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DISTANCE MEASUREMENT USING TDOA METHOD BASED ON LORA PROTOCOL

Abstract. The article focuses on the implementation of distance measurement between objects using the Time Difference of Arrival (TDoA) method, specifically through the Round-Trip Time of Flight (RTToF) technique, based on the LoRa protocol and utilized by the SX1280 transceiver. **The aim of the article** is to detail the temporal characteristics of packet exchange and formalize the calculation of distance. The key parameters significantly affecting measurement accuracy are identified as Bandwidth (BW) and Spreading Factor (SF). The research includes a comprehensive analysis of error sources, such as Reference Oscillator Error (timing offset) and Multipath Propagation, and provides formulas for their quantification. A multi-stage correction methodology is proposed, incorporating Frequency Error Correction (based on FEI), LNA Compensation (based on RSSI), Statistical Filtering (using the median), Polynomial Curve Correction, and Environment-Specific Correction. **The results obtained** from field measurements indicate that with this comprehensive correction approach, a ranging precision of approximately 1 meter can be achieved in controlled line-of-sight conditions. Furthermore, practical outdoor applications demonstrate mean errors below 10 meters even at distances exceeding 1 km. **Conclusions**: The implementation and comprehensive correction of RTToF measurements using the LoRa-based SX1280 module allow for the achievement of high accuracy while maintaining an acceptable balance between precision, time-on-air (energy consumption), and communication range, which is crucial for object detection and positioning systems.

Keywords: TDoA, LoRa, SX1280, RTToF, ToF, Ranging.

TDoA

Measuring the distance between objects is a key task in target detection systems, such as radars. To detect an object, a radar sends powerful radio pulses that reflect off the object, with part of the pulse energy returning to the radar. The propagation speed of the pulses is close to the speed of light, which is a known value. By receiving the pulse return time, the radar determines the distance to the object.

The TDoA method operates on a similar principle [2]. The master device sends a ranging request to a slave device and activates a timer. When the slave device receives the ranging request, it immediately returns a response to the master device. The master device stops the timer when the response arrives and stores it in a result register. The measurement result is the Time of Flight (ToF), from which we derive the distance between objects using the formula:

$$d = (T_f/2)\cdot c, \quad (1)$$

where d is the distance between objects; $T_f/2$ is the response reception time divided by 2, because the signal travels double the distance; c is the speed of light.

The slave takes time T_r to process, form, and send the response, which must be subtracted (Fig. 1):

$$d = ((T_f - T_r)/2)\cdot c, \quad (2)$$

Thus, the TDoA method involves message exchange between master and slave. During the exchange, the master activates a timer that records the time when it receives the response from the slave. From this time, the distance between objects is calculated.

This method is implemented on radio modules such as the SX1280 from Semtech, where it operates based on LoRa modulation at a 2.4 GHz frequency [1]. The SX1280 performs one round of exchange, and based on the response reception time, the master calculates the result, a number that is relative to the distance between objects.

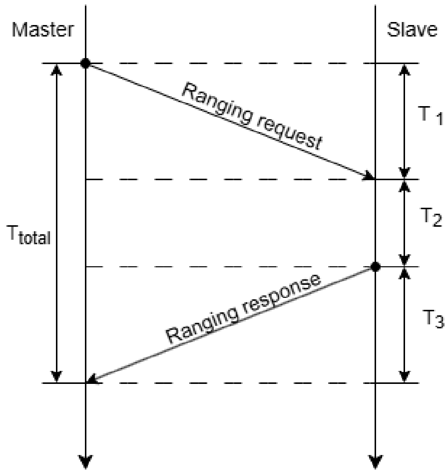

Fig. 1. TDoA timing diagram

There is also the ATA8352 radio module from Microchip [2]. This chip operates in the 6.2 GHz–8.3 GHz range and uses Impulse-Radio Ultra-Wideband for distance determination. Unlike the SX1280, the ATA8352 radio module supports Double-Sided Two-Way-Ranging (DS-TWR). DS-TWR application exchanges a sequence of data telegrams between the nodes and captures the timestamps of these data telegrams at the transmitter and receiver nodes to measure the distance between them.

Implementation of RTToF Method on SX1280 Radio Module and Data Processing Algorithm

The SX1280 module performs distance measurement using its integrated Ranging Engine [3]. Here, TDoA is implemented as Round Trip Time of Flight (RTToF). This is a simple form of TDoA where the measurement session consists of one round of ranging packet exchange. Each exchange is a complete measurement operation. However, for accurate measurements, it is advisable to conduct several exchanges to obtain a more precise result.

In RTToF, there are clearly defined roles: master and slave [3]. Before the actual measurement, roles must be explicitly assigned between radio modules. Also, distance measurement is a directional operation. The slave receives a logical address. The Master performs measurement with a specific slave in its coverage area, embedding the slave's address in the ranging packet.

The ranging packet structure is similar to a regular LoRa packet but with some differences [3] (Fig. 2). The preamble is the same as in a regular LoRa packet. The header includes the slave address and checksum. The payload carries no information. In this form, the Master sends this packet to the slave. The slave receives it and sends back a response that has no preamble or header, only payload. The timer on the master counts until the response from the slave arrives.

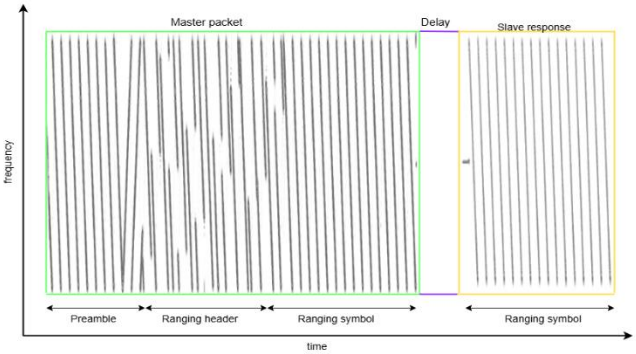

Fig. 2. Ranging packet spectrogram

The total packet time depends on such factors as: bandwidth, spreading factor, preamble length, number of ranging symbols, and the time to switch slave from RX to TX mode. In simplified form, the packet time $T_{ranging}$ is the time of one symbol T_s multiplied by their total number $N_{ranging\_symbol\_exchange}$ [1]:

$$T_{ranging} = T_s * N_{ranging\_symbols}. \quad (3)$$

The symbol time T_s depends on Spreading Factor SF and Bandwidth BW according to the equation [1]:

$$T_s = 2^{SF}/BW. \quad (4)$$

$N_{ranging\_symbol\_exchange}$ consists of the sum of master packet symbols $N_{symbols\_master}$, slave response symbols $N_{symbols\_slave}$, and transmission delay N_{symbol_delay} [1]:

$$N_{ranging\_symbol} = N_{symbols\_master} + + N_{symbol\_delay} + N_{symbols\_slave};$$

$$N_{ranging\_symbol} = N_{symbols\_master} + N_{symbol\_delay} + N_{symbols\_slave}. \quad (5)$$

As already mentioned, the packet from the master consists of the sum of preamble symbols $N_{preamble}$, header symbols N_{symbol_header}, and payload symbols $N_{ranging\_symbols}$ [1]:

$$N_{symbols\_master} = N_{preamble} + + N_{symbol\_header} + N_{ranging\_symbols}. \quad (6)$$

The response from the slave consists only of payload $N_{ranging\_symbols}$ [1]:

$$N_{symbols\_slave} = N_{ranging\_symbols}. \quad (7)$$

N_{symbol_delay} is the deterministic symbol equivalent duration of the silence between the end of ranging request reception and the beginning of ranging response transmission, which is defined as a constant $N_{symbol\_delay} = 2$ [1]. The preamble $N_{preamble}$ consists of the sum of preamble symbols $N_{symbol\_preamble}$ and the constant 4.25, which corresponds to special end-of-preamble symbols [1]:

$$N_{preamble} = N_{symbol\_preamble} + 4.25. \quad (8)$$

The number of ranging header symbols is fixed at 16 symbols $N_{symbol\_header} = 16$ [1]. This gives us the general formula for measuring the exchange time $T_{ranging}$ [1]:

$$T_{ranging} = 2^{SF}/BW \times (N_{symbol\_preamble} + +2 \cdot N_{ranging\_symbols} + 22.25). \quad (9)$$

From which we can separately extract the master component $T_{ranging\_master}$ and slave component $T_{ranging\_slave}$ [1]:

$$T_{ranging\_master} = 2^{SF}/BW \times (N_{preamble} + N_{ranging\_symbols} + 16); \quad (10)$$

$$T_{ranging\_slave} = (2^{SF}/BW) \cdot N_{ranging\_symbols}. \quad (11)$$

Ranging result Traw is stored in a specific register of the transceiver as raw data (a 24-bit two's complement number); thus, the result should be transformed into distance using the following formula [4]:

$$D = (T_{raw}/BW) \cdot 36621.09375. \quad (12)$$

It is evident that the key parameters are BW and SF. The SX1280 radio module for distance measurement supports BW of 400 kHz, 800 kHz, 1600 kHz, and SF from 5 to 10.

An individual ranging measurement on a single channel can be expected to have a ranging precision of approximately 1 m at high SF and high BW [5]. In the broader context of link design trade-offs, this implies that there is a compromise to be struck between accuracy, time-on-air (equivalently energy consumption), and the range of the link. Higher accuracy can be attained by increasing the number of measurements or increasing the SF and BW. Lower time on air can be achieved by reducing the SF and increasing BW. Longer range is possible by reducing the BW and increasing the SF. Recalling that SF and modem BW are the main variables available to the designer, the graphic illustrates this design compromise for a given LoRa modem setting (Fig. 3).

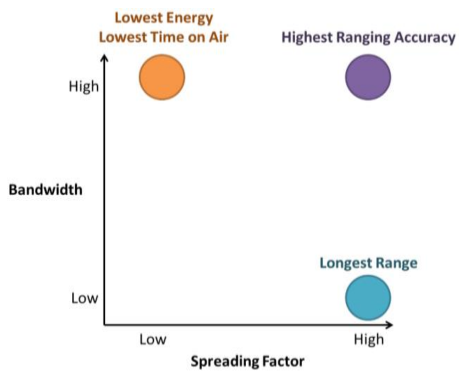

Fig. 3. Bandwidth and SF relation for a given application [5]

Result Correction Techniques and Measurement Accuracy

The accuracy of distance measurements using the SX1280 radio module is affected by several sources of error that must be considered and corrected to achieve optimal results.

We need to draw an important delineation between static sources of error and those that can change during the ranging operation. It is relatively simple to correct static bias, so it should be corrected through transceiver calibration., so it should be corrected by transceiver calibration. The remaining dynamic sources of error can be further divided into those internal to the radio and those due to the channel in which the ranging signals propagate. Assuming a perfect communication channel, we see only errors due to circuit level phenomenon: Reference oscillator drift and Analog group delay [4].

Reference oscillator drift is a frequency difference between master and slave oscillators. The timing measurements on the master and synchronization on the slave are performed using local crystal reference oscillators. Any timing offset between the crystals of the master and slave results in distance measurement error. Since the same reference oscillator is used to derive both the ranging timer and the RF carrier frequency, the measured frequency error between the transmitter and receiver can reliably indicate the timing (and thus distance) offset between devices.

For a worst-case offset of ±40 ppm and maximum response delay of 42.9 ms (at BW = 400 kHz, SF = 10), the theoretical maximum ranging error is approximately ±257 m. This error reduces to ±2 m at minimum settings [5]. The distance offset is not linear, especially at higher spreading factors.

Because the RF signal and the timing reference for the ranging synchronization operation are the same crystal reference oscillator, a simple frequency error measurement of the frequency error between master and slave, using the LoRa Frequency Error Indicator (FEI), can be used to accurately evaluate the timing (and equivalently, distance) error.

Analogue Group Delay Error occurs in a LNA. The SX1280 employs Automatic Gain Control (AGC) to adapt the LNA gain to the received signal strength. The delay through the LNA varies as a function of amplifier gain. Measurements have shown that variation in attenuation at a fixed distance can result in over 8 m of measurement error [4].

In non-line-of-sight (nLoS) conditions, signals propagate via multiple reflected paths of different lengths, causing frequency selectivity and distance overestimation. The multipath resolution capability, expressed as the difference in length approximately [8]:

$$d_r \approx c/BW. \tag{13}$$

For BW = 1600 kHz, this yields a measured distance of approximately 185 m, while true distance is 150 m. Field measurements have confirmed that multipath propagation typically causes ranging distance overestimation of 30 – 40 m in nLoS scenarios [8].

Due to this error several correction techniques were introduced [5–8].

Semtech applies correction based on FEI. Before ranging operations, the master gets the FEI factor from the slave node by a separate communication packet. After converting the raw ranging result to meters, a correction is applied based on the FEI obtained during the communication phase. The corrected result is calculated as:

$$d_{result} = d_{raw} - k_{FEI} \cdot FEI/1000, \tag{14}$$

where k_{FEI} is a gradient value stored as a function of SF and BW. It is a mapped collection provided by Semtech. For example, at SF9 and BW = 1600 kHz, k_{FEI}= -0.424[4]. Also, Semtech provides maps with LNA correction values. Same as k_{FEI} it a gradient value, but it is a function RSSI, SF and BW. It is applied as:

$$d_{result} = d_{raw} + d_{rssi\ error}, \tag{15}$$

where $d_{rssi\ error}$ is a corrective value got from RSSI map.

After applying corrections, the median value is calculated from multiple frequency-hopped ranging exchanges. The median has been found empirically to provide better immunity to outliers than the arithmetic mean, which is crucial for avoiding inaccurate channel measurements. Semtech performs 40 – 80 frequency-hopped exchanges across the 2.4 GHz ISM band using the Bluetooth Low Energy channel plan.

Even in line-of-sight conditions, measurements show range underestimation at short distances (< 10 m), overestimation at medium distances (10-80 m), and underestimation beyond 80 m. A polynomial correction is applied to linearize results:

$$d_{\text{corrected}} = \sum_{\text{k}=0}^{\text{n}} a_k \cdot d_{\text{median}}^{n-k}, \tag{16}$$

where the coefficients k are determined through field measurements and curve fitting. Different polynomial orders and coefficients are used for each SF-BW combination. For outdoor ranging up to 100 m, a 7th-order polynomial has been used successfully [4].

Stuart Robinson introduced an additional linear correction for practical applications. It can be derived from measurements in the specific operating environment [10]. Field tests have shown that applying a simple correction formula:

$$d_{corrected} = d_{raw} \cdot k_{adjust}. \tag{17}$$

To calibrate the distance measurement system, the SX1280 was used in its ranging mode to measure a known, long-distance baseline. A suitable location was identified where the master unit maintained a clear line of sight across the entire path. This known distance, precisely 4.405 km as verified by a 1:25,000 Ordnance Survey map, was compared against the average measured distance of 4.424 km reported by the device. The adjustment factor for the distance measurement system was determined to be $k_{adjust} = 0.99571$ [8].

Ranging accuracy measurements conducted between 10 m and 200 m demonstrated that the SX1280 can achieve accuracy comparable to laser range finders when averaging 2000 RTToF measurements across frequency-hopped channels. The accuracy improves with increased BW: measurements at 1600 kHz showed significantly tighter clustering around ground truth compared to 400 kHz configurations.

A critical finding is the relationship between measurement quantity and accuracy. Analysis at SF 9 with 1600 kHz BW revealed that 80 frequency-hopped ranging exchanges are sufficient to achieve approximately 1 m absolute accuracy at 170 m distance. Additional exchanges beyond this point provide diminishing returns [5].

Comparative studies between the SX1280 and coherent multi-channel ranging implementations show that for stationary line-of-sight scenarios, the SX1280 achieves mean ranging error of 75 m with standard deviation of 69 m at distances up to 500 m [6].

For distances exceeding 1 km, field measurements in rural environments demonstrate mean distance errors of 46.4 m with standard deviation of 83.6 m over an 8.2 km test route. The mean error increases with distance, reaching a maximum relative error of 9.6% at 950 m in areas with significant shadowing [6]. At extreme distances of 2 km in line-of-sight conditions, the SX1280 maintained a ranging precision of +2/-5 m using SF10 at 1600 kHz [7].

With this comprehensive correction approach, ranging precision of approximately 1 m can be achieved in controlled line-of-sight conditions, while practical outdoor applications can achieve mean errors below 10 m even at distances exceeding 1 km.

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Вимірювання відстані методом різниці прибуття (TDoA) на базі протоколу LoRa

В. В. Руденко

Анотація. Стаття присвячена реалізації вимірювання відстані між об'єктами з використанням методу різниці часу прибуття (Time Difference of Arrival, TDoA), зокрема через техніку часу двостороннього поширення сигналу (Round-Trip Time of Flight, RTToF), на основі протоколу LoRa та із застосуванням трансивера SX1280. **Мета статті** полягає в детальному описі часових характеристик обміну пакетами та формалізації розрахунку відстані. Ключовими параметрами, що суттєво впливають на точність вимірювання, визначено ширину смуги (Bandwidth, BW) та коефіцієнт розширення спектра (Spreading Factor, SF). Дослідження включає всебічний аналіз джерел похибок, таких як похибка опорного генератора (зсув синхронізації) та багатопроменеве поширення (Multipath Propagation), і надає формули для їх кількісної оцінки. Запропоновано багатоетапну методологію корекції, що включає корекцію частотної похибки (на основі FEI), компенсацію LNA (на основі RSSI), статистичну фільтрацію (за допомогою медіани), поліноміальну корекцію кривої та корекцію, специфічну для навколишнього середовища. **Результати** польових вимірювань показують, що за допомогою цього комплексного підходу до корекції можна досягти точності визначення відстані приблизно 1 метр в контрольованих умовах прямої видимості. Крім того, практичні зовнішні застосування демонструють середні похибки менше 10 метрів навіть на відстанях, що перевищують 1 км. **Висновки**: Реалізація та комплексна корекція вимірювань RTToF з використанням LoRa-модуля SX1280 дозволяють досягти високої точності, зберігаючи при цьому прийнятний баланс між точністю, часом перебування в ефірі (енергоспоживанням) та дальністю зв'язку, що є критично важливим для систем виявлення та позиціонування об'єктів.

Ключові слова: TDoA, LoRa, SX1280, RTToF, ToF, Ranging.