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Fine-Time Assistance for GNSS using Wi-Fi

Deric W. Waters*, Ariton E. Xhafa*, Ramanuja Vedantham*, and Karthik Ramasubramanian**
*SysAppl R&D Center, 12500 TI Blvd, Texas Instruments, Dallas, TX 75243, USA.
**Texas Instruments, Bagmane Tech Park, Banglaore, 560093, India
Email: {deric, axhafa, r-vedantham, karthikr}@ti.com

***Abstract*—This paper presents a method by which a GNSS receiver equipped with Wi-Fi can receive fine-time assistance from another Wi-Fi enabled device which knows the time of day accurately. This system is based partly on mechanisms in IEEE 802.11v. Using this method the benefits of fine-time assistance such as lower complexity for acquisition, faster time to first fix, and improved sensitivity can be applied to a broader set of devices without any newly installed permanent infrastructure. Instead of such infrastructure devices collaborate or cooperate with each other.**

Keywords—Cooperative positioning, Fine-time assistance, Wi-Fi positioning

I. INTRODUCTION

In many practical use cases GPS or GNSS receivers are in locations where it is difficult to acquire satellite signals. As the attenuation the signal must penetrate increases, the receiver must coherently and/or non-coherently integrate the received signal for longer in order to recover the correlation peak. Without assistance the search space can be quite large, so that typical consumer electronic devices can take a long time to compute a location or they may never acquire signals at all. Assisted GPS (AGPS) can significantly improve receiver sensitivity by reducing the search space.

The GNSS receiver can be assisted in many different ways, but generally the assistance goes to reduce at least one of the three dimensions that must be searched: time, frequency, and satellite index:

- Fine-Time injection: time of day with accuracy less than 1 millisecond.
  - CDMA cellular networks for example.
- Coarse-Time injection: time of day with accuracy worse than 1 millisecond.
  - GSM, UMTS, and WCDMA cellular networks provide time of day within a few seconds.
- List of visible satellites: reduce the number of PRN codes that must be searched.
- Frequency reference: reduce the range of Doppler frequencies that must be searched.
- Ephemerides + Coarse position: provides coarse estimates for satellite Doppler frequency that reduces the range of Doppler frequencies that must be searched.

In this paper, we are interested in fine-time injection assistance over a Wi-Fi network. Like other forms of assistance, the value of the fine-time assistance is the amount by which it reduces the search space. The search space reduction is inversely proportional to the accuracy in which the time of day is given to the receiver. For example, there are 1023 chips in the GPS sequence that has a 1ms duration. Let's say the complexity when the receiver searches over all 1023 possible rotations of the PRN sequence is C. If the time of day is given with an accuracy of X microseconds, then the complexity is reduced from C to ceil(1.023 * X) / 1023 * C, where ceil(x) is the smallest integer greater than x. If X =10 microseconds, then complexity is reduced by roughly 99%. In other words, fine-time injection can have a big impact on overall complexity.

It is becoming more and more common for electronic devices to have both WiFi and GNSS capabilities. Smartphones are a good example where both GNSS and WiFi are generally available, and many smartphones cannot benefit from conventional fine-time injection because they do not use CDMA cellular networks. There are also other popular consumer electronic devices that have both WiFi and GPS but cannot benefit from conventional fine-time injection because they do not have a cellular modem. Therefore, in this paper we propose a way for one device containing both WiFi and GPS to assist another device via fine-time injection. Specifically, mechanisms within the upcoming IEEE 802.11v standard [3] are leveraged to achieve fine-time injection over WiFi.

II. FINE-TIME ASSISTANCE OVER WI-FI

There are multiple modes by which one GPS+WiFi device can provide an accurate time estimate to another GPS+WiFi device. If device A is assisting device B, then the different modes are summarized as:

- Use Time Advertisement (TA) information element:
  - Device A inserts accurate timing information into a packet in a manner that Device B can decode it.
- Use Timing Measurement Action (TMA) frames:
  - Device A & Device B are peers with a peer-to-peer connection so that a series of packets can be exchanged to synchronize their clocks.

In this section we describe how fine-time assistance can be done in both modes.

Regardless of which mode is used for fine-time assistance the GPS and WiFi blocks in each device must be able to communicate. For example, if the WiFi block of device B decodes a packet and learns the time of day, it must send that to the GPS block to achieve the desired fine-time injection. Any unknown variable delays in this communication link will degrade the accuracy of the time assistance. Texas Instruments has a semiconductor chip that includes both GPS & WiFi that facilitates an expedient inter-connect between the two blocks. Furthermore, fixed delays in the inter-connect can be calibrated out to avoid degrading the accuracy of the time assistance.

On the other side, in order for Device A to provide accurate time assistance it must first know the time of day accurately. This may be achieved via a GNSS receiver, so that Device A computes the time of day from GNSS signals. Other timing sources could be used as well, such as a CDMA cellular signal, an Ethernet network connection, or via assistance from a third WiFi device. The error budget for the timing accuracy is summarized as:

$$e_{FineTime} = e_{Source} + e_{TxDelay} + e_{RxDelay} + e_{TOF}. \quad (1)$$

where e_{Source} is the error in the timing source (typically nanoseconds for GNSS, tens of microseconds for a CDMA network, or hundreds of microseconds for an Ethernet network [4]), $e_{TxDelay}$ includes uncalibrated delays at the transmitter, $e_{RxDelay}$ includes uncalibrated delay at the receiver, and e_{TOF} is the time of flight (TOF) between transmitter and receiver. The uncalibrated delays in the transmitter and receiver are implementation dependent, but with both GPS & WiFi blocks being co-located in the same chip they can be reduced to microseconds at least. The error due to propagation delay is limited by the range of the WiFi signal (typically this would be less than one microsecond ~ range less than 300m). All together, for two WiFi devices the overall error can easily be reduced to 10 microseconds or less, which leads to a huge complexity reduction for GNSS acquisition. With such accuracies even if the assistance is passed on from one device to another it can still be beneficial.

A. Using Time Advertisement Information Element

One way to provide fine-time assistance is to use the Time Advertisement (TA) information element. Access points (AP) can transmit this TA information element in probe responses (see Table 7-15 of [3]) or beacon frames (see Table 7-8 of [3]). Non-AP devices can transmit the TA information element as part of vendor specific fields in a probe request frame (Table 7-14 in [1]). The TA information element as defined in the specification [3] provides fields to specify the source of the time standard, an estimate of the offset between that source and the TSF timer, as well as an estimate of the error in offset.

Using the TA information element, a WiFi device can essentially communicate the time of transmission according to a time standard and the estimated accuracy of that time. If another device receives and processes a TA information element that is synched to GPS time, then it can know the time of arrival in GPS time within the accuracy specified in equation (1). If the accuracy reported in the TA information element is sufficiently accurate, then that device knows current time of day and can provide it to its GPS receiver.

An example of this mode of operation involves Device A (the assisting device) and Device B (the assisted device). Let us assume that Device A is a smartphone located in an area where it is able to decode the time of day from GPS. One such practical scenario is when the smartphone computes its location to within 50 meters using a WiFi AP location data base and it is able to get the ephemeris and pseudorange measurements for at least one satellite. In such a scenario e_{Source} is still less than 1 microsecond. Once it knows the time of day, Device A can become an AP and insert the TA element into its beacons and probe responses. To improve the quality of its assistance, Device A can account for known delays in its inter-connect and transmit chains. On the other side, Device B can listen to the channel passively for beacons that contain the TA element or it can send probe requests and check for TA elements in the response. Once it receives the TA element it can take the time of day contained in the TA element. Even without accounting for $e_{RxDelay}$ and e_{TOF} the typical accuracy of the fine-time injection would be better than 20 microseconds.

B. Using Time Measurement Action Frames

Section 11.22.5 of the IEEE 802.11v specification [3] defines a Timing measurement procedure that enables one WiFi device to synchronize its clock to another WiFi device. This can improve the accuracy of the fine-time assistance as described in the previous subsection by reducing delays in the transmitter and receiver ($e_{TxDelay}$ + $e_{RxDelay}$) as well as compensating for time of flight (reducing e_{TOF}).

Timing measurement action frames can only be sent between peers in a WiFi network [3]. So the first step in this procedure is for two devices to establish a peer-to-peer connection (more on this later). Then the device in need of assistance (Device B) can initiate a timing measurement action frame. Once Device B asks for assistance, Device A sends a packet (labeled M1) and records its time of departure (t1). Device B records the time of arrival of packet M1 as t2, then sends an acknowledgement packet back to Device A and records its time of departure as t3. Device A records the time of arrival for the acknowledgment as t4, then sends packet M2 to Device B containing both the values t1 and t4 that it measured. Upon receiving packet M2, Device B has the four quantities necessary to measure the relative clock offsets and the propagation time. The clock offset can be computed as:

$$\Delta b = \frac{(t2 - t1) - (t4 - t3)}{2} \qquad (2)$$

and the time of flight (TOF) as:

$$TOF = \frac{(t2 - t1) + (t4 - t3)}{2} \qquad (3\cancel{2})$$

If the time of departure in the TA information element sent by Device A is t_{TOD}, and the clock at Device B reads t_{TOA} when the packet carrying the TA information element arrived, then Device B can correct its clock by subtracting Δb from t_{TOA}.

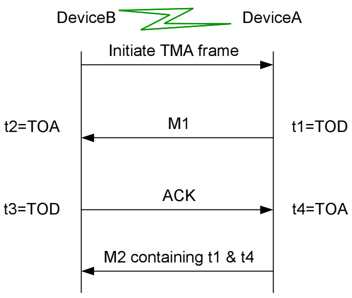

Figure 1. Timing measurement action frame protocol.

Establishing a Peer-to-Peer Connection:

If the two devices are connected to the same access point (AP), one device can initiate a Tunneled Direct Link Setup (TDLS) session with the other STA via the AP. In this scenario, the setup frames are encapsulated in data frames, which allows them to be transmitted through the AP[5]. The two devices may also specify the power-save mechanism enabled between the two; e.g., peer power save mode (PSM scheduled) or peer unscheduled automatic power save delivery (U-APSD). Once the devices have established a TDLS session, the timing measurement protocol can be executed once or multiple times between the two stations via the direct link. Once the timing measurements has finished, a TDLS teardown procedure [5] can be performed in order to conserve power at both STAs. Figure 1 illustrates the procedure of TDLS setup, timing measurement is performed between the two stations, and TDLS teardown between STA1 and STA2.

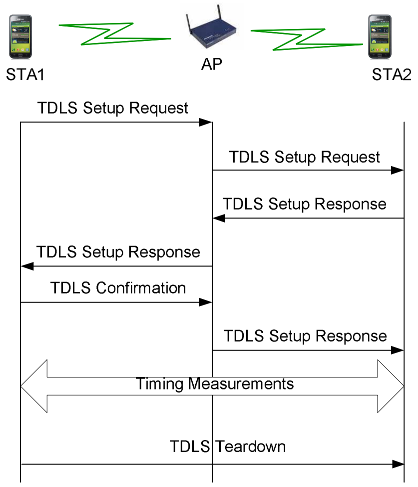

Figure 2. Figure 1~~2~~ TDLS setup, timing measurements and TDLS teardown.

III. PERFORMANCE IMPACT OF FINE-TIME INJECTION

In an abstract way the improvements from fine-time injection can be captured in terms of complexity reduction. However, the benefits of such complexity reductions are manifested in other more tangible ways. For example, the receiver can invest its computational resources more efficiently so that it can acquire weaker signals. Or the receiver can simply acquire satellite signals faster so that the time to first fix is reduced.

This section presents simulation results for performance of a GPS receiver with and without fine-time assistance. Over a total dwell time of 16 seconds, a coherent integration interval of pred ms is used. The GPS signal modulates data at 50 bits per second, so without a priori knowledge of the data bits pred cannot exceed 20ms. Without fine-time injection, the receiver does not know the location of the data-bit boundaries so pred is typically limited to 19ms.

In a first comparison, if fine-time injection enables the coherent integration interval to be increased from 19 to 20 ms then performance is improved by 2dB (the power level required to ensure 90% probability of detection reduces from -156dBm to -158dBm see Figure 2).

Another way to compare the performance improvement of fine-time injection is to compare systems that have equivalent complexity. Let's assume that the fine-time injection accuracy is sufficient to reduce the overall search space by a factor of 10 (a conservative assumption that $|e_{\mathrm{FineTime}}|<$ 102 microseconds). Then the system without fine-time injection can have equivalent complexity if it increases the size of the Doppler frequency bins by reducing pred. Reducing pred by a factor of 10 leads to a performance loss of 4.7dB (see pred=20 and pred=2 curves in Figure 2).

Implementing data wipe-off requires accurate knowledge of the data-bit boundaries. Without fine-time assistance data bits could be wiped off erroneously. As a result, typical receivers do not employ data-bit wipe-off unless fine-time assistance is available. So a system with fine-time assistance can increase pred beyond 20ms which can lead to significant performance gains. For example, Figure 2 shows that if pred is set to 80ms an performance gain of 4.3dB is possible over the best performing system without fine-time assistance (pred=19).

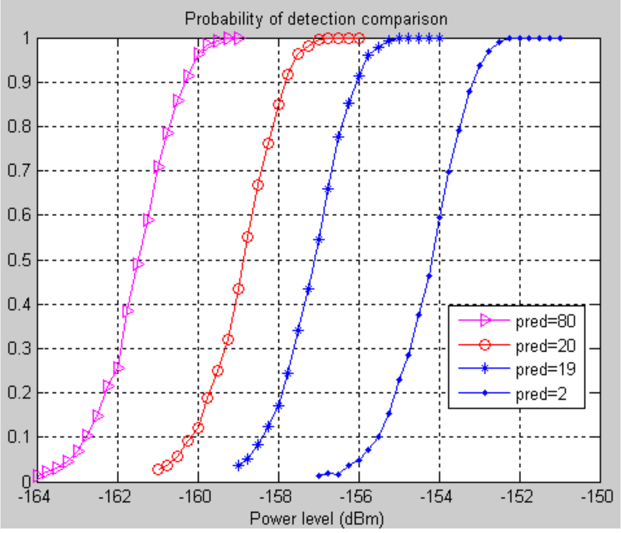

Figure 3. Performance results with different amounts of coherent integration in a GPS receiver. Coherent integration time = pred ms.

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