer systems supporting U-health services. This paper proposes a clock skew compensator to allow offset and skew compensations to be processed simultaneously. Our skew compensator can be easily integrated with traditional offset compensation schemes. The results of simulation and experiment show that the accuracy of time synchronization can be greatly improved through our skew compensation algorithm.

Keywords: WBAN (Wireless Body Area Networks), Wireless Home Networks, WUSB (Wireless Univeral Serial Bus), Wearable Computers

1 Introduction

Development in wireless communication and the miniaturization of computing devices, such as wearable and implantable sensors, enable next-generation communication known as body sensor networks (BSNs). Each BSN comprises several intelligent sensor nodes that should have a communication range of 3 m and dynamic data rates from 10 kbps to 10 Mbps according to application requirements [1]. Each sensor nodes monitors a human's biometric or surrounding environment information, and forward it to a hub.

A wearable medical system may encompass a wide variety of components: sensors, wearable materials, smart textiles, actuators, power supplies, wireless communication modules and links, control and processing units, interface for the user, software, and advanced algorithms for data extracting and decision making. Wearable computer systems use the wireless universal serial bus (WUSB) that refers to USB technology that is merged with WiMedia PHY/MAC technical specifications. WUSB can be applied to wireless personal area networks (WPAN) applications as well as wired USB applications such as PAN. Because WUSB specifications have defined high-speed connections between a WUSB host and WUSB devices for compatibility with USB 2.0 specifications, the wired USB applications are serviced directly [2-6].

A wireless body area network (WBAN), which describes the application of wearable computing devices, allows the integration of intelligent, miniaturized, low-power, invasive/non-invasive sensor nodes that monitor body functions and the surrounding environment [7].

In this paper, we focus on an integrated system of the wireless USB over the IEEE 802.15.6 wireless body area networks (WBAN) for wireless wearable computer systems supporting U-health services. This paper proposes a clock skew compensator to allow offset and skew compensations to be processed simultaneously. Our skew compensator can be easily integrated with traditional offset compensation schemes. The results of simulation and experiment show that the accuracy of time synchronization can be greatly improved through our skew compensation algorithm [8].

2 WUSB OVER WBAN ARCHITECTURE FOR BSNs

The WUSB channel is a continuous sequence of linked application-specific control packets, called micro-scheduled management commands (MMCs). WUSB maps the USB 2.0 transaction protocol onto the TDMA micro-scheduling feature. MMCs are used to advertise channel time allocations for point-to-point data communications between the host and the endpoints of the devices in the WUSB cluster. An MMC specifies the linked stream of wireless USB channel time allocation (WCTA) blocks up to the next MMC [4]. The information element (IE) fields in an MMC are called WUSB channel IEs and they include device notification time slots (DNTS), protocol time-slot allocations (Device Receive : DR, Device Transmit : DT) and host information.

In the WUSB over WBAN Architecture [9], in order to set up a wireless communication link to BSNs, secure WUSB private channels should be encapsulated within a WBAN superframe. This enables the MMC scheduling between WUSB host and its several peripheral devices without contention. In the Type-I/II access phase periods, the WBAN hub reserves time slots without contention to exchange WUSB data transactions with its WUSB devices [4]. In this scenario, the user carries a portable or BSN host device. This host device performs roles of the WUSB host and the WBAN hub simultaneously. Therefore, a wearable WUSB cluster and a WBAN cluster can be formed. The attached input-sensor nodes perform the functions of localization-based input interfaces for BSN's healthcare monitoring.

3 WUSB over WBAN Clock Skew Compensation

A clock generally consists of a periodic component such as an oscillator and a counting component. The time reported by a clock at some ideal time t is written as $C(t)$. We will write $C_A(t)$ as the time given by the local clock of Node A. The difference between the time of an ideal clock and a given clock is said to be the offset, $\theta(t)$. The relative offset between Node A and Node B from the viewpoint of Node B, $\theta_B^A(t)$, is defined as:

$$\theta(t) = t - C(t)\,. \qquad \theta_B^A(t) = C_A(t) - C_B(t)\,. \tag{1}$$

The difference between the rate these pulses are produced at the oscillator and the rate an ideal clock counts the desired interval, is called the skew (frequency offset). Let $\varepsilon(t)$ denote the skew. The clock skew is the slope of the change in offset compared to the local clock. The slope of the relative offset $\theta_B^A(t)$ is relative skew $\varepsilon_B^A(t)$. This value means the skew of Node A's timer from the viewpoint of Node B's timer and defined as:

$$\varepsilon(t) = \frac{1}{C'(t)} - 1 \ , \qquad \varepsilon_B^A(t) = \frac{C_A'(t)}{C_B'(t)} - 1 = \frac{\varepsilon_B(t)+1}{\varepsilon_A(t)+1} - 1 \tag{2}$$

If we refer the operating frequency of Node B's clock to f_B (e.g. 32.768 kHz), f_A and the relative skew ε_B^A have another form of definition as (3).

$$f_A = f_B(1+\varepsilon_B^A) \ , \qquad \varepsilon_B^A = \frac{f_A}{f_B} - 1 \tag{3}$$

In the context of WBANs, time synchronization refers to the problem of synchronizing clocks across a set of WBAN sensor nodes which are connected to one another over single-hop or multi-hop wireless networks. The time synchronization problem in WBANs generally involves two steps. The first is synchronizing the nodes in the network to one common absolute time by adjusting the clock offset among the nodes, and the second is correcting the clock skew relative to a certain standard frequency.

In the synchronization process of WBAN Node B's clock to synchronize with WBAN Node A's clock, we assume that two clocks have the identical initial value for the sake of simplicity. Since each oscillator has its unique clock frequency, the clock offset between two nodes keeps increasing. If WBAN Node B determines the relative offsets $\theta_B^A(t)$ and executes offset compensation at *t1, t2, t3,* and *t4*, the corresponding synchronized clock will be $C_B^O(t)$. Since the offset compensation does not take the impact of clock drift into account, $C_B^O(t)$ keeps the same varying rate and drifts away from $C_A(t)$. This suggests that the longer the synchronization (offset compensation) interval, the larger the synchronization error. In order to improve precision we can decrease the synchronization period, but this will introduce too much communication overhead. If the relative clock skew $\varepsilon_B^A(t)$ is accurately estimated, we can build a synchronized clock as $C_B^{OS}(t)$. $C_B^{OS}(t)$ approximately approaches $C_A(t)$ although it does not completely synchronize with $C_A(t)$.

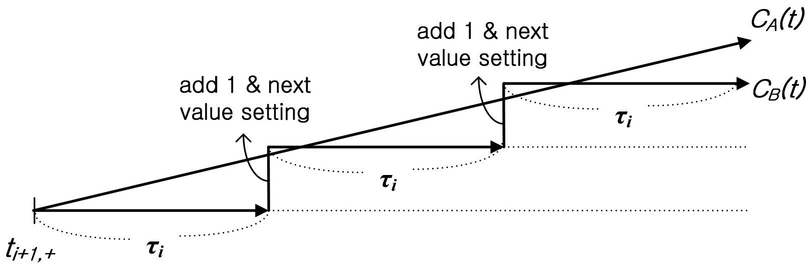

Fig. 1. Process of skew compensation

After completing *(i+1)*-th offset compensation, the new estimator of WBAN Node B's skew, $\hat{E}[i]$ can be obtained. We derive $\hat{E}[i]$ as follows.

$$\begin{aligned} \hat{E}[1] &= \frac{\varepsilon[0]+\varepsilon[1]}{2} = \varepsilon_{B,0}^{A} + \frac{1}{2}\varepsilon_{B,1}^{A}(1+\varepsilon_{B,0}^{A}) \\ \hat{E}[i] &= \frac{i}{i+1}\hat{E}[i-1] + \frac{1}{i+1}\varepsilon[i] \\ &= \hat{E}[i-1] + \frac{1}{i+1}\varepsilon_{B,i}^{A}(1+\hat{E}[i-1]) \end{aligned} \tag{4}$$

Our clock skew estimators are updated whenever new clock offset is obtained through two-way message exchange. However, it is possible that the offset value newly obtained is strange due to several reasons such as reset of a WBAN slave node and alternation of the WBAN sink hub node. In this case, the strange offset value is only used for offset compensation and should not be reflected to the skew estimator. Denoting ρ (ppm) as maximum drift rate of crystal, we reject outliers satisfying following condition, resetting i to zero. Based on the skew estimator $\hat{E}[i]$, any sensor node (WBAN Node B) can estimate the frequency of the sink node (WBAN Node A) as follows.

$$\left|\varepsilon_{B,i}^{A}\right| = \left|\frac{\hat{\theta}_{B,i+1}^{A}}{t_{i+1,-}-t_{i,+}}\right| > \rho \quad , \quad f_A = f_B(1+\hat{E}[i]) \tag{5}$$

Fig. 1 shows the procedure of skew compensation (frequency adjustment). If WBAN Node B obtains the skew estimator $\hat{E}[i]$ through *(i+1)*-th two-way message exchange, it calculates the count-value for skew compensation, τ_i, as follows.

$$\tau_i = \frac{1}{|\hat{E}[i]|} \tag{6}$$

Next, WBAN Node B sets up its compare register count to the value of $(t_{i+1,+} + \tau_i)$. When the timer of WBAN Node B reaches the value, the compare interrupt of WBAN Node B will be generated. In the compare interrupt service routine, WBAN Node B should execute two operations. First, to adjust its frequency continuously, Node B sets up its compare register count to the next value $(C_B(t)+ \tau_i)$, where $C_B(t)$ is the current timer count of WBAN Node B. Second, WBAN Node B just adds 1 to its current clock count if $\hat{E}[i]$ is bigger than zero, and subtracts 1 from its current clock count if not. In this way, although not adjusting its frequency perfectly, a WBAN sensor node can adjust its own frequency flexibly to some degree.

4 Simulation Results

To validate our skew compensation algorithm, we implemented it on the WBAN sensor node. For testing time synchronization, the WBAN sensor node used the 32.778 kHz real time clock. The maximum drift rate of crystal is ±25 ppm. We built a multi-hop (to the maximum 5) WUSB over WBAN network, which consists of 30 WBAN sensor nodes. To measure the synchronization precision, we make each WBAN sensor node report the clock offset (θ_i) to the WBAN Host sink node whenever it performs offset compensation after two-way message exchange. The WBAN Host sink node controls the initiation of two-way message exchange and its interval. Once initialized by the sink node, the synchronization procedure of exchanging two-way message can be driven to whole network along each network edge.

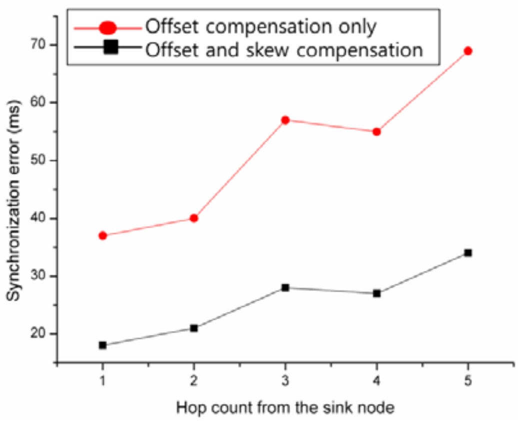

Fig. 2. Synchronization errors at each offset and skew compensation cases

First, for checking the effect of clock skew, we allowed WBAN sensor nodes to perform only offset compensation. The data reported from each WBAN sensor node are averaged according to hop count during 1 hour. After that, we allowed WBAN sensor nodes to perform both offset and skew compensation during the same time period. Fig. 2 shows this result, average of synchronization error at both systems. We thought that the synchronization errors in this figure mostly result from the relative skew. It is checked that the synchronization errors weakly tend to increase with respect to hop count from the sink node and that the effect of clock skew on synchronization error becomes considerable as time passes. But, through our clock skew compensator, the synchronization errors are reduced considerably.

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