TEA: Transmission Error Approximation for Distance Estimation between Two Zigbee Devices

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Abstract

This paper proposes a simple and cost-effective method named ***T****ransmission* ***E****rror* ***A****pproximation (TEA) for estimating the distance between two Zigbee devices. The idea is to measure and analyze statistically packet loss rates for approximate distance estimation. We have implemented an experimental prototype for the TEA using Zigbee protocol. Measurement results show that TEA is a cost-effective way of distance estimation and provides much better resolution than other methods based on signal strength when the distance is greater than 60 feet.*

1. Introduction

Following the technology wave of the Internet, a new emerging network technology, wireless personal area network (WPAN), has gained great momentum. The international standard, IEEE 802.15.4, named ZigBee has emerged with many technology promises. Hardware devices in compliance with the standard are now readily available. For example, a ZigBee wireless transceiver with built-in 8-bit microcontroller is available today in the market for less than $4 dollars. Existing technologies and products making use of the WPAN are mainly focused on home automation such as lighting, security, and utility controls; automotive networks, industrial automations, and interactive toys. Although there have been proposals for mobile positioning using sensor networks based on pre-existing infrastructure [1,2], ad hoc mobile network [3], or hybrid of the two [4], most of them need the infrastructure for positioning. Measuring the distance between two communication devices using the existing ZigBee standard and the existing hardware component is technically challenging because of the following reasons:

a) Traditional way of estimating the distance between two communicating devices uses analog devices by measuring the strength of the received signals. This can not be applied directly to digital devices without significant change to the hardware because noise and interference easily affect the measured results.

b) Measuring propagation delay between the two communication devices using sonic transceivers will increase the hardware cost and power consumption losing the advantages of economy of scale.

c) It is possible to estimate the direction of arrival signals using antenna array and examine the phase of the receiving signals. The distance can be determined based on the direction of arrival signals. This will require multiple antennas located far apart increasing the hardware cost significantly.

d) GPS [5] has been well known for positioning but with cost in a different order of magnitude from what we considered here.

e) Another type of positioning services relies on a pre-deployed sensor network. The distance between the device and pre-deployed sensors are estimated first, and the sensor network calculates the location of the device.

In this paper, we propose a simple and cost-effective method for estimating the distance between two Zigbee devices using commodity hardware components. With no special hardware needed, our method uses existing network layer protocol (SMAC) between two communication devices [6]. Our method makes use of the power management module on the MCU of a Zigbee device. By configuring and tuning of the power management functions, we transmit a sequence of packets of different sizes at network layer. Statistical analysis is then performed on packet loss rates (PLR). We called the method Transmission Error Approximation (TEA). Based on the analysis, we are able to approximately measure the distance between two Zigbee devices, and trigger desired actions depending on different applications such as pet leash, wireless child safety device, patient monitoring, and so on.

We have implemented an experimental prototype for measuring the approximate distance between two communication nodes using Zigbee protocol. Measurement results show that TEA is a cost-effective way of distance estimation and provides much better resolution than other methods based on signal strength when the distance is greater than 60 feet.

The following of the paper is organized as follows. Next section summarizes the related work. The detailed description of the TEA and theoretic analysis is given in section 3. Section 4 presents our implementation and numerical results followed by the discussions about security issue in section 5. We conclude our paper in section 6.

2. Related Work

In the current literature, distance between two wireless communication devices can be estimated using time-of-Arrival (ToA), angle-of-arrival (AoA), or Received Signal Strength Indication (RSSI) [7,8].

ToA is based on the speed of radio wave propagation and the measured time it takes for a radio signal to move between two objects. Combining this information allows the ToA system to estimate the distance between sender and receiver. ToA offers high levels of accuracy, but also requires relatively fast processing capabilities to resolve timing differences for fine-grained measurements. This problem is amplified over short distances, making ToA a poor choice for a ranging technique for positioning in wireless, ad-hoc sensing networks.

ToA measurements can be combined with acoustic measurements to achieve accuracy of a few percent of the transmission range. Acoustic signals, however, are temperature dependent, require unobstructed line-of-sight, are reliant on directionality, and require additional hardware.

Unlike the previous techniques, which measure distance, AoA techniques make use of antenna arrays to measure the angle at which a signal arrives. Angles can be combined with distance estimates or other angle measurements to derive positions. A major disadvantage of AoA techniques is the hardware requirement. The antenna arrays are expensive to be implemented and maintained, making AoA a poor choice for cost-conscious applications.

RSSI measures the attenuation in radio signal strength between sender and receiver. The power of the radio signal falls off exponentially with distance, and the receiver can measure this attenuation in order to estimate the distance to the sender. Experience has shown, though, that RSSI yields very inaccurate distances [9]. This is the method assumed to be supplying the range estimates to the positioning algorithms.

To our best knowledge, packet loss rate has not been used to measure distance between wireless devices. Our experiment show the TEA can measure the distance using commodity devices and has higher resolution than signal strength. Other benefits are that it does not rely on network infrastructure and is cost-efficient.

3. Details of the TEA

3.1 Distance estimation based on signal attenuation (RSSI)

Without extra hardware support, signal attenuation is the only distance measurement method in the current literature. In particular, let *d* denote the distance between the host device and the remote device, P_t denote the transmission power and P_r denote the received signal power. Then,

$$P_r = \frac{P_t}{d^{\alpha}} \tag{1}$$

where α is a constant between 2~4, depending on the wireless channel condition. When the transmitter sends pilot signals using a fixed transmission power, the receiver can obtain signal attenuation, defined as P_r / P_t , and therefore estimate the distance *d*.

Although the RSSI method is simple, it cannot achieve high accuracy for three reasons. First, since P_r can change rapidly due to the variation of wireless channel, mobility and moving obstacles on the transmission path, it is difficult to estimate P_r accurately. Second, the P_r value is affected by noise and interference. When noise and/or interference are not known and not negligible, the received signal power cannot accurately represents the distance. Third, equation (1) indicates that a small estimation error in P_r can result in a large error in distance estimation, especially when the distance is large. This can be verified by the following derivation.

$$P_r = \frac{P_t}{d^{\alpha}};$$

$$\Delta \mathrm{P_r} = -\frac{\alpha P_t}{d^{\alpha+1}} \Delta d;$$

$$\Delta d = -\frac{d^{\alpha+1}}{\alpha P_t} \Delta P_r;$$

where Δ d and $\Delta \mathrm{P_r}$ represent distance change and received power change respectively.

3.2 Distance estimation based on the packet transmission statistics

Our approach makes use of the commodity hardware devices that are in compliance with Zigbee standard. To exploit the economy-of-scale, we design and implement the TEA at network layer above the MAC/PHY without any hardware changes. Instead, we try to make use of the existing features of the transmitter/receiver hardware. In particular, we implement a special packet transmission protocol by varying power levels of the MCU. It is a common practice in today’s embedded MCUs to have a power management module for the purpose of power savings. Depending on the wireless channel condition in reality, we select an optimal packet size and number of packets for transmission at the calibration stage. During normal operation, we transmit a sequence of packets with predetermined length from the transmitter. The receiver will calculate the packet loss rate based on the packet ID received and the predefined protocol at the calibration stage. The result of the calculation is sent to the transmitter in an acknowledgement packet using the maximum transmission power level. Based on the packet loss rate, the approximate distance between the transmitter and receiver can be estimated. Generally, the TEA method contains the following two steps:

Step 1: the receiver estimates packet loss ratio and feedbacks this information to the transmitter. In particular, the transmitter sends a sequence of data packets to the receiver. Each data packet has a packet ID. For example, the first data packet has ID x, the second data packet has ID x+1, the third data packet has ID x+2, and so on. These data packets are transmitted with different transmission power levels. For the Zigbee implementation by FreeScale, there are 16 transmission power levels, denoted by $P_1, P_2, ..., P_{16}$. Assume that total N packets are transmitted. Among these N packets, q_i percent of packets are transmitted using transmission power P_i . We refer vector $q = [q_1, q_2, ..., q_{16}]$ as *packet distribution*.

The host device receives packets. Upon the packet IDs, it knows how many packets are lost and then obtains *packet loss ratio*. The packet loss ratio should be a vector. The receiver sends the PLR back to the transmitter using the maximum transmission power.

Step 2: the transmitter estimates distance based on the PLR. When the transmission power is P_i , the bit error rate is a function of receiving signal-to-interference ratio and is related with the modulation scheme. In Zigbee protocol, modulation scheme is OQPSK [10]. The bit error rate is calculated as:

$$ber_i = erfc\left(\sqrt{\frac{P_i / d^{\alpha}}{I}}\right) \quad , \quad \text{and}$$

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-y^2} dy \qquad (2)$$

where I is the noise/interference power, which can be estimated in the calibration stage [11].

The packet drop ratio is determined by bit error rate and the packet size. Let L denote the number of bits in each packet. Then, the packet loss ratio for each transmission power is calculated as

$$PLR_i = 1 - (1 - ber_i)^L \qquad (3)$$

The overall packet loss ratio is

$$PLR = \sum_{i=1}^{16} q_i \cdot PLR_i \qquad (4)$$

From (2)–(4), one can calculate packet loss ratio from the distance *d*, given q_i, P_i and L .

In Figures 1 and 2, we show how signal attenuation and packet drop ratio change with distance.

Figure 1 shows the received signal power (proportional to signal attenuation) as a function of the distance between the transmitter and the receiver. The upper plot shows the 16 curves, each of which is for a different transmission power. The lower plot shows the average. It can be seen that signal attenuation is not a good indicator of the distance. It can measure short distance. However, when the distance is large, the signal attenuation is not sensitive to distance changes. In other words, if there is a small error in the measurement of signal attenuation, the distance estimation will suffer from a large error.

Figure 2 shows the packet loss ratio as a function of the distance. The upper plot shows the curves for different transmission power and the lower plot is the overall PLR. Compared with signal attenuation, PLR is approximately a linear function with the distance for a large distance range. Obviously, the distance estimation based on PLR will be more accurate.

Figure 1 Received signal amplitude as a function of distance

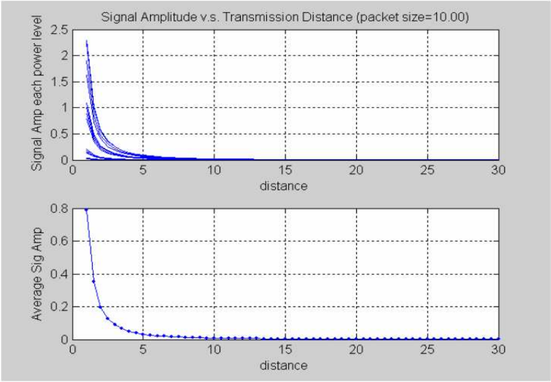
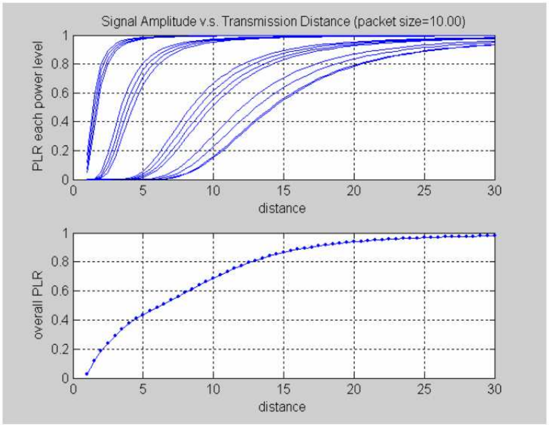


Figure 2 . Packet loss ratio as a function of distance



4. Implementation and Numerical Results

We have implemented our experimental prototype on Freescale's MCF5208EVB with MC13192 transceiver. This implementation includes two wireless communication parities, transmitter and host. The embedded MC13192 transceiver is in compliance with Zigbee protocol and communicates with the main board MCF5208EVB through GPIOs [12]. We make use of source code of Zigbee implementation from SBC tools to develop our experimental prototype. The transmitter sends 100 packets for three different packet sizes with different power levels. The host side receives packets and sends acknowledgements to the transmitter. In order to compare the TEA with RSSI, the strength of receive signal is carried in acknowledgement packet. Considering the effect of antenna direction and interferences, we fixed the transmitter and measured the data from the transmitter side for every measurement by changing the position of host device.

We have carried out experiments using our prototype implementation. The experiments were performed in a free space at a football field in a sunny day to minimize the interferences. We measured the PLR and signal amplitude for every 15 feet from 60 feet to 390 feet and for every 5 feet when distance is less than 60 feet. We analyzed our data using three different ranges: less than 60 feet, distance between 60 to 250 feet, and greater than 250 feet. The results for distance less than 60 feet are shown in figure 3. Both the TEA and RSSI are not effective. This is possibly due to the multi-path effects. The results for distance between 60 and 250 feet are shown in figure 4. The TEA can work for distance estimation. But the estimation is rough and not accurate because the power levels are not linear and are not uniformly distributed. As a result, the contributions of transmissions with different power levels are not equal. Our current design only averages packet loss rate associated with all different power levels to get the overall PLR. We will improve it in the future by weighting packet loss rates with different power levels differently. For the distance greater than 250, the TEA works perfectly and provides much better resolution than RSSI as shown in figure 5. When the distance is greater than 300 feet, the signal strength does not significantly attenuate. This shows the signal is very weak and not sensitive to distance changes. This point is in a good agreement with the theoretic analysis in section 3. But for this case, the TEA is still effective up to 390 feet distance. The function of packet loss ratio with distance is approximately linear.

5. Discussions

Theoretic analysis and practical implementation measurements both show the TEA can approximately estimate the distance between two wireless devices in a designed distance range. Compared to RSSI, the TEA can provide much better resolution and noise tolerance. In the following we will discuss another benefit of the TEA from the security point of view.

We assume that the attackers are outsiders. That is, they do not compromise the communication devices. What they can do is to interfere with signal and cause estimate error in distance. For the RSSI based methods, attackers can make the distance measurement become larger or smaller. They can reduce the received signal power by placing physical obstacles near the transmitter or receiver to block the direct-line-of-sight. As a consequence, the estimated distance will be larger than the real distance. They can also introduce interference or increase the noise level using a radio transmitter. This will increase the received signal power and the estimate distance can be smaller than the real distance. On the other hand, in the TEA method, attacks can only increase the estimated distance. Introducing physical obstacles and increase interference/noise both result in lower PLR, and therefore larger distance estimation.

Many applications use distance measure to detect events that cause the distance between two devices larger than a threshold. For example, when the device carried by a parent and the device carried by the child is larger than a threshold, the parent is notified. When a precious item is taken out of a house, alarm is issued. In this type of applications, the attack that increases the distance measure is far less dangerous than the attack that can reduce the distance measure. In this circumstance, TEA is preferable because attackers only cause false alarm but not miss detection.

Figure 3. TEA v.s. RSSI for distance less than 60 feet

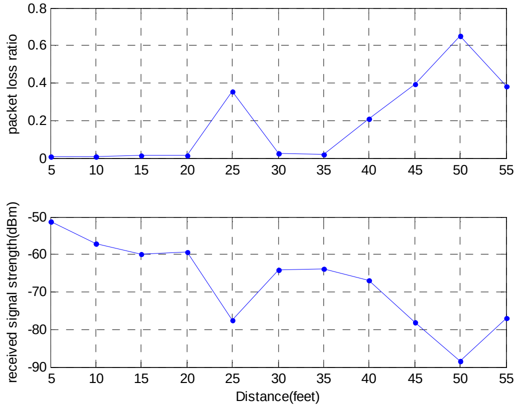


Figure 4. TEA v.s. RSSI for distance between 60 and 250 feet

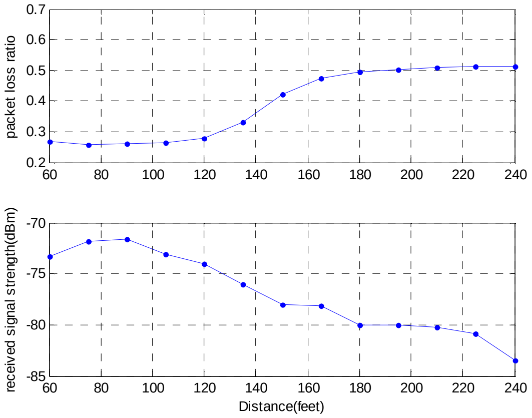
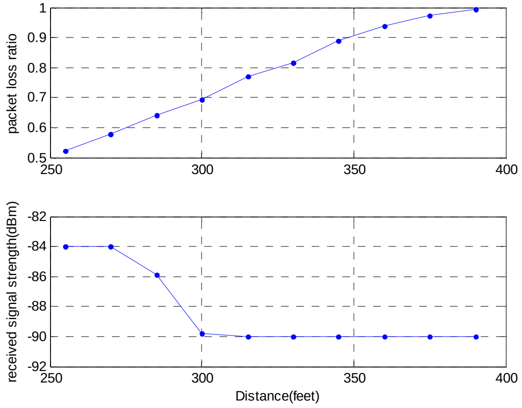


Figure 5. TEA v.s. RSSI for distance greater than 250 feet



6. Conclusions

In this paper, we have presented a cost-efficient method of estimating the approximate distance between two wireless communication nodes using Zigbee, referred to as **T**ransmission **E**rror **A**pproximation (TEA). A theoretic analysis has been carried out and an experimental prototype has been implemented using Freescale's MCF5208EVB and SBC tools. All experimental results are in a good agreement with theoretic derivations. Real measurements have demonstrated that the TEA is a cost-efficient way of distance measurements providing higher resolution than signal attenuation method when the distance is greater than 60 feet. We will focus on distance range less than 60 feet and interference considerations in the future work.

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