Let's Collide to Localize: Achieving Indoor Localization with Packet Collisions

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***Abstract*—A large fraction of indoor localization methods rely on anchor nodes that periodically transmit their coordinates using radio signals. Mobile nodes then use the received information to decode their own locations. For all these methods to work, the underlying assumption is that anchors should send their beacons at different times, i.e. the beacons should not collide. We propose a radically new approach for indoor localization: to overlap the transmissions of beacons (synchronized collisions). Our collision-based method leverages the capture effect, which states that when several radio signals collide, only the strongest (nearest) signal is detected. Compared to the state of the art, our simple change of perspective –from non-colliding to colliding beacons– provides two important advantages. First, the lifetime of the mobile nodes can be increased by three orders of magnitude (from days to years). Second, our method is more resilient to external interfering sources, such as WiFi stations. In this work-in-progress, we (i) provide a preliminary evaluation of our prototype, and (ii) describe the challenges that we are currently working on to produce a fully-fleshed commercial system. While indoor localization is a very active research area, to the best of our knowledge, we are the first ones to evaluate a collision-based approach.**

***Keywords*-Indoor localization, radio signals, capture effect.**

I. Introduction

Over the last decade, there has been several notable studies that have investigated the use of radio frequency signals for indoor localization [1], [2]. Most of these studies require received signal strength measurements (RSS) to decode the location of a node. Our method does not require RSS measurements, and hence, it does not fall into this category. Our study is more related to range-free methods. In these methods, upon reception of the beacons, mobile nodes determine their position by processing only the (x, y) coordinates of the anchors (no RSS involved). The information received from nearby anchors can be processed following simple centroid techniques [3], which average the received coordinates; based on distance vector routing [4], which use off-line hop-distance estimations to obtain geographical coordinates; or using complex geometric calculations such as APIT [5], where an irregular deployment of anchors is required to derive triangular sections.

Novelty and basic idea. Our study differs from the state-of-the-art in range-free methods in a fundamental way: we do not require beacons to be sent at different times, to the contrary, our method requires a precise overlap of the beacons transmissions. These overlapping transmissions can leverage the capture effect to decode the beacon (coordinates) coming from the anchor with the strongest signal. Hence, in essence, what our method does is to divide the space of interest into a sort of Voronoi diagram, similar to the bottom part of Figure 4. The Voronoi cells are defined by the coordinates of the anchors and the specific characteristics of the environment, such as walls. Mobile nodes are then localized by closest-proximity: when a node is within a given cell, it obtains the coordinates of the corresponding anchor. While conceptually simple, our idea has several important implications, and -as we will observe- its implementation needs to overcome non-trivial technical challenges.

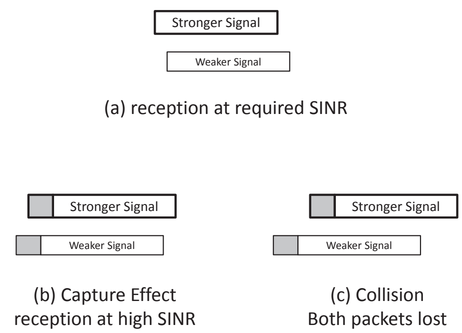
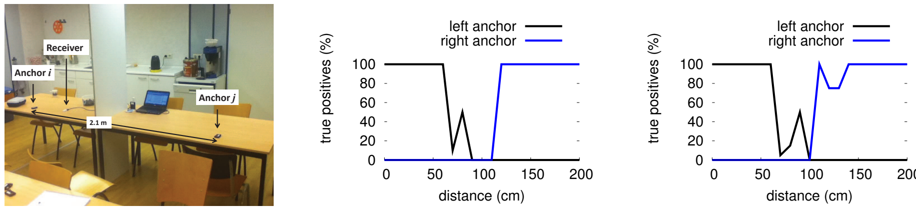


Figure 1. Collision and Capture Effects

II. The Collocal approach: Leveraging the capture effect

Our method, named Collocal, leverages a physical layer phenomena known as the *capture effect*. This effect is described in Figure 1. When two wireless signals collide there are three possible outcomes depending on (i) the relative strength of the signals, and (ii) their relative timing. If the strongest signal is received before the weakest signal, then the strongest signal is successfully decoded as long as the signal-to-interference noise ratio (SINR) is above a certain value, Figure 1(a). If the stronger signal arrives during the preamble of the weaker signal, then the SINR needs to be higher (than in the previous case) in order to decode the packet successfully, Figure 1(b). This is the capture effect. Finally, if the stronger signal arrives after the preamble of the weaker signal, then no packet is successfully received,



(a) scenario (b) results with a wall (c) results without a wall

Figure 2. A simple experiment

Figure 1(c). *In order to take advantage of the capture effect, Collocal needs to synchronize the transmission of beacons within the preamble length of each other.* In the next subsection we explain how we achieve this level of synchronization in our initial prototype; we now describe a simple experiment to convey the key idea of Collocal.

Figure 2(a) shows two anchor nodes that send overlapping beacons. The distance between the anchors is 2.1 meters and they both use the same output power, which was calibrated to cover the room in the figure. The beacons are sent at a rate of two packets per second. The receiver is moved from one anchor to the other in steps of 10 cm. At each point, the receiver collects data for 30 seconds (60 samples total). In this simple scenario, the room is divided in two cells and we want to localize the node in the right cell.

Figures 2(b) and 2(c) depict the performance of the system with and without a wall. A value of 100% indicates that the 60 samples (60 overlapping collisions) were correctly decoded into the right position. Collocal has three important regions. First, the reliable regions [0, 60] and [140, 200], where the signal of the strongest anchor is high enough for the capture effect to take place. Second, the unreliable region [60, 140], where there are no false positives, but the relative strength of signals (SINR) is not high enough for the capture to take place consistently. Third, the dead zone region [100], where the strength of both signals are similar and no detection is possible. Notice that the attenuation caused by the wall, in Figure 2(b), reduces the variance of the unreliable region.

A. Initial Prototype

Requirements. Our system targets applications requiring a coarse granularity (localization within a few meters) and a long lifetime. An example of this type of applications is tracking goods in a building for five years, or more, without replacing the battery. Commercial applications also pose constraints in terms of size and cost, the tags should be small (no big batteries allowed) and inexpensive. This set of constraints require a system with very low-power technology. To achieve these goals, Collocal needs to keep the mobile nodes sleeping as much as possible.

The design of Collocal has two main components: (i) time synchronization and (ii) data transmission. Both components are built upon existing knowledge in the state of the art. The novelty of our study is not on developing these components but on analyzing collision-based localization, hence, due to space limitations we only provide a brief description of our initial prototype.

Hardware. We use the nrf51822 system on chip (SOC) from Nordic Semiconductor. It is a 6x6mm IC that contains a cortex-M0 processor and a 2.4Ghz transceiver with a transmission rate of 2Mbps. With this hardware, the time synchronization required to leverage the capture effect should be less than 25 μsec. The radio transceiver has the capability of reading RSS values. We do not use this capability for Collocal, but we do use the RSS values to provide an upper bound for the best performance that can be expected from Collocal. This will be explained in more detail in the next Section.

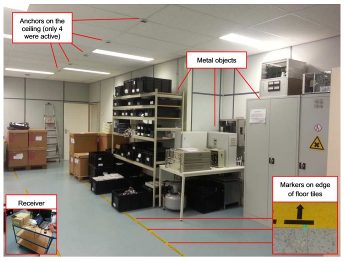
Time synchronization component. To achieve a high level of synchronization with low power consumption, we utilize a low-power low-resolution timer (32 KHz), in conjunction with, the high-power high-resolution timer of the processor (8 MHz). The low-resolution timer is always *on*, while the high resolution timer is turned *on* only sporadically – when a higher timing resolution is required. Overall, Collocal achieves a time synchronization within 3.8 μsec, which is vastly lower than the required 25 μsec.

Data transmission component. Besides sending localization beacons, anchors may need to report back the location of mobile nodes to a central repository (data collection), or they may need to send other control data to the network (data dissemination). To allow these data-transmission capabilities, we developed a simple TDMA protocol that exploits the well known concept of *spatial reuse* and Collocal's high level of synchronization. This basic TDMA protocol allows new incoming mobile nodes to synchronize their timers using a listening window of 31.25 ms, or a multiple of these windows depending on the network's configuration.

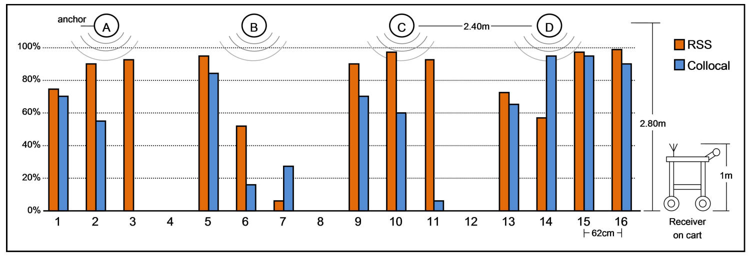
B. Advantages and disadvantages of Collocal

Our method provides two key advantages: a longer lifetime and higher resilience to interference. The main disadvantage of our method is its coarse granularity. These points are described below.

Increased node lifetime. In traditional range-free meth-



(a) scenario



(b) evaluation results

Figure 3. The anchors form a multi-hop topology: 7 anchors (6 hops). Only 4 anchors sent beacons, the other 3 act simply as routers.

ods, nodes are assumed to be *on* all the time (to receive the unsynchronized transmissions of beacons). Given that radio and processor idle time are the main sources of energy depletion in low-power embedded systems, it is central to reduce their duty cycling. In Collocal, mobile nodes only need to be *on* for a few milliseconds: (i) to receive the overlapping beacons ($\approx$ 1.5 ms)[1], (ii) to sporadically (re)synchronize with the network (31.25 ms<), and, if required, (iii) to report their location ($\approx$ 1.5 ms). Assuming a beaconing and reporting period of one second, the duty cycle of Collocal is $\approx 0.3\%$. This energy savings can increase the node's lifetime from days to years. Other low-power embedded systems, such as wireless sensor networks, have also shown this level of improvement after reducing their radio duty cycles [6][2].

High resilience to interference. Nowadays, it is central to design systems that can cope with external interference. WiFi, Bluetooth, and a variety of electro-domestic devices operate, and interfere, in the ISM bands. The accuracy of traditional range-free methods depends on their ability to detect most (all) nearby beacons. For example, in Figure 2(a), consider a receiver located at the same point as anchor i. If there is interference present during the transmission of beacon i, but not during the transmission of beacon j, the receiver would get an erroneous location. In networks exposed to the well-known burstiness of WiFi stations, this example would not be an uncommon scenario. A static node would show continuous "jumps" because its coordinates will be computed with different sets of beacons at every period; with the most inaccurate calculations corresponding to the instances where the nearest beacons are lost. In Collocal, resilience to interference is obtained by default. Since all beacons are sent at the same time, only two outcomes are possible. If the interference signal is lower than the strongest beaconing signal, Collocal is unaffected because the capture effect "filters out" this type of interference. If the interference signal is similar or higher than the strongest beaconing signal, no location can be decoded. Notice that in the latter case no system would be able to decode the signal either. To increase the resilience of Collocal, the beaconing frequency could be increased (at the cost of shorter duty-cycles, and hence, higher energy consumption).

The main disadvantage of our method is its coarse granularity. By granularity, we refer to the ability of the system to divide the space of interest into smaller subspaces (cells) that are uniquely identified. The finer the granularity the better the system. In general, for all range-free methods, the higher the number of anchors and the more homogeneous the deployment, the higher the granularity. While this statement is also true for Collocal, the key limitation of our method is that the number of cells is equal to the number of anchors. In other range-free methods, the number of cells is greater than the number of anchors because the overlap of the various transmission coverages dissect the space into smaller subregions.

III. Initial Evaluation

Our initial evaluation is depicted in Figure 3. We utilized four anchor nodes spaced every 2.4 meters in a production environment, as shown in Figure 3(a). The mobile node was placed on a cart and it was moved along 16 consecutive points spaced every 62 cm. At each point we collected approximately 100 samples. The various objects in the environment were selected to include the well-known multipath effects affecting wireless systems.

Collocal can not perform better than an "equivalent" RSS-based method. Hence, to provide a good basis of comparison, we also performed an evaluation with RSS measurements. We first allowed anchors to send unsynchronized beacons, i.e. no collisions. Then, the mobile node would assign its position to the anchor with the highest RSS, if two or more signals had a similar RSS (within a 3dB margin), the node would not assign itself to any position[3].

Figure 3(b) shows the performance of the RSS-based method and Collocal. The bars represent the number of true positives (there were no false positives for either method). These results capture two *current* limitations of Collocal:

[1]Most of this time is used to startup the transceiver, the message itself takes only 144 μsec

[2]Other range-free methods could also be enhanced to reduce the duty cycling of nodes, but this would require (complex) coordination mechanisms to make sure that nodes receive the beacons from all anchors in range.

[3]This is an "equivalent" RSS-method. Other methods, such as centroid calculations, would perform better (at the cost of using more energy and being more susceptible to interference).

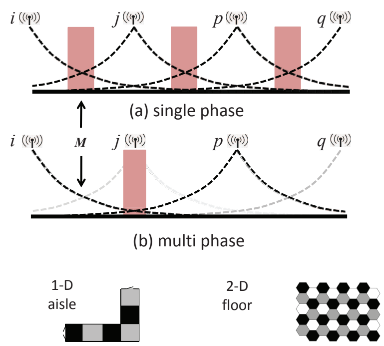


Figure 4. Multi-Phase Transmission

dead zones and bit corruption. First, note that sample points 4, 8 and 12 provide no localization. This is because the RSS signals of two or more anchors are similar, and hence, the capture effect can not take place. Second, and more importantly, at some points (2, 3, 6, 10 and 11), the performance of Collocal is significantly lower than the RSS method. The reason for this is that, in Collocal, the demodulation of the stronger signal is likely to lead to more bit errors because a *one* in a slightly weaker transmission can overwrite a *zero* in a stronger transmission. The result is something resembling a bitwise-OR on air of both messages, where a *one* is received instead of a *zero*. For example, if the strongest signal has the sequence 1000 and the weakest signal has a sequence 0010, the resulting sequence could be $10\underline{1}0$. This effect leads to significantly higher bit-error-rates than the more traditional unsynchronized RSS methods.

In the next section we describe some potential solutions to overcome the limitations of Collocal.

IV. Overcoming Dead Zones and Bit Corruption

For Collocal to become a plausible commercial alternative, we need to overcome two key challenges: dead zones and bit corruption. We are currently evaluating three approaches two overcome these limitations.

A. Multi-Phase Transmission.

As shown in our initial evaluations, the dead zone problem is aggravated when the density of anchors is increased. To alleviate the dead zone problem, the anchor nodes could be divided in different groups, with each group transmitting their beacons at different phases. Figure 4 depicts the basic idea. First, when all anchors transmit, as in Figure 4(a), a node at point M can not detect its position because it is on a dead zone. Then, only anchors i and p transmit and the node assigns its location to i, Figure 4(b). After that, only anchors j and q transmit and the node assigns its location to j. After the three phases have finished, the node at point M could correctly identify its final location to the middle area between i and j. The bottom part of Figure 4 depicts how multi-phase can be used on 1-D (aisles) and 2-D (floor) areas. In aisles we can have three phases: all anchors, black anchors and gray anchors; while on floors we can have four phases. It is important to note that the multi-phase approach involves some trade-offs: nodes would need to listen longer (use more energy), perform more processing (to merge the information from the different phases), and its granularity would be susceptible to interference (if the information of some phases is lost, the granularity will be coarser).

B. Directional Antennas.

Another way to reduce the "density of signals"' is to use directional antennas –which provide narrower coverages. In this way, neighboring anchors would interfere less with each other and reduce the extent of dead zones. We are currently evaluating multi-phase techniques and directional antennas and the results look promising. Our main challenge is bit corruption. Next, we explain a technique that we plan to investigate to ameliorate these effects.

C. Orthogonal Codes.

The high time synchronization of Collocal seems to create an on-the-air bit-OR operation. The overlapping at the bit level creates a higher bit-error-rate than usual. We want to explore more sophisticated coding schemes to overcome this problem. A possible direction is to use orthogonal codes to encode neighboring beacons. In this way we hope to decrease the cross-correlation of beaconing signals. The trade-off for using complex coding schemes would be to increase the use of computing resources at the mobile node.

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