Theory and Principle of Operation: Advanced Ranging

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LoRa® and Ranging

By exploiting the unique properties of the LoRa® physical layer, the SX1280 LoRa modem can provide both long-range data communication and Round Trip Time-of-Flight (RTToF) distance measurements (Semtech Corporation). In this paper we present a new mode of distance measurement operation. This new mode is called *Advanced Ranging*.

Instead of actively exchanging timing information, Advanced Ranging allows us to passively overhear ranging exchanges. This feature allows gains in terms of both additional position information and, in the context of a sensor network, higher capacity.

To understand how Advanced Ranging works, and how these benefits can be realized, we begin by first re-examining conventional RTToF ranging.

Ranging

The basic principle of RTToF distance measurement is illustrated below. In this first diagram, a ranging request is sent from the ranging Master to the ranging Slave. At the same moment that the Master transmits its request, it also starts an internal timer.
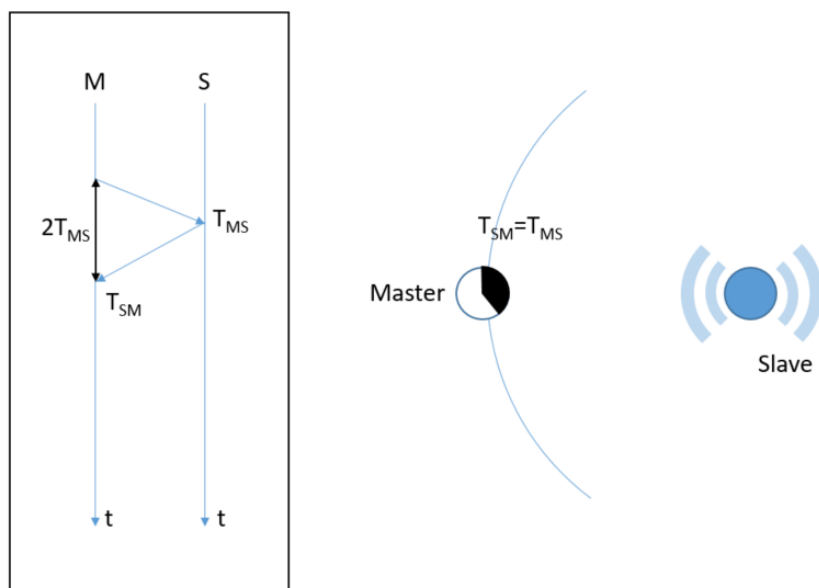
The radio wave propagates at the speed of light and, if in range, will arrive and be received by the ranging Slave in the time it takes the wave to propagate from Master to Slave, T_{MS}.

The image on the left shows the communication between Master, **M**, and Slave, **S**. The image on the right depicts a snapshot of the moment the Master's emitted ranging request arrives at the Slave. (We will follow these conventions throughout our explanation).
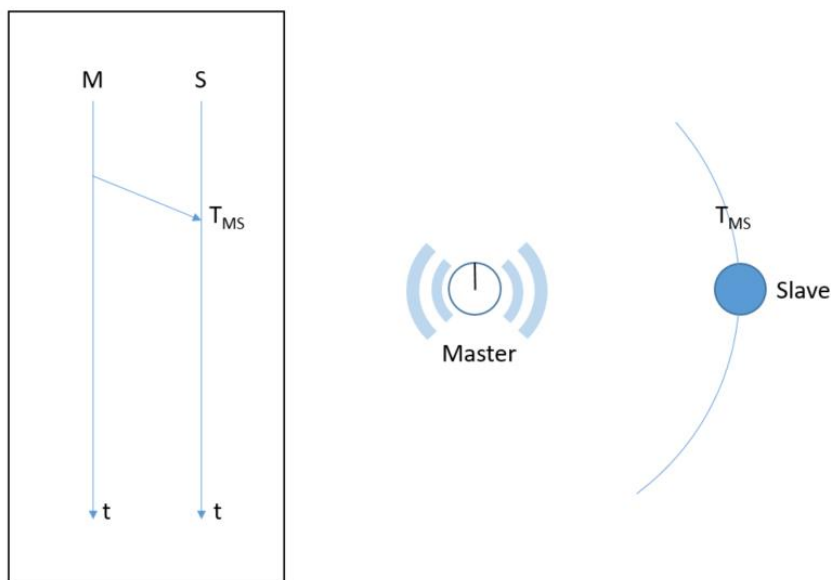
Figure 1: RTToF Principles: The Ranging Request

In a well-configured system, all of the processing delays are calibrated out [1] [2]. This means that we can consider the Slave acting as an active transponder that re-transmits a synchronised version of the ranging request. This ranging response takes time (T_{SM}) to propagate back from Slave to Master, which has timed the round trip delay to and from the Slave.

Figure 2: RTToF Principles: The Ranging Response

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The propagation from Master to Slave, and back again, follows the same physical path, which means that the round trip delay represents twice the time taken to propagate from Master to Slave. Because we know that the radio wave has propagated at the speed of light, time and distance are equivalent. Therefore, the output of the ranging measurement is a distance, representing the radius at which we could expect to locate the Slave.
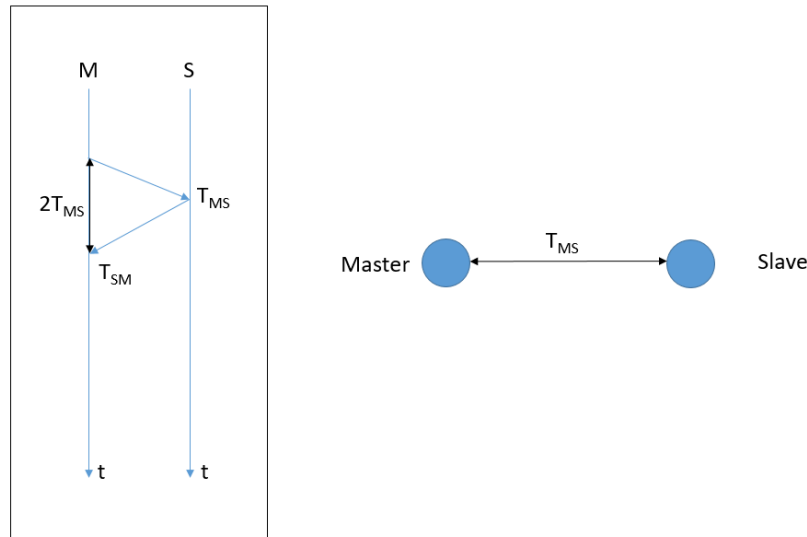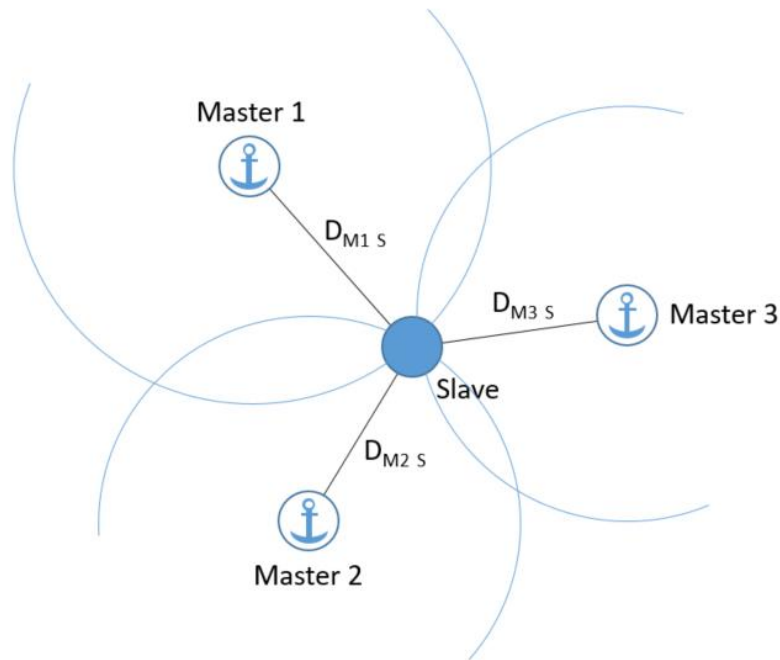

Figure 3: RTToF Distance Measurement

Ranging for Localization

The extension of RTToF ranging to localization is straightforward. In the image below, we indicate radios with fixed, known locations – known as anchors – with an anchor symbol. The mobile unit we are attempting to localize is in the center, which we will refer to as the *tag*.

Here, the anchors assume the role of ranging Master and perform a series of sequential ranging exchanges (as described above) to determine the distance from each Master to each Slave. We can then use these measurement results to trilaterate the location of the tag by finding the intersection of the range circles around each anchor, as illustrated:
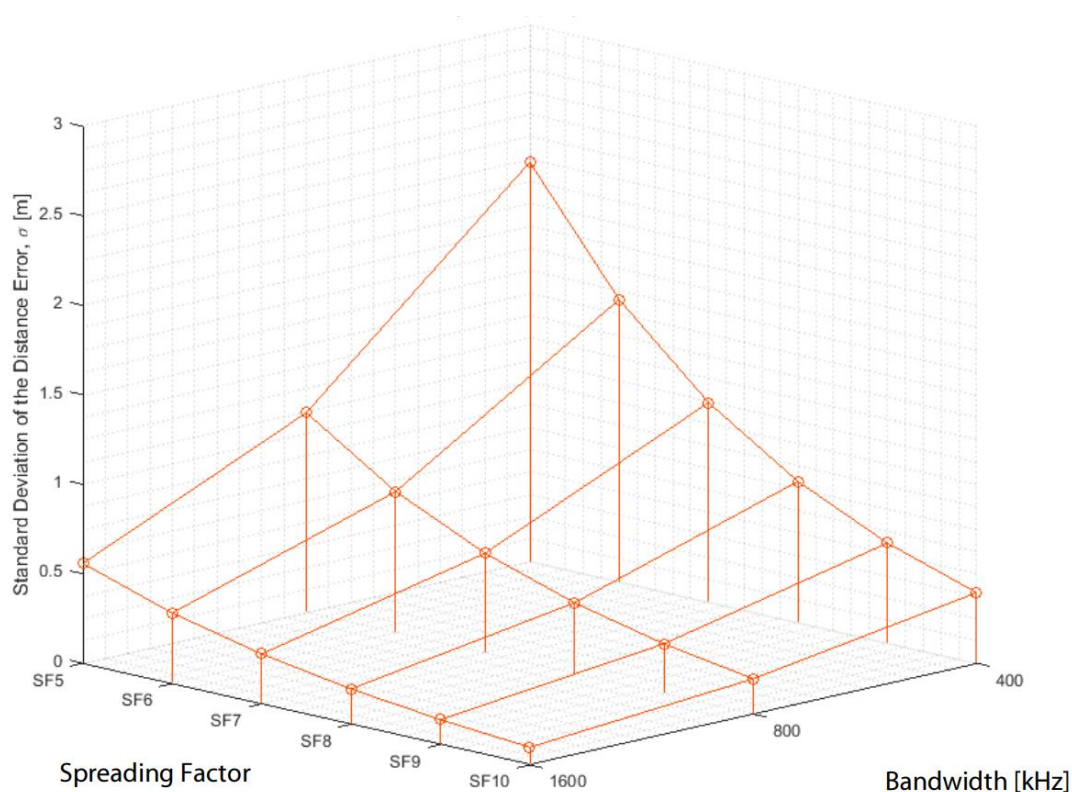
Figure 4: Distance Measurement Trilateration

Because the range is known at each Master, this example is well-suited to locating an object using a fixed infrastructure. However, it is worth noting that the roles of Master and Slave could be reversed between anchors and the tag. This second approach is better for circumstances where the mobile node is trying to determine its own location.

Ranging Performance

Localization, such as that depicted in the previous section, has a finite measurement accuracy. Recalling that accuracy is a measure of the absolute precision of the ranging operation, and that the precision is a measure of the spread of the results, the underlying precision of the round trip time-of-flight ranging of the SX1280 is shown below, in the Cramer-Rao Lower Bound (CRLB) model for theoretical Line-of-Sight (LoS) conditions [1]:

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Figure 5: The Theoretical LoS Ranging Precision: the Cramer Rao Lower Bound (CRLB)

The diagram above portrays the theoretical ideal. However, the situation is complicated by the presence of multipath propagation. This is shown diagrammatically (in plan-view) below. In the following example, because the direct path between the Master and Slave locations is obstructed, the radio waves follow a reflected path. These reflected paths are all longer than the Line-of-Sight (LoS) path and so tend to result in an over-estimation of range. This effect is most marked when the path between Master and Slave is non-Line-of-Sight (nLoS). However, multipath effects can also be present in LoS environments, e.g., from walls and ceilings.

The following diagram shows how an nLoS environment between ranging Master and Slave results in multipath propagation.
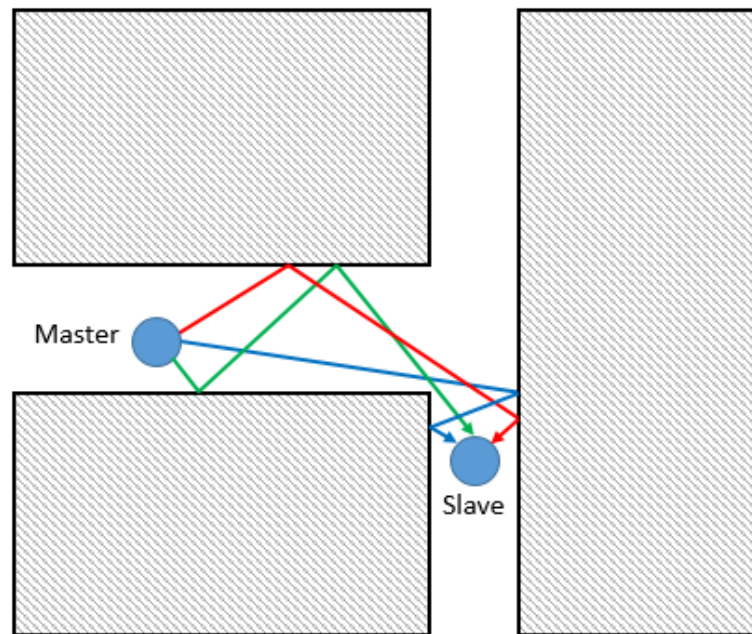
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Figure 6: LoS Environment resulting in Multipath Propagation

Dilution of Precision

The position of the gateways relative to the object being located is critical in determining the resulting accuracy. The dilution of precision with respect to the location of an object is based upon the geometry of the anchor infrastructure. This is known as the geometric dilution of precision (GDOP).

In our simplified case, we concern ourselves only with the two-dimensional (2D) horizontal dilution of precision (HDOP). The method for calculating the HDOP is beyond the scope of this paper; we follow the method outlined in [3]. Here, we take a hypothetical localization case with four anchor units and position them at a range of 5km—one each to the North, South, East and West—and calculate the resulting dilution of precision.

The results are shown below in 2D plan view, with the intensity of the color map showing the increase in HDOP, which corresponds to a reduction in precision. Interpretation of the figure is straightforward: we multiply the underlying precision, or spread of results, of our ranging location estimate by the HDOP to determine the resulting location precision. Thus an HDOP >1 implies a degradation in precision.
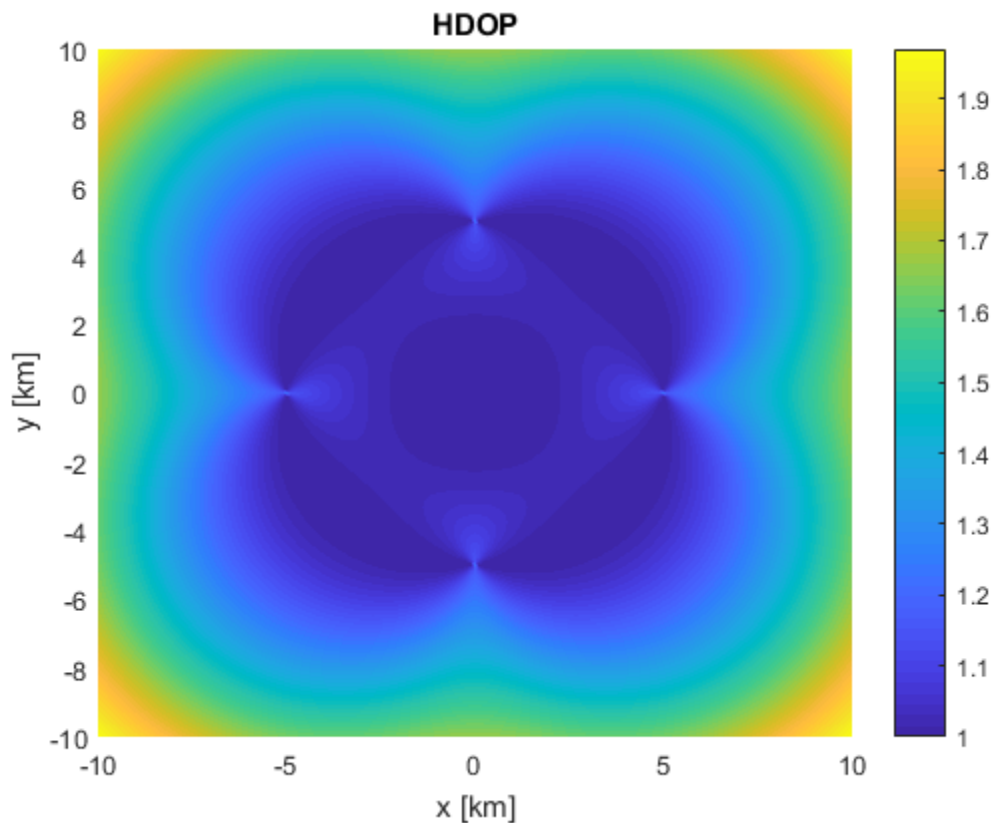
Figure 7: HDOP of Ranging Measurement

The implication of this theoretical result is that a tag will be a located with greater precision within the area delimited by the four anchors and, as we travel outside of this area, so the attainable location precision reduces.
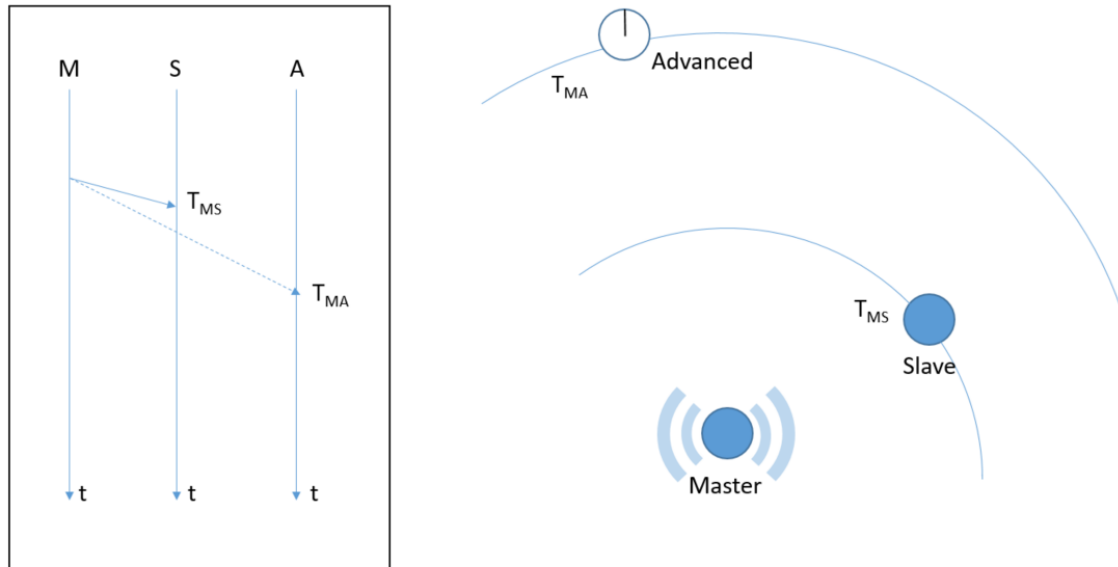
Advanced Ranging

To understand the use of the SX1280 Advanced Ranging mode, consider the following example. In this scenario, we repeat our RTToF ranging exchange between Master and Slave, this time adding a third SX1280 in Advanced Ranging mode.

In advanced mode the SX1280 overhears the RTToF ranging exchange and simply measures the time elapsed between the ranging request and the response, albeit from a separate location. Just as with RTToF ranging, there is no notion of absolute time, only the relative time between operations.

We start with a conventional ranging exchange. As illustrated below, the Master sends a ranging request, which is received by the Slave and the advanced mode radio at two different times. The advanced mode radio starts its timer upon reception of the request.


Figure 8: Ranging request, received by the Slave and the advanced mode radio at two different times.

As you can see in the diagram, the ranging request is sent by the Master and will arrive at the Slave at some time, T_{MS}, and at the advanced mode radio at some other time, T_{MA}. (Here, the subscripts indicate the radio role; T_{MA} is, therefore, the time elapsed as the wave propagates from Master to the Advanced Ranging radio). In the inset image, we show the ranging request from the Master arriving at two different times: at the Slave and the advanced mode radios. (Note that the distance between the radios is not represented in the x-axis of this diagram – explaining the differing gradients of the propagation times).

Upon reception of the ranging request, the advanced mode radio will start its internal clock.

As with a conventional exchange, after an elapsed time of T_{MS} (the time taken for the ranging request to arrive at the Slave) the Slave will synchronize with the incoming request and send back the ranging response. The ranging response then takes time, T_{MS} again, to arrive back at the Master (assuming $T_{MS} = T_{SM}$). The ranging response from the Slave arrives at the advanced mode radio at some other time, T_{SA}.

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In the next diagram, the Slave sends the ranging response back to the Master after a delay of T_{MS} (the time taken in the previous step) for the request to arrive at the Slave.
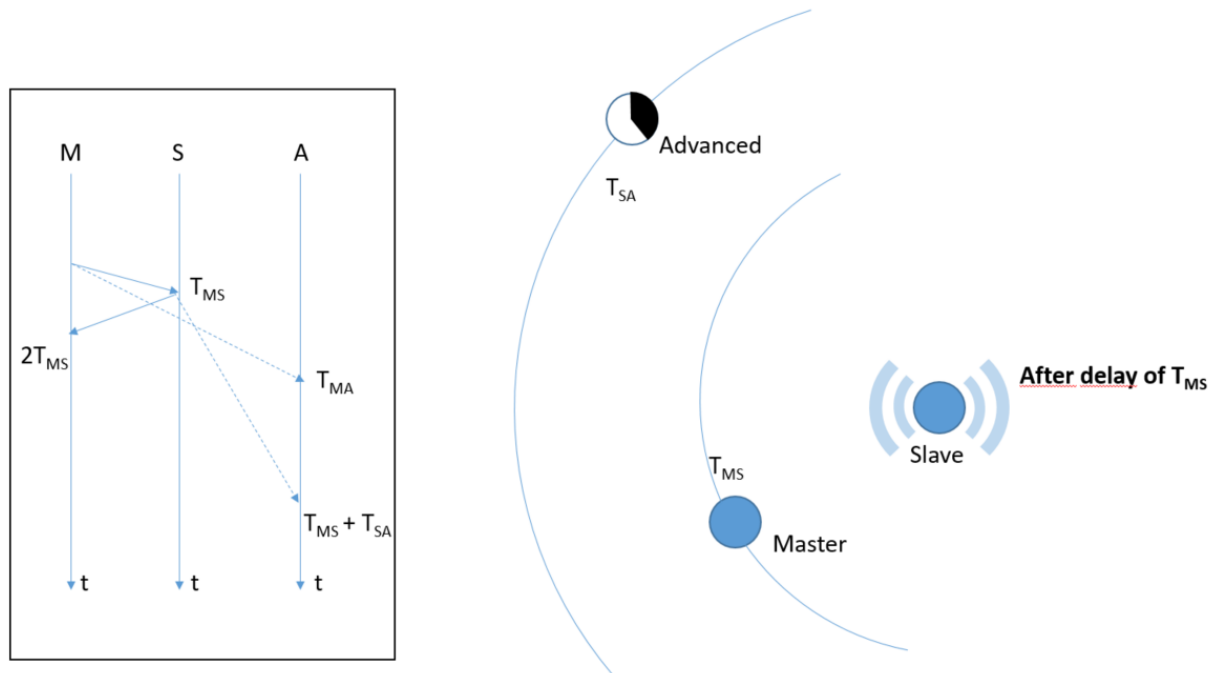
<p style="text-align:center">Figure 9: Ranging response sent from Salve to Master after a delay of TMS</p>

When the ranging response arrives at the advanced mode radio, it stops its internal timer, recording the time difference between the arrival of the ranging request and the ranging response. The timing implications of this are shown below. Here we see the time difference, ΔT, measured by the advanced mode radio and how it relates to the Master-Slave, Slave-Advanced, and Master-Advanced delays.

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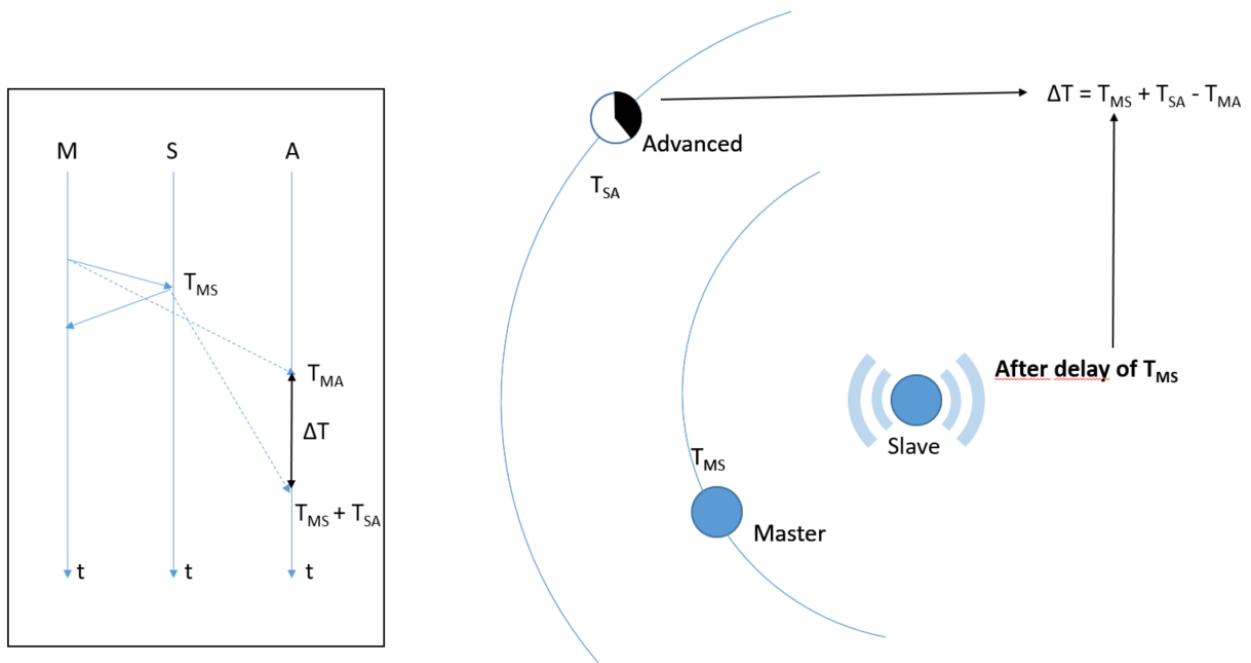
Figure 10: Expression for the Delay between Ranging Request and Ranging Response Measured by Advanced Ranging.

Looking more closely at this diagram, we can see that this gives us the geometric relationship between the various time differences and the ΔT timing measurement. This relationship is depicted below.

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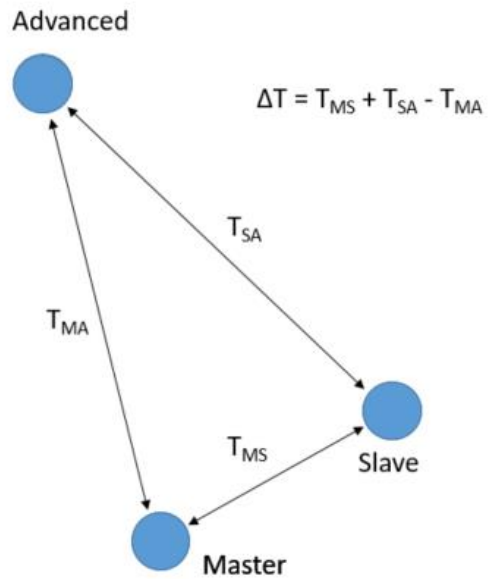**Semtech**

$$\Delta T = T_{MS} + T_{SA} - T_{MA}$$

Figure 11: The geometric relationship between the times measured in Advanced Ranging.

Advanced Ranging for Localization

The extension of Advanced Ranging to localization is more complex than the conventional ranging case, and depends on which element of the system is attributed the Master, Slave, and Advanced Ranging roles. Below, we examine these three roles from the perspective of the tag.

Advanced Ranging Tag

In our first example, the Master and Slave are static anchors and the Advanced Ranging node is the tag to be located. We also add a third anchor, which does not take part in this first exchange.
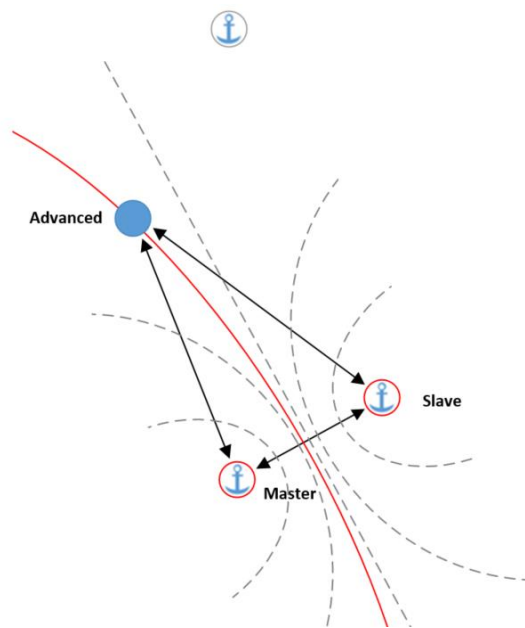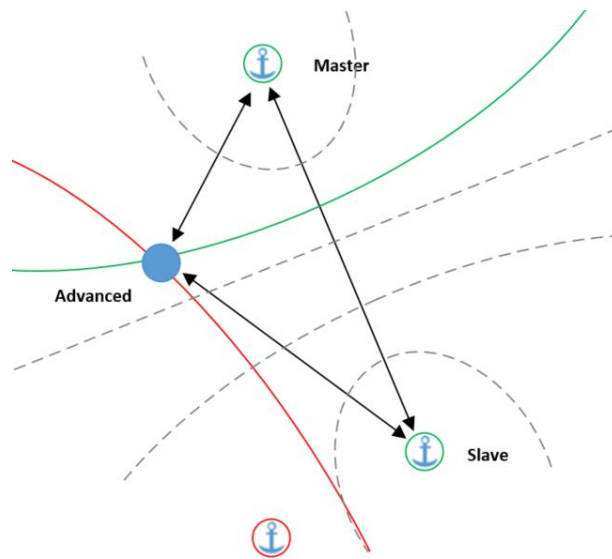
Figure 12: Advanced Raining with the Advanced Ranging node to localize

The grey dotted lines represent lines of equal delay, ΔT, between the Master and Slave anchors. Thus, a single Advanced Ranging measurement places the Advanced-mode SX1280 on one of these curves of constant delay (which are hyperbolas, with the anchors at the foci).

To provide a location it is necessary, therefore, to perform additional time-difference measurements between additional anchors, as shown below, for the second time difference measurement—this time using a new combination of Master and Slave anchor nodes.

Note that, to obtain a 2D location, it is necessary to perform three time-difference measurements. Here is a representation of the second time-difference measurement for the same devices:

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Figure 13: The Second Time-Difference Measurement in the Localisation Process

An important facet of this mode of operation is that an unlimited number of tags could theoretically listen to the Master-Slave exchanges between anchors—with important implications for the localization capacity of such a system. Where the tag object is to be located, this capacity is then only limited by the repatriation of the time difference measurements to the attendant network infrastructure. In the case of a tag locating itself, there is no such constraint.

Advanced Ranging Anchors

In this system, there is obvious scope for the anchors that are inactive to also assume the Advanced Ranging mode. However, it can be shown that overhearing information from the other anchors serves only to improve our knowledge of the location of the Master and Slave anchors.

Where the anchor locations are already known, additional information about their fixed locations is of no assistance in determining the location of the tag. Instead, it raises the possibility of our Advanced Ranging mode tag switching to Master or Slave mode, for a single ranging exchange, to improve our location knowledge.

GDOP Implications

Just as for RTToF ranging, the geometry of the anchor locations also determines localization accuracy. We plot the HDOP for the same scenario as before. Here we see that the area within that encircled by the anchors has a similar HDOP to the ranging case. The big difference is seen outside of this area. The HDOP outside is seen to rapidly increase, such that, over the same distance, where

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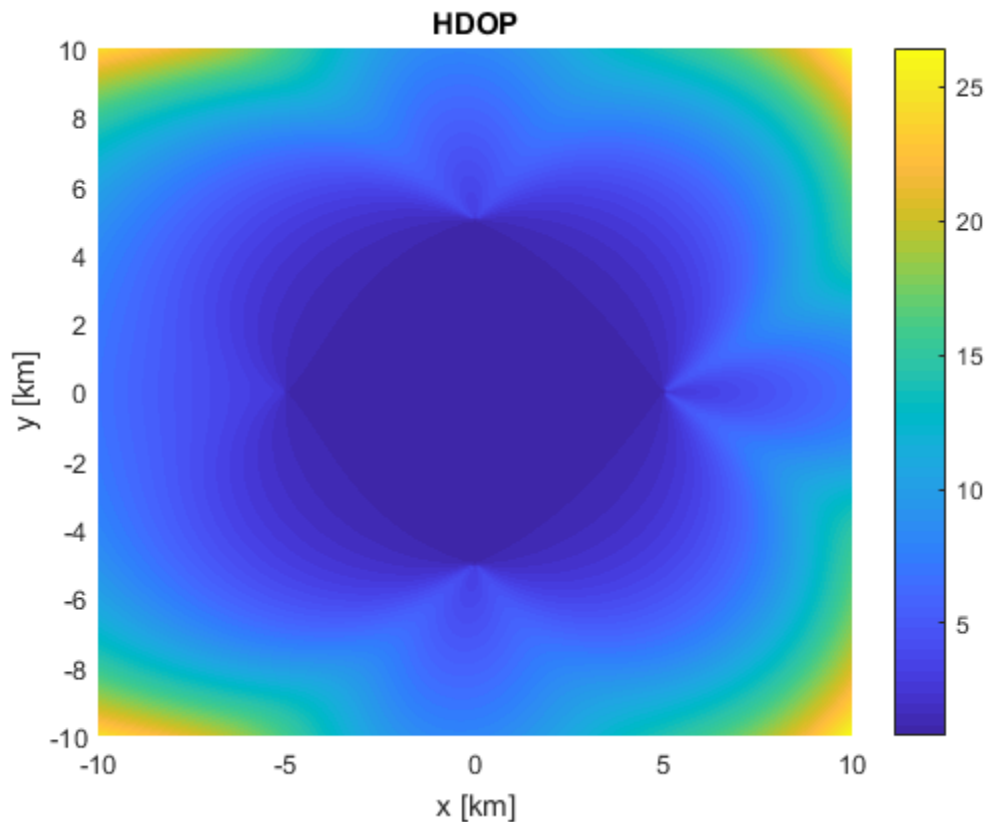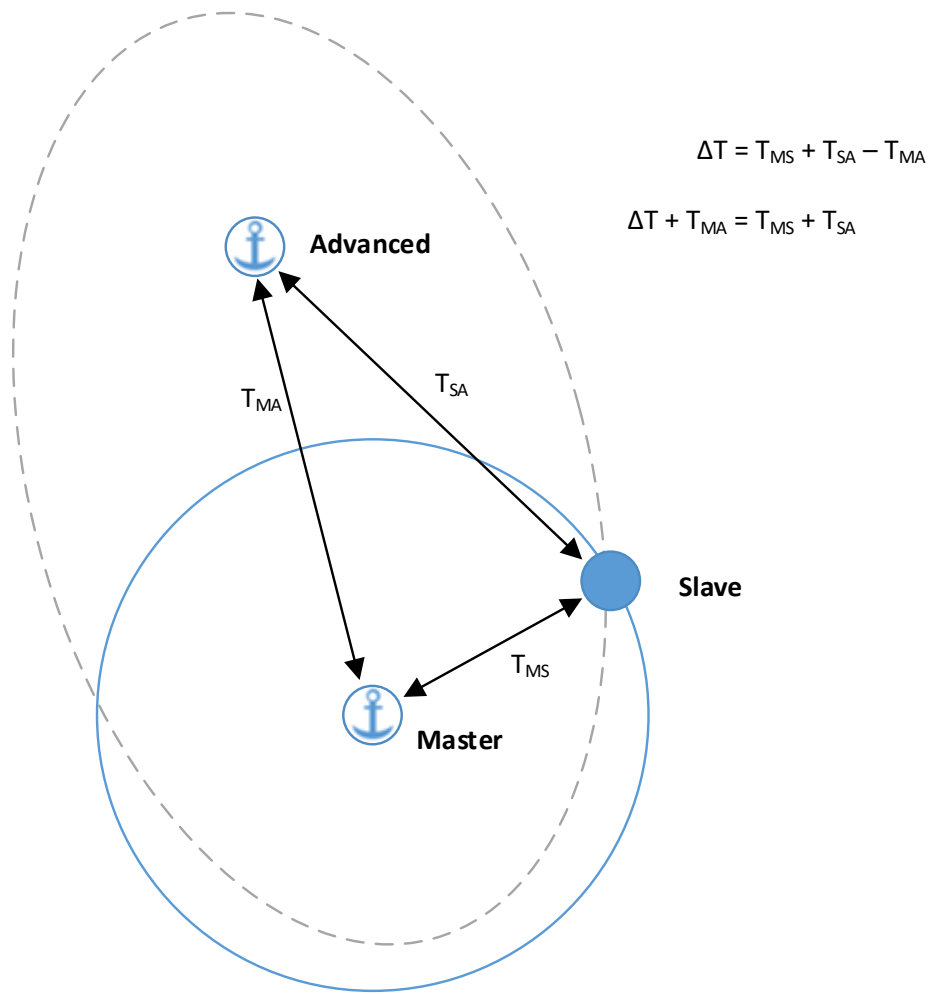we saw a two-fold degradation in precision in Figure 7, we now see more than a twenty-fold degradation:

Figure 14: HDOP of Advanced Ranging

Summary

This mode of operation poses great gains in terms of capacity as the tag is a passive receiver of the ranging information. However, these gains come at the cost of a more complex localization problem with degraded HDOP at the periphery of the coverage area and, where applicable, the added management required for recovery of the time difference data from the tag.

Tag as Slave: Single Measurement

The alternative to operating the tag in advanced mode is to perform a conventional RTToF ranging exchange between the tag and a single anchor, with the remaining anchors within range in advanced mode. This situation is illustrated below:

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$$\Delta T = T_{MS} + T_{SA} - T_{MA}$$

$$\Delta T + T_{MA} = T_{MS} + T_{SA}$$

Figure 15: Advanced Ranging with the Tag in Slave Mode

As part of the fixed anchor infrastructure, the Master and advanced mode ranging node locations are known and concomitantly the Master-Advanced time, T_{MA}, is also known. This means that the tag, instead of being located on a line of constant delay, is instead located on an ellipse with the two foci of which are the two anchor locations shown above by the grey dotted line.

We also have the RTToF measurement between Master and Slave, T_{MS}, which further narrows the possible tag location to any intersection between the Advanced Ranging ellipse and RTToF circle (blue).

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GDOP Implications

We examine again the HDOP of this scenario as shown in Figure 16. Here, we take our four-anchor localization system (based upon having the tag in Advanced Ranging mode). This time, however, we also include the influence of the single anchor (here the anchor on the right), which also performs the single Master-Slave distance measurement we outlined above.
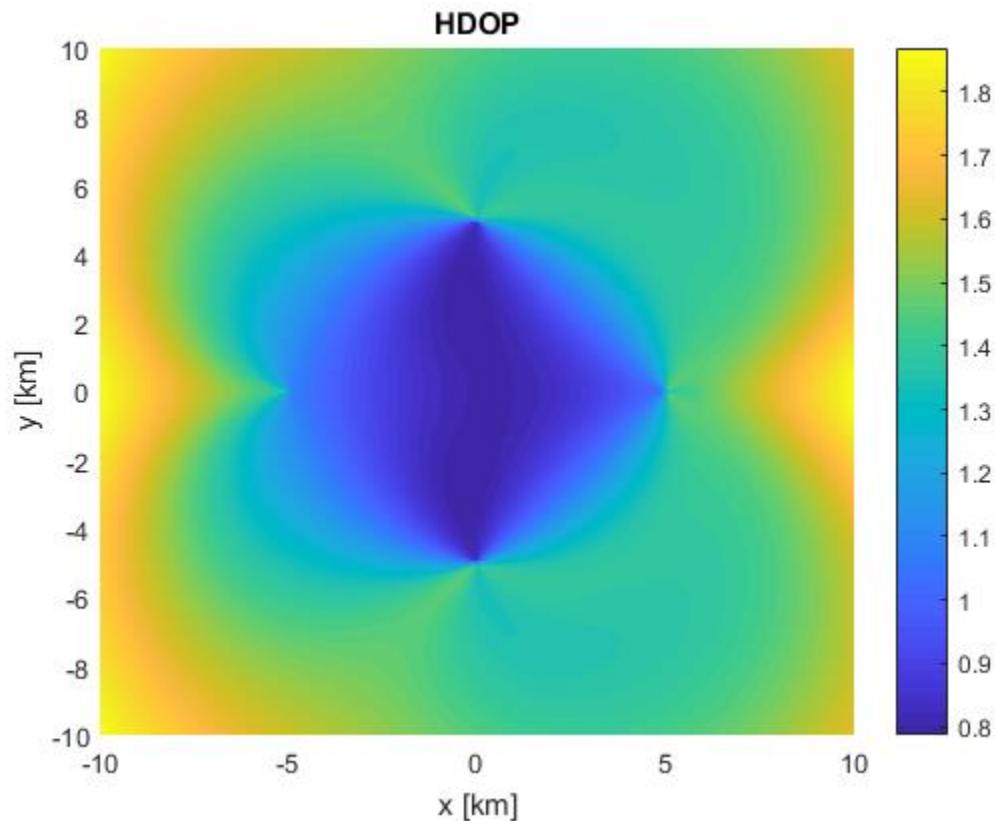

Figure 16: HDOP of Hybrid Ranging

A single ranging measurement reduces the HDOP back down to the same level we saw in the ranging-based solver—but with only a single (more costly) RTToF exchange. By virtue of the additional measurement, the single ranging measurement, aggregated with the Advanced Ranging measurements, results in a higher precision at the center of the HDOP plot than was possible in either previous example.

Summary

Here we see that we have much of the capacity advantage of the tag in Advanced Ranging mode— the ability of multiple nodes to receive the same exchanges increases the localization capacity of an

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Advanced Ranging based system. (Noting that spectral capacity may be required to uplink the ΔT measurement results, depending upon the architecture of the localization system). However, for the cost of an additional RTToF ranging exchange per-tag-localized, our HDOP improves by an order of magnitude. Our system HDOP becomes close to that described in the Ranging for Localization section above, where each ranging measurement required ranging exchanges between each tag and anchor.
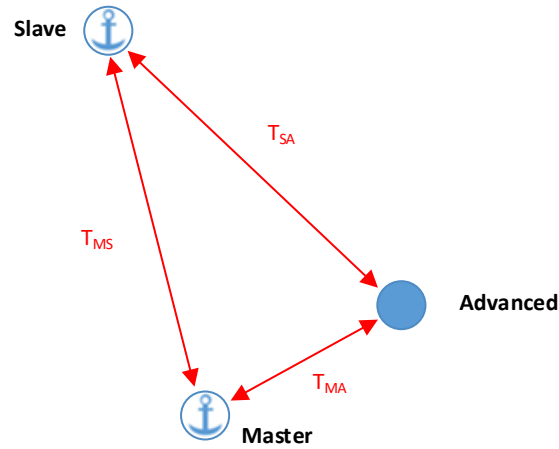
Hybrid Modes of Operation

In this next example, to reduce the complexity of the solution, we show a hybrid technique combining tag-as-Slave and tag-as-Advanced Ranging techniques of the two previous examples to reduce the complexity of the solution back to solving for a single circle whilst using Advanced Ranging.

In the first step, anchor calibration, we perform what looks like one of the anchor-to-anchor exchanges we used our first Advanced Ranging localization steps. This gives us definite knowledge of channel and distance between our fixed anchors, T_{MS}. (T_{SA} and T_{MA} can also be exploited for location.)

The subsequent phase, tag measurement, is a tag-as-Slave exchange from one Master anchor, the other listening in advanced mode. As we see from the figure above – we already know $T_{MA}' = T_{MS}$ of the previous, calibration measurement step.

Assuming the channel is unchanged in the interim between our measurements, we then have a perfect knowledge of both terms T_{MA}' and T_{MS}' of our Advanced Ranging equation. With only one unknown, we can therefore compensate both terms—reducing the equation to a direct measurement of the radius from Advanced anchor to Slave, T_{SA}'.

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Step 1: Anchor Calibration
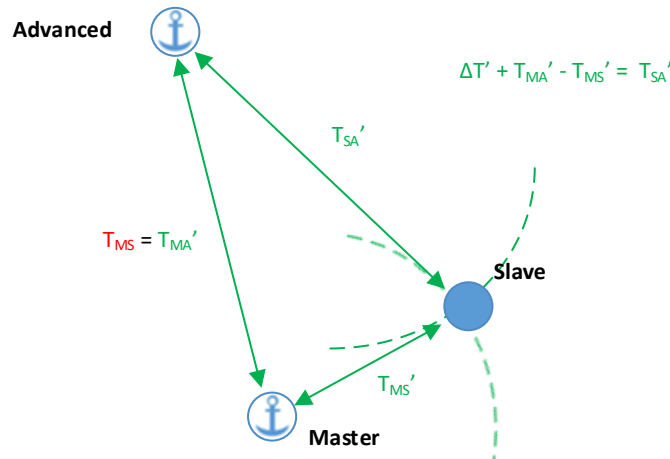

Step 2: Tag Measurement

Figure 17: The two steps of a hybrid measurement where anchors and tag swap Slave and Advanced Ranging roles

Advanced Ranging for Proximity

Another interesting application of the SX1280's Advanced Ranging functionality is to increase the accuracy of distance measurements by adding Advanced Ranging radios at the Master location. In a conventional ranging exchange, the Master initiates the ranging exchange with a slave and receives

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the synchronized response from the Slave, from which it can calculate the elapsed round-trip time of flight (a single result).
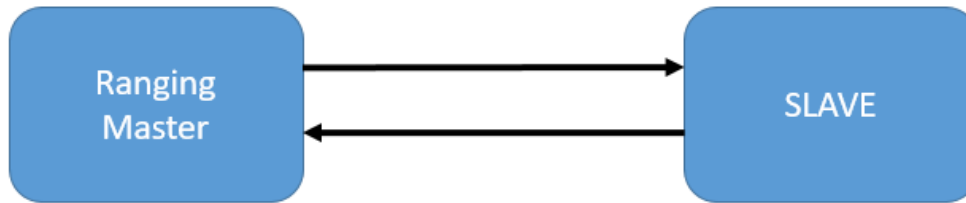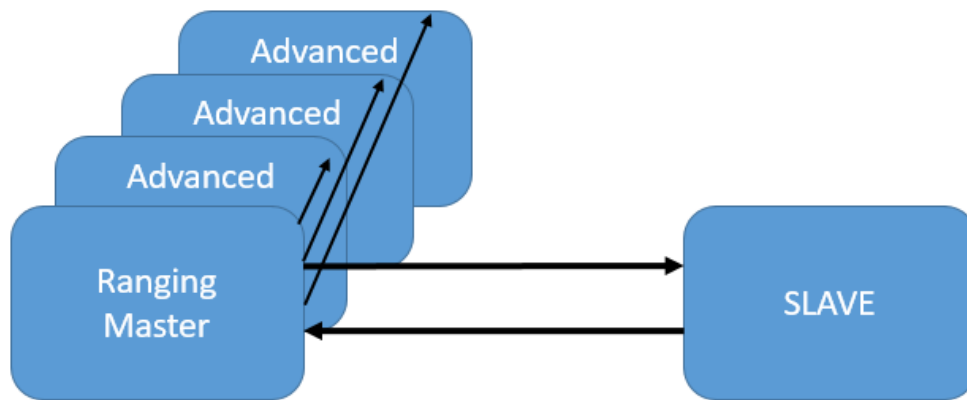

Figure 18: Conventional Master-Slave Round Trip Time of Flight Measurement, generating a single Result.

The basic principle of employing Advanced Ranging for enhanced proximity measurement is illustrated in the image below. We have already seen that, in Advanced Ranging mode, the radio can overhear the exchange between Master and Slave, timing the difference between the time of the Master's request and the Slave's response. In the case of an enhanced proximity measurement, we simply add Advanced Ranging radios in the same location as the Master.

The basic principle of employing Advanced Ranging for enhanced proximity measurement is illustrated in the image below. We have already seen that in Advanced Ranging mode the radio can overhear the exchange between Master and Slave, timing the difference between the time of the Master's request and the Slave's response. In the case of an enhanced proximity measurement, we simply add Advanced Ranging radios in the same location as the Master.

In the example below we have added three additional radios in Advanced Ranging mode. In this configuration, the Advanced Ranging radios are so close to the ranging Master that the Advanced Ranging radios' timers will start at a time equivalent to the Master's start time. The principle here is that, where the Master-Slave RTToF Exchange is Overheard, Each Radio Generates a Ranging Result.

Similarly, the collocated Master and Advanced Ranging radios will all receive the ranging response from the Slave at the same time.

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Figure 19. Using Advanced Ranging to Gather Multiple Ranging Results

The output of the four collocated radios is therefore four ranging distance measurements. However, with adequate antenna diversity, different multipath propagation paths may be taken, resulting in additional spatial diversity of the results. i.e., there are three additional and useful ranging results available for the cost of a single exchange from the perspective of the Slave's energy consumption and the spectral occupation of the signal.

Conclusion

In this theoretical introduction to the operation of Advanced Ranging, we have shown the additional capabilities it can bring to localization and proximity systems:

- In the case of co-localized Master and Advanced Ranging radios, additional range information can be obtained at no additional energy cost for the Slave and no additional cost in bandwidth or radio channel capacity.

- In the case of localization, the Advanced Ranging feature permits the overhearing of ranging exchanges in a fixed Master-Slave infrastructure. This can allow an unlimited number of Advanced Ranging end-nodes to obtain localization information, where the equivalent conventional ranging would demand multiple ranging exchanges between anchor and end node. This results in improved localization capacity and energy consumption.

The numerous architectures and device roles possible when combining ranging and Advanced-Ranging are beyond the scope of this short introduction. However, with the basic principles of the

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operation of Advanced Ranging defined, designers can evaluate the increased capacity and reduced consumption that Advanced Ranging can bring to an application.

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[1]   T. Cooper, *Application Note: An Introduction to Ranging with the SX1280 Transceiver (AN1200.29),* Semtech Corporation, 2017.

[2]   T. Cooper, *Application Note: Design of the SX1280 Ranging Protocol and Result Processing (AN 1200.50),* Semtech Corporation, 2019.

[3]   N. Levanon, *Lowest GDOP in 2-D scenarios,* IEEE, 2000, pp. 147(3):149 - 155.

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