**IEEE P802.15**

**Wireless Personal Area Networks**

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| Re: | Draft text covering relative positioning and location topics, and including two way ranging mechanisms |
| Abstract | Text for inclusion in IEEE 802.15.8 in due course. |
| Purpose | Presentation of the text to get feedback on it, to allow it be further developed and refined and eventually incorporated into the draft text of the IEEE 802.15.8 standard currently under development in the 802.15 TG8. |
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*Notes on this text:*

*(Explanatory notes and notes to the editor are in RED like this one. Some minor additional directions may be given using WORD comment facility)*

*This text is provided with a view to its integration into the 802.15.8 draft. The primary goal of this text is to capture the ranging and localization functionality to be supported by the 802.15.8 standard. In writing this some assumptions have been made as to the form of the interface being provided to the upper layers, in particular:*

* *The use of* *PIB elements to configure some aspects of MAC/PHY operation,*
* *The use of MAC data service primitives (MCPS-DATA.request, MCPS-DATA.confirm and MCPS-DATA.indication) into which parameters are defined to communicate certain information*
* *The ability of the MAC frame encoding to convey data between PDs in Information Elements (IE) to support a standardized ranging method*

*As a result of this it is expected that some revision this text may be done before its integration into the main 802.15.8 draft.*

# Definitions, acronyms, and abbreviations

## Definitions

## Acronyms and abbreviations

*Add the following new acronyms. [I am assuming MAC data frames will include this AR bit to request acknowledgement, probably in the ‘frame control’ field like 802.15.4 does].*

AR acknowledgment request

TOF time of flight

*Place the text below in a new section, [and remove any similar place holding clauses on positioning or ranging, e.g. MAC work items doc 802.15-15-0074-00-0008 nominates a section “5.1.8 Ranging” and the P802.15.8\_D0.8 draft has an empty clause “13 – Relative positioning”].*

# Relative positioning and location

## Overview

The UWB PHY has the capability, using a *ranging counter*, of very accurately time-stamping the precise instants that the RMARKER is received and transmitted at the PD antenna. The RMARKER is defined to be the beginning of the first symbol of the PHR of the frame. This time-stamping ability is the enabler that allows the upper layers to perform accurate relative positioning and locating. The relative positioning and locating methods supported by this standard are: single-sided two-way ranging, double-sided two-way ranging and, “one-way” ranging for the time-difference of arrival location method. The units of the ranging counter are defined in 10.4.1.

In a typical physical realization of this standard, the timestamps will be captured by digital logic internal to the transmitter and receiver implementations. The PD then needs to adjust the reported timestamp to account for the time difference offset between the time when the internal physical timestamp is captured and the time when the RMARKER actually launches or arrived at the antenna. This is described further in 10.4.2. These offsets are separately defined for transmitter and receiver as the configurable PIB elements *phyTxRmarkerOffset* and *phyRxRmarkerOffset*.

## Service access points for message time stamps

### Frame transmission timestamping

The MCPS-DATA.request initiates a data frame transmission and the MCPS-DATA.confirm primitive reports the result.

Where acknowledged transmission is employed, (i.e. the AckTX parameter in the MCPS-DATA.request was true), and the MCPS-DATA.confirm primitive is reporting a correctly acknowledged transmission then the TxRangingCounter parameter shall be the transmit timestamp of the transmitted data frame and the RxRangingCounter parameter shall be the receive timestamp of the acknowledgment frame.

Where non-acknowledged transmission is employed, (i.e. the AckTX parameter of the MCPS-DATA.request was false), the MCPS-DATA.confirm primitive simply reports the completion of the transmission. Here then the TxRangingCounter parameter shall be the transmit timestamp of the transmitted data frame and the RxRangingCounter parameter shall be invalid.

### Frame reception timestamping

The arrival of a received data frame is reported via the MCPS-DATA.indication primitive.

Where acknowledged transmission is employed, (i.e. the AR bit is set in the MAC frame control field of the received data frame), the MCPS-DATA.indication primitive shall be issued after the acknowledgement is transmitted, and the RxRangingCounter parameter shall be the receive timestamp of the data frame and the TxRangingCounter parameter shall be the transmit timestamp of the acknowledgment frame.

Where non-acknowledged transmission is employed, (i.e. the AR bit is not set in the MAC frame control field of the received data frame), the MCPS-DATA.indication primitive is issued when the frame is received. Here then the RxRangingCounter parameter shall be the receive timestamp of the data frame and the TxRangingCounter parameter shall be invalid.

### Control of ranging and the transfer of timestamps

*To add a standardized way of transferring the ranging information end-to-end (and securely if security procedures are used), while still giving the upper layers flexibility and responsibility for using the MAC to implement the ranging method, the text here is introducing the concept of information elements (IE). This is assuming that TG8 will want to adopt the use of information elements in a similar way to 802.15.4e where there are Header IE to convey information between MAC layers and Payload IE (and Nested IE) to carry information of interest to upper layers (and sometimes MAC also).*

Information elements are employed to control two-way ranging and transfer ranging data between the two PD participating in a ranging exchange. With reference to the ranging methods defined in 2.3.2 and 2.3.3, to complete the calculation of the time-of-flight (TOF) between two PD, participating in a ranging exchange, it is necessary to combine measurements made by both PD. That is one PD will need to transfer its timestamp measurements to the other. Information elements are defined to control two-way ranging and support the transfer of ranging information between the PD participating in the ranging exchange. Table 1 names the information elements, gives the information element identifiers corresponding to these IE and gives a reference to the clause where the information element usage is defined.

*The table below is a list of information elements being defined in this clause (the table cross-references the sub-clauses defining each IE’s usage). In the final 802.15.8 standard text the IE’s ID in this table should probably be moved to the appropriate MAC clause and combined with other IE defined elsewhere.*

**Table 1 – information element IDs**

|  |  |  |  |
| --- | --- | --- | --- |
| **IE ID value** | **IE Name** | **Acronym** | **Sub-clause** |
| 0xNNN | Ranging Request Reply Time IE | RRRT IE | 2.2.3.1 |
| 0xNNN | Ranging Reply Time Instantaneous IE | RRTI IE | 2.2.3.2 |
| 0xNNN | Ranging Reply Time Deferred IE | RRTD IE | 2.2.3.3 |
| 0xNNN | Ranging Preferred Reply Time IE | RPRT IE | 2.2.3.4 |
| 0xNNN | Ranging Control Double-sided TWR IE | RCDT IE | 2.2.3.5 |
| 0xNNN | Ranging Round Trip Measurement IE | RRTM IE | 2.2.3.6 |
| 0xNNN | Ranging Time-of-Flight IE | RTOF IE | 2.2.3.7 |

#### Ranging Request Reply Time IE

The Ranging Request Reply Time IE (RRRT IE) is used as part of a ranging exchange to request a ranging reply time from the remote PD participating in the ranging exchange. The Ranging Request Reply Time IE has a zero length Content field. The procedures for using the RRRT IE are defined in 2.4.

#### Ranging Reply Time Instantaneous IE

The Ranging Reply Time Instantaneous IE (RRTI IE) content shall be time difference between the receive time of most recently received RFRAME and the transmit time of the RFRAME containing the IE. The reference for these time values is the RMARKER. The Ranging Reply Time Instantaneous IE is appropriate for use where the PD is able to accurately pre-determine the transmission time of the frame containing the IE and complete the calculations to timestamp the last received RFRAME in time to calculate and insert this RRTI IE into the transmitted frame. The content field of the Ranging Reply Time Instantaneous IE shall be formatted as shown in Figure 1. The units of time are defined in 10.4.1. The procedures for using the RRTI IE are defined in 2.4.

|  |
| --- |
| **Octets : 4** |
| RX to TX Reply Time |

**Figure 1 – Ranging Reply Time Instantaneous IE Content field format**

#### Ranging Reply Time Deferred IE

The Ranging Reply Time Deferred IE (RRTD IE) content shall be time difference between the receive time of most recently received RFRAME and the transmit time of the responding RFRAME transmitted, sent most recently before the frame containing this IE. The reference for these time values is the RMARKER. The Ranging Reply Time Deferred IE is employed as part of completing two-way ranging exchanges, and used in the case where the PD cannot determine the reply time until after the reply has been sent, and in this case the RRTD IE carries the reply time in a subsequent frame. The content field of the Ranging Reply Time Deferred IE shall be formatted as shown in Figure 2. The units of time are defined in 10.4.1. The procedures for using the RRTD IE are defined in 2.4.

|  |
| --- |
| **Octets : 4** |
| RX to TX Reply Time |

**Figure 2 – Ranging Reply Time Deferred IE Content field format**

#### Ranging Preferred Reply Time IE

The Ranging Preferred Reply Time IE is sent by a PD to communicate its ability to send a ranging response that can employ the RRTI IE and it communicates its preferred reply time for this. When this is known it can be used to modify the ranging exchange to minimize the number of messages needed for a ranging measurement and thus save power, see Figure 12 and its associated description in 2.4.3 for details. The content field of the Ranging Preferred Reply Time IE shall be formatted as shown in Figure 3. The units of time are defined in 10.4.1. While these units are very precise an actual implementation may have some quantization in the reply times that it can support. The value reported in the RRTI IE or RRTD IE shall be the actual resultant reply time of the appropriate individual ranging reply.

|  |
| --- |
| **Octets : 4** |
| Preferred Reply Time |

**Figure 3 – Ranging Preferred Reply Time IE Content field format**

The Ranging Preferred Reply Time IE is applicable in both single-sided and double-sided two-way ranging exchanges. When the reply time is known, it can be used to delay turning on the receiver until the expected reply time which gives a power saving.

#### Ranging Control Double-sided TWR IE

The Ranging Control Double-sided TWR IE (RCDT IE) is used to control the double-sided two-way ranging exchange with the remote PD. The content field of the Ranging Control Double-sided Ranging IE shall be the formatted as shown in Figure 4. The Control Info shall have one of the values defined in Table 1. The procedures for using the RCDT IE are defined in 2.4.

|  |
| --- |
| **Octets : 1** |
| Control Info |

**Figure 4 – Ranging Control Double-sided TWR IE Content field format**

**Table 2 – values of the Control Info field in the Ranging Control Double-sided TWR IE**

|  |  |
| --- | --- |
| **Control Info value** | **Meaning** |
| 0 | This frame is initiating DS-TWR and indicates that the initiating end does not require the ranging result. |
| 1 | This frame is initiating DS-TWR and requesting that the ranging result is sent back at end of exchange |
| 2 | This frame is continuing the DS-TWR, forming the request for the 2nd TX-to-RX round trip measurement |

#### Ranging Round Trip Measurement IE

The Ranging Round Trip Measurement IE (RRTM IE) content shall be time difference between the transmit time of the RFRAME initiating a round trip measurement and the receive time of the response RFRAME that completes a round trip measurement. The reference for these time values is the RMARKER. This IE is employed as part of completing a double-sided two-way ranging exchange. The content field of the Ranging Round Trip Measurement IE shall be formatted as shown in Figure 5. The units of time are defined in 10.4.1. The procedures for using the RRTM IE are defined in 2.4.

|  |
| --- |
| **Octets : 4** |
| TX to RX round trip time |

**Figure 5 – Ranging Round Trip Measurement IE Content field format**

#### Ranging Time-of-Flight IE

The Ranging Time-of-Flight IE (RTOF IE) is used after a double-sided two-way ranging exchange to communicate the resultant time-of-flight estimate to the far end if this is requested. The content field of the Ranging Time-of-Flight IE shall be formatted as shown in Figure 5. The units of time are defined in 10.4.1. The procedures for using the RTOF IE are defined in 2.4.

|  |
| --- |
| **Octets : 4** |
| TX to RX round trip time |

**Figure 6 – Ranging Round Trip Measurement IE Content field format**

## Ranging and localization methods

### Preface

The ranging and localization methods supported by the UWB PHY are based on its capability of very accurate time-stamping. The three main time based techniques for performing ranging and localization are: simple single-sided two-way ranging, described in 2.3.2, double-sided two-way ranging, described in 2.3.3, and, time difference of arrival, described in 2.3.4. Supplementing this, angle-of-arrival (AOA) and received signal strength indication (RSSI) localization techniques are described in 2.3.9 and 2.3.10.

### Single-sided two-way ranging

Single sided single-sided two-way ranging (SS-TWR) involves a simple measurement of the round trip delay of a single message from one node to another and a response sent back to the original node.



**Figure 7 – single-sided two-way ranging**

The operation of SS-TWR is as shown in Figure 7, where device A initiates the exchange and device B responds to complete the exchange and each device precisely timestamps the transmission and reception times of the message frames, and so can calculate times *Tround* and *Treply* by simple subtraction. And the resultant time-of-flight, *Tprop*, may be estimated by the equation:

$$\hat{T}\_{prop}=\frac{1}{2}\left(T\_{round}-T\_{reply}\right)$$

The times *Tround* and *Treply* are measured independently by device A and B using their respective the local clocks, which both have some clock offset error *eA* and *eB* from their nominal frequency, and so the resulting the time-of-flight estimate has a considerable error that increases as the reply times get larger. Some typical values for this are presented in Annex A. Depending on the size of ranging error that is acceptable to the application, SS-TWR may be an appropriate choice for the range measurements especially if the reply time *Treply* is minimized and the clock error is low. It should be noted that the reply time *Treply* is not just the RX-to-TX turnaround time but also includes the message length.

### Double-sided two-way ranging

Double-sided two-way ranging (DS-TWR), is an extension of the basic single-sided two-way ranging in which two round trip time measurements are used and combined to give the a time of flight result which has a reduced error even for quite long response delays.



**Figure 8 –double-sided two-way ranging**

The operation of DS-TWR is as shown in Figure 8, where device A initiates the first round trip measurement to which device B responds, after which device B initiates the second round trip measurement to which device A responds completing the full DS-TWR exchange. Each device precisely timestamps the transmission and reception times of the messages, and the resultant time-of-flight estimate, *Tprop*, may be calculated using the expression:

$$\hat{T}\_{prop}=\frac{(T\_{round1}×T\_{round2}-T\_{reply1}×T\_{reply2})}{(T\_{round1}+T\_{round2}+T\_{reply1}+T\_{reply2})}$$

Note that this formula does not require symmetric reply times. The typical clock induced error is in the low picosecond range even with 20 ppm crystals, and asymmetric response times. The derivation of this formula and the error calculation are given in Annex A. At these error levels the precision of determining the arrival time of the RMARKER is a more significant.

### Double-sided two-way ranging with three messages

The four messages of DS-TWR, shown in Figure 8, can be reduced to three messages by using the reply of the first round-trip measurement as the initiator of the second round-trip measurement. This is shown in Figure 9.



**Figure 9 –double-sided two-way ranging with three messages**

### Time difference of arrival (TDOA)

Time difference of arrival (TDOA) is a technique to locate a mobile node based on the arrival times of a message from the mobile node at a number of fixed nodes, where the fixed nodes are synchronized in some way so that the arrival times can be compared. For any pair of fixed synchronized nodes the difference in arrival time of a message from a mobile node places that node on a hyperbolic surface. With more fixed nodes receiving the message, locating the mobile sender is a matter of finding the best fit solution solving the intersection of the hyperbolic surfaces. By virtue of supporting accurate receive timestamps this standard supports TDOA localization.

### Localization

Two-way ranging gives a distance between two nodes, but does not give the position of either. If a node of fixed known position determines the range R to another mobile node. This essentially places it somewhere on a spherical surface of radius R centered on the fixed position node. To ascertain the 3D position of a mobile node thus requires measuring the range to four fixed nodes and intersecting the resultant spheres. Relative location is possible with all mobile nodes, depending on their relative geometries, but fixing bearing and true position always requires some fixed nodes, or other information about the system. For TDOA based localization the same is true, fixed known position nodes are needed to solve the TDOA data and locate the mobile device.

Localization thus requires system knowledge and the combination of TWR or TDOA data from multiple nodes in order to resolve the position of a mobile node. This then is an upper layer function and beyond the scope of this standard. This standard simply facilitates localization as a result of the capabilities of the PHY to provide accurate timestamps and the capabilities of the MAC to communicate the results to the upper layers.

### Angle of arrival (AOA)

The angle of arrival (AOA) of a signal can in general only be determined in a device that is equipped with additional antennae and receiver sections able to measure the difference in phase or arrival time of the signals at the antennae and use this with respect to the antenna separation to infer an angle to the sender. In peer-to-peer situations where there is no fixed infrastructure to give a point of reference, devices with the capability to measure AOA can use this data in conjunction with TOF measurements to better estimate their position relative to each other. Typically, to resolve ambiguities in the solution the results may be combined with compass bearing data, or, successive measurements made during a known movement, captured by an inertial measurement unit (IMU), may be combined to obtain the solution.

### Received signal strength indication (RSSI)

Where accurate two-way ranging has not been performed, or is not supported by the PHY, a measure of RSSI can be used to give a rough indication of the proximity of the sender. The accuracy of RSSI based location is generally quite poor due to the variation in the RF channel conditions.

## Ranging procedures

### General ranging procedures

The layers above the MAC are responsible for the decision to participate in a two-way ranging exchange between a pair of PD, and for the final calculation of the resulting range. The ranging procedures appropriate to the ranging methods described in 2.3 are defined in the clauses below using message sequence charts.

### Ranging procedure for SS-TWR with deferred reply time result

For a single-sided TWR with a deferred reply time result, the ranging exchange is initiated by a ranging frame including the RRRT IE requesting the ranging reply time information. The replying ranging frame completes the round trip measurement, and the MCPS-DATA.confirm gives the initiating side timestamps that define the round trip time. At the responding side, the MCPS-DATA.indication supplies the responding side timestamps that define the reply time for the round trip measurement. This reply time is communicated to the initiating side in the RRTD IE carried by the subsequent message. Figure 10 shows the message sequence chart for this exchange. At the point labelled (R) the initiating end has sufficient information to calculate the range between the two PD according to the formula given in 2.3.2.



**Figure 10 – message sequence chart for single-sided TWR** **with deferred reply time result**

[*Note to TG8: When specifying the ACK frame format, please include both source & destination addresses, and of course the sequence number of frame being acknowledged. This will avoid ACKs from two sources getting confused, which was a flaw in 802.15.4 not addressed until 4e.*]

### Ranging procedure for SS-TWR with embedded reply time result

For a single single-sided TWR with an embedded reply time result, the ranging exchange is initiated by a ranging frame including the RRRT IE requesting the ranging reply time information. The replying ranging frame completes the round trip measurement, and the MCPS-DATA.confirm gives the initiating side timestamps that define the round trip time. At the responding side, the MCPS-DATA.indication supplies the responding side timestamps that define the reply time for the round trip measurement. This reply time is communicated to the initiating side in the RRTI IE carried by the ACK message. Figure 11 shows the message sequence chart for this exchange. At the point labelled (R) the initiating end has sufficient information to calculate the range between the two PD according to the formula given in 2.3.2.



**Figure 11 – message sequence chart for single-sided TWR with embedded reply time result**

Even though a device is capable of generating a Ranging Reply Time Instantaneous IE, depending on the timing required for the ACK transmission and the time required to calculate the timestamp of the received ranging message, it may not be possible for the responding device to have the RRTI IE value available in time for the ACK message. The Ranging Preferred Reply Time IE provides a mechanism for an RRTI capable device to indicate how long it needs to prepare the frame with the RRTI. When this time is known, the ranging initiating device then does not request an ACK but rather expects a response message after the RPRT IE specified time. Figure 12 shows the message sequence chart for this exchange. The communication of the RPRT IE may happen at any convenient time before the ranging exchange. Again at the point labelled (R) the initiating end has sufficient information to calculate the range between the two PD according to the formula given in 2.3.2.



**Figure 12 – message sequence chart for single-sided TWR after RPRT IE**

### Ranging procedure for DS-TWR with deferred timestamp information

Double-sided two-way ranging essentially involves completing single sided ranging exchanges initiated at either end and combining the results. The DS-TWR exchange is initiated by a ranging data frame carrying a Ranging Control Double-sided TWR IE (RCDT IE) with control field set according to Table 2. This frame and its acknowledgement define the first round trip measurement, while the RCDT IE delivery in the MCPS-DATA.indication tells the next higher layer to initiate the second round trip measurement of the exchange by the sending of a data frame in the other direction. This data frame includes Ranging Request Reply Time IE and an RCDT IE with control field set according to Table 2 to indicate this is the continuation of the exchange and requesting the result of the first round trip measurement. The acknowledgement to this message completes the second round trip measurement. A subsequent message from the initiator conveys the first round trip time measurement in an RRTM IE and the reply time for the second first round trip time measurement an RRTD IE. Figure 13 shows the message sequence chart for this exchange. At the point labelled (R) the responding end has sufficient information to calculate the range between the two PD according to the formula given in 2.3.3. The subsequent reporting of the ranging result the initiating end, in the RTOF IE, shall depend on the value of the control field in the initiating RCDT IE.



**Figure 13 – message sequence chart for DS-TWR with deferred reply time result**

### Ranging procedure for DS-TWR with embedded timestamp information

To achieve the three message DS-TWR exchange described in Figure 9 requires that the initiating end is able to embed the reply time as part of completing the second round trip measurement and additionally that the parties have previously exchanged Ranging Preferred Reply Time IE to communicate the reply times that each will use. These reply times do not have to be the same. When the reply times are known it allows the receiver to be turned at the appropriate time that the response is expected, saving power compared to turning the receiver on immediately after the transmission. With reference to the message sequence chart of Figure 14, the DS-TWR is initiated by a ranging data frame carrying a Ranging Control Double-sided TWR IE (RCDT IE) with control field set according to Table 2 to indicate, in this instance, that the initiating end does not require a report of the ranging result. The responding side completes the first round trip measurement and initiates the second with ranging data frame carrying a Ranging Control Double-sided TWR IE (RCDT IE) with control field set according to Table 2 to indicate this is the continuation of the exchange and requesting the result of the first round trip measurement and also carrying a Ranging Request Reply Time IE to request the reply time for the second round trip measurement. The original initiator completes the exchange by sending a final ranging data frame carrying the first round trip time measurement in an RRTM IE and the reply time of this second first round trip measurement in an RRTI IE.



**Figure 14 – message sequence chart for DS-TWR with three messages**

At the point labelled (R) the responding end has sufficient information to calculate the range between the two PD according to the formula given in 2.3.3. Where the initiator of the ranging exchange wants the result this shall be requested in the control field of the initial frame’s RCDT IE, and the responding end shall convey the Ranging Time-of-Flight IE in a subsequent message as is done at the end of the exchange shown in Figure 13.

# MAC services

*The items below are just place holders of note for the editor and authors of the MAC clauses. They are part of the API to/from the ranging procedures captured above and so need to be part of the MAC service layer API definition. This is not complete, as we need to fully define the passing IE from MAC to upper layers and vice-versa, and we may will need other PIB values.*

## MAC data service

### MCPS-DATA.request

*The following items are referred to in the text above and so need to be included in the parameters of the MCPS-DATA.request primitive. A larger set of parameters will be present in the complete table. The editor should integrate these.*

Table 5 –MCPS-DATA.request parameters

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Type** | **Valid range** | **Description** |
| AckTX | Boolean | FALSE, TRUE | TRUE if acknowledged transmission is used, FALSE otherwise. |
| Ranging | Boolean | FALSE, TRUE | TRUE if ranging bit in PHR is to be set, FALSE otherwise. |
| IeList | Set if IEs as described in Table 1 |  | Determines/supplies the IEs to be sent, including: RRRT IE, RRTD IE, RPRT IE, RRTM IE, RCDT IE and RTOF IE |
| RequestRrtiTx | Boolean |  | This parameter requests that the PD inserts an RRTI IE in the sent data frame. If the MCPS-DATA.request is early enough the data frame shall be sent at the configured *macRngRrtiTime* otherwise shall be sent as soon as possible thereafter. |

### MCPS-DATA.confirm

*The following items are referred to in the text above and so need to be included in the parameters of the MCPS-DATA.confirm primitive. A larger set of parameters will be present in the complete table. The editor should integrate these.*

Table 6 –MCPS-DATA.confirm parameters

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Type** | **Valid range** | **Description** |
| TxRangingCounter | Unsigned Integer |  | The timestamp of the transmitted data frame |
| RxRangingCounter | Unsigned Integer |  | For an acknowledged transmission this is the timestamp of the received acknowledgement frame. For a non-acknowledged transmission this parameter is invalid. |
| IeList  | IEs received in the ACK |  | For an acknowledged transmission this reports the IEs received in the ACK including: RRTI IE |
| TxRrtiValue | Unsigned Integer |  | This reports the value sent in the RRTI IE where this was requested by the RequestRrtiTx parameter of the MCPS-DATA.request. |
| AoaAzimuth | Float | -π to +π | For an acknowledged transmission this is the AOA of the received signal in azimuth measured in radians, relative to some PD specific axis defined by its antenna arrangement or orientation. This parameter is valid only when the AoaPresent parameter is either AZIMUTH or BOTH.  |
| AoaElevation | Float | -π to +π | For an acknowledged transmission this is the AOA of the received signal AOA of the received signal in elevation measured in radians. This parameter is valid only when the AoaPresent parameter is either ELEVATION or BOTH.  |
| AoaPresent | Enumeration | NONE,BOTH,AZIMUTH,ELEVATION | Indicates validity of AoaAzimuth and AoaElevation parameter. For a non-acknowledged transmission or where AOA is not supported this parameter value shall be NONE. |
| Rssi | Integer | 0x00–0xff | For an acknowledged transmission this reports the received signal strength for the ACK frame. This is a measure of the RF power level at the antenna based on the gain setting in the RX chain and the measured signal level in the channel. For the UWB PHY the RSSI value is measured during the frame Preamble and locked when a valid SFD is detected. A value of zero indicates that RSSI measurement is not supported or was not measured for this frame.  |

### MCPS-DATA.indication

*The following items are referred to in the text above and so need to be included in the parameters of the MCPS-DATA.indication primitive. A larger set of parameters will be present in the complete table. The editor should integrate these.*

Table 7 –MCPS-DATA.indication parameters

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Type** | **Valid range** | **Description** |
| RxRangingCounter | Unsigned Integer |  | The timestamp of the received data frame |
| TxRangingCounter | Unsigned Integer |  | If the received frame had the AR bit set, then this is the timestamp of the transmitted acknowledgement frame, otherwise this parameter is invalid. |
| IeList | Set if IEs as described in Table 1 |  | Reports the IEs received including: RRRT IE, RRTD IE, RRTI IE, RPRT IE, RRTM IE, RCDT IE and RTOF IE |
| AoaAzimuth | Float | -π to +π | AOA of the received signal in azimuth measured in radians, relative to some PD specific axis defined by its antenna arrangement or orientation. This parameter is valid only when the AoaPresent parameter is either AZIMUTH or BOTH.  |
| AoaElevation | Float | -π to +π | AOA of the received signal in elevation measured in radians. This parameter is valid only when the AoaPresent parameter is either ELEVATION or BOTH.  |
| AoaPresent | Enumeration | NONE,BOTH,AZIMUTH,ELEVATION | Indicates validity of AoaAzimuth and AoaElevation parameter. Where AOA is not supported this parameter value shall be NONE. |
| Rssi | Integer | 0x00–0xff | The received signal strength for received frame. This is a measure of the RF power level at the antenna based on the gain setting in the RX chain and the measured signal level in the channel. For the UWB PHY the RSSI value is measured during the frame Preamble and locked when a valid SFD is detected. A value of zero indicates that RSSI measurement is not supported or was not measured for this frame.  |

## PIB

*The following items are referred to in the text above and so need to be included in the PIB. A larger set of parameters will be present in the complete table. The editor should integrate these.*

**Table 8 – PIB attributes**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Attribute** | **Type** | **Range** | **Description** | **Default** |
| *phyTxRmarkerOffset* | Unsigned Integer |  | The propagation time from the internal transmit timestamp to the transmit antenna. The units of this are defined in 10.4.1. The PD adds this offset to its internal transmit timestamp to get the reported TxRangingCounter value. |  |
| *phyRxRmarkerOffset* | Unsigned Integer |  | The propagation time from the receive antenna to the internal receiver timestamp. The units of this are defined in 10.4.1. The PD subtracts this offset from its internal receive timestamp to get the reported RxRangingCounter value. |  |
| *macRngAckRrtiSupport* | Boolean | READ ONLY | Read only value indicating whether the PD is able to generate an RRTI IE within the *standard ACK response time* and insert it into a ranging ACK frame. |  |
| *macRngAckRrtiEnable* | Boolean |  | When set the PD MAC shall automatically generate and insert an RRTI IE in a ranging ACK frame, where the RFRAME being acknowledged carried an RRRT IE and where *macRngAckRrtiSupport* indicates that the PD is capable of doing this. |  |
| *macRngMinRrtiTime* | Unsigned Integer | READ ONLY | This is a read only value reporting the minimum RX to TX response time that the PD supports for inserting an RRTI IE into a MAC data frame. The units of this are defined in 10.4.1. A value of zero shall indicate that the PD cannot support RRTI insertion, i.e. so the upper layers know to employ an RRTD IE in the ranging exchanges. |  |
| *macRngRrtiTime* | Unsigned Integer |  | This sets the desired RX-to-TX response time for the PD to use when inserting an RRTI IE into a MAC data frame. The units of this are defined in 10.4.1. The value set should take account of the *macRngMinRrtiTime* and any upper layer delays in initiating transmission, be reflected in the preferred response time indicated via RPRT IE exchanges. |  |

# Annex A

(informative)

## The mathematics of two-way ranging

### Single-sided two-way ranging error due to clock offset

With reference to Figure 7, the times *Tround* and *Treply* are measured independently by device A and B using their respective the local clocks, which have some clock offset error *eA* and *eB* from their nominal frequency. As a result *Tprop* is then actually:

$$T\_{prop}=\frac{1}{2}\left(T\_{round}×(1+e\_{A})-T\_{reply}×(1+e\_{A})\right)$$

And, the error in the range estimate equation (given in 2.3.2) is:

$$\hat{T}\_{prop}-T\_{prop}=\frac{1}{2}\left(T\_{round}-T\_{reply}\right)-\frac{1}{2}\left(T\_{round}×(1+e\_{A})-T\_{reply}×(1+e\_{B})\right)$$

Or:

$$\hat{T}\_{prop}-T\_{prop}=\frac{1}{2}\left(-T\_{round}×e\_{A}+T\_{reply}×e\_{B}\right)$$

Or, since *Treply* is 500 to 5000 times bigger than *Tprop*, for the purpose of simplifying the error estimate we can take *Treply* as (almost) the same as *Tround* and can be use *Treply* in place of *Tround* to give an error estimate:

$$error=\hat{T}\_{prop}-T\_{prop}≈\frac{1}{2}\left(e\_{B}-e\_{A}\right)×T\_{reply}$$

Based on this equation, Table 3 presents the typical errors in SS-TWR time-of-flight estimation depending on the reply time, *Treply*, and the total clock offset error.

**Table 3 – typical clock induced error in SS-TWR time-of-flight estimation**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| clock error*Treply* | 2 ppm | 5 ppm | 10 ppm | 20 ppm | 40 ppm |
| 100 µs | 0.1 ns | 0.25 ns | 0.5 ns | 1 ns | 2 ns |
| 200 µs | 0.2 ns | 0.5 ns | 1 ns | 2 ns | 4 ns |
| 500 µs | 0.5 ns | 1.25 ns | 2.5 ns | 5 ns | 10 ns |
| 1 ms | 1 ns | 2.5 ns | 5 ns | 10 ns | 20 ns |
| 2 ms | 2 ns | 5 ns | 10 ns | 20 ns | 40 ns |
| 5 ms | 5 ns | 12.5 ns | 25 ns | 50 ns | 100 ns |

Table 3 shows that quite accurate results are achievable when short messages are used (e.g. with shorter preamble lengths and higher data rates) to give small reply time and more accurate clock sources are employed in the PDs. Note: the reply time *Treply* is not just the RX-to-TX turnaround time but also includes the message length. An error of 1 ns in time-of-flight is equivalent to a 30 cm error in distance.

### Derivation of double-sided two-way ranging formula

Figure 15 shows the two round trips of double sider ranging and defines the terms used for the round trip times, Ra and Rb, and the reply times, Da and Db, for the pair of devices, A and B, participating in the two way ranging exchange to measure the time of flight, *Tf*.



**Figure 15 – terms used in deriving the double-sided two-way ranging formula**

In Figure 15, device A transmits a packet, P1, to device B. Device B receives this signal, and a short time later, Db, it transmits a packet, P2, back to A. The packet, P2, arrives at device A at a time Ra after transmitting packet P1. These then have the relationship:

$R\_{a}=2T\_{f}+D\_{b}$ *(1)*

So

$T\_{f}=\frac{1}{2}(R\_{a}-D\_{b})$ *(2)*

In practice, the times are measured by real clocks in A and B, which will run independently either faster or slower than an ideal clock, synchronised to their local reference frequency generator which can be assumed to be a constant frequency over the duration of the ranging exchange. Let us say that Clocks A and B run respectively at *ka* and *kb* times the frequency of an ideal, true, clock. Any time measurements will be multiplied by these constants, *ka* or *kb*. Denoting the actual time estimates for Ra and Da as $\hat{R}$a and $\hat{D}$a respectively, and similarly $\hat{R}$b and $\hat{D}$b as the estimates of Rb and Db. Then, since Ra is measured at A by A’s clock:

$\hat{R}\_{a}=k\_{a}R\_{a}$ *(3)*

And, similarly

$\hat{D}\_{a}=k\_{a}D\_{a}$ *(4)*

$\hat{R}\_{b}=k\_{b}R\_{b}$ *(5)*

$\hat{D}\_{b}=k\_{b}D\_{b}$ *(6)*

Using $\hat{R}$a, $\hat{D}$a etc. as estimates for Ra, Da etc. we introduce a measurement error, so for example if $\hat{T}\_{f}$ is an estimate of $T\_{f}$we can say for a single round trip exchange

$\hat{T}\_{f1}=\frac{1}{2}(\hat{R}\_{a}-\hat{D}\_{b})= \frac{1}{2}(k\_{a}R\_{a}-k\_{b}D\_{b})$  *(7)*

And, the error in the estimation is

$\hat{T}\_{f1}-T\_{f}= \frac{1}{2}((k\_{a}-1)R\_{a}-\left(k\_{b}-1\right)D\_{b})$ *(8)*

For the UWB physical layer the values of the expressions ($k\_{a}-1)$ and $(k\_{b}-1)$ may be up to 20 ppm, i.e. 20x10-6, and for accurate ranging it is important to keep the error below 100ps (1x10-10) which means the delays e.g. $\hat{D}$b must be kept below about 5 µs which is not possible where even short UWB frames are typically > 100 µs long. The solution is to use two round trip delays.

We know from (4) that

$D\_{a}=\frac{\hat{D}\_{a}}{k\_{a}}$ (10)

And similarly

$D\_{b}=\frac{\hat{D}\_{b}}{k\_{b}}$ (11)

Then from (10) and (1) we can say

$R\_{a}=2T\_{f}+\frac{\hat{D}\_{b}}{k\_{b}}$ (12)

And from (12) and (3)

$\hat{R}\_{a}=2k\_{a}T\_{f}+\frac{k\_{a}\hat{D}\_{b}}{k\_{b}}$ (13a)

And similarly

$\hat{R}\_{b}=2k\_{b}T\_{f}+\frac{k\_{b}\hat{D}\_{a}}{k\_{a}}$ (13b)

In (12) and (13) we have quantities that we can measure, $\hat{R}$a,$ \hat{R}$b,$ \hat{D}$a and $\hat{D}$b. But we have no way of measuring $k\_{a}$ or $k\_{b}$. And the errors in these quantities swamp the value of *Tf.* There is however one thing we can do. If we multiply $\hat{R}$a by$ \hat{R}$b, the bulk of the value of the product will be the product of $\hat{D}$a and $\hat{D}$b. For this term in the product, the $k\_{a}$ and $k\_{b}$ constants cancel each other out.

Then, from (12) & (13)

$\hat{R}\_{a}\hat{R}\_{b}=4k\_{a}k\_{b}T\_{f}^{2}+\frac{k\_{a}\hat{D}\_{b}}{k\_{b}}\frac{k\_{b}\hat{D}\_{a}}{k\_{a}}+2k\_{b}T\_{f}\frac{k\_{a}\hat{D}\_{b}}{k\_{b}}+2k\_{a}T\_{f}\frac{k\_{b}\hat{D}\_{a}}{k\_{a}}$ (14)

$\hat{R}\_{a}\hat{R}\_{b}=4k\_{a}k\_{b}T\_{f}^{2}+\hat{D}\_{a}\hat{D}\_{b}+2T\_{f}(k\_{a}\hat{D}\_{b}+k\_{b}\hat{D}\_{a})$ (15)

$\hat{R}\_{a}\hat{R}\_{b}-\hat{D}\_{a}\hat{D}\_{b}=4k\_{a}k\_{b}T\_{f}^{2}+2T\_{f}(k\_{a}\hat{D}\_{b}+k\_{b}\hat{D}\_{a})$ (16)

And, from (16) and (13)

$\frac{\hat{R}\_{a}\hat{R}\_{b}-\hat{D}\_{a}\hat{D}\_{b}}{\hat{R}\_{a}+\hat{D}\_{a}}=\frac{4k\_{a}k\_{b}T\_{f}^{2}+2T\_{f}(k\_{a}\hat{D}\_{b}+k\_{b}\hat{D}\_{a})}{2k\_{a}T\_{f}+\frac{k\_{a}\hat{D}\_{b}}{k\_{b}}+\hat{D}\_{a}}$ (17)

On left hand side, taking out *2Tf* and multiplying above and below by *kb*

$\frac{\hat{R}\_{a}\hat{R}\_{b}-\hat{D}\_{a}\hat{D}\_{b}}{\hat{R}\_{a}+\hat{D}\_{a}}=2T\_{f}k\_{b}\frac{2k\_{a}k\_{b}T\_{f}+(k\_{a}\hat{D}\_{b}+k\_{b}\hat{D}\_{a})}{2k\_{a}k\_{b}T\_{f}+k\_{a}\hat{D}\_{b}+k\_{b}\hat{D}\_{a}}$ (18)

So finally

$\frac{\hat{R}\_{a}\hat{R}\_{b}-\hat{D}\_{a}\hat{D}\_{b}}{\hat{R}\_{a}+\hat{D}\_{a}}=2T\_{f}k\_{b}≈2T\_{f}$ (19a)

And similarly

$\frac{\hat{R}\_{a}\hat{R}\_{b}-\hat{D}\_{a}\hat{D}\_{b}}{\hat{R}\_{b}+\hat{D}\_{b}}=2T\_{f}k\_{a}≈2T\_{f}$ (19b)

We now have two possible estimates for *Tf*, and since *ka* and *kb* are very close to unity, i.e. 0.99998 < *ka*, *kb* < 1.00002, we can estimate *Tf*  as follows

$\hat{T}\_{fa}=\frac{1}{2}\frac{\hat{R}\_{a}\hat{R}\_{b}-\hat{D}\_{a}\hat{D}\_{b}}{\hat{R}\_{b}+D\_{b}}$ (20)

$\hat{T}\_{fb}=\frac{1}{2}\frac{\hat{R}\_{a}\hat{R}\_{b}-\hat{D}\_{a}\hat{D}\_{b}}{\hat{R}\_{a}+\hat{D}\_{a}}$ (21)

These estimates are very close to the actual *Tf* because *ka* and *kb* are very close to one and, crucially, their accuracy is independent of the response delays employed at A and at B.

Whether a system should use formula (20) or formula (21) would depend on whether it expects which clock it expects to be more accurate. For example, if the system knows B has a higher accuracy clocks then it should use formula 21. If it expects neither to be more accurate than the other and it is more accurate to use the average result from (20) and (21) since this will always be as good as, or better than, the worst of the two (21) and (20).

This average can be approximated by the following formula that combines (20) and (21):

$\hat{T}\_{fab}=\frac{\hat{R}\_{a}\hat{R}\_{b}-\hat{D}\_{a}\hat{D}\_{b}}{\hat{R}\_{a}+\hat{D}\_{a}+\hat{R}\_{b}+\hat{D}\_{b}}$ (22)

For double-sided two-way ranging it is generally suggested that the delay times $\hat{D}$a and $\hat{D}$b have to be nearly equal for the overall error to be acceptably small, but this is not a restriction when employing equations (20), (21) and (22), that burden is removed, so it is NOT required the use of the same response time at each end. This gives much more implementation flexibility within the individual nodes participating in a ranging exchange and also facilitates more efficient implementations when a group of N nodes want to find the ½·N·(N-1) distances between each other. Here, instead of separated ranging exchanges, messages can be combined, (e.g. a response from node B to Node A could also act as a ranging initiation message other nodes), to do the distance measurements with a much reduced over the air traffic, perhaps as few as 2·N messages.

### Asymmetric double-sided two-way ranging error due to clock offset

Formulas (19a) and (19b) give the time of flight results (TOF) results including the clock offset errors. For the average formula then we can similarly say

$$\hat{T}\_{fab}=T\_{f}\left(\frac{k\_{b}+k\_{b}}{2}\right)$$

Thus, the error in the estimated $\hat{T}\_{fab}$ is:

$$Error=T\_{f}-\hat{T}\_{fab}=T\_{f}-T\_{f}\left(\frac{k\_{b}+k\_{b}}{2}\right)$$

Or

$$Error=T\_{f}× \left(1-\frac{k\_{b}+k\_{b}}{2}\right)$$

To size this error, if devices A and B have clocks, where each are 20 ppm away from the nominal clock in directions make their combined error additive and equal to 40 ppm, then *ka* and *kb* might both be 0.99998 or 1.00002.

Even with a fairly larger UWB operating range of say 100 m, the TOF is just 333 ns, so the error is: 20×10-6 × 333×10-9 seconds, which 6.7×10-12 or 6.7 picoseconds.

Again note that these error levels do NOT require the use of the same response time at each end.

At these error levels the precision of determining the arrival time of the RMARKER is actually the more significant source of error. This depends on implementation but for the UWB PHY it might typically be expected to fall in a range from 1 ns down to 100 ps.