

METHOD OF DETERMINING A DISTANCE BETWEEN NODES OF A WIRELESS COMMUNICATION NETWORK

CROSS-REFERENCE TO RELATED APPLICATION

- 5 **[0001]** This application claims the benefit of priority of Singapore Patent Application No. 10201400165Y, filed 24 February 2014, the contents of which being hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

- 10 **[0002]** The present invention generally relates to a ranging technique, and more particularly, to a method of determining a distance between nodes of a wireless communication network, and the associated wireless communication device and system.

BACKGROUND

- 15 **[0003]** Location awareness has become an indispensable feature of value added applications such as asset management, yard or parking management, and personnel tracking. Expensive sensing devices such as Global Positioning System (GPS) are limited to outdoor use and are unfavourable for an indoor locating system. Owing to this, the last few years have witnessed an increased demand for real time locating systems based on
20 wireless personal area networks (WPAN). This has fuelled a wealth of research and development efforts that are moving towards commercialization and standardization.

- [0004]** Ranging is the basic and most important principle of a real time locating system. Ranging is a process or method of determining the distance between any two nodes of a wireless communication network. In general, ranging techniques can be
25 classified into two categories: synchronous ranging schemes and asynchronous ranging schemes. The former requires all the nodes to be globally synchronized while the later does not require any time synchronization between nodes.

- [0005]** Time Difference of Arrival (TDOA) is a synchronous ranging scheme where a mobile node periodically broadcasts a beacon signal containing its time of departure. The
30 anchor nodes receive the beacon and measure the arrival time. The distance between the nodes is calculated by multiplying the speed of signal propagation with the difference

between the times of arrival and departure. This ranging procedure is one-way or unidirectional and can be implemented easily due to global synchronization between the nodes. However, synchronizing every node is not an easy task and requires an expensive and precise oscillator to mitigate clock offset and/or clock drift.

- 5 **[0006]** In an asynchronous ranging scheme, each node uses its own timing information to measure the Time of Flight (TOF) of the ranging signal instead of using global synchronization. Hence, each node has to measure a round trip time (RTT) in order to obtain the propagation time and consequently the distance between two nodes. This ranging procedure is two-way or bidirectional and can be realized using relatively
- 10 simple circuitry without the need for a precise crystal oscillator. For example, for a mobile node to determine its location, the mobile node may perform the ranging procedure with at least three or four anchor nodes. A series of ranging procedures may result in the asynchronous ranging scheme requiring longer ranging time and locating time than its synchronous counterparts.
- 15 **[0007]** One of the challenges in an asynchronous ranging scheme is ranging accuracy. In general, ranging accuracy of the TOF-based method depends on the signal bandwidth used in the transaction. However by assuming the receiver's operating bandwidth to be higher than the signal bandwidth, the resolution of the sampling clock affects the timing accuracy of ranging transactions. Since high frequency clocks provide better timing
- 20 resolution, their use results in higher ranging accuracy. Although ranging accuracy can be increased by using a higher frequency sampling clock, it is not always practical or desirable to increase the rate of the sampling clock since it incurs higher complexity and higher power consumption in the device. In practice, timing drift in clock's crystal can also cause ranging inaccuracy. Timing drift is dependent on the angular frequency of the
- 25 device's oscillator and any change in this frequency will generate a ranging error. For example, other parameters that affect timing drift include the surrounding temperature and pressure of the network environment that the nodes operate in. One method of reducing error due to timing drift is to use low part per-million (ppm) devices. However, such devices are expensive and are unfavorable for a low cost locating system.
- 30 **[0008]** Other techniques for distance estimation between nodes in a wireless communication network include Received Signal Strength Indication (RSSI)

measurement and Direction Finding (DF) measurement methods. In brief, the RSSI measurement method relies on measuring the RSSI indicating the power of each received radio signal and the coordinates of the corresponding transmitter of the radio signals. The DF measurement method measures the Angle-of-Arrival (AOA) of a tracked node at several base stations and then calculates its position by triangulation.

[0009] The above-mentioned conventional techniques suffer from various drawbacks. For example, RSSI is largely unreliable in indoor environments, TDOA requires precise timing synchronization between nodes or base stations, and AOA requires expensive phased antenna arrays for measurements.

[0010] A need therefore exists to provide a ranging technique that seeks to overcome, or at least ameliorate, one or more of the deficiencies of conventional ranging techniques discussed above, and in particular, which reduces ranging errors in a wireless communication network, while minimizing implementation costs. It is against this background that the present invention has been developed.

SUMMARY

[0011] According to a first aspect of the present invention, there is provided a method of determining a distance between nodes of a wireless communication network, the method comprising:

performing a ranging operation for determining a distance between a first node and a second node of the wireless communication network, the ranging operation comprises:

transmitting, at the first node, a range request packet to the second node; and

receiving, at the first node, a range reply packet from the second node in response to the range request packet; and

determining the distance based on a response delay at the first node and a response delay at the second node in relation to said ranging operation,

wherein the response delay at the second node corresponds to a time period between receiving the range request packet and transmitting the range reply packet, and the response delay at the first node corresponds to a time period

between receiving the range reply packet and transmitting a subsequent range request packet to the second node in a subsequent ranging operation.

[0012] Preferably, the distance is determined based on the response delay at the first node, the response delay at the second node, a round-trip time of the ranging operation measured at the first node, and a round-trip time of the ranging operation measured at the second node, wherein the round-trip time measured at the first node corresponds to a time period between transmitting the range request packet and receiving the range reply packet, and the round-trip time measured at the second node corresponds to a time period between transmitting the range reply packet and receiving the subsequent range request packet.

[0013] Preferably, the distance is derived based on a time of flight of the range request packet or the range reply packet between the first and second nodes, the time of flight being determined according to the equation:

$$t_P = \frac{1}{4}[(t_{round_B} - t_{reply_A}) + (t_{round_A} - t_{reply_B})]$$

where t_P is the time of flight, t_{round_A} is the round-trip time of the ranging operation measured at the first node, t_{round_B} is the round-trip time of the ranging operation measured at the second node, t_{reply_A} is the response delay at the first node, and t_{reply_B} is the response delay at the second node.

[0014] Preferably, the range reply packet received from the second node comprises data indicating the response delay at the second node.

[0015] In a preferred embodiment, the method comprises performing N number of iterations of the ranging operation for determining the distance between the first node and the second node, wherein N is greater than 1.

[0016] Preferably, each iteration commences after receiving, at the first node, the range reply packet of the immediately previous iteration, subject to the response delay at the first node.

[0017] Preferably, the distance is determined based on the response delay at the first node and the response delay at the second node, in relation to each of said N number of iterations of the ranging operation.

[0018] Preferably, the distance is determined based on the response delay at the first node, the response delay at the second node, the round-trip time of the ranging operation measured at the first node, and the round-trip time of the ranging operation measured at the second node, in relation to each of said N number of iterations of the ranging operation.

[0019] Preferably, the distance is derived based on the time of flight of the range request packet or the range reply packet between the first and second nodes determined according to the equation:

$$t_P = \frac{1}{4N} \sum_{i=1}^N [(t_{round_B_i} - t_{reply_A_i}) + (t_{round_A_i} - t_{reply_B_i})]$$

where t_P is the time of flight, $t_{round_A_i}$ is the round-trip time of the ranging operation measured at the first node for the i^{th} iteration, $t_{round_B_i}$ is the round-trip time of the ranging operation measured at the second node for the i^{th} iteration, $t_{reply_A_i}$ is the response delay at the first node for the i^{th} iteration, and $t_{reply_B_i}$ is the response delay at the second node for the i^{th} iteration.

[0020] Preferably, the range request packet and the range reply packet each comprises data indicating an iteration number associated therewith.

[0021] According to a second aspect of the present invention, there is provided a wireless communication device comprising:

a transmitter configured to transmit a range request packet to a node of a wireless communication network for performing a ranging operation to determine a distance between the device and the node;

a receiver configured to receive a range reply packet from the node in response to the range request packet; and

a distance computing module configured to determine the distance based on a response delay at the device and a response delay at the node in relation to the ranging operation,

wherein the response delay at the node corresponds to a time period between receiving the range request packet and transmitting the range reply packet, and the response delay at the device corresponds to a time period between

receiving the range reply packet and transmitting a subsequent range request packet to the node in a subsequent ranging operation.

[0022] Preferably, the distance computing module is configured to determine the distance based on the response delay at the device, the response delay at the node, a round-trip time of the ranging operation measured at the device, and a round-trip time of the ranging operation measured at the node, wherein the round-trip time measured at the device corresponds to a time period between transmitting the range request packet and receiving the range reply packet, and the round-trip time measured at the node corresponds to a time period between transmitting the range reply packet and receiving the subsequent range request packet.

[0023] Preferably, the distance computing module is configured to determine the distance based on a time of flight of the range request packet or the range reply packet between the device and the node, the time of flight being determined according to the equation:

$$t_p = \frac{1}{4}[(t_{round_B} - t_{reply_A}) + (t_{round_A} - t_{reply_B})]$$

where t_p is the time of flight, t_{round_A} is the round-trip time of the ranging operation measured at the device, t_{round_B} is the round-trip time of the ranging operation measured at the node, t_{reply_A} is the response delay at the device, and t_{reply_B} is the response delay at the node.

[0024] Preferably, the range reply packet received from the node comprises data indicating the response delay at the node.

[0025] In a preferred embodiment, the device is configured to perform N number of iterations of the ranging operation for determining the distance between the device and the node, wherein N is greater than 1.

[0026] Preferably, each iteration commences after the receiver receives the range reply packet of the immediately previous iteration, subject to the response delay at the device.

[0027] Preferably, the distance computing module is configured to determine the distance based on the response delay at the device and the response delay at the node, in relation to each of said N number of iterations of the ranging operation.

5 [0028] Preferably, the distance computing module is configured to determine the distance based on the response delay at the device, the response delay at the node, the round-trip time of the ranging operation measured at the device, and the round-trip time of the ranging operation measured at the node, in relation to each of said N number of iterations of the ranging operation.

10 [0029] Preferably, the distance computing module is configured to derive the distance based on the time of flight of the range request packet or the range reply packet between the device and the node, the time of flight being determined according to the equation:

$$t_P = \frac{1}{4N} \sum_{i=1}^N [(t_{round_B_i} - t_{reply_A_i}) + (t_{round_A_i} - t_{reply_B_i})]$$

where t_P is the time of flight, $t_{round_A_i}$ is the round-trip time of the ranging operation measured at the device for the i^{th} iteration, $t_{round_B_i}$ is the round-trip time of the ranging operation measured at the node for the i^{th} iteration, $t_{reply_A_i}$ is the response delay at the device for the i^{th} iteration, and $t_{reply_B_i}$ is the response delay at the node for the i^{th} iteration.

[0030] Preferably, the range request packet and the range reply packet each comprises data indicating an iteration number associated therewith.

20 [0031] According to a third aspect of the present invention, there is provided a system for a wireless communication network, the system comprising:

a plurality of nodes in the wireless communication network, and

a wireless communication device according to the above-described second aspect of the present invention configured to determine a distance to one or more of the plurality of nodes.

25 [0032] According to a fourth aspect of the present invention, there is provided a computer program product, embodied in a computer-readable storage medium, comprising instructions executable by a computer processor to perform a method of

determining a distance between nodes of a wireless communication network according to the above-described first aspect of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

5 [0033] Embodiments of the present invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

FIG. 1 depicts a wireless communication system for illustrating the asynchronous ranging technique according to an embodiment of the present invention;

10 FIG. 2 depicts a schematic diagram illustrating the ranging signal/packet flow between a request Device A and a reference Device B based on two-way ranging (TWR) for determining the distance between Devices A and B;

FIG. 3 depicts a flow diagram illustrating a method of determining a distance between nodes of a wireless communication network according to an embodiment of the present invention;

15 FIGs. 4A and 4B depict an exemplary wireless communication device and an exemplary reference node according to an embodiment of the present invention;

FIG. 5 depicts a schematic diagram illustrating the ranging signal/packet flow between a request Device A and a reference Device B based on SDS-TWR with multiple iterations according to the example embodiment for determining the distance between Devices A and B;

FIGs. 6A, 6B and 6C show the ranging signal/packet flow between Devices A and B based on the SDS-TWR-MI ranging technique at the first ranging iteration, n^{th} ranging iteration, and the last ranging iteration, respectively;

25 FIG. 7 depicts a schematic representation of a ranging frame in the exemplary implementation according to an embodiment of the present invention;

FIGs. 8A and 8B depict graphs illustrating the performance (accuracy) of the SDS-TWR-MI ranging technique according to the example embodiment over a range of 100m and 20m, respectively; and

30 FIG. 9 depicts a graph showing a simulation result where the nodes operate at different sampling clock frequencies.

DETAILED DESCRIPTION

[0034] Embodiments of the present invention provide a ranging technique with reduced ranging errors in a wireless communication network, while minimizing implementation costs. For example, the ranging technique is capable of reducing ranging errors due to timing resolution of the sampling clock, timing drift in the node's oscillator, and/or variations in the response time (response delay) of a node in the wireless communication network, according to embodiments of the present invention. In particular, while conventional techniques may attempt to reduce ranging errors by, for example, using a precise crystal oscillator and/or a higher frequency sampling clock such as at a frequency of 50 MHz or higher, the ranging technique according to embodiments of the present invention surprisingly found that the ranging errors may be satisfactorily reduced by taking into account the variations in the response time (response delay) of the nodes in the wireless communication network involved in the ranging operation. Advantageously, this ranging technique neither requires the use of a precise crystal oscillator (thus minimizing costs) nor the use of a higher frequency sampling clock (thus minimizing complexity and power consumption). The response time or delay of a node may be defined as the time period or delay between the end of a received packet (e.g., range request packet) and the beginning of the next transmission (e.g., range reply packet) at the same node. When there are variations in the node's response time, the ranging error was found to increase and this is addressed by the ranging technique according to embodiments of the present invention as will be described hereinafter.

[0035] The ranging technique according to embodiments of the present invention is an asynchronous ranging technique and is preferably based on Two-Way Ranging (TWR). TWR measures a signal's Time of Flight (TOF) between two wireless nodes and requires no timing synchronization between the nodes. TWR can be achieved using basic RF transmission, thereby making low-cost system-on-chip (SOC) a viable hardware platform for implementation. FIG. 1 depicts a wireless communication system 100 for illustrating the asynchronous ranging technique. The wireless communication system 100 comprises a request node 110 (e.g., a tag or transceiver of a mobile device or a car positioning system) which may perform a ranging operation for determining its current

position/location, and a plurality of reference/anchor nodes 120 (e.g., readers at base stations with known location) in the wireless communication network which the ranging operation may be conducted with in order for the request node 110 to determine its current location. Instead of using clock synchronization, asynchronous ranging technique based devices perform ranging by using their own clock as a time reference, hence precise and expensive oscillators are not required. In the asynchronous ranging technique, the time of flight (TOF) of the ranging signal between the request node 110 and the reference node 120 is calculated from the measured round trip time (RTT) of the ranging signal. In order for the request node 110 to determine its current location, the request node 110 may measure the RTT of the ranging signal with at least three reference nodes 120 in a sequential manner as shown in FIG. 1.

[0036] FIG. 2 depicts a schematic diagram 200 illustrating the ranging signal/packet flow between a request Device A and a reference Device B based on TWR. In the example shown in FIG. 2, Device A uses its own clock as a time reference. Device A initiates the ranging phase/operation by sending a range request packet (REQ) to Device B at time t_{AT} . Device B receives the REQ message at time t_{BR} , and then replies Device A with a range reply packet (acknowledgment packet (ACK)) at time t_{BT} after a fixed or predefined time delay which may be referred to as response time or delay (t_{reply_B}). This response delay is known to Devices A and B. After the same propagation time (e.g., if Device A is fixed or moving slowly (e.g., less than 10m/s) that it could be regarded as moveless, (i.e., TOF (t_p)), the ACK message is received at Device A at time t_{AR} .

[0037] Accordingly, the RTT (t_{round_A}) measured/recorded by Device A with its own time clock can be obtained, and the relationship of the above time slots (t_{round_A} , t_{reply_B} , t_p) may be expressed as follow:

$$t_{round_A} = 2t_p + t_{reply_B} \quad (1)$$

[0038] The TOF (t_p) of the ranging signal/packet may thus be derived as follow:

$$t_p = \frac{t_{round_A} - t_{reply_B}}{2} \quad (2)$$

[0039] The TOF (t_p) of the ranging signal/packet may also be expressed in terms of time points (t_{AR} , t_{AT} , t_{BT} , t_{BR}) as follow:

$$t_p = \frac{t_{round_A} - t_{reply_B}}{2} = \frac{(t_{AR} - t_{AT}) - (t_{BT} - t_{BR})}{2} \quad (3)$$

[0040] Accordingly, based on the above derivations, it can be seen that the key device used in TOF-based ranging is the timer. From the timing principle, time is counted based on the frequency of the oscillator. Therefore, by assuming that a counter (the counter of the device counts the pulses of the device clock which is synchronized with sampling speed) is used at each node to precisely record all the time counts (N) with its own operating sampling clock frequency (f_A and f_B , for Devices A and B, respectively), another representation of TOF (t_{pT}) can be expressed in terms of counter value as follow:

$$t_{pT} = \frac{(N_{AR} - N_{AT})}{2f_A} - \frac{(N_{BT} - N_{BR})}{2f_B} \quad (4)$$

Thus, the distance (d) between Devices A and B may be obtained by multiplying the TOF (t_{pT}) with the speed of signal propagation (c) as follow:

$$d = c \times t_{pT} \quad (5)$$

[0041] As mentioned hereinbefore, the ranging technique according to embodiments of the present invention advantageously reduces ranging errors by taking into account the variations in the response time (response delay) of the nodes in the wireless communication network involved in the ranging operation. Based on this, according to a preferred embodiment, a method 300 of determining a distance between nodes of a wireless communication network is provided and illustrated in FIG. 3. In particular, the method 300 comprises a step 302 of performing a ranging operation for determining a distance between a first node 110 (e.g., request device or tag) and a second node (e.g., reference device or reader) of the wireless communication network. The ranging operation comprises transmitting, at the first node 110, a range request packet to the second node 120, and receiving, at the first node 110, a range reply packet from the second node 120 in response to the range request packet. The method 300 further comprises a step 304 of determining the distance based on a response delay at the first node 110 and a response delay at the second node 120 in relation to the ranging operation. The response delay at the second node 120 corresponds to a time period between receiving the range request packet and transmitting the range reply packet, and the response delay at the first node 110 corresponds to a time period between receiving

the range reply packet and transmitting a subsequent range request packet to the second node 120 in a subsequent ranging operation.

[0042] In a preferred embodiment, the distance is determined based on the response delay at the first node 110, the response delay at the second node 120, the round-trip time of the ranging operation measured at the first node 110, and the round-trip time of the ranging operation measured at the second node 120. The round-trip time measured at the first node 110 corresponds to a time period between transmitting the range request packet and receiving the range reply packet, and the round-trip time measured at the second node 120 corresponds to a time period between transmitting the range reply packet and receiving the subsequent range request packet.

[0043] In an example embodiment, the distance is derived based on a time of flight (TOF) of the range request packet or the range reply packet between the first and second nodes, whereby the TOF is determined according to the equation:

$$t_P = \frac{1}{4}[(t_{round_B} - t_{reply_A}) + (t_{round_A} - t_{reply_B})] \quad (6)$$

where t_P is the TOF, t_{round_A} is the round-trip time of the ranging operation measured at the first node 110, t_{round_B} is the round-trip time of the ranging operation measured at the second node 120, t_{reply_A} is the response delay at the first node 110, and t_{reply_B} is the response delay at the second node 120. With the TOF, the distance can then be easily determined by multiplying the TOF with the speed of signal propagation.

[0044] Accordingly, by taking into account the response delays at both the first node (request device) 110 and the second node (reference device) 120 for a ranging operation, it can be seen from Equation (6) that the ranging technique by the method 300 described is able to obtain better ranging accuracy than conventional TWR. In particular, the ranging error is advantageously scaled by a factor of $\frac{1}{4}$. In this embodiment, the range reply packet from the second node 120 is configured to comprise data indicating the response delay at the second node 120.

[0045] According to a further embodiment of the present invention, N number of iterations of the ranging operation is performed for determining the distance between the first node 110 and the second node 120, whereby N is greater than 1 (i.e., multiple iterations). In particular, each iteration commences after receiving, at the first node 110,

the range reply packet of the immediately previous iteration, subject to the response delay at the first node 110. By performing multiple iterations of the ranging operation for determining the distance between two nodes, the ranging error has been found to be significantly reduced.

5 [0046] In the further embodiment, the distance may be determined based on the response delay at the first node 110 and the response delay at the second node 120, in relation to each of the N number of iterations of the ranging operation. In a preferred embodiment, the distance is determined based on the response delay at the first node, the response delay at the second node 120, the round-trip time of the ranging operation
10 measured at the first node 110, and the round-trip time of the ranging operation measured at the second node 120, in relation to each of the N number of iterations of the ranging operation.

[0047] As an example, the distance is derived based on the TOF of the range request packet or the range reply packet between the first and second nodes determined according
15 to the equation:

$$t_P = \frac{1}{4N} \sum_{i=1}^N [(t_{round_B_i} - t_{reply_A_i}) + (t_{round_A_i} - t_{reply_B_i})] \quad (7)$$

where t_P is the TOF, $t_{round_A_i}$ is the round-trip time of the ranging operation measured at the first node 110 for the i^{th} iteration, $t_{round_B_i}$ is the round-trip time of the ranging
operation measured at the second node 120 for the i^{th} iteration, $t_{reply_A_i}$ is the response
20 delay at the first node 110 for the i^{th} iteration, and $t_{reply_B_i}$ is the response delay at the second node 120 for the i^{th} iteration. With the TOF, the distance can then be easily determined by multiplying the TOF with the speed of signal propagation.

[0048] Accordingly, by performing multiple iterations of the ranging operation for determining the distance between two nodes, it can be seen from Equation (7) that the
25 ranging technique with multiple iterations according to the further embodiment is able to obtain an even better ranging accuracy than conventional TWR. In particular, the ranging error is advantageously scaled by a factor of $\frac{1}{4N}$, where N is the number of iterations performed. Preferably, the range request packet and the range reply packet each

comprises data indicating an iteration number associated therewith so that the nodes are able to be aware of the current ranging iteration number.

[0049] According to an embodiment of the present invention, there is also provided a wireless communication device 400 corresponding to the methods as described above. In particular, the wireless communication device 400 comprises a transmitter 402 configured to transmit a range request packet to a node 450 (e.g., a reference device or reader) of a wireless communication network for performing a ranging operation to determine a distance between the device 400 and the node 450, a receiver 404 configured to receive a range reply packet from the node 450 in response to the range request packet, and a distance computing module 406 configured to determine the distance based on a response delay at the device 400 and a response delay at the node 450 in relation to the ranging operation. As mentioned hereinbefore, the response delay at the node 450 corresponds to a time period between receiving the range request packet and transmitting the range reply packet, and the response delay at the device 400 corresponds to a time period between receiving the range reply packet and transmitting a subsequent range request packet to the node 450 in a subsequent ranging operation (e.g., in the next iteration of ranging operation). It will be appreciated to a person skilled in the art that the transmitter 402 and the receiver 404 may be integrated together as a transceiver. By way of example only and without limitation, the device 400 may be, or part of, a mobile phone, portable computer, car location system, and so on.

[0050] The node 450 being the reference device or reader may comprise a receiver 454 configured to receive the range request packet from the device 400, a processor 456 configured to process the range request packet and generate a range reply packet, and a transmitter 452 configured to transmit the range reply packet to the device 400 as part of the ranging operation. Similarly, it will be appreciated to a person skilled in the art that the transmitter 452 and the receiver 454 may be integrated together as a transceiver. For example, the node 450 may be at a base station in the wireless communication network having a known location.

[0051] According to an embodiment of the present invention, there is provided a system for a wireless communication network such as the system as shown in FIG. 1. The system 100 comprises a plurality of nodes 120 each configured as described above with

reference to FIG. 4B, and a wireless communication device 110 configured as described above with reference to FIG. 4A for determining a distance to one or more of the plurality of nodes 120. For example, since the locations of the nodes 120 are known, the current location of the wireless communication device 110 may be derived based on the distances determine between the wireless communication device 110 and a plurality of nodes (preferable with at least three nodes).

[0052] According to an embodiment of the present invention, there is provided a computer program product, embodied in a computer-readable storage medium, comprising instructions executable by a computer processor to perform the method 300 of determining a distance between nodes of a wireless communication network as described above with reference to FIG 3.

[0053] Some portions of the description are explicitly or implicitly presented in terms of algorithms and functional or symbolic representations of operations on data within a computer memory. These algorithmic descriptions and functional or symbolic representations are the means used by those skilled in the data processing arts to convey most effectively the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self-consistent sequence of steps leading to a desired result. The steps are those requiring physical manipulations of physical quantities, such as electrical, magnetic or optical signals capable of being stored, transferred, combined, compared, and otherwise manipulated.

[0054] Unless specifically stated otherwise, and as apparent from the following, it will be appreciated that throughout the present specification, discussions utilizing terms such as “scanning”, “calculating”, “determining”, “replacing”, “generating”, “initializing”, “outputting”, or the like, refer to the action and processes of a computer system, or similar electronic device, that manipulates and transforms data represented as physical quantities within the computer system into other data similarly represented as physical quantities within the computer system or other information storage, transmission or display devices.

[0055] The present specification also discloses apparatus for performing the operations of the methods. Such apparatus may be specially constructed for the required purposes, or may comprise a general purpose computer or other device selectively

activated or reconfigured by a computer program stored in the computer. The algorithms and displays presented herein are not inherently related to any particular computer or other apparatus. Various general purpose machines may be used with programs in accordance with the teachings herein. Alternatively, the construction of more specialized
5 apparatus to perform the required method steps may be appropriate.

[0056] In addition, the present specification also implicitly discloses a computer program or software/functional module, in that it would be apparent to the person skilled in the art that the individual steps of the methods described herein may be put into effect by computer code. The computer program is not intended to be limited to any particular
10 programming language and implementation thereof. It will be appreciated that a variety of programming languages and coding thereof may be used to implement the teachings of the disclosure contained herein. Moreover, the computer program is not intended to be limited to any particular control flow. There are many other variants of the computer program, which can use different control flows without departing from the spirit or scope
15 of the invention.

[0057] Furthermore, one or more of the steps of the computer program may be performed in parallel rather than sequentially. Such a computer program may be stored on any computer readable medium. The computer readable medium may include storage devices such as magnetic or optical disks, memory chips, or other storage devices
20 suitable for interfacing with a general purpose computer. The computer program when loaded and executed on such a general-purpose computer effectively results in an apparatus that implements the steps of the methods described herein.

[0058] The software or functional modules described herein may also be implemented as hardware modules. More particularly, in the hardware sense, a module is
25 a functional hardware unit designed for use with other components or modules. For example, a module may be implemented using discrete electronic components, or it can form a portion of an entire electronic circuit such as an Application Specific Integrated Circuit (ASIC). Numerous other possibilities exist. Those skilled in the art will appreciate that the system can also be implemented as a combination of hardware and software
30 modules.

[0059] Hereinafter, the present invention will be described more fully with reference to the accompanying drawings, in which exemplary embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the exemplary embodiments set forth herein. Rather, these
5 embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. In the drawings, lengths and sizes of layers and regions may be exaggerated for clarity.

[0060] The terminology used herein is for the purpose of describing particular
10 embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises" and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps,
15 operations, elements, components, and/or groups thereof.

[0061] The invention illustratively described herein may suitably be practiced in the absence of any element or elements, limitation or limitations, not specifically disclosed herein. Thus, for example, the terms "comprising", "including", "containing", etc. shall be read expansively and without limitation. Additionally, the terms and expressions
20 employed herein have been used as terms of description and not of limitation, and there is no intention in the use of such terms and expressions of excluding any equivalents of the features shown and described or portions thereof, but it is recognized that various modifications are possible within the scope of the invention claimed. Thus, it should be understood that although the present invention has been specifically disclosed by
25 preferred embodiments and optional features, modification and variation of the inventions embodied therein herein disclosed may be resorted to by those skilled in the art, and that such modifications and variations are considered to be within the scope of this invention.

[0062] The method 300 of determining a distance between nodes of a wireless
30 communication network will now be described in further details according to an example embodiment of the present invention with reference to FIG. 5, and in particular, with

multiple iterations of the ranging operation for determining a distance between Devices A and B. In the example embodiment, the exemplary asynchronous ranging technique used is symmetric double sided two-way ranging (SDS-TWR). FIG. 5 depicts a schematic diagram 500 illustrating the ranging signal/packet flow between a request Device A 400 and a reference Device B 450 based on SDS-TWR with multiple iterations (SDS-TWR-MI (Multiple Iterations) or SDS-MWR (Multi-Way Ranging)) according to the example embodiment for determining the distance between Devices A and B. SDS-TWR-MI may be considered to be an extension to the SDS-TWR by performing it with multiple iterations between Devices A and B, and importantly, whereby each device measures and reports their response time or delay (t_{reply_A} , t_{reply_B}) to each other.

[0063] In an embodiment, the response delay of Device B 450 is transmitted as a part of the range reply packet (Acknowledgment Packet (ACK)). The response delay of the Device B may be defined as the timer count difference between the last bit reception of the range request packet and the first bit transmission of the range reply packet. Therefore, Device A 400 would be able to receive the response delay of Device B 450 and determine the distance between Devices A and B based on the response delay measured at the Device A 400 and its own measured response delay (i.e., at Device A 400) in relation to the ranging operation. By including the response delay in the range reply packet, this also minimizes radio overhead by avoiding sending additional packets for conveying the response delay to other device.

[0064] In the example embodiment shown in FIG. 5, the RRTs ($t_{round_A_i}$, $t_{round_B_i}$) measured/recorded by Devices A and B respectively, where i represents the i^{th} iteration ($0 < i < N$) of total N iterations, may be expressed as follow:

$$t_{round_A_i} = 2Nt_p + t_{reply_B_i} \quad (8)$$

$$t_{round_B_i} = 2Nt_p + t_{reply_A_i} \quad (9)$$

[0065] By combining Equations (8) and (9), the TOF (t_p) may be expressed as follow:

$$t_p = \frac{1}{4}[(t_{round_B_i} - t_{reply_A_i}) + (t_{round_A_i} - t_{reply_B_i})] \quad (10)$$

[0066] Therefore, for N iterations, the TOF (t_p) may be expressed as follow:

$$t_p = \frac{1}{4N} \sum_{i=1}^N [(t_{round_B_i} - t_{reply_A_i}) + (t_{round_A_i} - t_{reply_B_i})] \quad (11)$$

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[0067] In practical scenario, taking into account the finite sampling frequency (Δ_i) and the clock drift (e_A, e_B) for each device, the ranging error ($\hat{t}_p - t_p$) may be obtained as follow:

$$\hat{t}_p - t_p = \frac{1}{4N} \sum_{i=1}^N [\{(e_A - e_B) * (t_{reply_B_i} - t_{reply_A_i})\} + \{2 * (e_A + e_B) * t_p\} + \Delta_i] \quad (12)$$

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where the Δ_i can be expressed in terms of the time periods of the sampling clocks as follow:

$$\Delta_i = \{2 * \delta_{A_i} * T_A * (1 + e_A)\} + \{(\delta_{B_i} + \delta_{B(i+1)}) * T_B * (1 + e_B)\} \quad (13)$$

[0068] It was found that the propagation term ($2 * (e_A + e_B) * t_p$) of Equation (12) is very small compared to the response delay at the nodes. Thus, the propagation term may be ignored in Equation (12) to arrive at:

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$$\hat{t}_p - t_p = \frac{1}{4N} \sum_{i=1}^N [\{(e_A - e_B) * (t_{reply_B_i} - t_{reply_A_i})\} + \Delta_i] = \frac{1}{4N} \sum_{i=1}^N \varepsilon_i \quad (14)$$

where $\varepsilon_i = \{(e_A - e_B) * (t_{reply_B_i} - t_{reply_A_i})\} + \Delta_i$.

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[0069] Therefore, from the above Equations, it can be seen that the SDS-TWR-MI ranging technique described is able to significantly reduce ranging error by taking into account the variations in the nodes' response delays. In particular, by performing multiple iterations and taking into account the nodes' response delays at each iteration, the ranging error is advantageously scaled by a factor of $\frac{1}{4N}$, where N is the number of iterations perform.

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[0070] For illustration purposes only, FIGs. 6A, 6B and 6C show the ranging signal/packet flow between Devices A and B based on the SDS-TWR-MI ranging technique at the first ranging iteration, n^{th} ranging iteration, and the last ranging iteration, respectively.

5 **[0071]** In an exemplary implementation according to an embodiment of the present invention, a low cost chipset was configured to perform the SDS-TWR-MI ranging technique. FIG. 7 depicts a schematic representation of a ranging frame 700 in the exemplary implementation. The synchronization header 702 comprises a preamble sequence 704 followed by a Start of Frame Delimiter (SFD) 706. During the receive
10 mode, the synchronization header 702 is used by the receiver signal demodulator to identify and synchronize to the incoming data frame. On reception, the receiver adjusts its frequency and synchronizes to the received preamble sequence 704. Compliant packets are identified by a continuous search and correlation of the received preamble sequence 704 with a local copy. The physical header 708 is also known as the frame
15 length field since it defines the number of bytes in the Medium Access Control (MAC) Protocol Data Unit (MPDU) or PSDU 710. Timing extraction for time of flight (TOF) estimation is provided through the start of frame delimiter byte. On reception and synchronization of compliant packets, the start of frame delimiter byte triggers timing extraction via a free running timer.

20 **[0072]** A 16-bit medium access control (MAC) timer is configurable to capture the rising edge of the start of frame delimiter 706 on transmission and reception of ranging frames 700. This timer is configured to operate in the free running mode and the round-trip time information is extracted by subtracting the final timer value from the initial timer value. Switching between transmit and receive modes of the transceiver is
25 performed through software for each ranging iteration.

[0073] In this exemplary implementation, precise round trip time measurements are extracted by using a 32 MHz crystal oscillator along with its medium access control (MAC) capture timer. The ranging frame format as shown in FIG. 7 provides a modifiable data payload field 720 which may be configured/tailored to implement the
30 ranging technique according to embodiments of the present invention described herein. For example, in order that the request node 110 (e.g., tag and location sensor) to be able

to keep track of the on-going ranging iteration, the data payload 720 of the ranging frame 700 may contain a two-byte data field for indicating the current ranging iteration number. In addition, the response delay at each node 110, 120 is measured and transmitted as a two-byte data field in the data payload 720 of the ranging frame 700.

5 **[0074]** For evaluating the performance of the SDS-TWR-MI ranging technique according to the example embodiment described above, the SDS-TWR-MI ranging technique was implemented on a prototype hardware platform in an experiment. Testing of the prototype hardware was performed in order to corroborate the simulation results and was conducted in a Non Line of Sight (NLOS) environment. The results obtained
10 were documented in terms of the counter readings obtained from the prototype hardware. Performing such a test allows the SDS-TWR-MI ranging technique to demonstrate its capability in improving ranging accuracy with low cost off the shelf prototype hardware. For the purpose of this demonstration, testing was carried out over a range of 100m as showed in FIG. 8A and 20m as showed in FIG. 8B. FIG. 8A depicts a graph illustrating
15 readings obtained / distance measured (filled circle) over a range of 100 m at 2 m intervals compared with the actual distance (hollow circle). FIG. 8B depicts a graph illustrating the readings obtained / distance measured (line marked with crosses) against the actual distance over a range of 20 m. In FIG. 8B, there is also shown a line of reference marked with asterisks representing the ideal case where the distance measured
20 matches the actual distance for ease of comparison.

[0075] From FIGs. 8A and 8B, it can be observed that the maximum ranging error has been advantageously reduced to about 2m (i.e., ranging error of 2m or less). This significant reduction in ranging error is due to the capability of the SDS-TWR-MI ranging technique to overcome the inaccuracies introduced by the resolution of the
25 sampling clock, clock drift, and variations in the response time of devices. Accordingly, the above results demonstrate that the SDS-TWR-MI ranging technique is highly beneficial to implement low cost real-time system (e.g., locating system) based on wireless communication networks (e.g., wireless personal area networks).

[0076] To demonstrate the effectiveness of the analytical results justifying the
30 increase in ranging accuracy with the SDS-TWR-MI ranging technique, certain simulation results are provided below. Simulations were performed over a distance range

of 100m. The frequency of the sampling clock is considered to be in the range of 4MHz to 16MHz (based on the sampling frequency of TI CC2430 reported). To calibrate the ranging measurements, the minimum round trip time for each iteration set was calculated by assuming the nodes to be in close proximity ($< 1\text{m}$). This value has been subtracted from each ranging measurement in the iteration set before converting the same into a distance estimate.

[0077] FIG. 9 shows the simulation results where both the nodes operate with different sampling clock frequencies. In particular, in the simulation, the sampling frequency of Device A 400 was set at 8 MHz, whereas the sampling frequency of Device B 450 was set at 7 Mhz, 8 Mhz, and 9 Mhz to demonstrate the effects of different sampling frequencies at the two devices on the SDS-TWR-MI ranging technique. It can be observed from FIG. 9 that even for the case where there is a significant difference between the two sampling frequencies between the two devices, the SDS-TWR-MI ranging technique is able to achieve ranging accuracy similar to the case when both the sampling frequencies are equal. Hence, this demonstrates that the SDS-TWR-MI ranging technique can be used successfully even when the sampling frequencies of the nodes are different or unknown.

[0078] Although the ranging accuracy can be improved by performing multiple SDS-TWR iterations, it is evident from Equation (14) that this results in an increase in the total ranging time. An increase in total ranging time gives rise to several problems such as higher collision probability of radio signals, increased battery power consumption in mobile nodes and reduction in the number of ranging requests handled by an anchor/reference node. Therefore, preferably, the number of iterations to be performed is chosen in manner that strikes a balance between ranging accuracy and total ranging time. It was found through experiments that the accuracy does not appear to improve much after 100 iterations. Therefore, preferably, the number of iterations (N) is less than 100. In various embodiments, the number of iterations (N) is in the range of 2 to 100, 2 to 50, 2 to 20, 2 to 10, 2 to 5, 4 to 30, 4 to 15, and 6 to 10. In an embodiment, the number of iterations to be performed may also depend on whether the requesting device 110 is moving or the speed at which the requesting device 110 is moving. Preferably, the faster the requesting device 110 is moving, the less the number of iterations is performed. This

is because each iteration takes a period of time, and if the requesting device 100 is moving fast (thus its current location is rapidly changing), performing too many iterations may decrease the accuracy in the distance determined and thus its current location.

[0079] Accordingly, embodiments of the present invention provide a ranging
5 technique based on a different formulation of the errors in MWR measurements due to finite sampling clock and clock drift. The ranging technique provides a simple and effective remedy to improve ranging accuracy by performing multiple SDS-TWR iterations. By measuring and reporting the response delay at each node, the SDS-TWR-MI ranging technique is able to reduce ranging error due to variations in a nodes' response delay.
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[0080] Through mathematical analysis of Equation (14), it can be deduced that the ranging error is scaled by a factor of $\frac{1}{4N}$ by performing N iterations of SDS-TWR which results in a significant reduction in ranging error. It is also shown that the ranging technique is capable of maintaining ranging accuracy under conditions where there are
15 considerable differences between the sampling clock frequencies of different nodes. Furthermore, since the ranging technique is based on SDS-TWR, it can be implemented with ease on commercially available low cost transceivers and easily integrated into existing inventory systems. It can be also appreciated that the ranging technique disclosed herein is advantageously independent of time synchronization between the request node
20 110 (e.g., tags) and the anchor nodes 120 (e.g., sensors).

[0081] In an embodiment, it was found that implementing the SDS-TWR-MI ranging technique on a transceiver with spread spectrum capability yielded better results.

[0082] While embodiments of the invention have been particularly shown and described with reference to specific embodiments, it should be understood by those
25 skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

What is claimed is:

- 5 1. A method of determining a distance between nodes of a wireless communication network, the method comprising:
 - performing a ranging operation for determining a distance between a first node and a second node of the wireless communication network, the ranging operation comprises:
 - 10 transmitting, at the first node, a range request packet to the second node; and
 - receiving, at the first node, a range reply packet from the second node in response to the range request packet; and
 - determining the distance based on a response delay at the first node and a response delay at the second node in relation to said ranging operation,
 - 15 wherein the response delay at the second node corresponds to a time period between receiving the range request packet and transmitting the range reply packet, and the response delay at the first node corresponds to a time period between receiving the range reply packet and transmitting a subsequent range request packet to the second node in a subsequent ranging operation.
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 2. The method according to claim 1, wherein the distance is determined based on the response delay at the first node, the response delay at the second node, a round-trip time of the ranging operation measured at the first node, and a round-trip time of the ranging operation measured at the second node, wherein the round-trip time measured at the first node corresponds to a time period between transmitting the range request packet and receiving the range reply packet, and the round-trip time measured at the second node corresponds to a time period between transmitting the range reply packet and receiving the subsequent range request packet.

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3. The method according to claim 2, wherein the distance is derived based on a time of flight of the range request packet or the range reply packet between the first and second nodes, the time of flight being determined according to the equation:

$$t_p = \frac{1}{4}[(t_{round_B} - t_{reply_A}) + (t_{round_A} - t_{reply_B})]$$

- 5 where t_p is the time of flight, t_{round_A} is the round-trip time of the ranging operation measured at the first node, t_{round_B} is the round-trip time of the ranging operation measured at the second node, t_{reply_A} is the response delay at the first node, and t_{reply_B} is the response delay at the second node.

- 10 4. The method according to any one of claims 1 to 3, wherein the range reply packet received from the second node comprises data indicating the response delay at the second node.

- 15 5. The method according to any one of claims 1 to 4, wherein the method comprises performing N number of iterations of the ranging operation for determining the distance between the first node and the second node, wherein N is greater than 1.

- 20 6. The method according to claim 5, wherein each iteration commences after receiving, at the first node, the range reply packet of the immediately previous iteration, subject to the response delay at the first node.

7. The method according to claim 5 or 6, wherein the distance is determined based on the response delay at the first node and the response delay at the second node, in relation to each of said N number of iterations of the ranging operation.

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8. The method according to claim 7, wherein the distance is determined based on the response delay at the first node, the response delay at the second node, the round-trip time of the ranging operation measured at the first node, and the round-trip

time of the ranging operation measured at the second node, in relation to each of said N number of iterations of the ranging operation.

9. The method according to claim 8, wherein the distance is derived based on the time of flight of the range request packet or the range reply packet between the first and second nodes determined according to the equation:

$$t_P = \frac{1}{4N} \sum_{i=1}^N [(t_{round_B_i} - t_{reply_A_i}) + (t_{round_A_i} - t_{reply_B_i})]$$

- where t_P is the time of flight, $t_{round_A_i}$ is the round-trip time of the ranging operation measured at the first node for the i^{th} iteration, $t_{round_B_i}$ is the round-trip time of the ranging operation measured at the second node for the i^{th} iteration, $t_{reply_A_i}$ is the response delay at the first node for the i^{th} iteration, and $t_{reply_B_i}$ is the response delay at the second node for the i^{th} iteration.

10. The method according to claim 9, wherein range request packet and the range reply packet each comprises data indicating an iteration number associated therewith.

11. A wireless communication device comprising:
- a transmitter configured to transmit a range request packet to a node of a wireless communication network for performing a ranging operation to determine a distance between the device and the node;
 - a receiver configured to receive a range reply packet from the node in response to the range request packet; and
 - a distance computing module configured to determine the distance based on a response delay at the device and a response delay at the node in relation to the ranging operation,
- wherein the response delay at the node corresponds to a time period between receiving the range request packet and transmitting the range reply packet, and the response delay at the device corresponds to a time period between

receiving the range reply packet and transmitting a subsequent range request packet to the node in a subsequent ranging operation.

12. The device according to claim 11, wherein the distance computing module is configured to determine the distance based on the response delay at the device, the response delay at the node, a round-trip time of the ranging operation measured at the device, and a round-trip time of the ranging operation measured at the node, wherein the round-trip time measured at the device corresponds to a time period between transmitting the range request packet and receiving the range reply packet, and the round-trip time measured at the node corresponds to a time period between transmitting the range reply packet and receiving the subsequent range request packet.

13. The device according to claim 12, wherein the distance computing module is configured to determine the distance based on a time of flight of the range request packet or the range reply packet between the device and the node, the time of flight being determined according to the equation:

$$t_p = \frac{1}{4}[(t_{round_B} - t_{reply_A}) + (t_{round_A} - t_{reply_B})]$$

where t_p is the time of flight, t_{round_A} is the round-trip time of the ranging operation measured at the device, t_{round_B} is the round-trip time of the ranging operation measured at the node, t_{reply_A} is the response delay at the device, and t_{reply_B} is the response delay at the node.

14. The device according to any one of claims 11 to 13, wherein the range reply packet received from the node comprises data indicating the response delay at the node.

15. The device according to any one of claims 11 to 14, wherein the device is configured to perform N number of iterations of the ranging operation for

determining the distance between the device and the node, wherein N is greater than 1.

16. The device according to claim 15, wherein each iteration commences after the receiver receives the range reply packet of the immediately previous iteration, subject to the response delay at the device.
17. The device according to claim 15 or 16, wherein the distance computing module is configured to determine the distance based on the response delay at the device and the response delay at the node, in relation to each of said N number of iterations of the ranging operation.
18. The device according to claim 17, wherein the distance computing module is configured to determine the distance based on the response delay at the device, the response delay at the node, the round-trip time of the ranging operation measured at the device, and the round-trip time of the ranging operation measured at the node, in relation to each of said N number of iterations of the ranging operation.
19. The device according to claim 18, wherein the distance computing module is configured to derive the distance based on the time of flight of the range request packet or the range reply packet between the device and the node, the time of flight being determined according to the equation:

$$t_p = \frac{1}{4N} \sum_{i=1}^N [(t_{round_B_i} - t_{reply_A_i}) + (t_{round_A_i} - t_{reply_B_i})]$$

where t_p is the time of flight, $t_{round_A_i}$ is the round-trip time of the ranging operation measured at the device for the i^{th} iteration, $t_{round_B_i}$ is the round-trip time of the ranging operation measured at the node for the i^{th} iteration, $t_{reply_A_i}$ is the response delay at the device for the i^{th} iteration, and $t_{reply_B_i}$ is the response delay at the node for the i^{th} iteration.

20. The device according to claim 19, wherein the range request packet and the range reply packet each comprises data indicating an iteration number associated therewith.

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21. A system for a wireless communication network, the system comprising:
a plurality of nodes in the wireless communication network, and
a wireless communication device according to any one of claims 11 to 20
configured to determine a distance to one or more of the plurality of nodes.

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22. A computer program product, embodied in a computer-readable storage medium, comprising instructions executable by a computer processor to perform a method of determining a distance between nodes of a wireless communication network according to any one of claims 1 to 10.

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