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Hybrid Localization techniques in LoRa-based WSN

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Abstract—**The emerge of the Internet of Things (IoT) paradigm in various smart applications such as; smart farming and water system monitoring, has been the highlight of this era. Innovative solutions providing better coverage and minimized power consumption by end nodes such as Low Power Wide Area Networks (LP-WAN) has facilitated the advances towards improved IoT connectivity. Long Range Wide Area Network (LoRaWAN) technology stands out as one leading platform of LP-WANs receiving vast attention from both the industries and the academia. Performance evaluation of LoRaWAN is promising, even in the field of localization of end node devices in outdoor low-density platforms. Considering harsh environmental sensor network, where there is a need to deploy a higher dense WSN (i.e sensor every $10m^2$) and there is unexpected infrequent random displacement of sensor location due to environmental conditions. The accuracy of LoRaWAN in updating the network with revised sensors' coordinates might be unfulfilled. Given the acoustic range of localization to be around few meters with fine precision, in this work, we propose the use of hybrid ultrasonic and LoRa signals to enhance the localization of a high density outdoor WSN.**

Keywords; Localization / Localisation. , Internet of Things, LoRa, LoRaWAN.

I. INTRODUCTION

The future of IoT depends on exploring better solutions for various parameters, including, reduced bandwidth communication, lower transmission data exchange between nodes to ensure a longer lifetime, long range links, low cost end-nodes and coherent connection of higher number of devices. Those requirements extend the usage of traditional enabling technologies used in WSN and cellular systems, i.e. WiFi, bluetooth , etc.

Interestingly, the majority of these requirements are fulfilled by Low-Power Wide Area Networks (LPWAN), shaping it as one of the most promising solutions for IoT enabling technologies. Several LPWAN standards are presented in the literature [1] [2] [3], among which, SigFox and LoRa (Long Range modulation) have attracted the most attention.

Sigfox [4] technology based on Ultra-Narrow band modulation, aims to connect remote devices to an access point operating on the 868-MHz frequency band, where each transmitted message use a bandwidth of 100 Hz with adaptive data rates depending on the operational region. Limitations for each end device includes; maximum uplink of 40 messages per day, with a payload size of 12 octets.

The SigFox interface circuitry wakes up, transmits a message from the end-device; then, the end-device listens for a short duration in case there is a downlink to the end-device [4]. In other words, the downlink traffic is supported by active end-device, which makes Sigfox an interesting choice for data acquisition, but perhaps less so for command-and-control scenarios.

LoRa, on the other hand, has an open specification and gateway infrastructures, has attracted enormous investigations lately. LoRa targets scenarios adopting limited powered end nodes, where nodes do not need to transmit more than few bytes a day and where data traffic can be triggered either by the end-device/sensor or by an external entity wishing to communicate with the end-device. It offers a tradeoff between the lower data rates and longer transmission range.

Object tracking using GPS has shown extreme usefulness, but the concern that IoT platforms use low powered devices and relatively inexpensive hardware, GPS systems would increase the node size, deployment cost and is considered energy inefficient. Localization of sensor nodes in WSN and IoT applications is a challenging task, especially when considering the limitations of end devices employed.

Considerable work in the current literature is concerned with exploiting the performance of LoRa and its connectivity. While, exploring the prospects of localizing IoT nodes in outdoor and indoor scenarios is still an open issue. An interesting aspect of LoRa is that, a typical data frame transmitted to a various gateways can be used for geolocation, with no overheads. However, range of accuracy limitations of geolocation using LoRa signals need research to explore better and more robust solutions.

The aim of this paper is to: (i) Provide an overview of LoRa and understanding its limitations in localization; (ii) Reviewing the current positioning techniques found in literature and the possible sources of errors ; (iii) Based on the previous work reviewed, proposing a hybrid localization technique based on LoRa and acoustic signals as a solution for enhanced positioning systems.

II. LP-WAN: LORA

By defining the physical (PHY) and Medium Access Control (MAC) layers of the OSI model, LoRaWAN presents an adaptive solution to fulfill the need of diverse end-users.

Specifically, in the PHY layer, LoRaWAN utilizes its own enhanced modulation, namely LoRa, which is based on a chirp spread spectrum (CSS) modulation [5], where each data symbol is encoded by linear frequency modulated pulses whose frequency increases or decreases over a certain amount of time to encode information [6] and through which, the timing and frequency offsets between transmitter and receiver are equivalent, immensely reducing the complexity of the receiver architecture [7]. CSS is similar to Frequency Shift Key (FSK) modulation with low power consumption characteristics however, CSS shows significant increase in the communication range in trade of lower data rates.

LoRa modulation allows several parameters to be customized with respect to the system design: Bandwidth (B), Spreading Factor (SF) and Code Rate (CR). SF is the logarithm to the base 2 of the number of chirps per signal. SF is basically the duration of the chirp, LoRa operates with spread factors from 7 to 12; where SF7 is the shortest time on air and SF12 is the longest. Each step up in spreading factor doubles the time on air to transmit the same amount of data. In other words, reducing the SF decreases the transmission time but results in lower SNR. Also, a shorter transmission time require the use of a higher bandwidth but reduces the maximum receiver sensitivity [8]. A LoRa symbol is made of 2^{SF}chirps covering the channel bandwidth given, thus each symbol encodes SF bits of information. All SF values ensures orthogonal transmissions at different data rates. These user-adaptive parameters influence the modulation bitrate, the transmitted signal resistance to channel noise and multipath, and the degree of complexity of information decoding [2]. Finally, LoRa uses Forword Error Coding (FEC) to allow the recovery from transmission errors resulting from interference, which in consequence adds some encoding overhead to the transmitted packet.

Communication protocol (LoRaWAN) is defined in the higher layer (MAC layer), as for the system architecture and other high-level application interfaces. The choice of protocol and network architecture have the most influence in determining the battery lifetime of a node, the network capacity, the quality of service, the security, and the variety of applications served by the network [9]. With regard to the network architecture, LoRaWAN uses a star of stars topology allowing user devices to connect directly to the most adequate gateway, which in turns, connects to a central network server using broadband links. In aim of fulfilling the limitation of the devices' available energy, LPWAN usually limits the downlink transmission from base stations/gateways to end devices.

To facilitate that, LoRaWAN defines 3 device classes based upon their power limitations and information need, known as class A, B and C. The mostly implemented, class A devices are open for reception after each uplink transmission, by opening two listening windows, giving the longest battery durability. Similar to class A, class B devices schedule extra receiving windows for downlinks, that are enabled by the broadcast of beacons from gateways. Finally, class C are continuously listening after their uplink transmissions.

Depending on the region of operation, the open protocol operates on different bands and consequently, duty-cycle limitations may exist. In Europe, LoRa operates in the 868 MHz band with a configurable channel bandwidth of either 125 kHz or 250 kHz and a duty-cycle of 1%. LoRa's long range capability favor it usage, since single gateway can cover an entire city depending on the environmental obstacles. Choosing the optimal class is vital for applications with response time or minimum power consumption requirements [8].

Various research has focused on the performance evaluation of LoRa in WSN networks. In [10], authors studied the performance of LoRaWAN under different environmental conditions; urban, suburban and rural. Their results emphasized the importance of studying the channel conditions of the deployment scenario prior to the system implementation in aim of having a robust network. The first localization experiment based on LoRa in [11], considering different activities of walking, cycling and driving showed a median accuracy of 200m from the raw Time Difference of Arrival (TDoA) output data and stated that in 90% of the cases, the error was less than 500m.

III. Localization

A. *Localization Techniques and Sources of Error*

Different positioning schemes can be used to locate a node in a WSN through collecting information from radio signals traveling between target and reference nodes. There has been various classification of the techniques used in positioning systems [12]. One mostly common range-based classification divides the approaches into three categories; time of arrival, signal strength based schemes and direction of arrival.

Time of arrival (TOA) is defined as the time at which a received signal is first sensed at a receiver. To measure TOA, time resulted from propagation should be calculated in addition to the transmission time itself. This propagation delay , when divided by the velocity of the transmitted signal, is then translated to separation distance between a Tx-Rx pair.

An extension of time of arrival approaches is TDOA, as it calculates the differences in time of arrival of a mobile signal at multiple (two or more) pairs of stations. Each TDOA measurement provides a hyperbolic curve along which the unknown node may exist. Thus, the need of more than one measurement to form an intersection of these curves then yields an estimate of the position. Assuming that the transmitted signal from the unknown node location is received by multiple base stations, and that all of the base stations have a synchronized time reference, estimation techniques may be employed at the base station to determine the TDOA.

Global Positioning Systems (GPS) utilizes the TOA technique for its exceptionally accurate measurements; however, it requires high processing capability. The accuracy of TOA approaches depends on various factors, including; (i) receivers synchronization, (ii) strength of the signal (SNR) received at each base station/ gateway and (iii) Channel effects. To maintain the receiver synchronization, Cesium clocks and/or reference timing from GPS can be adopted.

On the other hand, Received Signal Strength (RSS) is a measure of the received signal strength / voltage at the receiver's side. Sometimes, referred to as the measured received power, i.e. the squared magnitude of the received signal strength. Different forms of signals can be used by sensors within a WSN to ensure communication such as using RF, acoustic or other form of signals. Consequently, measuring the received signal strength during standard communication does not pose any additional energy or bandwidth demand, making RSS measurements relatively inexpensive and simple to implement.

Complementary to RSS and TOA, Angle of Arrival (AOA) provides information about the direction of the unknown node rather than the distance. More specifically, it measures the angles of the target node with respect to the reference nodes, usually by means of antenna arrays. This can be done by either using a sensor array and employing array signal processing techniques at the sensor nodes [13] or by using the RSS ratio between two (or more) directional antennas located on the sensor. Direction of arrival approaches require multiple antenna elements which can be of higher complexity, greater cost and size.

Practically, signals arriving at the receiver side are of various amplitudes and phases of the original transmitted signal. They add constructively or destructively, depending on the frequency, causing frequency-selective or flat fading. In a desirable scenario, where frequency-selective effects are diminished, environment-dependent errors caused by shadowing, such as the attenuation of a signal due to obstructions (walls, trees, buildings, and more) that a signal must pass through or diffract around on the path between the transmitter and receiver are still present. The effect shadowing have on RSS measurements is unfortunately unpredictable. Thus, the use of RSS indicators are considered useful , when the sources of error are understood and taken into consideration.

B. Localization in LoRa

It was earlier last year, that the LoRa Alliance Strategy Committee [14] stated that the accuracy of LoRa signals used in geolocation can reach up to, 20-200m using the TDOA technique depending on conditions and a lower accuracy of 1000-2000m when using Received Signal Strength Indicator (RSSI) measures.

When a LoRa signal passes through a channel experiencing flat fading i.e the bandwidth of the propagation channel is greater than that of the transmitted signal, while the spectral properties of the signal remain uniform at reception, the amplitude of the signal fluctuates with time due to changes in the gain of the channel caused by multipath that can hugely affect the measured RSSI. In [15], authors constructed a simple experiment between a pair of Tx-Rx LoRa modules, for an indoor static distance of 10 m. The random fluctuations in the RSSI measurements gives an indication of how challenging the approach is .

Frequency-selective fading is said to occur when the bandwidth of the propagation channel is less than that of the transmitted signal. In has been thoroughly discussed in [7], that the relatively broadband nature and high bandwidth time product of LoRa provides for excellent immunity to multipath and fading mechanisms.

As for the TDOA approach to obtain accurate calculations, readings from different receivers should be obtained given that their clocks are firmly synchronized. To extract the time-stamp i.e the exact time of arrival of a signal by a LoRa module, [15] discusses the 3 different methods. All three approaches achieve microsecond level time-stamping i.e an accuracy of approximately 300 m only, which is insufficient for meter-level ranging and localization.

C. Ultrasonic Localization

Many wave energy signals are currently used as a non-contact measurement of displacement, location and duration of events. Simply, the wave pulses propagates from the transmitter through channel and then received. The measure of distance/direction of those waves help triangulate a specified coordinate.

Ultrasonics offers an economical method for position estimation but have traditionally been limited by some problems. Hardware level issues and system model enhancement has been investigated in many researches using several approaches that facilitated the use of ultrasonic [16].

Work in [17] studied the use of an ultrasonic system in indoor positioning, and calculates the position of a mobile platform at cm level accuracy. Authors in [18], introduced the use of ultrasonic sensors to improve the accuracy of indoor/outdoor localization of smart phones, given the low efficiency of GPS systems indoors. Moreover, various experiments has been carried out by [19] where one strikes out when they employed two ultrasonic emitters on-board of a mobile rod and then applied trilateration TOA estimation to a set of eight receivers for estimating the position of each emitter in an outdoor archaeological site.

IV. Proposed Hybrid Solution

This paper will address the localization techniques of various range of signals in the scenarios of mixed sensors node environment, aims to enhance actuary of localization. This section aims to explore the use of ultrasonic signals in outdoor low power WSN where the location of a mobile sensor can be tracked in specific areas and where LoRa networks can be built in. The hybrid localization technique proposed can be divided into two stages; ultrasonic updated measurement stage following, the LoRa to gateway transmission.

Every up-link packet from a LoRa device has a series number, time-stamp, and device ID. The Things Network (TTN) hub of LoRa end-devices and gateways shows the received information needed e.g. time-stamp, RSS, Time-on-air (TOA), packet number and the received SNR values. Fig. 1 shows a screen-shot of the received information between a public gateway and our LoRa device, from which valuable information can be extracted and processed for positioning.

While, the Time of Flight (TOF) between any two terminals remains unknown, the difference between the reception time of synchronized receivers can be measured. By ways of explanation, if the first transmitted signal is referenced by t=0, and the replicas received by further receivers is sensed at t_1, t_2 and t_3, then TDOA can be calculated as; $\Delta t_{1j} = t_j - t_1$, for $j \in \{2,3\}$. For more sophisticated systems, a least squares estimation method may be used to estimate the values of the unknowns.

Complementary, acoustic communication between a LoRa device and lower-complexity sensor with an ultrasonic transducer offers enhanced location update. While RF signals can cover 1 ft (0.3 m) in 1 ns, acoustic signals propagate with much lower speed covering 1 ft (0.3 m) in about 1 ms. For the echo signal to measure the unknown distance between 2 sensors, it calculates the TOF and divides it by the speed of sound (340 m/s). Upon acquisition of the updated information, LoRa devices consequent uplink can transmit those updates to the gateway. This setup, though simple, yet it provides an efficient and more accurate sensor mapping.

In this context, we design the system using four transmitters (3-LoRa and ultrasonic end devices and 1-ultrasonic based) and 3 receivers (LoRa gateway) that are considered to lie on a single plane as shown in Fig. 2. Each receiver is located at a known position (u_k, v_k), for k=1,2,3, through the use of time-synchronous GPS. While, the transmitters are located at unknown positions: $Tx_1(x_1, y_1)$, $Tx_2(x_2, y_2)$ $Tx_3(x_3, y_3)$ and $Tx_4(x_4, y_4)$. The distance between the ultrasonic sensor $Tx_4(x_4, y_4)$ from each LoRa device , $d_{z,4}$, for z=1,2,3 are the indices of each LoRa Tx, and can be found by;

$$d_{z,4} = \sqrt{(x_4 - x_z)^2 + (y_4 - y_z)^2} \ . \quad (1)$$

The first LoRa device to sense the signal (Tx_1) is considered to be at a distance (d) from the ultrasonic sensor. Another LoRa device will be the second one to sense the signal (Tx_2) with a separation distance of $(d + c\,\Delta T_{24})$, where c is the velocity of sound. The third device (Tx_3) will respectively have a separation of $(d + c\,\Delta T_{34})$. That said, the LoRa devices can be thought of having different circular coverage regions with no circle having more than one device centered in it. Consequently,

$$d = \sqrt{(x_1 - x_4)^2 + (y_1 - y_4)^2} \ , \quad (1)$$

$$d + c\,\Delta T_{24} = \sqrt{(x_2 - x_4)^2 + (y_2 - y_4)^2} \ , \quad (2)$$

$$d + c\,\Delta T_{34} = \sqrt{(x_3 - x_4)^2 + (y_3 - y_4)^2} \ . \quad (3)$$

Simple multiplication of the equations and solving (1) for d^2 gives;

$$d^2 = x_1^2 - 2\,x_1 x_4 + x_4^2 + y_1^2 - 2\,y_1 y_4 + y_4^2 \ , \quad (4)$$
$$(d + c\,\Delta T_{24})^2 = x_2^2 - 2\,x_2 x_4 + x_4^2 + y_2^2 - 2\,y_2 y_4 + y_4^2$$
$$(d + c\,\Delta T_{34})^2 = x_2^2 - 2\,x_2 x_4 + x_4^2 + y_2^2 - 2\,y_2 y_4 + y_4^2$$

Subtracting the second equation in (4) from the first, we get;

$$(-2\,x_1 + 2\,x_2)\,x_4 + (-2\,y_1 + 2y_2)\,y_4 = d^2 - (d + c\,\Delta T_{24})^2 - x_1^2 + x_2^2 - y_1^2 + y_2^2. \quad (5)$$

Similar to (5);

$$(-2\,x_2 + 2\,x_3)\,x_4 + (-2\,y_2 + 2y_3)\,y_4 = d^2 - (d + c\,\Delta T_{34})^2 - x_2^2 + x_3^2 - y_2^2 + y_3^2. \quad (6)$$

which can be solved for the location of the transmitter (x_4, y_4) and the distance (d) from the first LoRa device. The speed of sound c is assumed to be known, and is treated as a constant. An equivalent calculation is assumed when estimating the location of each LoRa device from the gateways.

Distances between each LoRa device and the ultrasonic sensor forms a clear trajectory i.e hyperbola, the intersections of which can determine the point where the sensor lies. This method is widely known as the trilateration technique for positioning. We sketch the trilateration of the 3 LoRa transmitters in Fig. 2, the same concept is then repeated for 3 gateways to estimate each LoRa device's position. It is fair to say that, for simplicity we only considered a single ultrasonic sensor, while this method is still valid when computing the distances of more than a single ultrasonic sensor, as long as the sensor lies within its estimated range from 3 LoRa devices, exhibiting an accuracy of few mm error.

Finally, the updated location of those sensors can be passed along to the gateway/ base-station employed, where a Geolocation program can form an accurate sensor map.

Figure 1. Screen-shot of the Console application on TTN

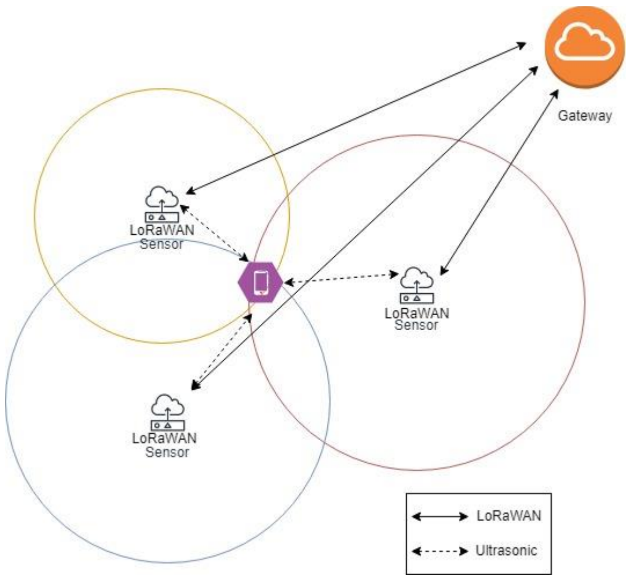

Figure 2. Proposed Hybrid System

V. Conclusion and Future Work

There are many challenges and factors to be considered when implementing a LP-WAN. Several technologies and protocols are present in the literature. LoRa and LoRaWAN has the potential to create feasible LPWANs but only when their strengths and weakness limitations are considered.

In this work, we surveyed different range-based localization techniques and their sources of errors in detail. Following which, we shed the light on LoRa and LoRaWAN technology then finally proposed the novel idea of using ultrasonic signals as an aiding approach for localization in outdoor environments adopting LoRaWAN. Based on previous work regarding LoRaWAN and ultrasonic ranging techniques, and the theoretical basis found in literature, we anticipate that the implementation of such hybrid localization system will bring higher accuracy to current positioning systems.

Future work requires implementing the system on LoRa-based Arduino chips and ultrasonic-based end nodes. Not to mention, the consideration of environmental effects e.g wind effect on speed of sound, and consider their influence on the received signal to detect signal arrival times. The results from the experimental design will then be compared to previous LoRa localization work to evaluate the accuracy for the formulation presented in this work.

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