Synchronization and Time Resolution Improvement for 802.11 WLAN OWPT Measurement

Xinrui. Wang, Tien-Fu. Lu, Lei. Chen

***Abstract*-This paper proposes novel algorithms for synchronizations and time resolution improvements of One Way Propagation Time (OWPT) measurement in the 802.11 Wireless Local Area Network (WLAN). In OWPT measurement, the Mobile Station (MS) records each 802.11 Beacon frame's arrival time. The Beacon frame's arrival time minus its Timestamp, which is recorded when the Beacon frame is transmitted from an Access Point (AP), is the Beacon frame's Propagation Time. The Propagation Time represents the distance between the MS and the AP. Different from microseconds (*μs*) time resolution Timestamp, the MS can use its high frequency clock to record the Beacon frame's arrival time in nanoseconds (*ns*). The proposed algorithms can utilize the *ns* resolution arrival Time to improve the OWPT measurement time resolution from *μs* to *ns* and to highly synchronize the MS with all APs. These algorithms provide opportunity to apply OWPT in 802.11 WLAN for highly accurate indoor localization. In theory, without considering other indoor localization error sources, these algorithms can improve the localization accuracy to sub-meter.**

***Index Terms*-Synchronization, OWPT, 802.11 WLAN, Indoor Localization, Time Resolution Improvement**

I. INTRODUCTION

Indoor localization technologies have attracted considerable research interest over the last 20 years due to a wide range of application areas. Indoor localization technologies are the foundation of domestic robots navigation and mapping. The location information can also be used for tracking people, goods and equipment in buildings to benefit home entertainment, stock management and improving office work efficiency etc. The widely applied outdoor localization technology GPS, however, is hard to apply in indoor environments and dense urban areas. As the satellites' signals are reflected and/or diffracted by building structures, the receivers can not receive clear and strong enough satellite signals for localization purposes in these areas.

Many indoor localization technologies have been under continuous development in the previous decades to replace GPS in providing indoor localization services. Generally, these localization technologies can be categorised by the type of sensors being used, including target sensors, distance proximity sensors, visual cameras and wireless sensors. With the target sensors localizations, infrared sensors or Radio Frequency IDs (RFID) are mounted on MS with relevant receivers on walls, or vice versa. The positions of the receivers (or sensors) fixed on the walls are recorded. When the MS is detected by one of the sensors or receivers on the walls, the MS's location is considered to be the same position as the sensor or the receiver. Distance proximity sensors, like sonar sensors, laser range finders etc. detect distances between the MS and objects, which are normally building structures, such as walls, corners and doors etc. The MS locates itself according to its distances away from these objects. Visual camera localization utilizes images of the surroundings. The MS compares the landmarks on the pictures which it is taking with the pre-taken pictures of the whole building from a database. The matching pre-taken picture's location is assumed to be the location of the MS. Wireless signals measurement was originally developed for wireless sensors network localization. Now with the 802.11 WLAN being applied since 1999, nowadays, many workplaces, hospitals, schools, libraries and public places have WLAN to provide Internet access. All of these places are typical domestic robots application areas. Hence, many researchers are working on applying wireless signals measurement technologies on WLAN for indoor localization. By contrast with other localization technologies, including wireless sensors network, one of the most significant benefits to apply wireless signals measurement on WLAN for localization is low cost. Usually, WLAN is built by Internet Service Providers (ISP), especially in public areas. When the localization is implemented, there is no need to distribute targets or to build the localization networks. MSs can utilize the existing WLAN infrastructures. With an off the shelf wireless adapter, MSs are able to receive enough information from WLAN for localization. The price of a wireless adapter is much cheaper than a visual camera or a laser range finder.

Wireless signal measurement localization technologies can be further divided into three sub-categories, according to the different wireless signal features employed for localization. They are Angle-of-Arrival (AOA), Received-Signal-Strength (RSS) and Time-of-Arrival (TOA) [1].

AOA measures the angles from incident waves to a reference direction, such as, the orientation of the robot. The MS records wireless signals amplitude responses with an anisotropy antenna or phase responses with an antenna array. The received signal amplitude or phase responses represent the angles between the APs and the MS. Then the MS's position can be estimated using triangulation with the angles

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from 3 or more different APs. The localization accuracy of AOA depends on the sensitivity of the antenna, or on the size of the antenna array.

RSS builds a signal strength fingerprint map of the working area based on real-time measurements [2] or wireless signal propagation models [3]. The signal strength fingerprint map consists of many sample points' signal strength and their coordinates refer to the working area. These sample points are distributed through the whole working area. When the MS is locating, it compares the receiving signal strength with the signal strength fingerprint map. The position of the sample point which has the most similar signal strength is assumed to be the MS position.

TOA measures the time lapsed when the signal transfers from AP to MS or from MS to AP then back to MS. These two different measurement patches are called One Way Propagation Time (OWPT) and Round Trip Time (RTT) respectively. The distance between the AP and the MS is calculated from OWPT or RTT. With three or more APs, these APs' positions and the distances between these APs and the MS can be used to calculate the MS's position with Trilateration.

Comparing these three different wireless signal measurement localization technologies, TOA is chosen for further developing. AOA is not suitable for WLAN. MSs and APs usually equip small antenna in WLAN for convenience. And omni-directional antennas are normally chosen to receive more signals. So the WLAN hardware limits the AOA measurement accuracy. RSS demands considerable labour and computing ability to build the signal strength fingerprint map. But at the same time, the existing signal strength fingerprint map changes follow the changes of the indoor environment; for example, when a door is opened or closed, bulky furniture is moved or even the movements of people. Most of the former RSS localization deviations were between 5 and 10 meters. The localization deviations are too loose to apply for accurate indoor localization applications. TOA measures the signal transferring time between an AP and a MS. The keystone of the TOA measurements is the time measurement accuracy and time resolution. The localization accuracy improves as the time measurement accuracy is enhanced.

In the remain part of the paper, Section II compares two different TOA measurements, Round Trip Time (RTT) and One Way Propagation Time (OWPT). In Section III, the novel OWPT measurement algorithms are presented and discussed. The algorithms are used to synchronize AP and MS in OWPT measurement and to improve the OWPT measurement time resolution to *ns*. Section IV describes the simulation model. The simulation results are analysed and evaluated in Section V, followed by Section VI. Conclusion.

II. RELATED WORK

TOA measurement requires to accurately measure the time when a wireless frame transfers between an AP and a MS. However, the time resolution of all standard 802.11 frames is limited by the hardware and protocols to μs. As the wireless signals transfer in light speed, 1 μs time resolution leads to 300 meters localization resolution which makes it pointless for indoor localization applications. Besides the low time resolution, the synchronization errors between APs and MSs, and the processing time delays inside an AP and a MS also cause enormous time measurement errors. To improve the time resolution and eliminate the synchronization errors and processing time delays, two TOA measurement algorithms, RTT and OWPT, are introduced.

A. Round Trip Time (RTT)

To improve the time measurement resolution and avoid synchronization errors between an AP and a MS, most researchers chose RTT to measure the time when a frame is transferred between an AP and a MS. Fig. 1 demonstrates the process of RTT measurement. At first, the MS sends a Probe Request frame to an AP and records the sending time T_1. After the AP receives the request frame, a Probe Response frame is sent back to the MS and the MS records the Probe Response frame arrival time T_2. Ideally, half of the time lapsed between the time T_1 and the time T_2 is the propagation time T when the signal travels between the MS and the AP. Because all the time information is recorded by the MS clock, there's no need for synchronization between the AP and the MS. A *ns* time resolution clock on the MS could record the time T_1 and T_2. With these two advantages, RTT can measure the propagation time T in *ns* resolution and eliminate the synchronization errors.

The shortcoming of the RTT is that the time measurement includes the unknown time delay in AP. In a wireless network, the MS is not the only client which sends requests or data to an AP. As shown in Fig. 1, when the AP receives the probe request, other requests and data frames which are sent by other clients may have already arrived in the AP. The AP processes these tasks based on time sequence. The MS Probe Request has to wait in the AP stack until the AP finishes all the prior tasks. After the AP processes the Probe Request, then a Probe Response is sent out. As existing 802.11 protocols do not require the AP to record a frame's arrival time, the Probe Response only contains the AP's transmitting time in μs time resolution. ΔT, which is the time delay in the AP, is unknown. ΔT would differ from time to time, depending on how busy the wireless network is. In a busy

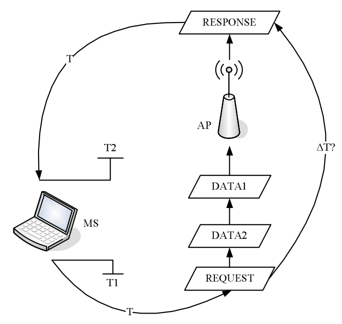


Fig. 1. RTT

wireless environment, such as public places or offices, large volumes of data are continually being exchanged between the AP and other wireless devices, like laptops, computers, PDAs etc. In these situations, RTT's localization accuracy would be deteriorated by the enlarged ΔT.

Many former researchers noticed the time delays in AP causing RTT measurement errors. Several methods were employed to eliminate the time delays in AP. In [4], a calibration was implemented before RTT measurements. A MS and an AP were put together to set T equal to 0. The difference between T_2 and T_1 was the AP time delay ΔT. In calibration, a group of ΔT were collected. In one RTT measurement, a ΔT was randomly chosen from the calibration ΔT set. The chosen ΔT was extracted from the RTT measurement. Another method was described in the project of Gunther et al. [5]. They utilized the WLAN feature that the AP and the MS send Acknowledgement frames (ACK) after they receive the Probe Requests and Probe Responses, respectively. ACK is a lower level frame which takes a much shorter time to process in an AP. They measured the time delay between the MS sent out Probe Request and received AP's ACK as the RTT. They also measured the time delay between the MS received the Probe Response till it sent out ACK. This is the processing delay in MS. The AP delay ΔT was replaced by the delay on MS and extracted from RTT to improve the RTT measurement accuracy. However, neither of these two methods can record the AP delay, ΔT, directly. The localization deviations of the above two algorithms were unstable, it ranged from 2 meters to more than 20 meters. To more accurately measure the time delay ΔT, two Intel engineers, Mr. Golden and Mr. Bateman, customized an AP and a MS to measure the time between when a frame arrived at an AP and when the AP sent the response. In this scenario, they measured the ΔT directly in every RTT measurement. In their experiment, highly accurate RTT measurement was achieved. Their results showed the RTT localization Root Mean Square Error (RMSE) to be between 1.1 and 5.5 meters [6]. As mentioned before, however, existing 802.11 WLAN hardware and protocols do not support the RTT measurement proposed in [6]. The hardware and the protocols must to be modified to implement this highly accurate RTT measurement. To improve the TOA measurement accuracy in existing WLAN, OWPT measurement is explored in this paper.

B. *One Way Propagation Time (OWPT)*

Compared with RTT, OWPT measurement is quite simple. OWPT measures the time on both MS and AP sides. As shown in Fig. 2., when a frame transfers from an AP to a MS, the transmitting time T_1 and arrival time T_2 are recorded by AP and MS respectively. The signal transferring time T is calculated from the difference between T_1 and T_2. OWPT measurement does not contain the time delay in the AP or MS, giving OWPT a big advantage over the RTT measurement. However, in OWPT measurement, APs and MSs are required to be highly synchronized, otherwise the

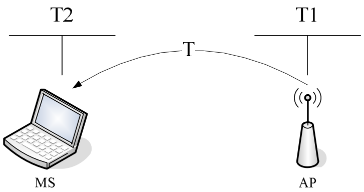


Fig. 2. OWPT

difference between T_1 and T_2 would be meaningless. To achieve sub-meter localization accuracy, the synchronization has to be on *ns* scale. Another challenge is that AP can only provide μs time resolution information. So, to reach an acceptable indoor localization accuracy, the OWPT has to be specifically measured in *ns* resolution when the time information from AP is in μs resolution. Due to the strict synchronization and time resolution requirements, in the literature, so far no researcher has tried to apply the OWPT on WLAN. There has only been a similar system called the Cricket system which was developed for OWPT measurement.

Priyantha et al. described the Cricket system in their paper [7]. In the Cricket System, the beacon nodes transmit an ultrasonic signal and a RF signal at the same time. When the receiver receives the RF signal, it treats the RF signal as a synchronization trigger and starts to count until an ultrasonic signal arrives. The time between receiving the RF signal and the ultrasonic signal is estimated as the ultrasonic signal transferring time. The distance between the receiver and the beacon node is calculated from multiplying the ultrasonic signal transferring time with the speed of sound. In their experiments, Priyantha et al. achieved the localization accuracy of about 1.2 * 1.2 meters. However, in WLAN, signals are transferring in light speed. It is impossible to find anything transferring faster than the frames to synchronize an AP and a MS.

If OWPT is going to be applied on WLAN, efficient algorithms have to be found to implement synchronization and OWPT measurement in *ns*.

III. OWPT Synchronization and Time Measurement Resolution Improvement Algorithms

A. *Introduction*

Beacon frames are the most suitable frames for OWPT measurement in 802.11 WLAN. Every AP in WLAN periodically transmits Beacon frames with the broadcasting time, which is stored in a piece of the Beacon frame field and called Timestamp. Timestamp is generated by an AP clock and records the time when the first bit of the Beacon frame hits the Physical Layer for transmission. The time resolution of Timestamp is governed by 802.11 protocols as μs, unless customized APs, commercial APs can not provide higher than 1 μs time resolution Timestamp [8]. When a MS receives the Beacon frames, every Beacon frame's arrival time is recorded by the MS. Usually, a main part of a MS is a computer or a laptop. There are many high frequency microchips in a MS to process tasks, and manage the power etc. For example, a normal CPU working frequency is much higher than 1 GHz, corresponding to less than 1 *ns* time resolution. If one of the high frequency microchip is employed as the MS clock to record the Beacon frames arrival time, at least the Beacon frames arrival time can be recorded with less than 1 *ns* time resolution. When the OWPT is calculated from the Timestamp and arrival time, these two different time resolutions introduce the possibility of improving the OWPT time resolution to *ns* and synchronize the AP and the MS to *ns* scale.

B. OWPT Measurement Time Resolution Improvement

When the Beacon frames are received, the MS obtains the Beacon frames Timestamps in μs and arrival time in *ns*. Unfortunately, to improve the OWPT measurement time resolution to *ns* is not simply subtracting the Timestamp from the arrival time, even though the results are presented in *ns* time resolution. Because of loose time resolution, there is a time delay Δt between the Beacon frame Timestamp T and the Beacon frames broadcasting time t, as shown in Fig. 3. The Δt is inherited to the OWPT measurement.

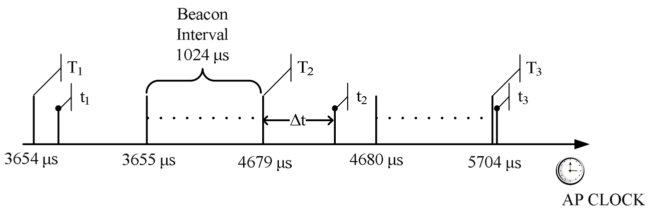


Fig. 3. Beacon Frame Broadcasting Time

Equation (1) shows the resolutions of different time elements which consist in the Beacon frames broadcasting time.

$$t \times 10^{-9} = T \times 10^{-6} + \Delta t \times 10^{-9} \tag{1}$$

t Beacon frame broadcasting time, *ns*

T Beacon frame Timestamp, μs

Δt Time delay between Timestamp and broadcasting time, *ns*

If $\Delta t \rightarrow 0$, (2) can be derived from (1):

$$t \times 10^{-9} = T \times 10^{-6} \tag{2}$$

Equation (2) reveals that the μs time resolution Timestamp can be utilized as the Beacon frame broadcasting time with *ns* time resolution if the time delay Δt is small enough.

According to 802.11 protocols, when a Beacon frame is transmitted, the time is copied from an AP clock into a Beacon frame Timestamp field. If a Beacon frame's Timestamp records the time T_1, the Beacon frame would be transmitted at any moment $T_1+\Delta t_1$ within next 1μs. The time delay Δt ranges from 0 *ns* to 999 *ns*. Randomly ranged Δt deteriorates the accuracy of OWPT measurement. To eliminate Δt, a Beacon frames selection algorithm is proposed, which utilizes the character of the randomly changed Δt, as illustrated in Fig. 4

Beacon frames are transmitted after every Beacon Interval. If the Beacon Interval is set to 1 time unit, an AP transmits a Beacon frame every 1024 μs. A MS can receive 1000 Beacon frames in approximately 1 second. If the MS is assumed to stay at the same location for about 1 second, the 1000 received beacon frames would have the same propagation time ΔT. The MS, however, can only obtain the Beacon frames' Timestamp T_n and arrival time t_n. The pseudo propagation time $\Delta T'$ is calculated in (3):

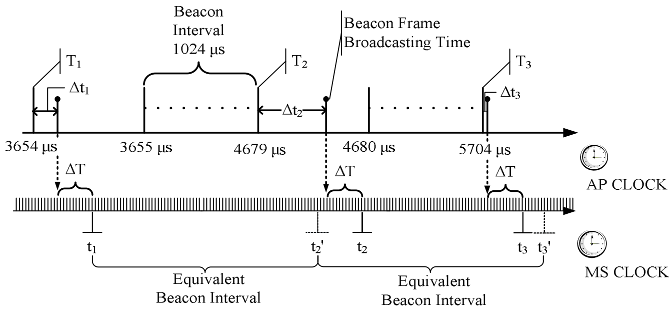


Fig. 4 Beacon Frame Transferring Time Measurement Resolution Improvement

$$\Delta T_n' = t_n - T_n = \Delta t_n + \Delta T , \qquad n \in [1,1000] \tag{3}$$

Since the existence of random time delay Δt, the pseudo propagation time $\Delta T'$ is also randomly changed. As shown in Fig. 4, the time delay Δt_3 is shorter than the time delay Δt_1 and the time delay Δt_2. If a group of 1000 Beacon frames are collected, one Beacon frame with shortest Δt can be chosen to calculate the most accurate OWPT. Since the Beacon Interval is known, after one Beacon Frame is received, the next Beacon Frame's arrival time t_{n+1} can be predicted by:

$$t_{n+1}' = t_n + BeaconInterval \tag{4}$$

When comparing the predicted arrival time t_{n+1}' with the actual arrival time t_{n+1}, there are two conditions. One is $t_{n+1}' < t_{n+1}$, like t_2' and t_2 in Fig. 4, which indicates Δt_{n+1} is bigger than Δt_n. In this scenario, t_{n+1}' is chosen as the more accurate arrival time to avoid enlarging the time delay Δt. Another condition is $t_{n+1}' > t_{n+1}$, like t_3' and t_3 in Fig. 4. As the former arrival time t_n is always chosen to keep the shortest time delay Δt, $t_{n+1}' > t_{n+1}$ indicates Δt_{n+1} is shorter than all the other former time delays Δt. In this scenario, t_{n+1} is chosen as arrival time to further reduce the time delay Δt, and this Beacon frame is considered as the shortest Δt Beacon frame so far. To implement this algorithm, every 1000 beacon frames are collected as a measurement group. Within the 1000 received Beacon frames, the Beacon frame with shortest time delay Δt is chosen to calculate ΔT for this measurement group.

Since the Beacon frame with shortest time delay Δt is chosen to measure the OWPT, even though the Timestamp is still in μs time resolution, the proposed algorithm can accurately improve the OWPT measurement time resolution to *ns*.

C. OWPT Synchronization Between AP and MS

A pre-calibration is applied to synchronize APs and MSs before localization. The pre-calibration process is developed from the OWPT Measurement Time Resolution Improvement algorithm which is like the other side of the same coin. The Timestamp of the Beacon frame comes from a 64-bit counter. It counts every μs from the commencement of the AP. When the counter reaches its maximum value, it wraps around. As it is a 64-bit counter, it will take 580,000 years to reach its maximum value. In the MS, a same 64-bit counter is used to

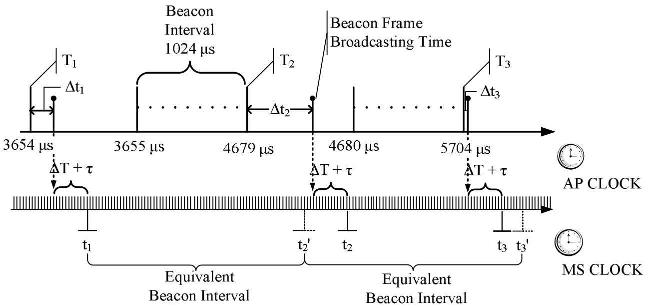


Fig. 5 Synchronization Between APs and MSs

record Beacon frames arrival time. So once the OWPT measurement starts, there is a certain synchronization bias between AP and MS, as shown in Fig. 5.

In Fig. 5, the synchronization bias τ is considered in the OWPT measurement. The MS calculates the Beacon frames' pseudo transferring time in (5), and the MS is assumed to be static during pre-calibration:

$$\Delta T_n' = t_n - T_n = (\Delta T + \tau) + \Delta t_n \tag{5}$$

To calculate the synchronization bias τ, (5) is converted to (6):

$$\tau = t_n - T_n - \Delta T - \Delta t_n \tag{6}$$

T_n and t_n are the Timestamp and the arrival time of the Beacon frame; *Δt* is the time delay between the Timestamp and broadcasting time of this Beacon frame; *ΔT* is the Beacon frame propagation time. In pre-calibration, an AP and a MS are placed within a measured distance, which determines the *ΔT* in *ns*. The positions of the MS and the AP are chosen in a Line of Sight (LOS) situation to avoid any Multipath influences on the Beacon frames' propagation time measurement. The synchronization bias τ which is calculated directly from (6) contains a random error of *Δt.* This random error ranges from 0 to 999 *ns*. Hence, the *Δt* elimination algorithm which was described earlier, is applied in (6) to remove the *Δt* in the pre-calibration. Unlike the OWPT Measurement Time Resolution Improvement scenario, the pre-calibration has no strict processing time requirement. The pre-calibration can take 1 minute and it is still acceptable. For 1 minute, *n* will be 60,000. That allows much more Beacon frames can be received in pre-calibration. With a much bigger *n,* there is greater possibility to reduce the *Δt* to 0. When $\Delta t \to 0$, (7) is derived from (6):

$$\tau = t_n - T_n - \Delta T - \Delta t_n \tag{7}$$

After the pre-calibration, τ can be accurately measured in *ns* time resolution and with high accuracy. Once the pre-calibration is finished, the synchronization bias τ can be used for the OWPT measurements until one of the clocks on the AP or on the MS stops working.

Another benefit of the synchronization pre-calibration is that a MS can synchronize with all the APs at the same time. When a MS is placed on the chosen pre-calibration spot, the distances between the MS and all the APs are known. The pre-calibration processes can be applied on every AP. APs broadcast Beacon frames in sequence, so even though the Beacon Interval is 1024 *µs,* the MS can receive two adjacent Beacon frames from two APs in several *µs.* After the 1 minute pre-calibration, a MS can receive enough Beacon frames from all the APs in the working area to synchronize with each of them.

The pre-calibration synchronization processes overcome one of the biggest challenges of OWPT measurement. With synchronized APs and MSs, as well *ns* time resolution measurement, OWPT can provide accurate Beacon frames propagation time measurement in WLAN.

IV. Simulation Model

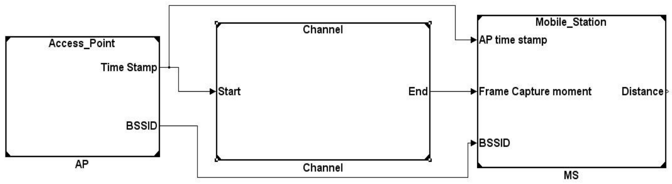


Fig. 6 AP-Channel-MS Model

An AP-Channel-MS simulation Model was built to test the proposed OWPT Measurement Time Resolution Improvement algorithm and synchronization algorithm. The AP-Channel-MS simulation model is a simplified version of 802.11 g wireless network. The model consists with three function blocks: AP, Channel, and MS, as shown in Fig. 6.

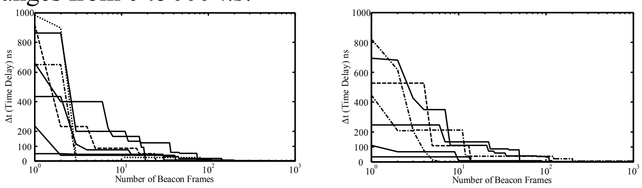
Instead of simulating all the WLAN frames and real network working situations, the simplified model only simulates the scenario that an AP broadcasts Beacon frames; a MS receives Beacon frames after Beacon frames propagated through the Channel. The Beacon frame is also simplified. In the OWPT measurement, the most critical parameter is time. Therefore, in the model, the Beacon frame only contains the Timestamp and the Basic Service Set Identifier (BSSID). BSSID, which is generated by an AP, is unique for each AP. It can be employed to identify which AP transmits the Beacon frames, so it connects the Beacon frames OWPT measurement with specific position information.

In the AP block, there are two timers working together. One timer represents the AP clock and its working frequency is 1 MHz. This timer generates the Beacon frames Timestamp and counts the Beacon Interval. The Beacon Interval is set to be 1 time unit in the simulation, which is 1024 *µs*. After every Beacon Interval, another timer, which has a working frequency of 1 GHz, starts to count the random delay *Δt* before transmitting a Beacon frame. A Random Integer Generator generates random integer series. One integer in the random series represents the number of *ns* delay for one Beacon frame. The integer is in the range between 0 and 999. The Random Integer Generator generates a random series according to an Initial Seed. Different Initial Seeds lead the generator to generate irrelevant random series.

After the Beacon frames transmit through the Channel block, the third block, MS, is responsible for analysing the received Beacon frames. The OWPT Measurement Time Resolution Improvement and synchronization algorithms are implemented here. The MS has its own receiver clock which works at 1 GHz frequency. When the MS receives a Beacon frame, at first, the time difference between the arrival time and the Timestamp of the Beacon frame is calculated. Then the time differences of different Beacon frames in the same measurement group are processed by the algorithms described in Section III to improve the time measurement resolution or to synchronize AP and MS in OWPT measurements. According to the algorithm chosen, the output can be the synchronization bias between AP and MS or the most accurate OWPT measurement in one measurement group.

V. Simulation Results and Evaluation

Fig. 7 is the simulation results of OWPT Measurements Time Resolution Improvement. Each line in Fig. 7 stands for a measurement group with 1000 OWPT measurements. The horizontal axis shows the number of beacon frames which have been processed. The vertical axis shows the time delay *Δt* between the Timestamp and the broadcasting time. *Δt* ranges from 0 to 999 *ns*.



a. b.

Fig. 7 *Δt* Attenuation

There are 15 measurement groups displayed in Fig. 7 (a) and (b) separately. Each group employs a random series to introduce various *Δt* for each beacon frame in that group. By changing the initial seeds, different groups have irrelevant random series. There are 8 groups which *Δt* starts with more than 500 *ns* delay. The highest *Δt* is 983 *ns*. Utilizing the proposed algorithms, all the *Δt* are attenuated dramatically. After 10 beacon frames are received, the *Δt* in most of groups is under 200 *ns*. The biggest delay at this stage is just 212 *ns*, while the smallest *Δt* is 1 *ns*. When 100 beacon frames are received by the MS, the highest *Δt* is 39 *ns,* corresponding to a 11.7 meters localization deviation. When the simulation finishes, there are only three groups' *Δt* bigger than 0. These *Δt* are 5 *ns*, 4 *ns* and 1 *ns* respectively. The biggest *Δt* leads to a 1.5 meters localization deviation. Hence in the simulation, the proposed algorithm successfully eliminates the time delay Δt in 98% of OWPT measurement groups. In these groups, the OWPT measurement time resolution is accurately improved to *ns*. In the worst situation of the remaining 2% OWPT measurement groups, the proposed algorithm can still achieve a 1.5 meters localization deviation. What's more, all of these results are achieved in only 1 second measurement.

The simulation result of OWPT Synchronization between AP and MS algorithm are illustrated in Fig. 8. The solid line in Fig. 8 is the synchronization bias *τ* which is expected to be measured when the pre-calibration finishes. As the synchronization algorithm is developed from the OWPT Measurement Time Resolution Improvement algorithm, the simulation results show the similar measurement errors attenuation curves. The time for pre-calibration is much

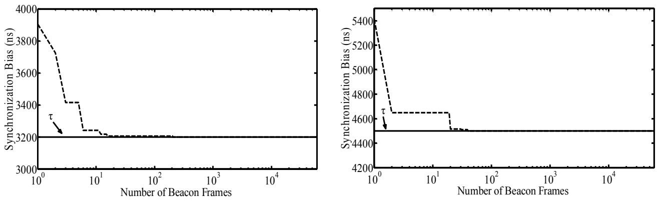


Fig. 8 Synchronization Bias *τ* Measurement

longer than the time to eliminate the time delay. The more beacon frames are received the higher accuracy of the OWPT synchronization can be achieved. As shown in Fig. 8., in 1 minute, after 60,000 Beacon frames were received, the OWPT synchronization algorithm measures the synchronization bias *τ* with high accuracy.

The simulation results confirm that the proposed algorithms can efficiently improve the OWPT measurement time resolution and synchronize AP and MS in OWPT measurement.

VI. Conclusion

This paper presents algorithms to improve the OWPT resolution to *ns* and to highly synchronize AP and MS in OWPT measurements by utilizing a *ns* resolution MS clock and a *μs* AP clock. Lower time resolution and synchronization used to be two obstacles which limited the application of OWPT. The proposed algorithms provide the possibility to apply OWPT measurements on WLAN for indoor localization. In the next stage, the proposed algorithms will be implemented on 802.11 WLAN hardware and the algorithms will be evaluated in experiments. Multipath effects should also be explored in the future to further improve the OWPT measurement accuracy.

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