An Accuracy Enhanced IEEE 1588 Synchronization Protocol for Dynamically Changing and Asymmetric Wireless Links

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***Abstract*—IEEE 1588 is the clock synchronization protocol for networked measurement and control system, and widely used for both wire-line and wireless network environments. IEEE 1588 was initially considered for wire-line networks, but its application is extended to wireless network especially for indoor wireless networks which can not use Global Positioning System (GPS) technology. However, the conventional IEEE 1588 assumes symmetric/asymmetric fixed data rate links, and time accuracy errors are caused for dynamically changing wireless links. We propose an enhanced synchronization algorithm for IEEE 1588 in order to compensate the offset error due to the dynamically changing data rate of the wireless link and to enhance the accuracy of time.**

***Index Terms*—Synchronization, IEEE1588, wireless link.**

I. Introduction

IEEE 1588 is the precision time protocol (PTP) between the master and slave clocks for clock synchronization in networked measurement and control systems [1]. And, it is widely considered as the synchronization scheme for wireless networks also. Especially, when we consider indoor network environments, GPS can not be used, and network based synchronization is required [2][3][4]. Two main functions of the IEEE 1588 are establishing a master-slave hierarchy of clocks in which each slave synchronizes to its master, and making the necessary information available for the slave to perform this synchronization. IEEE 1588 employs stamping certain messages as in Figure 1, where D_{wd}, D_{ad}, D_{au}, and D_{wu} are transmission delays for each link, and D_{pd} and D_{pu} represent the processing delays in the respective switches.

The master sends the synchronization ($Sync$) message at a default rate of once every two seconds, and the master clock measures the time $T1$ at which the $Sync$ message is sent. When a slave clock receives the $Sync$ message, it measures and stores the time of receipt $T2$. The slave periodically sends $Delay\_Req$ messages and stores their transmission time with a timestamp $T3$. When the master clock receives the $Delay\_Req$ message, it sends a $Delay\_Resp$ message, which contains the time stamp $T4$ of the reception time for the matching request message. Comparing these time stamps, the slave clock calculates the path delay between the master to the slave using Equation (1), where α is (O_{mwd}+D_{pd}+O_{mad}), β is (O_{mau}+D_{pu}+O_{mwu}).

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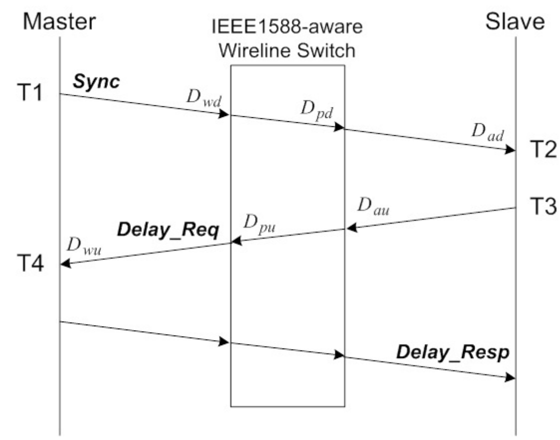

Fig. 1. IEEE 1588 messaging timing diagram.

$$D_{onepath} = \frac{(T2 - T3) + (T4 - T1) - \alpha - \beta}{2} \quad (1)$$

The variable Os are defined in Equation (2) and (3), where D_a is $\frac{D_{ad}+D_{au}}{2}$, and D_w is $\frac{D_{wd}+D_{wu}}{2}$.

$$O_{mad} = D_{ad} - D_a, O_{mau} = D_{au} - D_a \quad (2)$$

$$O_{mwd} = D_{wd} - D_w, O_{mwu} = D_{wu} - D_w \quad (3)$$

Using Equations (1), (2) and (3), the offset, time synchronization error of the slave clock, with respect to the master, can be calculated as in Equation (4).

$$Offset = (T2 - T1) - D_{onepath} - \alpha \quad (4)$$

The slave clock adjusts its time to minimize the offset value, thereby synchronizing with the master. The use of the two-way exchange of the timing messages allows the actual propagation time between the master and slave nodes to be corrected. If uncorrected, this time would appear as an offset or bias in the times of the two clocks. The latest IEEE 1588, which was publically released in July 2008, considers the asymmetric links, and Equation (4) shows the corrected offset value for the asymmetric links using the delay differentiation between the up and down links. When asymmetric link is used, the difference of transmission and propagation delay between paired uplink and downlink should be known before the IEEE 1588 messaging is accomplished. And, the difference should not be changed during the IEEE 1588 messaging procedures between master and slave. But, specific procedure for the identification of the difference between uplink and downlink is not clear in the standard. This characteristic causes the inaccuracy problem when IEEE 1588 is applied

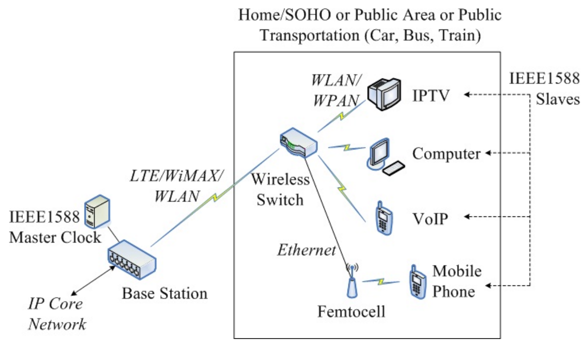

Fig. 2. IEEE 1588 PTP for wireless network.

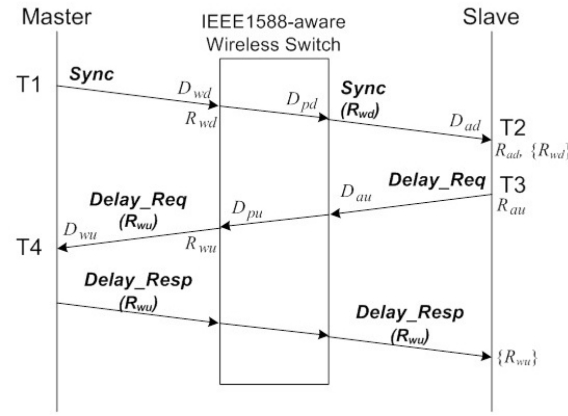

Fig. 3. Dynamic data rate awareness procedure.

for mobile wireless network environments where the data rate is dynamically changed for channel condition, user mobility, and service characteristics.

Especially, if we consider wireless Ad-Hoc network as in Figure 2, master node is located at the wired network, and slave nodes are connected to a relay node. Communication between the relay node and slave nodes, and the relay node and master node are mobile wireless links like Wireless Local Area Network, $2^{nd}/3^{rd}/4^{th}$ generation mobile broadband technologies (such as Long Term Evolution (LTE), and Mobile WiMAX), and Wireless Personal Area Network. Wireless links exhibit dynamically changing data rate characteristics. The first reason for the dynamic data rate is due to the speed of the mobile station. If the mobile station is in a pedestrian state, the data rate is near stable without fluctuation. However, as the mobile station increases in speed, the data rate becomes unstable and fluctuates due to the rapidly changing mobile wireless link quality. The second reason for the dynamically changing data rate characteristics is common for the latest packet-oriented wireless technologies. Wireless data link is a shared high-speed pipe for multiple simultaneous users. Thus, the single pipe is shared time-wise between multiple users, and the allocated time slot size and duration vary for each scheduled interval. Also, wireless link condition, such as mobility and error conditions, causes dynamically changing data rate. The third reason is the asymmetric duplexing mechanism of conventional packet wireless technologies. For example, Mobile-WiMAX and LTE prefers Time Division Duplexing for human web services, where a single channel is shared between the uplink and downlink. However, due to the asymmetric traffic characteristics of the conventional packet services such as the Web, a larger bandwidth is allocated to the downlink compared to that of the uplink. These dynamic and asymmetric characteristics cause offset error in time synchronization between the IEEE 1588 master and slave. However, conventional works on IEEE 1588 over wireless links focus on the experimental systems and the performance measurements of conventional IEEE 1588 standard over wireless links. And, its enhancement is in initial phase [2][3][4].

We propose herein an enhanced IEEE 1588 synchronization algorithm to calculate the asymmetric ratio of a dynamically changing wireless link. The proposed algorithm enables the exact offset time and can reduce the bias error for time synchronization. The proposed algorithm is described in Section II. The performance of the proposed algorithm is evaluated in Section III. Section IV concludes and presents suggestions.

II. An Enhanced Synchronization Algorithm

The goal of the proposed algorithm is to calculate the asymmetric ratio of dynamically changing wireless communication links. The proposed algorithm is described in Figure 3.

In mobile wireless networks, the mobile device and the base station know the data rate for each message transferred over the wireless link. Conventional cellular base stations allocate the data rate for uplink and downlink based on the available bandwidth, the air condition, and its associated buffer status. Thus mobile device and the base station know the data rate which is selected from the pre-defined data rate sets.

In the proposed algorithm, the mobile station stores the data rate for IEEE 1588 message transmission and reception. As in Figure 3, the new parameter R_{ad} (the data rate used to transmit a message from the wireless switch to the slave node via the wireless link), and R_{au} (the data rate used to transmit a message from the slave node to the wireless switch via the wireless link), R_{wd} (the data rate used to transmit a message from the wireless switch to the slave node via the wireless link), and R_{wu} (the data rate used to transmit a message from the slave node to the wireless switch via the wireless link) are proposed. Using these new parameters, we can re-define D_{ad}, D_{au}, D_{wd} and D_{wu} as shown in Equation (5) and (6).

$$D_{ad} = \frac{B_{Sync}}{R_{ad}}, D_{au} = \frac{B_{DelayReq}}{R_{au}} \tag{5}$$

$$D_{wd} = \frac{B_{Sync}}{R_{wd}}, D_{wu} = \frac{B_{DelayReq}}{R_{wu}} \tag{6}$$

In Equation (5) and (6), B_{Sync} and $B_{DelayReq}$ are the sizes of the $Sync$ message and $Delay\_Req$ message, respectively. Thus, in the proposed algorithm, we can dynamically calculate O_{mad}, O_{mau}, O_{mwd} and O_{mwu} using the actual data rate used to transmit and receive IEEE 1588 messages.

Using Equations (5) and (6), the offset, which is time synchronization error of the slave clock, with respect to the master, can be calculated as in Equation (1), (2), (3) and (4).

We can calculate the exact offset value of the slave for the dynamically changing wireless links especially for Ad-Hoc networks. We can also eliminate the bias error in the time synchronization between IEEE 1588 master and slave for

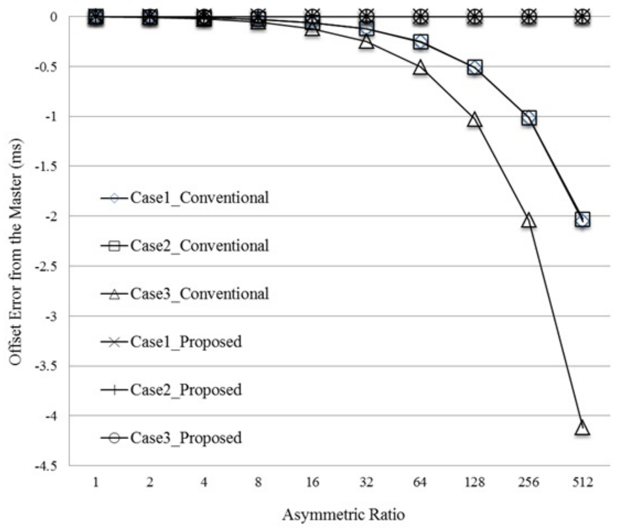

Fig. 4. Offset bias error in the slave clock.

TABLE I
PERFORMANCE EVALUATION PARAMETERS

	Case1	Case2	Case3
D_{pd}	207.4ns	207.4ns	207.4ns
D_{pu}	237.4ns	237.4ns	237.4ns
R_{ad}	100Mbps	100Mbps	100Mbps
R_{wd}	100Mbps	100Mbps	100Mbps
R_{au}	100Mbps−200Kbps	100Mbps	100Mbps−200Kbps
R_{wu}	100Mbps	100Mbps−200Kbps	100Mbps−200Kbps

non-fixed asymmetric wireless communication links through simple enhancements at the network elements.

III. PERFORMANCE EVALUATION

The performances of the proposed algorithm and conventional algorithm were evaluated via analysis and simulation. We assumed the same environments as in Annex C.2.1 of the IEEE 1588 standard document, and the standard message sizes for $Sync$, $Delay\_Req$, and $Delay\_Res$ are used as in IEEE 1588 standard. Offset from Master is +25.2ns. And, in Table 1, D_{pd} and D_{pu} are fixed values. But, R_{ad}, R_{wd}, R_{au}, and R_{wu} are mean values with exponential distribution. According to R_{au} and R_{wu}, mean values are decreased in order to investigate the effect of the asymmetric ratio.

In order to compare the accuracies of the proposed algorithm and the conventional algorithm, we calculated the offset bias error (E_{offset}) as in Equation (7).

$$E_{offset}(ms) = CalculatedOffset - RealOffset \quad (7)$$

Figure 4 shows the calculated offset error in the slave (relative to that of the master) according to the asymmetric ratio between the wireless uplink and downlink.

The offset error for the conventional algorithm increased as the asymmetric ratio between the uplink and the downlink increased. These results show that conventional IEEE 1588 cannot provide accurate synchronization for dynamically changing asymmetric wireless systems. According to simulation cases, larger error is caused in Case 3, where the asymmetric ratio and data rate are dynamically changed for both R_{au} and R_{wu}. Also the conventional method cannot satisfy the strict accuracy requirement for synchronization in 3G/4G base stations, which is commonly used for 3G/4G Femtocell and Relay-node implementation [5]. However, the proposed algorithm shows that the offset errors for all asymmetric ratios are theoretically near $10^{-3}ns$ level in given condition. This is due to the wireless link data rate awareness characteristic of the enhanced synchronization algorithm, which enables the exact transmission calculation of IEEE 1588 message transmission delays for dynamically changing downlinks and uplinks.

IV. CONCLUSION

The quality of a time-based transfer like IEEE 1588 depends heavily upon the packet delay variation between the master and the slave. The time transfer accuracy in mobile wireless links is severely affected by the dynamic data rate change due to the movement of the mobile station, the shared pipe characteristics of the conventional packet-oriented wireless technologies and the asymmetric duplexing method. The proposed algorithm is efficient for synchronization using dynamically changing asymmetric wireless links. As a result, the bias error in the slave is reduced to $10^{-3}ns$. Thus, we enable IEEE 1588-based accurate time synchronization for mobile wireless Ad-hoc networks, which uses dynamically changing wireless links and IEEE 1588 time synchronization protocols between the master node, the wireless switch, and the slaves.

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