WIP: Augmenting Vehicle Safety With Passive BLE

Noah T. Curran[§] and Kang G. Shin
University of Michigan
{ntcurran,kgshin}@umich.edu

William Hass, Lars Wolleschensky, Rekha Singoria,
Isaac Snellgrove, and Ran Tao
Lear Corporation
{whass01,lwolleschensky,rsingoria,isnellgrove,rtao02}@lear.com

***Abstract*—On urban roadways, "dooring" remains a serious problem to the safety of pedestrians, cyclists, and other vulnerable road users (VRUs). Existing solutions that address this concern remain inadequate, as they either place unreasonable expectations on the pedestrians or rely on prohibitively expensive additions to the vehicle's sensing capabilities. Consequently, typical consumer vehicles are not yet equipped with such a technology, and practical dooring prevention still remains a safety concern.**

To address this problem, we propose a driver safety system for dooring prevention called `S-Door` that uses existing resources available in every modern vehicle: Bluetooth Low-Energy (BLE). Since a modern vehicle is distributively equipped with multiple BLE transceivers, we leverage each transceiver to observe BLE advertising data (AD) packets that consumers' smart devices passively transmit. From these AD packets, we extract information that we can use to localize the VRU device without pairing with the device. With this information, we propose two methods for localization based on BLE versions ≤ 5.0 and ≥ 5.1, respectively. Our solutions are capable of alerting the driver of all instances of an oncoming VRU. Due to `S-Door`'s use of existing vehicle BLE hardware, we may extend this application to modern vehicles through a firmware update—no physical modification is necessary.

I. INTRODUCTION

In the recent decade, vehicle and pedestrian safety has established itself as a primary concern of automotive companies. In an effort to reduce the effects of human error, the automotive industry has deployed several technologies. One such technology is an Advanced Driver Assistant System (ADAS), which uses proximity sensing to improve the safety and efficiency of vehicles. In order to provide ADAS the vision needed to issue alerts and perform subsequent actions, vehicles are equipped with expensive sensors, such as radar, ultrasonic, or camera. Likewise, vehicles may be equipped with expensive aftermarket solutions in order to provide similar features [7]. Because of the high cost to provide such sensors, typical consumer vehicles are often provided with lost-cost alternatives or ADAS features are omitted entirely. Moreover, ADAS technology has mostly overlooked "dooring"—the act of opening a car door into the path of other road users, usually vulnerable road users (VRUs) such as cyclists or pedestrians. The vision sensors are unable to perform proximity sensing of VRUs in densely populated urban environments, where it may be unable to detect a VRU that is hidden behind another object or around a corner. As such, the vision sensors of vehicles are ineffective in the environments that are most dangerous to VRUs.

To further motivate this issue, city-level statistics reveal the prevalence and danger of dooring for the primary VRU group of cyclists. In Chicago, around one cyclist-related dooring accident occurs each day and over 80% were seriously injured [22]. San Francisco, despite being a city that is one of the most bike accessible in the U.S. [14], has a rate of 0.56 doorings per day [17]. One of Canada's most bikable cities, Vancouver, published that dooring is one of its most commonly reported cycling collision [19], [25].

As mentioned earlier, these solutions rely on expensive sensing systems, such as cameras, radar, and ultrasonic sensors. While these technical advancements have demonstrated their merit for preventing dooring, their limited capability has prevented their broader impact and adoption. Considering these limitations, we establish the following constraints for a viable solution:

1) It must use commonly available vehicle resources;
2) It must provide proximity sensing of VRUs around obstacles;
3) It must detect VRUs that may be at risk of a dooring accident with near perfection while maintaining a low rate of false alarms; and
4) It must not require voluntary opt-in from either VRUs or vehicle occupants.

We present a novel solution, `S-Door`, that satisfies these constraints effectively. We make use of the Bluetooth Low-Energy (BLE) transceivers readily available in all modern vehicles, which are equipped with several BLE transceivers for use in passive entry passive start systems, audio applications, and comfort features. Thus, we can make use of the set of BLE transceivers in a distributed fashion.

To provide a dooring-prevention safety system, we use the BLE transceivers available in modern vehicles to scan for passive advertising data (AD) packets from VRU BLE devices. The AD packets are identified by each BLE transceiver in the vehicle and used to provide proximity sensing to `S-Door`. When the VRU is close and a trigger is tripped—such as attempting to open a door—the occupants of the vehicle are warned of the potential danger. We expand on this in § III. Since we use the passive AD packets, no pairing of BLE devices occurs, so no opt-in is required by either the VRU or the occupants of the vehicle.

II. BACKGROUND

Since the inception of the BLE standard, there has been an interest in providing the features necessary for device proximity detection. In successive iterations of the standard, more robust localization features have enabled a wide set of potential applications. Generally, BLE devices implementing these localization features pair with one another in order to exchange information. There is prior work that uses paired BLE devices to localize VRUs for various vehicle-related safety applications (§ II-A). However, in the case of dooring prevention, we are uninterested in the pairing process. To understand how we

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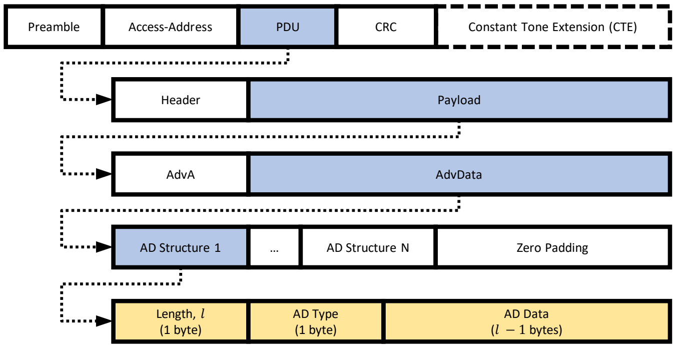


Fig. 1: The standard BLE v5.3 AD packet format and the expansion toward the AD packet.

can localize nearby devices without pairing, we provide the necessary background on BLE AD packets—the information shared between BLE devices before pairing (§ II-B).

A. Prior Work on Using BLE for VRU Safety

Since the prior work pairs BLE devices, we briefly describe the pairing process. During pairing, one BLE device is a *central* device that receives BLE AD packets transmitted from a second BLE device called the *peripheral* device. The peripheral device communicates information available for transmission to the central device. After establishing a paired connection, the peripheral device periodically transmits this information with its respective identifier for the central device to receive.

Prior work primarily takes advantage of pairing to communicate information that is used in localization, such as the iBeacon's proximity sensing and indoor positioning systems [2]. The proximity sensing information contains data that allows the central device to determine the peripheral device's physical location. Researchers have used an iBeacon-equipped biking helmet to inform nearby vehicles of the biker's proximity [1]. In another instance, a VRU is equipped with BLE-embedded armbands that pair with the detection nodes attached to the trailer of a truck when it wants to warn the vehicle of the VRU's presence [8], [9].

These proposed solutions require the VRU's BLE device to voluntarily scan for and connect to the vehicle-hosted central BLE device(s). This is not practical, as some smart devices are not always allowed to passively form a new BLE connection. Additionally, it is unrealistic to assume VRUs will voluntarily use special equipment, such as a BLE-equipped helmet. Instead, the vehicle should hold the responsibility of ensuring safe operation. Contrary to the goals of the prior work, we wish to leave the VRU's equipment unmodified.

The authors of [21] use BLE AD packets to detect the presence of a VRU, but do not perform proximity sensing. Since this work does not localize the VRU, it is not capable of supporting a dooring-prevention ADAS. For instance, we must be capable of determining which side of the vehicle the VRU is located. In another related work, VRU devices broadcast AD packets to nearby vehicles [18]. However, these AD packets contain data from a GPS, including position, velocity, and heading. Since this requires modification of the VRU device to provide this information in the BLE AD packets, it works against our goals.

B. BLE AD Packets

BLE AD packets are standardized as part of the BLE core specification [4]. We provide a visual summary of the BLE standard for an AD packet in Fig. 1. The preamble, access-address, Protocol Data Unit (PDU), and Cyclic Redundancy Check (CRC) fields of the AD packet are required, and the Constant Tone Extension (CTE) is optional. The optional CTE field is for Angle-of-Arrival (AoA), which we discuss in detail in § III-A. The field of interest to us is the PDU field, which has header data and a payload. The payload is further split into a field containing the advertising device address (AdvA) and useful data related to the advertising (AdvData). AdvData is segmented into parts that include a one byte field to define the length (l), a one byte field to define the type (defined in [6]), and an $l-1$ byte field containing the data. While there are many reserved numbers for the AD packet type, there are just a few relevant for our purposes:

- ***Manufacturer Specific Data***: Includes a two byte standard company identifier alongside other company defined data. We use this to rule out companies that do not manufacture BLE equipment that can be mobile.
- ***TX Power Level***: The power level used to transmit the AD packet. This is used for proximity estimation.
- ***LE Bluetooth Device Address***: A MAC address for identifying the device that transmitted the AD packet. The address is used to uniquely identify and track nearby devices as AD packets asynchronously arrive. The BLE standard allows for this address to be random and private, and advises for the address to be changed every 15 minutes. For our purposes, we track devices for periods of time shorter than 15 minutes, so this is a permissible constraint.

III. `S-Door`

The typical scenario for our work involves two entities: the host-vehicle of `S-Door` and a nearby VRU with a BLE-enabled device. `S-Door` interacts with the VRU's BLE-enabled device in the following steps:

1) From the VRU's device, `S-Door` distributively obtains a series of AD packets, which contain the requisite information described in § II-B.
2) `S-Door` uses the AD packet's data to calculate the distance of the VRU from each receiver.
3) Because the BLE receivers are locally distributed, `S-Door` is able to determine the relative direction of the VRU and determine if an alert is necessary.

Because an important part of this work is both accurately alerting a driver when dangerous events are about to occur while also maintaining a sufficiently low number of false alarms, *True Positive Rate* (TPR) and *False Positive Rate* (FPR) are used in our evaluation. We calculate TPR and FPR with $TP/(TP+FN)$ and $FP/(FP+TN)$, respectively. Below we define these components of TPR and FPR, and visualize in Fig. 2.

True Positive (TP). A VRU is nearby and behind the vehicle and `S-Door` correctly identifies both conditions are met.

False Positive (FP). A VRU is not nearby or behind the vehicle and `S-Door` incorrectly identifies both conditions are met.

True Negative (TN). A VRU is not nearby or behind the vehicle and `S-Door` correctly identifies either condition is not met.

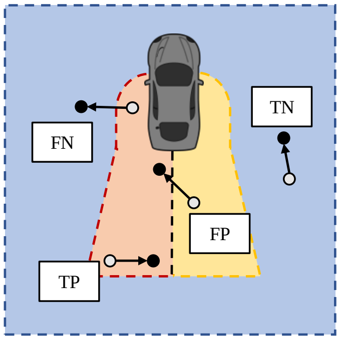


Fig. 2: Visual of FP, FN, TP, TN.

False Negative (FN). A VRU is nearby and behind the vehicle and `S-Door` incorrectly identifies either condition is not met.

A. System Design

In our pursuit of building and evaluating `S-Door`, there are questions that `S-Door` must take into consideration.

First, how far away (in meters) is the BLE device? On arrival to the central BLE devices located on-vehicle, each AD packet is given a *Received Signal Strength Indicator* (RSSI) value. The closer the central BLE device is to the peripheral BLE device, the higher the RSSI is. Furthermore, each BLE receiver will individually assign an RSSI to a particular AD packet. RSSI is logarithmically related to the distance between the transmitter and receiver. This relationship is due to simplifications in the logarithmic distance path loss model made possible by a reference toward a measured RSSI at a 1 meter distance [3], [24]:

$$RSSI = -10n\log_{10}(d) + A \tag{1}$$

$$d = 10^{\frac{A-RSSI}{10n}}. \tag{2}$$

While the log-distance path loss model is designed for indoor attenuation, it is also valid in outdoor spaces that are more densely populated, i.e., urban environments where dooring VRUs is a concern. Here, n is the path loss exponent dependent on the environment, with a value between 2 in free space and 6 when obstructed in an indoor environment. This value should be empirically determined for a given environment [16]. For short-ranged outdoor spaces, where our application scenario finds itself, the ITU recommends $n = 2.12$ [20]. d is the distance between the BLE devices. Finally, A is the measured RSSI at 1 meter. While this value may be available as part of an AD packet, the source device of an AD packet may not have a configured value for A *or* may choose not to provide it. In this case, we can predict a theoretical value from the Friis transmission formula [11], [12]:

$$A = P_{TX} + G_{TX} + G_{RX} + L_{path}, \tag{3}$$

where P_{TX} is the TX power level provided in the AD packet, G_{TX} and G_{RX} are the transmitter and receiver antenna gain, and $L_{path} = 20\log_{10}(\frac{\lambda}{4\pi})$ is the path loss over 1 meter. We obtain P_{TX} from the AD packet and set $L_{path} = -40$ dBm since BLE utilizes the 2.4GHz-2.4853GHz ISM band, which has a wavelength $\lambda \in [0.1206, 0.1249]$. Finally, G_{TX} and G_{RX} are measured values that are difficult to determine for practical purposes, but we can reasonably estimate that this value will lie somewhere between -5 and 0 dBi.

Second, is the VRU's BLE device in front of, or behind the vehicle? To the left or right? Due to the physically distributive nature of the BLE receivers in a vehicle, we can compare the RSSIs for a particular AD packet to determine which are the lowest. Thus, if for a particular AD packet the RSSI is lowest for a BLE receiver in the rear of the vehicle, then we can deduce that the VRU is located behind the vehicle.

Using the estimated locality of the device over a time series, we can additionally track the trajectory of the BLE device. Such information can help inform us of whether the VRU may be behind the vehicle, attempting to pass the vehicle, or already moving away from the vehicle. This information will also help reduce the number of false positive alerts.

However, there is a challenge that `S-Door` must overcome. Because of the narrow width of the vehicle, the BLE devices on the vehicle may have distance estimations that have overlapping error margins. This issue is most apparent at long distances since the relationship between RSSI and distance is logarithmic. To overcome this challenge, we can take two approaches based on the BLE standard of the VRU's BLE device.

Starting with the BLE v5.1 core specification, there has been a formal standard for supporting Angle-of-Arrival (AoA) for direction-finding [13]. Smartphones first began support of BLE v5.1 or greater in 2020 and most mainstream smartphones on the market today support it. The standard enables direction-finding without pairing and outlines steps for how to make use of it [4], [5]. To support AoA, AD packets append extra information called the *Constant Tone Extension* (CTE) at the end of their data transmission. For VRUs in possession of a device enabled with BLE v5.1+ and making use of the optional CTE field, we are capable of obtaining fine-grained information about whether they are approaching the vehicle from the left or right.

However, since this field is a new feature of the BLE standard and even newer feature available to smartphones, we must account for the currently common case where a VRU's device is not transmitting AD packets with the CTE appended. Our second option is to locally define the positioning of the BLE receivers in the vehicle, collect AD packet information, and store temporary averages for the RSSI of each local region of the vehicle over time. We trace the path of the VRU and this can give us a sense of which direction they are approaching from. Due to the logarithmic relationship between RSSI and distance, the RSSI becomes more accurate the closer the VRU gets to the vehicle.

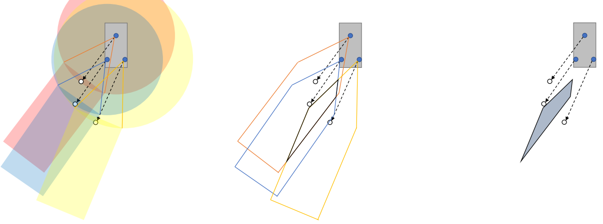
B. Implementation

In prior work on indoor localization, the use of Kalman filter, weighted trilateration, and channel diversity greatly improve distance estimation accuracy [15]. We seek to improve the state-of-the-art for dooring prevention. To fit our set of requirements, we propose adding novel techniques to the existing state-of-the-art to improve localization accuracy.

Taking the data received from three or more BLE transceivers, two options exist for pin-pointing the precise location of an incoming AD packet. The first is trilateration, which uses the estimated distance to trace three circles around each BLE transceiver and finds overlaps. However, there may not be a common point of intersection between the radii surrounding each receiver, if any intersection occurs at all. Weighted trilateration resolves this issue through pair-wise weights between each receiver calculated by the ratio of their radii [15]. However, there is no such method for extrapolating outside of the bounds of the receivers, such as in our case.

Algorithm 1: TRI^2: Triangulation-Trilateration

```
Data: A list $\boldsymbol{X}$, where $X_i = (RSSI_i, d_i, \theta_i, p_i)$.
Result: $p$, the predicted position of the VRU.
$\boldsymbol{S} \leftarrow \emptyset$;
/* Step 1: Create circle
   sectors and rectangles to union
   them and generate pentagons.        */
foreach $X_i \in \boldsymbol{X}$ do
    $C_i \leftarrow CircSector(d_i, \theta_i - \delta, \theta + \delta, p_i)$;
    $R_i \leftarrow Rect(2(l+d_i), d_i \frac{\sin(2\delta)}{\sin(\frac{1}{2}(180-2\delta))}, p_i)$;
    $\boldsymbol{S}.append(UnionShapes(C_i, R_i))$;
end
/* Step 2:
   Intersect generated pentagons.      */
$I \leftarrow IntersectShapes(\boldsymbol{S})$;
/* Step 3: Find
   weighted center of the polygon.     */
$p \leftarrow WeightedCenterShape(I)$;
```



(a) `Step 1.` (b) `Step 2.` (c) `Step 3.`

Fig. 3: Visual example of Alg. 1.

This guides us to the second option, triangulation, which uses the AoA to find the direction the signal is coming from alongside the distance in the direction to find the location. However, in order for triangulation to be effective, the distance estimation for each received signal needs to be precise. It is well-documented that estimating distance with RSSI can be imprecise, so this limits the effectiveness of triangulation for precise location tracking. Furthermore, triangulation is also traditionally used when the point of interest resides between the transceivers.

To loosen the constraint from the existing triangulation and trilateration algorithms that requires the received signal to be within the bounds of the receivers, we propose a novel algorithm we call *triangulation-trilateration* (TRI^2), presented in Alg. 1. A visual representation of this algorithm is outlined in Fig. 3.

TRI^2 first uses the methods outlined in trilateration to create circles around each of the receivers with a radius equivalent to the distance estimation for that receiver, d. Then, we use the triangulation methods to take the AoA estimated θ and add $\pm\delta$ to create a bounds around θ. From the receiver, vectors in the direction of $\theta \pm \delta$ are of length d. At this point, each receiver has an associated circle sector with radius d and angle 2δ pointing in the direction of θ. Next, lines parallel to θ continue onward from where the lines stopped at length d. This is a rectangle with width[1] of $d\frac{\sin(2\delta)}{\frac{1}{2}(180-2\delta))}$ and length of $2(l+d)$ where l is the longest distance between two receivers. Here, we can take the final intersection of the rectangles and circle sectors of all of the receivers [10], which should be an arbitrary polygon I. Using the insights from the weighted trilateration methods, we can take a weighted center of I as the estimated locality of the received signal.

Fig. 4: The prototype and testbed of `S-Door`.

In the case that the AoA is not available, as will be common while the technology becomes more pervasive, we may regress to the more naive approach of using raw RSSI values. Since the strength of signal becomes more reliable at closer distances, we can at least attempt to notify the driver of nearby VRUs.

IV. EVALUATION

In this section, we provide some evaluation for the prototype of `S-Door`. We expand on the future evaluation in § V.

A. Experiment Testbed

For our on-vehicle receivers that passively monitor for BLE AD packets, our implementation uses three *Nordic Semiconductor nrf52833-DK* boards. We position these boards on the roof of the vehicle with one toward the center-front of the vehicle and two toward the left-rear and right-rear of the vehicle. These three boards transmit received AD packet data over SPI to a centrally located *Raspberry Pi 4 Model B*, which is then responsible for processing the data and delivering the alert to the occupants of the vehicle. A picture of our testbed is included in Fig. 4.

B. Data Collection

While conducting our experiments, we mount our prototype on the roof of a parked car in order to simulate the structural conditions `S-Door` would encounter in the wild. The car used for our experiments is a subcompact crossover SUV. During the experiments, we tuck the laptop into the vehicle to power the boards and record data. For a particular trial, we save the results of `S-Door` to the local storage of the Raspberry Pi at the conclusion of the trial in order to retroactively analyze the results. We consider the scenarios of a VRU walking, running,

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[1] We obtain the width by applying the Law of Sines on the triangle inscribed in the circle sector [23].

and biking during our data collection. For each scenario we run 10 trials and collect a time series of the distances of the VRU from each BLE transceiver on the vehicle.

C. Localization Accuracy

During our evaluation, we use the TPR and FPR metrics defined in § III. For all three of the scenarios, `S-Door` is able to detect the VRU with a TPR of 100%. In other words, as the VRU gets close to the vehicle, we are able to reliably detect their presence. However, `S-Door` has some deficiencies where it cannot reliably detect the VRU at farther distances, leading to some false positives in most trials. At these further distances, `S-Door`often predicts the VRU is closer than they actually are, triggering the alert. While one solution is to reduce the trigger distance to account for this error, this significantly diminishes `S-Door`'s ability to deliver an alert in a timely manner. Since our experiments show that the VRU is always identified when it is nearby (*i.e.*, TPR=100%), these false positives may be tolerable to a cautious driver.

We envision that when implemented into a real vehicle, `S-Door` can use sensor fusion. Since `S-Door` accurately detects the presence of the VRU, short-range sensing can validate when a VRU has entered the proximity of the vehicle in order to reduce the number of false positives.

V. FUTURE WORK

There are four areas of inquiry for future work.

First, a more thorough evaluation of the AoA transmission capabilities of smartphone BLE. While most major smartphones are equipped with BLE v5.1, the efficacy of `S-Door` hinges on their adoption of the CTE field for enabling AoA.

Second, an implementation of `S-Door` in a real vehicle in order to determine whether it can meet real-time deadlines. Furthermore, we believe that sensor fusion may reduce the occurrence of false positives. Candidate sensors include side cameras, radar, and ultrasonic; however, many vehicles do not have access to any of these sensors, so this will not improve all car models.

Third, `S-Door` should be tested in a more diverse set of environments. Our experiments occurred on a day with clear weather and in a downtown environment. Future experiments should investigate the impact of different weather conditions, such as rain, snow, and fog. The future experiments should also investigate different kinds of urban roads, with varying levels of safety for VRUs. This includes roads without bike lanes, bike lanes without protections, and bike lanes with protections. Additionally, we should have more trials to represent different VRU behavioral patterns and locations of the BLE-enabled device.

Finally, we should assess the privacy implications of `S-Door`. Because we exploit AD packets to track the location of real people, we should determine if there are ethical concerns and, if so, whether there is a more ethical way to collect such information. A user-study may illuminate the perception of VRUs to this privacy concern, as well as their acceptance of the system.

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