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(54) Title: APPARATUS, METHOD AND COMPUTER PROGRAM FOR LOCALIZING A TAG

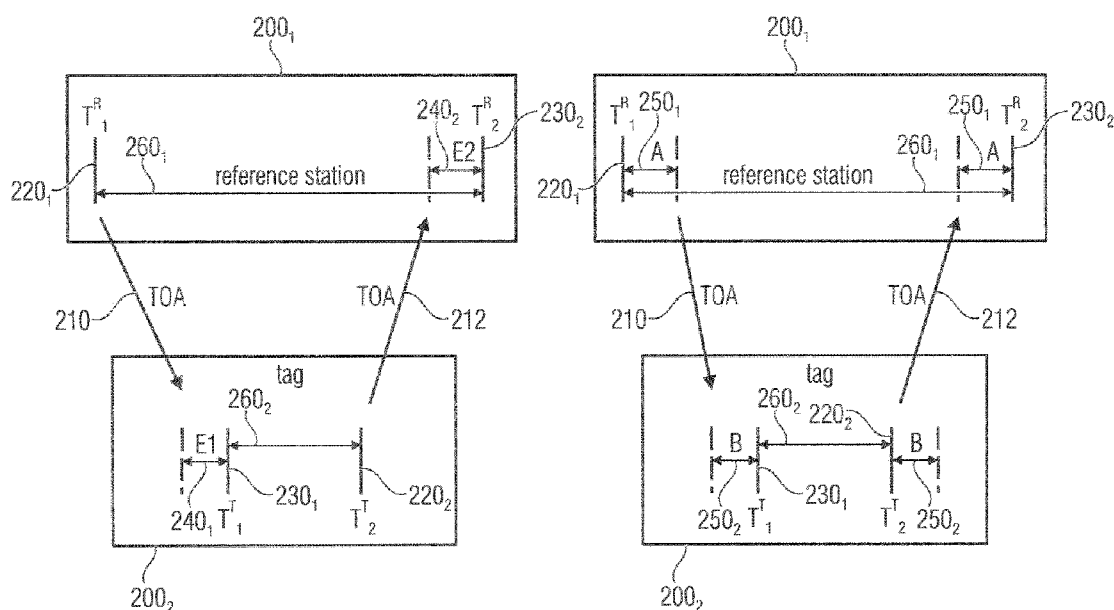


Fig. 2

(57) **Abstract:** Apparatus, method and computer program for localizing a tag Apparatus (100) for localizing a tag (200₂). The apparatus is configured for obtaining a time-of-arrival of one or more signals (210, 212, 214), based on transmission-time-stamps (220, - 220₃) and reception-time-stamps (230₁ - 230₃) of two or more signals. Furthermore the apparatus is configured for obtaining a first time-difference-of-arrival on the basis of a difference between reception time stamps obtained at a first station and describing reception times of two signals, one transmitted by the reference station and one transmitted by the tag, at the first station. The apparatus is configured for obtaining a second time-difference-of-arrival on the basis of a difference between reception time stamps obtained at a second station and describing reception times of two signals, one transmitted by the

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Apparatus, method and computer program for localizing a tagDescription

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Technical field

Embodiments according to the invention relate to an apparatus, a method and a computer program for localizing a tag.

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Background of the invention

Localization systems become indispensable from everyday life. Satellite navigation [8, 18] displaced the paper maps and facilitate autonomous operating cars and airplanes. With increasing requirements in logistics and manufacturing, precise information about the position become mandatory. Depending on the operating conditions for the localization, different measurement principles [12, 16, 21] and techniques [4, 20, 7] exist. The most common measurement techniques are time of arrival (TOA) [4] and time difference of arrival (TDOA) [20]. The difference between both techniques is that the TOA is obtaining the distance between two stations by the signal traveling time and TDOA by time difference between the stations. Two way ranging (TWR) is using the TOA technique to obtain the distance between two stations [5]. In contrast to one way ranging like satellite based applications, does TWR responding the transmitted signal. Therefore it is not necessary that the transmitting stations are synchronous. In applications where it is necessary to obtain not just the distance but also the position of the target (Tag) with respect to the other stations (Anchors), TWR is less suitable, due to the low update time. The triangulation in a two dimensional space requires at least three distance measurements. TWR requires the distances between the tag and every anchor before the triangulation. With an increasing number of tags the update is time decreasing. In contrast to TOA, TDOA is more suitable for applications with many tags. In TDOA applications, the anchors are not responding. The multilateration is obtained by the difference of the timestamps between the anchors. Geometrically speaking are TOA equations circles and TDOA hyperboloids in a two dimensional space. Similar to satellite navigation systems, which are based on TOA, is it necessary that the clocks of the TDOA anchors are synchronized. The synchronization can be performed by wire [1] or with an additional station [12]. Apart from the measurement technique the measurement equipment is equally important.

Indoor positioning is in general a challenge for RF based localization systems. Reflections could cause interference with the main signal and lead to fading. In contrast to narrow band signals, ultra-wideband (UWB) signals are more robust to fading [9, 14]. The
5 Decawave transceiver [13] is based on the ultra-wideband (UWB) technology and is compliant with the IEEE802.15.4-2011 standard [10]. It supports six frequency bands with center frequencies from 3.5 GHz to 6.5 GHz and data rates up to 6.8 Mb/s. The bandwidth varies with the selected center frequencies from 500 up to 1000 MHz. In [11, 6, 19], different methods wireless TDOA clock synchronization are presented. They all have in com-
10 mon that they use a fixed and known time interval for the synchronization signal.

Therefore, it is desired to arrive at a concept which reaches a better compromise between optimizing a synchronization between clocks of stations used for the localization of the tag and a maximization of efficiency and accuracy of a localization of the tag.
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This is achieved by the subject-matter of the independent claims of the present application.

Further embodiments according to the invention are defined by the subject-matter of the
20 dependent claims of the present application.

Summary of the invention

An embodiment according to this invention is related to an apparatus for localizing a tag.
25 The apparatus is configured for obtaining a time-of-arrival of one or more signals, based on transmission-time-stamps and reception-time-stamps of two or more signals sent between a reference station and a tag. The time-of-arrival can be indicated as TOA and defines, for example, a time-of-flight of a signal transmitted by the reference station and received by the tag. Thus, for example, two signals are sent between the reference station
30 and the tag, whereby both signals comprise the same time-of-arrival, since a distance between the reference station and the tag is, for example, constant during a determination of the time-of-arrival. Therefore, the time-of-arrival of only one of the two signals is sufficient to obtain by the apparatus. For a determination of the time-of-arrival, a clock-drift-correction and/or an antenna-delay-correction and/or a signal-power-correction can be
35 used. According to an embodiment, the clock-drift-correction and/or the signal-power-correction can be determined parallel or contemporaneous to the determination of the

time-of-arrival if the time-of-arrival is based on the transmission-time-stamps and reception-time-stamps of at least three signals. In other words, the clock-drift-correction and/or the signal-power-correction can be based on the transmission-time-stamps and reception-time-stamps of the two or more signals.

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The apparatus is configured for obtaining a first time-difference-of-arrival on a basis of a difference between reception time stamps obtained at a first station and describing reception times of two signals, one transmitted by the reference station and one transmitted by the tag, at the first station. Furthermore, the apparatus is configured for obtaining a second time-difference-of-arrival on the basis of a difference between reception time stamps obtained at a second station and describing reception time stamps of two signals, one transmitted by the reference station and one transmitted by the tag, at the second station. The time-difference-of-arrival can be indicated as TDOA. The two signals on which the reception time stamps obtained at the second station are based may be equal to the two signals on which the reception time stamps obtained at the first station are based, or may be different from the two signals on which the reception time stamps obtained at the first station are based. The two signals received by the first station and/or the two signals received by the second station are, for example, transmitted in a time-synchronized manner, for example, such that a difference of transmission times is predetermined or can be computed. Thus, the time-difference-of-arrival defines, for example, a difference in a time-of-flight of the two signals. In other words, the reference station can comprise a different distance to the first station or the second station than the tag to the first station or the second station, whereby a difference in these two distances can result in the respective time-difference-of-arrival.

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For a determination of the first time-difference-of-arrival and/or the second time-difference-of-arrival, a clock-drift-correction and/or a signal-power-correction and/or an antenna-delay-correction can be used.

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The apparatus is configured for calculating a position of the tag based on the time-of-arrival and the at least two time-difference-of-arrivals, represented, for example, by the first time-difference-of-arrival and the second time-difference-of-arrival. According to an embodiment, the apparatus is configured to receive the time-of-arrival from a station calculating the time-of-arrival, like the reference station or the tag, to receive the first time-difference-of-arrival from a station calculating the first time-difference-of-arrival, like the first station, and/or to receive the second time-difference-of-arrival from a station calculat-

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ing the second time-difference-of-arrival, like the second station. Alternatively, the apparatus can be configured to receive the transmission-time-stamps and reception-time-stamps from the corresponding stations to calculate the time-of-arrival, the first time-difference-of-arrival and/or the second time-difference-of-arrival by itself. Optionally, it is possible that the apparatus is part of the tag and/or the reference station, whereby the apparatus is configured to calculate the time-of-arrival by itself and to receive the first time-difference-of-arrival by the first station and the second time-difference-of-arrival by the second station. It is also possible that the apparatus is part of the first station and/or the second station, whereby the apparatus is configured to determine or calculate a first time-difference-of-arrival and/or the second time-difference-of-arrival by itself and to receive the time-of-arrival, for example, from the reference station or the tag.

Embodiments of the apparatus are based on the idea that a fusion of time-of-arrival and time-difference-of-arrival measurements is very efficient and optimizes an accuracy for localizing the tag. It is, for example, advantageous, that with the fusion of TOA and TDOA a number of equations to be solved can be maximized and simultaneously, errors based on the different clocks of the different stations, for example, used for localizing the tag can be minimized. According to an embodiment, the apparatus is configured to solve an equation system comprising a first equation based on the time-of-arrival, a second equation based on the first time-difference-of-arrival and a third equation based on a second time-difference-of-arrival to localize the tag. Thus, it is already possible to localize the tag with only a reference station, a tag and two stations for a two-dimensional space. Based on the transmission-time-stamps and the reception-time-stamps, the time-of-arrival, the first time-difference-of-arrival and/or the second time-difference-of-arrival can provide a wireless clock calibration to achieve a high accuracy.

According to an embodiment, the first time-difference-of-arrival is based on a difference between a first reception time stamp information of the first station and a second reception time stamp information of the first station. The first reception time stamp information describes, for example, with respect to a clock of the first station when the first station receives a first signal transmitted by the reference station, and the second reception time stamp information of the first station describes, for example, with respect to the clock of the first station when the first station receives a second signal transmitted by the tag. The second time-difference-of-arrival is, for example, based on a difference between a first reception time stamp information of the second station and a second reception time stamp information of the second station. According to an embodiment, the first reception time

stamp information of the second station describes, for example, with respect to a clock of the second station, when the second station receives the first signal transmitted by the reference station, and the second reception time stamp information of the second station describes, for example, with respect to the clock of the second station when the second station receives the second signal transmitted by the tag. Thus, the first time-difference-of-arrival is, for example, associated with a difference between reception time stamps of a first signal transmitted by the reference station and received by a first station and a second signal transmitted by the tag and received by the first station. The second time difference of arrival is, for example, associated with a difference between reception time stamps of a first signal transmitted by the reference station and received by the second station and a second signal transmitted by the tag and received by the second station. In other words, the first time difference of arrival represents, for example, a time-difference between receiving-time-stamps of the first signal and the second signal by a first station and the second time difference of arrival represents, for example, a time-difference between receiving-time-stamps of the first signal and the second signal by the second station.

According to an embodiment, the first time-difference-of-arrival is calculated, for example, by the apparatus or by another device, using a signal-power-correction to correct the first reception time stamp information of the first station and the second reception time stamp information of the first station. The second time-difference-of-arrival is, for example, calculated using a signal-power-correction to correct the first correction time stamp information of the second station and the second reception time stamp information of the second station. According to an embodiment, the signal-power-correction used to calculate the first time-difference-of-arrival and/or the second time-difference-of-arrival is configured to at least partially compensate an influence of a signal power on time stamps of the first station and/or the second station. The signal-power-correction is, for example, obtained for the stations, for example, the reference station, the tag, the first station and/or the second station before the localization of the tag, for example, for different signal power levels. According to an embodiment, the signal-power-correction is independent of the station transmitting the signal, whereby the signal-power-correction can be applied to the first reception time stamp information corresponding to the signal transmitted by the reference station as well as to the second reception time stamp information associated with the second signal transmitted by the tag without the need to have knowledge about the station transmitting the signal received by the first station and/or the second station.

According to an embodiment, the first time-difference-of-arrival and/or the second time-difference-of-arrival is calculated, for example, by the apparatus or by another device, using an offset, describing a time delay between a transmission of the two signals, one transmitted by the reference station and one transmitted by the tag. The offset represents
5 a time-synchronization, for example, such that a difference of transmission times between the first signal and the second signal is predetermined or can be computed. If both signals are, for example, sent at the same time, the offset is zero. By using the offset for the calculation of the first time-difference-of-arrival and/or the second time-difference-of-arrival, it is possible to base the calculation only on the reception time stamp information of the first
10 signal and the second signal at the first station and/or the second station, independent of the transmission time stamp information of the first signal and the second signal.

According to an embodiment, the offset is determined based on the time-of-arrival, based on a first reception-time-stamp of the tag and based on a first transmission-time-stamp of
15 the tag. The first reception-time-stamp of the tag describes, for example, when a first signal, transmitted by the reference station, is received by the tag, and the first transmission-time-stamp of the tag describes, for example, when a second signal is transmitted by the tag. This embodiment is based on the idea that the reference station transmits the first signal and the tag transmits the second signal after receiving the first signal. Thus, the
20 time-of-arrival describes, for example, the time needed by the first signal from the reference station to the tag, for example, the time difference between the first reception-time-stamp of the tag and a first transmission-time-stamp of the reference station describing, when the first signal is transmitted by the reference station. Thus, the offset represents, for example, a summation of the time-of-arrival and a difference between the first trans-
25 mission-time-stamp of the tag and the first reception-time-stamp of the tag describing a computational time of the tag before the second signal is transmitted by the tag. According to an embodiment, a clock-drift-correction and/or an antenna-delay-correction and/or a signal-power-correction is used for the determination of the offset. With these corrections, it is possible to determine the offset very accurately and thus achieve a very precise syn-
30 chronization of a transmission of the first signal and a transmission of the second signal.

According to an embodiment, the clock-drift-correction used for the determination of the offset is based on transmission-time-stamps and reception-time-stamps related to a third signal transmitted by the reference station and received by the tag, e.g. transmitted from
35 the reference station to the tag. Furthermore, the clock-drift-correction can be based on transmission-time-stamps and reception-time-stamps related to a first signal transmitted

by the reference station and received by the tag. According to an embodiment, the first signal and the third signal used for the clock-drift-correction have same signal power levels. Thus, the clock-drift-correction is, for example, based on a clock-drift-error describing a time-difference between a difference of transmission time stamps of the first signal and the third signal and a difference of reception-time-stamps of the first signal and the third signal. According to an embodiment, the clock-drift-correction can be determined with the same two signals as used for the determination of the first time-difference-of-arrival and/or the second time-difference-of-arrival plus the third signal, which results in a very efficient clock-drift-correction, whereby a very precise synchronization can be achieved.

According to an embodiment the offset K is determined according to

$$K = TOA + \Delta T_{1,2}^T + \left(\frac{C_{1,3}^{RT}}{\Delta T_{1,3}^T} \cdot (\Delta T_{1,2}^T + E_1) \right) + E_1 + 2B.$$

The value TOA represents the time-of-arrival, e.g. clock-drift corrected, signal-power-level-corrected and/or antenna-delay corrected, of the one or more signals transmitted between the reference station and the tag. The value $\Delta T_{1,2}^T$ represents a difference between a first transmission time stamp of the tag describing when a second signal is transmitted by the tag and a first reception time stamp of the tag describing when a first signal transmitted by the reference station is received by the tag. The deviation $C_{1,3}^{RT}$ represents a difference between a difference of transmission time stamps associated with a transmission of two signals having same signal power levels, transmitted by the reference station, and a difference $\Delta T_{1,3}^T$ of reception time stamps associated with a reception of the two signals having same signal power levels by the tag. The difference of transmission time stamps represents, for example, a difference between a second transmission time stamp of the reference station describing when a third signal is transmitted by the reference station and a first transmission time stamp of the reference station describing when a first signal is transmitted by the reference station. The difference $\Delta T_{1,3}^T$ of reception time stamps represents, for example, a difference between a third reception time stamp of the tag describing when the third signal transmitted by the reference station is received by the tag and a first reception time stamp of the tag describing when the first signal transmitted by the reference station is received by the tag. The first signal and the third signal have, for example, same signal power levels. The value E_1 represents a signal power-correction, e.g. a predetermined value associated with an actual signal power level, associated with a correction of reception time stamps of the tag for received signals with a first signal power level and the value B represents an antenna-delay correction related to the tag, e.g. a predetermined value. The signal power-correction corrects, for example, the first reception

time stamp of the tag dependent on the signal power level of the first signal. Since signals transmitted by the same station at the same transmission time stamp can result in different reception time stamps at the same station receiving the two signals, the signal power-correction approximates, for example, the two different reception-time-stamps to one
5 common reception-time-stamp, describing when a reference signal with a predetermined reference signal power level is received. According to an embodiment, the antenna-delay-correction can correct time delays associated with a station transmitting and/or receiving signals, wherein the antenna time delay represents, for example, a time difference between a reception of a signal by an antenna of the station and a reception time stamp determined by a clock of the station associated with the received signal. Alternatively or additionally, the antenna-delay-correction can correct transmission time stamps of the station. According to an embodiment, the antenna-delay-correction corrects a time delay between a transmission time stamp of a signal transmitted by the station determined by the clock of the station and an actual time, when the signal is transmitted by the antenna of
10 the station.

According to an embodiment the first time-difference-of-arrival and the second time-difference-of-arrival are determined according to $TDOA_i = \Delta T_{1,2}^{Si} - E_4 + E_3 + K$. The index i , e.g. $i \in [1;N]$, wherein $N \geq 2$, represents a number of a station S_i , at which the reception
20 time stamps describing the reception times of the two signals, one transmitted by the reference station and one transmitted by the tag, and used to determine the difference $\Delta T_{1,2}^{Si}$ between the reception time stamps are obtained. The value E_3 represents a signal power-correction, e.g. a predetermined value associated with an actual signal power level, associated with a correction of reception time stamps of the Station S_i for received signals with
25 a first signal power level. The value E_4 represents a signal power-correction, e.g. a predetermined value associated with an actual signal power level, associated with a correction of reception time stamps of the Station S_i for received signals with a second signal power level. The value K represents an offset describing a time delay between a transmission of the two signals, one transmitted by the reference station and one transmitted by the tag.
30 The signal power-correction E_3 corrects, for example, the first reception time stamp of the station S_i dependent on the signal power level of the first signal and the signal power-correction E_4 corrects, for example, the second reception time stamp of the station S_i dependent on the signal power level of the second signal. Since the signal power correction is, for example, independent of the station transmitting the signals, E_3 and E_4 can be applied for a plurality of reception time stamps of the same receiving station for received
35 signals with same signal power levels, wherein E_3 corresponds to a first signal power level

and E_4 corresponds to a second signal power level. According to an embodiment the signal power-correction approximates, for example, reception-time-stamps to one common reception-time-stamp, describing when a reference signal with a predetermined reference signal power level would be received.

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According to an embodiment, the first time-difference-of-arrival is calculated, for example, by the apparatus or by another device, using a clock-drift-correction to correct a difference between reception time stamps obtained at the first station and/or to correct signal-power-corrections correcting the reception time stamps obtained at the first station. Furthermore
10 or alternatively, the second time-difference-of-arrival is, for example, calculated, for example, by the apparatus or by another device, using a clock-drift-correction to correct a difference between reception time stamps obtained at the second station and/or to correct signal-power-corrections correcting the reception time stamps obtained at the second station. The clock-drift-correction used to calculate the second time-difference-of-arrival can
15 be the same or differ from the clock-drift-correction used to calculate the first time-difference-of-arrival. The reception time stamps obtained at the first station and the signal-power-corrections corresponding to the first station are associated, for example, with a clock of the first station. The reception time stamps obtained at the second station and/or the signal-power-corrections associated with the second station are, for example, associated
20 with a clock of the second station. Since the clock of the first station and the clock of the second station can differ from each other, a clock-drift-correction is used to, for example, determine the first time-difference-of-arrival and/or the second time-difference-of-arrival corresponding to a common clock, like a clock of the reference station, whereby the apparatus can be configured to localize the tag based on the first time-difference-of-arrival, the second time-difference-of-arrival corresponding to a common clock instead of
25 two different clocks, whereby the first time-difference-of-arrival is comparable to the second time-difference-of-arrival.

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According to an embodiment, the clock-drift-correction used to calculate the first time-difference-of-arrival is based on a transmission time stamp and a reception time stamp related to a third signal transmitted by the reference station and received by the first station, for example, transmitted from the reference station to the first station. Optionally or additionally, transmission time stamps and reception time stamps related to a first signal transmitted by the reference station and received by the first station are used to determine
35 the clock-drift-correction used to calculate the first time-difference-of-arrival. According to an embodiment, the clock-drift-correction used to calculate the second time-difference-of-

arrival is based on a transmission time stamp and a reception time stamp related to the third signal transmitted by the reference station and received by the second station, for example, transmitted from the reference station to the second station. Optionally or additionally, transmission time stamps and reception time stamps related to the first signal transmitted by the reference station and received by the second station can be used to determine the clock-drift-correction used to calculate the second time-difference-of-arrival. According to an embodiment, the first signal is transmitted by the reference station and received by the first station and/or the second station, and the third signal is transmitted by the reference station and received by the first station and/or the second station, where- in the first signal and the third signal have same signal power levels. Thus, the clock-drift-correction is, for example, based on a clock-drift-error describing a time-difference between a difference of transmission time stamps of the first signal and the third signal and a difference of reception-time-stamps of the first signal and the third signal. According to an embodiment, the clock-drift-correction can be determined with the same two signals as used for the determination of the time-of-arrival, which results in a very efficient clock-drift-correction, whereby a very precise synchronization can be achieved.

According to an embodiment the first time-difference-of-arrival and the second time-difference-of-arrival are calculated according to

$$TDOA_i = \Delta T_{1,2}^{Si} + \left(\frac{C_{1,3}^{Si}}{\Delta T_{1,3}^{Si}} \cdot (\Delta T_{1,2}^{Si} + E_3 - E_4) \right) - E_4 + E_3 + K,$$

The index i , e.g. $i \in [1;N]$, wherein $N \geq 2$, represents a number of a station S_i , at which the reception time stamps describing the reception times of the two signals, one transmitted by the reference station and one transmitted by the tag, and used to determine the difference $\Delta T_{1,2}^{Si}$ between the reception time stamps are obtained. The deviation $C_{1,3}^{Si}$ represents a difference between a difference of transmission time stamps associated with a transmission of two signals having same signal power levels, transmitted by the reference station, and a difference $\Delta T_{1,3}^{Si}$ of reception time stamps associated with a reception of the two signals having same signal power levels by the station S_i . The difference of transmission time stamps represents, for example, a difference between a second transmission time stamp of the reference station describing when a third signal is transmitted by the reference station and a first transmission time stamp of the reference station describing when a first signal is transmitted by the reference station. The difference $\Delta T_{1,3}^{Si}$ of reception time stamps represents, for example, a difference between a third reception time stamp of the station S_i describing when the third signal transmitted by the reference station is received by the station S_i and a first reception time stamp of the station S_i describing when the first

signal transmitted by the reference station is received by the station Si. The first signal and the third signal have same signal power levels. The value E_3 represents a signal power-correction, e.g. a predetermined value associated with an actual signal power level, associated with a correction of reception time stamps of the Station Si for received signals with a first signal power level. The value E_4 represents a signal power-correction, e.g. a predetermined value associated with an actual signal power level, associated with a correction of reception time stamps of the Station Si for received signals with a second signal power level. The value K represents an offset describing a time delay between a transmission of the two signals, one transmitted by the reference station and one transmitted by the tag. The signal power correction can have functionalities and/or features as described above regarding signal power corrections.

The first time-difference-of-arrival and the second time-difference-of-arrival are calculated according to

$$TDOA_i = \left(\frac{C_{1,3}^{Si}}{\Delta T_{1,3}^{Si}} \cdot (\Delta T_{1,2}^{Si} + E_3 - E_4) \right) + 0.5 \cdot \left(\Delta T_{1,2}^T + \frac{C_{1,3}^{RT}}{\Delta T_{1,3}^T} \cdot (\Delta T_{1,2}^T + E_1) \right) + \Delta T_{1,2}^{Si} + 0.5 \cdot \Delta T_{1,2}^R - A + B + 0.5 \cdot (E_1 - E_2) - E_4 + E_3,$$

wherein the index i, e.g. $i \in [1; N]$, wherein $N \geq 2$, represents a number of a station Si, at which the reception time stamps describing the reception times of the two signals, one transmitted by the reference station and one transmitted by the tag, and used to determine the difference $\Delta T_{1,2}^{Si}$ between the reception time stamps are obtained. The deviation $C_{1,3}^{Si}$ represents a difference between a difference of transmission time stamps associated with a transmission of two signals having same signal power levels, transmitted by the reference station, and a difference $\Delta T_{1,3}^{Si}$ of reception time stamps associated with a reception of the two signals having same signal power levels by the station Si. The difference of transmission time stamps represents, for example, a difference between a second transmission time stamp of the reference station describing when a third signal is transmitted by the reference station and a first transmission time stamp of the reference station describing when a first signal is transmitted by the reference station. The difference $\Delta T_{1,3}^{Si}$ of reception time stamps represents, for example, a difference between a third reception time stamp of the station Si describing when the third signal transmitted by the reference station is received by the station Si and a first reception time stamp of the station Si describing when the first signal transmitted by the reference station is received by the station Si. The first signal and the third signal have same signal power levels. The value E_1 represents a signal power-correction, e.g. a predetermined value associated with an actual

signal power level, associated with a correction of reception time stamps of the tag for received signals with a first signal power level. The value E_2 represents a signal power-correction, e.g. a predetermined value associated with an actual signal power level, associated with a correction of reception time stamps of the reference station for received signals with a second signal power level. The value E_3 represents a signal power-correction, e.g. a predetermined value associated with an actual signal power level, associated with a correction of reception time stamps of the Station S_i for received signals with a first signal power level. The value E_4 represents a signal power-correction, e.g. a predetermined value associated with an actual signal power level, associated with a correction of reception time stamps of the Station S_i for received signals with a second signal power level. The value $\Delta T_{1,2}^T$ represents a difference between a first transmission time stamp of the tag describing when a second signal is transmitted by the tag and a first reception time stamp of the tag describing when a first signal transmitted by the reference station is received by the tag. The deviation $C_{1,3}^{RT}$ represents a difference between a difference of transmission time stamps associated with a transmission of two signals having same signal power levels, transmitted by the reference station, and a difference $\Delta T_{1,3}^T$ of reception time stamps associated with a reception of the two signals having same signal power levels by the tag. The difference of transmission time stamps represents, for example, a difference between a second transmission time stamp of the reference station describing when a third signal is transmitted by the reference station and a first transmission time stamp of the reference station describing when a first signal is transmitted by the reference station. The difference $\Delta T_{1,3}^T$ of reception time stamps represents, for example, a difference between a third reception time stamp of the tag describing when the third signal transmitted by the reference station is received by the tag and a first reception time stamp of the tag describing when the first signal transmitted by the reference station is received by the tag; the first signal and the third signal have same signal power levels. The value $\Delta T_{1,2}^R$ represents a difference between a first reception time stamp of the reference station describing when the second signal transmitted by the tag is received by the reference station and a first transmission time stamp of the reference station describing when the first signal is transmitted by the reference station. The value A represents an antenna-delay correction related to the reference station, e.g. a predetermined value, and the value B represents an antenna-delay correction related to the tag, e.g. a predetermined value.

According to an embodiment, the time-of-arrival is calculated based on a transmission time stamp and a reception-time-stamp of a first signal transmitted by the reference sta-

tion and received by the tag and a transmission-time-stamp and a reception-time-stamp of a second signal transmitted by the tag and received by the reference station. Thus, the first signal is transmitted from the reference station to the tag and the second signal is transmitted back from the tag to the reference station, which represents, for example, a two way ranging (TWR). Thus, with the knowledge about the transmission time stamps and reception time stamps of the first signal and the second signal, the time-of-arrival can be calculated very accurately. To improve the accuracy in the calculation of the time-of-arrival, a clock-drift-correction and/or a signal-power-correction and/or an antenna-delay-correction can be used to correct the transmission time stamps and/or the reception time stamps of the first signal and the second signal.

According to an embodiment the time-of-arrival TOA is calculated according to

$$TOA = 0.5 \cdot \left((T_2^R - T_1^R) - (T_2^T - T_1^T) - E_1 - E_2 \right) - A - B.$$

The value T_1^R represents a first transmission time stamp of the reference station describing when a first signal is transmitted from the reference station. The value T_1^T represents a first reception time stamp of the tag describing when the first signal transmitted from the reference station is received by the tag. The value T_2^T represents a first transmission time stamp of the tag describing when a second signal is transmitted from the tag. The value T_2^R represents a first reception time stamp of the reference station describing when the second signal transmitted from the tag is received by the reference station. The value E_1 represents a signal power-correction, e.g. a predetermined value associated with an actual signal power level, associated with a correction of the first reception time stamp T_1^T of the tag, based on a first signal power level of the first signal. The value E_2 represents a signal power-correction, e.g. a predetermined value associated with an actual signal power level, associated with a correction of the first reception time stamp T_2^R of the reference station, based on a signal power level of the second signal. The value A represents an antenna-delay correction related to the reference station, e.g. is a predetermined value, and the value B represents an antenna-delay correction related to the tag, e.g. is a predetermined value. The signal power correction can have functionalities and/or features as described above regarding signal power corrections. The antenna delay correction can have functionalities and/or features as described above regarding an antenna delay correction.

According to an embodiment, the clock-drift-correction used to calculate the time-of-arrival is based on a transmission time stamp and a reception time stamp related to a third signal

transmitted by the reference station and received by the tag. Optionally or additionally, transmission time stamps and reception time stamps related to a first signal transmitted by the reference station and received by the tag can be used to determine the clock-drift-correction. The first signal and the third signal have, for example, the same signal power levels. Thus, the clock-drift-correction is, for example, based on a clock-drift-error describing a time-difference between a difference of transmission time stamps of the first signal and the third signal and a difference of reception-time-stamps of the first signal and the third signal. According to an embodiment, the clock-drift-correction can be determined with the same two signals as used for the determination of the first time-difference-of-arrival and/or the second time-difference-of-arrival, which results in a very efficient clock-drift-correction, whereby a very precise synchronization can be achieved.

According to an embodiment, the time-of-arrival is calculated using a clock-drift-correction to correct a difference between a first transmission time stamp of the tag and a first reception time stamp of the tag. The first transmission time stamp of the tag describes, for example, when a second signal is transmitted by the tag, and the first reception time stamp of the tag describes, for example, when a first signal transmitted by the reference station is received by the tag. According to an embodiment, a signal-power-correction correcting the first reception time stamp obtained at the tag is performed to calculate the time-of-arrival. Furthermore, a signal-power-correction correcting a first reception time stamp of the reference station, describing when the second signal is received by the reference station, is performed to calculate the time-of-arrival. Thus, the influence of a signal power level on the reception-time-stamps and an influence of a clock-drift caused by a difference between the clock of the reference station and a clock of the tag, can at least partially be compensated by the clock-drift-correction and/or the signal-power-correction. Thus, it is possible to determine the time-of-arrival very accurately.

According to an embodiment the time-of-arrival TOA is calculated according to

$$TOA = 0.5 \cdot \left(\Delta T_{1,2}^R - \Delta T_{1,2}^T - \frac{C_{1,3}^{RT}}{\Delta T_{1,3}^T} \cdot (\Delta T_{1,2}^T + E_1) - E_2 - E_1 \right) + Z.$$

The deviation $C_{1,3}^{RT}$ represents a difference between a difference of transmission time stamps associated with a transmission of two signals having same signal power levels, transmitted by the reference station, and a difference $\Delta T_{1,3}^T$ of reception time stamps associated with a reception of the two signals having same signal power levels by the tag. The difference of transmission time stamps represents, for example, a difference between a second transmission time stamp of the reference station describing when a third signal is

transmitted by the reference station and a first transmission time stamp of the reference station describing when a first signal is transmitted by the reference station. The difference $\Delta T_{1,3}^T$ of reception time stamps represents a difference between a third reception time stamp of the tag describing when the third signal transmitted by the reference station is received by the tag and a first reception time stamp of the tag describing when the first signal transmitted by the reference station is received by the tag. The first signal and the third signal have same signal power levels. The value $\Delta T_{1,2}^R$ represents a difference between a first reception time stamp of the reference station describing when the second signal transmitted by the tag is received by the reference station and a first transmission time stamp of the reference station describing when the first signal is transmitted by the reference station. The value $\Delta T_{1,2}^T$ represents a difference between a first transmission time stamp of the tag describing when a second signal is transmitted by the tag and a first reception time stamp of the tag describing when a first signal transmitted by the reference station is received by the tag. The value E_1 represents a signal power-correction, e.g. a predetermined value associated with an actual signal power level, associated with a correction of reception time stamps of the tag for received signals with a first signal power level. The value E_2 represents a signal power-correction, e.g. a predetermined value associated with an actual signal power level, associated with a correction of reception time stamps of the reference station for received signals with a second signal power level and the value Z represents a constant offset, e.g. a zero line for the signal power and the antenna offset. Z can also be equal to zero.

According to an embodiment, the apparatus is configured to calculate the position of the tag using a distance information describing a distance between the reference station and the tag, which is based on the time-of-arrival. Furthermore, the apparatus is, for example, configured to use a first distance difference information describing a difference between a distance between the reference station and the first station and a distance between the tag and the first station, which is based on the first time-difference-of-arrival. The apparatus can be configured to use a second distance difference information describing a difference between a distance between the reference station and the second station, and a distance between the tag and the second station, which is based on the second time-difference-of-arrival. Information about absolute or relative positions of the reference station, the first station and of the second station can be used by the apparatus to calculate the position of the tag. Thus, the apparatus can be configured to determine based on the information about the positions of the reference station, of the first station and of the second station, an overlap region or an overlap point of the distance information describing a

distance between the reference station and the tag, the first distance difference information and the second distance difference information. This overlap region or overlap point can, for example, represent the position of the tag. Thus, using the time-of-arrival, the first time-difference-of-arrival and the second time-difference-of-arrival can result in a two-dimensional position of the tag calculated by the apparatus.

According to an embodiment, the apparatus is configured to calculate the position of the tag using an intersection of a first circle or sphere, a first hyperbola or a first hyperboloid and a second hyperbola or a second hyperboloid. The intersection of the first circle, the first hyperbola and the second hyperbola results, for example, in a two-dimensional position of the tag and the intersection of the sphere, the first hyperboloid and the second hyperboloid results, for example, in a three-dimensional position of the tag. The sphere can also represent a spherical surface, the first hyperboloid can also represent a hyperboloid surface and the second hyperboloid can also represent a second hyperboloid surface.

The first circle or sphere is, for example, determined by an information about a position of the reference station and the time-of-arrival TOA from which a distance, which can be used as the radius, can be derived. Thus, the position of the reference station represents, for example, a center of the first circle or the sphere and the time-of-arrival defines, for example, the radius of the first circle or sphere. The first hyperbola or the first hyperboloid is, for example, determined by an information about a position of the reference station and of the first station and the first time-difference-of-arrival, from which a distance difference of points of the first hyperbola or of the first hyperboloid from the reference station and the first station can be derived. The second hyperbola or the second hyperboloid can be determined by an information about a position of the reference station and of the second station and the second time-difference-of-arrival from which a distance difference of points of the second hyperbola or of the second hyperboloid from the reference station and the second station can be derived.

According to an embodiment, the apparatus is configured to solve a system of three or more equations to calculate the position of the tag. A first of the equations describes, for example, a first circle or a first sphere centered at a position of the reference station, wherein a radius of the first circle or of the first sphere is determined by the time-of-arrival. This is based on the idea that the time-of-arrival can represent a distance between the reference station and the tag. A second of the equations describes, for example, a first hyperbola or a first hyperboloid, foci of which are at a position of the reference station and at a position of the first station. An absolute difference of distances of points of the first

hyperbola or of the first hyperboloid from the foci is, for example, determined by the first time-difference-of-arrival. This is based on the idea that the first time-difference-of-arrival can represent a distance difference between the distance of the reference station to the tag and a distance between the second station and the tag. A third of the equations describes, for example, a second hyperbola or a second hyperboloid, foci of which are at a position of the reference station and at a position of the second station. An absolute difference of distances of points of the second hyperbola or of the second hyperboloid from the foci is, for example, determined by the second time-difference-of-arrival. This is, for example, based on the idea that the second time-difference-of-arrival can represent a distance difference between a distance of the reference station to the tag and a distance of the second station to the tag. According to an embodiment, the apparatus is configured to use an information about absolute or relative positions of the reference stations of the first station and of the second station to solve the system of the three or more equations to calculate the position of the tag.

According to an embodiment, the apparatus is configured to calculate the position of the tag using a multiplication of the time-of-flight with a propagation speed of a signal, using a multiplication of the first time-difference-of-arrival with the propagation speed of the signal and using a multiplication of the second time-difference-of-arrival with the propagation speed of the signal, based on a lateration. The propagation speed of the signal represents, for example, a speed of light. This is based on the idea that time distances multiplied with the propagation speed of the signal can represent distances in a two-dimensional and/or three-dimensional space, from which the position of the tag can be calculated by the apparatus, for example, using an information about a position of the reference station, of the first station and of the second station.

According to an embodiment, the multiplication of the time-of-flight with a propagation speed of the signal represents a distance between the reference station and the tag. The multiplication of the first time-difference-of-arrival with the propagation speed of the signal represents, for example, a difference between a distance between the reference station and the first station and a distance between the tag and the first station.

The multiplication of the second time-difference-of-arrival with the propagation speed of the signal represents, for example, a difference between a distance between the reference station and the second station and a distance between the tag and the second station. Thus, for example, the multiplication of the time-of-flight with the propagation speed

of the signal can be equalized with the distance between the reference station and the tag, the multiplication of the first time-difference-of-arrival with the propagation speed of the signal can be equalized with the difference between the distance between the reference station and the first station and the distance between the tag and the first station, and the multiplication of the second time-difference-of-arrival with the propagation speed of the signal can be equalized with the difference between the distance between the reference station and the second station and the distance between the tag and the second station. Thus, for example, an equation system is achieved, which can be solved by the apparatus using an information about absolute or relative positions of the reference station, of the first station and of the second station to calculate the position of the tag.

According to an embodiment the apparatus is configured to calculate the position of the tag by solving an equation system according to

$$\begin{aligned} TOA \cdot c_0 &= \sqrt{(x_R - x_T)^2 + (y_R - y_T)^2}, \text{ and} \\ TDOA_i \cdot c_0 &= \sqrt{(x_T - x_{Si})^2 + (y_T - y_{Si})^2} \\ &\quad - \sqrt{(x_R - x_{Si})^2 + (y_R - y_{Si})^2} \\ &\text{and/or} \end{aligned}$$

$$\begin{aligned} TOA_n \cdot c_0 &= \sqrt{(x_{R_n} - x_T)^2 + (y_{R_n} - y_T)^2 + (z_{R_n} - z_T)^2}, \text{ and} \\ TDOA_i \cdot c_0 &= \sqrt{(x_T - x_{Si})^2 + (y_T - y_{Si})^2 + (z_T - z_{Si})^2} \\ &\quad - \sqrt{(x_{R_n} - x_{Si})^2 + (y_{R_n} - y_{Si})^2 + (z_{R_n} - z_{Si})^2} \end{aligned}$$

The value TOA represents the time-of-arrival. The value TDOA represents the time-difference-of-arrival and the value c_0 represents a propagation speed of a signal. The value x represents a first coordinate in a 3D-space or in a 2D-space, the value y represents a second coordinate in a 3D-space or in a 2D-space and the value z represents a third coordinate in a 3D-space. The Index R indicates a reference station, the Index T indicates a Tag and the Index Si indicates an i -th station. According to an embodiment the index i , e.g. $i \in [1; N]$, wherein $N \geq 2$, represents a number of a station Si , at which the reception time stamps describing the reception times of the two signals, one transmitted by the reference station and one transmitted by the tag, and used to determine the difference $\Delta T_{1,2}^{Si}$ between the reception time stamps, are obtained. The Index n , e.g. $n \in [1; N]$, wherein $N \geq 1$ or $N \geq 2$, represents a number of a reference station R . If more than one TOA is determined, more than one reference station is, for example, used. Thus between each reference station and the tag is, for example, a different TOA determined.

According to an embodiment the apparatus is configured to obtain a first transmission time stamp information, with respect to a clock of the reference station, of the reference station describing when the reference station transmits a first signal with a first signal power level, a first reception time stamp information of the first station describing, with respect to a clock of the first station, when the first station receives the first signal transmitted by the reference station, a first reception time stamp information of the second station describing, with respect to a clock of the second station, when the second station receives the first signal transmitted by the reference station and a first reception time stamp information of the tag describing, with respect to a clock of the tag, when the tag receives the first signal transmitted by the reference station. Additionally or alternatively the apparatus is configured to obtain a first transmission time stamp information, with respect to a clock of the tag, of the tag describing when the tag transmits a second signal, e.g., the signal power level of the second signal can be the first signal power level or alternatively a second signal power level, a second reception time stamp information of the first station describing, with respect to a clock of the first station, when the first station receives the second signal transmitted by the tag, a first reception time stamp information of the second station describing, with respect to a clock of the second station, when the second station receives the second signal transmitted by the tag and a first reception time stamp information of the reference station describing, with respect to a clock of the reference station when the reference station receives the second signal transmitted by the tag. Additionally or alternatively the apparatus is configured to obtain a second transmission time stamp information, with respect to a clock of the reference station, of the reference station describing when the reference station transmits a third signal with the first signal power level, a third reception time stamp information of the first station describing, with respect to a clock of the first station, when the first station receives the third signal transmitted by the reference station, a third reception time stamp information of the second station describing, with respect to a clock of the second station, when the second station receives the third signal transmitted by the reference station and a second reception time stamp information of the tag describing, with respect to a clock of the tag, when the tag receives the third signal transmitted by the reference station.

According to an embodiment, the apparatus is configured to obtain a first signal-power-correction for correcting the first reception time stamp information of the tag and the second reception time stamp information of the tag based on the first signal power level of the first and the third signal. Since the first signal and the third signal have the same signal power level and since the first reception time stamp information of the tag and the second

reception time stamp information of the tag both correspond to a clock of the tag, the first reception time stamp information as well as the second reception time stamp information of the tag can be corrected by the same first signal-power-correction. The apparatus is, for example, configured to obtain a second signal-power-correction for correcting the first reception time stamp information of the reference station based on a signal power level of the second signal. Furthermore, the apparatus is, for example, configured to obtain a third signal-power-correction for correcting the first reception time stamp information of the first station and the third reception time stamp information of the first station based on the first signal power level of the first and third signal. Since the first signal and the third signal have the same signal power levels and since the first reception time stamp information of the first station and the third reception time stamp information of the first station both correspond to a clock of the first station, the third signal-power-correction can correct the first reception time stamp information as well as the third reception time stamp information of the first station. The apparatus is, for example, configured to obtain a fourth signal-power-correction for correcting the second reception time stamp information of the first station based on a signal power level of the second signal. According to an embodiment, the apparatus is configured to obtain a fifth signal-power-correction for correcting the first reception time stamp information of the second station and the third reception time stamp information of the second station based on the first signal power level of the first and the third signal as the apparatus can be configured to obtain a sixth signal-power-correction for correcting the second reception time stamp information of the second station based on the signal power level of the second signal. Furthermore, the apparatus can be configured to use the signal-power-corrections in order to correct respective time stamp information. Also, the first reception time stamp information of the tag, the second reception time stamp information of the tag, the first reception time stamp information of the first station, the third reception time stamp information of the first station, the first reception time stamp information of the second station and the third reception time stamp information of the second station are based on the first signal power level of the first and the third signal the respective time stamp information can be corrected by different signal-power-corrections based on the station receiving the first and the third signal. Thus, the signal-power-correction depends, for example, on the station receiving a signal and on the signal power level of the received signal. Signal-power-corrections can, for example, be applied to all reception time stamp information used by the apparatus or by the a device calculating the TOA, the first time difference of arrival and/or a second time difference of arrival for the apparatus. Thus, the apparatus is configured to reduce an influence of different signal power levels of signals used for the localization of the tag.

According to an embodiment the first signal-power-correction is related to the tag, the second signal-power-correction is related to the reference station, the third signal-power-correction and the fourth signal-power-correction are related to the first station and the fifth signal-power-correction and the sixth signal-power-correction are related to the second station. The signal-power-correction is, for example, a power correction curve or an information describing a power correction curve or a databank comprising one, two or a plurality of time stamp power correction values, wherein each time stamp power correction value is associated with a signal power level of a signal, for example, of a signal received by a station, for which the time stamp power correction information is determined. The first signal-power-correction, the second signal-power-correction, the third signal-power-correction, the fourth signal-power-correction, the fifth signal-power-correction and the sixth signal-power-correction are based on a deviation between a first time interval and a second time interval. The first time interval describes, for example, a difference between a transmission of two signals having different signal power levels and the second time interval describes, for example, a difference between a reception of the two signals having different signal power levels by the station related to the respective signal-power-correction. The first time interval is described by a difference of transmission time stamps related to a first clock and the second time interval is described by a difference of reception time stamps related to a second clock representing a clock of the station related to the respective signal-power-correction. Thus the first time interval can be the same for all signal-power corrections and the second time interval can differ for each signal-power-correction. According to an embodiment the second time interval for the first signal power correction describes difference between a reception of the two signals having different signal power levels by the tag. The signal power corrections are obtained, for example, by the apparatus, using a clock-drift-correction which is based on transmission time stamp information and reception time stamp information of at least two signals having same signal power levels. Thus, for example, two of the at least three signals have the same signal power level and one of the three signals has a signal power level differing from the signal power level of the two signals having same signal power levels. Alternatively, the apparatus can be configured for determining the signal power corrections on the basis of transmission time stamp information and reception time stamp information associated with more signals, wherein at least two signals have same signal power levels and at least two signals have different signal power levels like, for example, four signals with two signals having a first signal power level, a signal having a second signal power level and a signal having a third signal power level. For example, a determination based on three signals

can comprise two signal-power-corrections because two signal power levels are analyzed, wherein the signal-power-correction related to the signal power level of the two signals having same signal power level is, for example, zero. Thus, for example, a determination based on four signals can comprise three signal-power-correction or two signal-power-correction because either three signal power levels or two signal power levels are analyzed.

According to an embodiment the apparatus is configured to obtain a first antenna-delay correction value for correcting transmission time stamps and reception time stamps related to the reference station. The apparatus is, for example, configured to obtain a second antenna-delay correction value for correcting, e.g. all, transmission time stamps and, e.g. all, reception time stamps related to the tag. The apparatus is, for example, configured to obtain a third antenna-delay correction value for correcting, e.g. all, transmission time stamps and, e.g. all, reception time stamps related to the first station. The apparatus is, for example, configured to obtain a fourth antenna-delay correction value for correcting, e.g. all, transmission time stamps and, e.g. all, reception time stamps related to the second station and the apparatus is, for example, configured to use the first antenna-delay correction value, second antenna-delay correction value, third antenna-delay correction value and/or fourth antenna-delay correction value to obtain the time-of-arrival, the first time-difference-of-arrival and the second time-difference-of-arrival.

According to an embodiment the clock-drift-correction is determined using time-interpolation or time-extrapolation of a deviation between a first difference of transmission time stamps associated with a transmission of two signals having same signal power levels and a second difference of reception time stamps associated with a reception of the two signals having same signal power levels. The two signals, on which the first difference is based and the two signals on which the second difference is based are, for example, the same two signals. The first difference is related to a first clock and the second difference is related to a second clock and the deviation between the first difference and the second difference is, for example, caused by a deviation between the first clock and the second clock. The apparatus is configured to use the clock-drift-correction to obtain the time-of-arrival, the first time-difference-of-arrival and the second time-difference-of-arrival. If the first clock and the second clock would run simultaneously, i.e., synchronized, the first difference would equal the second difference, since no clock drift or nearly no clock drift occurs. If the clock drift correction is determined using the time-interpolation, then, for example, the clock drift correction is determined for a signal, which transmission is timed

between the transmission of the two signals having same signal power levels and if the clock drift correction is determined using the time-extrapolation, the clock drift correction is determined for a signal, whose transmission is timed after the transmission of the two signals having same signal power levels. By the time-interpolation or the time-extrapolation a
5 very exact clock drift correction can be determined, whereby a high accuracy in determining the position of the tag can be achieved.

An embodiment according to this invention is related to a method for localizing a tag. The method comprises obtaining, e.g. calculating, a time-of-arrival, e. g. a run-time of a signal
10 between a reference station and a tag, of one or more signals, based on transmission-time-stamps and reception-time-stamps, e. g. received from the ref. and tag by the apparatus, of two or more signals send between a reference station and a tag, e.g. using a clock-drift-correction and/or an antenna-delay-correction and/or a signal-power-correction. The method comprises obtaining, e.g. calculating, e.g. using a clock-drift-correction and/or
15 a signal-power-correction and/or an antenna-delay-correction, wherein the antenna-delay correction is, for example, used to calculate an Offset K, a first time-difference-of-arrival on the basis of a difference between reception time stamps obtained at a first station and describing reception times of two signals, one transmitted by the reference station and one transmitted by the tag, for example, in a time-synchronized manner, for example,
20 such that, for example, a difference of transmission times is predetermined or can be computed, at the first station. Furthermore the method comprises obtaining, e.g. calculate, e.g. using a clock-drift-correction and/or a signal-power-correction and/or an antenna-delay-correction, a second time-difference-of-arrival on the basis of a difference between reception time stamps obtained at a second station and describing reception times of two
25 signals, one transmitted by the reference station and one transmitted by the tag, for example, in a time-synchronized manner, for example, such that, for example, a difference of transmission times is predetermined or can be computed, at the second station, wherein, for example, the two signals on which the reception time stamps obtained at the second station are based may be equal to the two signals on which the reception time stamps
30 obtained at the first station are based, or may be different from the two signals on which the reception time stamps obtained at the first station are based. The method comprises calculating a position of the tag based on the time-of-arrival and the at least two time-difference-of arrivals.

35 An embodiment according to this invention is related to a Computer program having a program code for performing, when running on a computer, a method.

Brief description of the drawings

The drawings are not necessarily to scale; instead, emphasis is generally being placed on illustrating the principles of the invention. In the following description, various embodiments of the invention are described with reference to the following drawings, in which:

Fig. 1 shows a schematic view of an apparatus for localizing a tag according to an embodiment of the invention;

10 Fig. 2 shows a schematic view of a determination of a time-of-arrival obtained by an apparatus according to an embodiment of the present invention;

Fig. 3 shows a schematic view of a determination of a time-of-arrival, to be obtained by an apparatus according to an embodiment of the present invention, using a clock-drift-correction and/or a signal-power-correction;

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Fig. 4 shows a schematic view of a fusion of a determination of a time-of-arrival and a determination of a time-difference-of-arrival, to be obtained by an apparatus according to an embodiment of the present invention;

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Fig. 5 shows a schematic view of a fusion of a determination of a time-of-arrival and a determination of a time-difference-of-arrival, to be obtained by an apparatus according to an embodiment of the present invention, using a clock-drift-correction and/or a signal-power-correction;

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Fig. 6 shows a schematic view of a constellation of stations for a two-dimensional localization of a tag by an apparatus according to an embodiment of the present invention;

30 Fig. 7 shows results of a fusion of a time-of-arrival and at least two time-difference-of-arrivals for localizing a tag determined by an apparatus according to an embodiment of the present invention;

Fig. 8 shows a schematic view of a determination of a clock-drift-correction and/or a signal-power-correction used to correct a time-of-arrival and/or a first time-difference-of-arrival and/or a second time-difference-of-arrival to be

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obtained by an apparatus for localizing a tag according to an embodiment of the present invention;

Fig. 9a shows a schematic diagram of a measured signal power level versus a real signal power level used for a determination of a signal-power-correction according to an embodiment of the present invention; and

Fig. 9b shows a schematic diagram of a signal power level correction curve usable to correct a time-of-arrival and/or a first time-difference-of-arrival and/or a second time-difference-of-arrival to be obtained by an apparatus for localizing a tag according to an embodiment of the present invention.

Detailed Description of the Embodiments

Equal or equivalent elements or elements with equal or equivalent functionality are denoted in the following description by equal or equivalent reference numerals even if occurring in different figures.

In the following description, a plurality of details is set forth to provide a more throughout explanation of embodiments of the present invention. However, it will be apparent to those skilled in the art that embodiments of the present invention may be practiced without these specific details. In other instances, well-known structures and devices are shown in block diagram form rather than in detail in order to avoid obscuring embodiments of the present invention. In addition, features of the different embodiments described herein after may be combined with each other, unless specifically noted otherwise.

Herein, the following notation can be used: A time stamp can be indicated as T_i^x , wherein i represents the corresponding signal and x corresponds to the station determining the time stamp. The index x can be R (reference station), T (tag), and/or S (anchor station). The index i can be in the range of 1 to n , wherein n is a positive integer of at least 2. Thus, for example, the time stamp T_1^R represents a time stamp corresponding to a first signal determined by a reference station. A difference between two time stamps $T_M^x - T_N^x$ can be indicated as $\Delta T_{N,M}^x$, wherein the index N and the index M represent values of the index i in the range of 1 to n and the two time stamps T_M^x and T_N^x represent times determined by the same station, see index x . A clock drift error obtained from the time stamps of a signal N and a signal M , for example, transmission time stamps and reception time

stamps of both signals, can be indicated by $C_{N,M}$. A time stamp power correction information can comprise a time stamp error due to the signal power level, which can be indicated as E_i , wherein the index i is associated with a defined signal power level. Furthermore, an antenna delay and a signal-power-correction offset can be indicated by A , B and/or C . A time difference between a reference station and a tag can be indicated as K and a speed of light can be indicated by c_0 . Moreover a position of the reference station can be represented by (x_R, y_R, z_R) , a position of a base station (i.e. an anchor station, e.g., a first station and/or a second station) can be represented by (x_S, y_S, z_S) and a position of the tag can be represented by (x_T, y_T, z_T)

Fig. 1 shows an apparatus 100 for localizing a tag, configured for obtaining a time-of-arrival TOA 110, a first time-difference-of-arrival TDOA₁ 120 and a second time difference of arrival TDOA₂ 130. Furthermore the apparatus 100 is configured for calculating a position 140 of the tag based on the time-of-arrival 110 and the at least two time-difference-of arrivals 120, 130.

According to an embodiment the apparatus 100 is configured to calculate the time-of-arrival 110 and the at least two time-difference-of arrivals 120, 130 by itself, or to receive the time-of-arrival 110 and/or the at least two time-difference-of arrivals 120, 130 from an external device performing the calculation of the time-of-arrival 110 and/or of the at least two time-difference-of arrivals 120, 130.

According to an embodiment the time-of-arrival 110, e.g. a time-of-flight of a signal transmitted between a reference station and a tag, is based on transmission-time-stamps and reception-time-stamps of two or more signals sent between a reference station and a tag. The apparatus 100 or an external device can be configured to determine the TOA 110 using, e.g., a clock-drift-correction and/or an antenna-delay-correction and/or a signal-power-correction. According to an embodiment one of the two or more signals is transmitted by the reference station and received by the tag and another signal of the two or more signals is transmitted by the tag and received by the reference station.

The TOA 110 is the same for the two or more signals. Thus to determine the TOA 110 the apparatus 100 or an external device can calculate a time difference between a transmission-time-stamp, describing when a first signal of the two or more signals is transmitted, and a last reception-time-stamp, describing when a last signal of the two or more signals is received either by the reference station or the tag, and to subtract time-differences between a reception of a signal and a transmission of the next signal, i.e. a processing time

of the reference station and/or the tag, to obtain an overall TOA, which can be divided by the number of the two or more signals, to determine the TOA 110 for one signal.

5 According to an embodiment the apparatus 100 is configured to receive, e.g., from the reference station and the tag, the transmission time stamps and the reception time stamps of the two or more signals send between the reference station and the tag to calculate the TOA 110.

10 According to an embodiment the TOA 110 can be calculated according to an embodiment described with regard to Fig. 2, Fig. 3, Fig. 4 and/or Fig. 5 by the apparatus 100 or by an external device, providing the calculated TOA 110 for the apparatus 100.

15 According to an embodiment the first time-difference-of-arrival TDOA_1 120 is based on a difference between reception time stamps obtained at a first station and describing reception times of two signals, one transmitted by the reference station and one transmitted by the tag, at the first station. The apparatus 100 or an external device can be configured to determine the TDOA_1 120 using, e.g., a clock-drift-correction and/or a signal-power-correction and/or an antenna-delay-correction. The determination of the TDOA_1 120 is, for example, performed in a time-synchronized manner, for example, such that a difference of
20 transmission times is predetermined or can be computed. The TDOA_1 represents, for example, a difference between a TOA of a first signal, transmitted by the reference station and received by the first station, and a TOA of a second signal, transmitted by the tag and received by the first station.

25 According to an embodiment the apparatus 100 is configured to receive, e.g., from the first station, the reception time stamps of the two signals transmitted by the reference station and by the tag to calculate the TDOA_1 120. The apparatus 100 is according to an embodiment part of the first station, whereby the apparatus 100 is configured to calculate the TDOA_1 by itself.

30 According to an embodiment the TDOA_1 120 can be calculated according to an embodiment described with regard to Fig. 4 and/or Fig. 5 by the apparatus 100 or by an external device, providing the calculated TDOA_1 120 for the apparatus 100.

35 According to an embodiment the second time-difference-of-arrival TDOA_2 130 is based on a difference between reception time stamps obtained at a second station and describing reception times of two signals, one transmitted by the reference station and one transmit-

ted by the tag, at the second station. The apparatus 100 or an external device can be configured to determine the TDOA_2 130 using, e.g., a clock-drift-correction and/or a signal-power-correction and/or an antenna-delay-correction. The determination of the TDOA_2 130 is, for example, performed in a time-synchronized manner, for example, such that a difference of transmission times is predetermined or can be computed. The TDOA_2 130 represents, for example, a difference between a TOA of a first signal, transmitted by the reference station and received by the second station, and a TOA of a second signal, transmitted by the tag and received by the second station.

10 According to an embodiment the apparatus 100 is configured to receive, e.g., from the second station, the reception time stamps of the two signals transmitted by the reference station and by the tag to calculate the TDOA_2 130. The apparatus 100 is according to an embodiment part of the second station, whereby the apparatus 100 is configured to calculate the TDOA_2 130 by itself.

15 According to an embodiment the TDOA_2 130 can be calculated according to an embodiment described with regard to Fig. 4 and/or Fig. 5 by the apparatus 100 or by an external device, providing the calculated TDOA_2 130 for the apparatus 100.

20 According to an embodiment the two signals on which the reception time stamps obtained at the second station are based may be equal to the two signals on which the reception time stamps obtained at the first station are based, or may be different from the two signals on which the reception time stamps obtained at the first station are based.

25 According to an embodiment the apparatus 100 is configured to calculate the position 140 of the tag using a distance information describing a distance between the reference station and the tag, which is based on the time-of-arrival TOA 110, using a first distance difference information describing a difference between a distance between the reference station and the first station and a distance between the tag and the first station, which is based on the first time-difference-of-arrival TDOA_1 120 and using a second distance difference information describing a difference between a distance between the reference station and the second station and a distance between the tag and the second station, which is based on the second time-difference-of-arrival TDOA_2 130. According to an embodiment the apparatus 100 is configured to obtain information about absolute or relative positions of the reference station, of the first station and of the second station and to use this information to calculate the position 140 of the tag. According to an embodiment the

position information of the reference station, of the first station and of the second station can be predetermined and can be saved on the apparatus 100 or alternatively the apparatus 100 can be configured to receive this position information from an external device.

5 According to an embodiment the apparatus 100 is configured to calculate the position 140 of the tag using an intersection of a first circle or sphere, e.g., a spherical surface, a first hyperbola or a first hyperboloid, e.g., a first hyperboloid surface, and a second hyperbola or a second hyperboloid, e.g., a second hyperboloid surface. The position 140 of the tag represents, for example, the intersection or an area around the intersection, wherein the
10 area around the intersection can represent an uncertainty of the apparatus 100 and/or of other processing units, stations and/or devices used to calculate the intersection. Alternatively the position 140 of the tag can represent an average of a plurality of intersections determined by the apparatus 100 or the position 140 of the tag can represent an area around the average.

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According to an embodiment the apparatus 100 is configured to calculate a two-dimensional position 140 of the tag based on an intersection of the first circle, the first hyperbola and the second hyperbola. According to an embodiment the apparatus 100 is configured to calculate a three-dimensional position 140 of the tag based on the first
20 sphere, the first hyperboloid and the second hyperboloid.

According to an embodiment the first circle or sphere is determined by the apparatus 100 based on information about a position of the reference station and the time-of-arrival TOA 110, from which a distance, which can be used as the radius, can be derived. According
25 to an embodiment the first hyperbola or the first hyperboloid is determined by the apparatus 100 based on information about a position of the reference station and of the first station and the first time-difference-of-arrival $TDOA_1$ 120, from which a distance difference of points of the first hyperbola or of the first hyperboloid from the reference station and the first station can be derived. According to an embodiment the second hyperbola or the
30 second hyperboloid is determined by the apparatus 100 based on information about a position of the reference station and of the second station and the second time-difference-of-arrival $TDOA_2$ 130, from which a distance difference of points of the second hyperbola or of the second hyperboloid from the reference station and the second station can be derived.

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According to an embodiment the apparatus 100 is configured to solve a system of equations, e.g., of three or more equations, to calculate the position 140 of the tag. A first of the equations describes, for example, the first circle or the first sphere centered at a position of the reference station. The apparatus 100 is, for example, configured to determine a
5 radius of the first circle or of the first sphere using the time-of-arrival TOA 110. A second of the equations describes, for example, the first hyperbola or the first hyperboloid, foci of which are at a position of the reference station and at a position of the first station. The apparatus 100 is, for example, configured to determine an absolute difference of distances of points of the first hyperbola or of the first hyperboloid from the foci using the first
10 time-difference-of-arrival TDOA₁ 120. A third of the equations describes, for example, the second hyperbola or the second hyperboloid, foci of which are at a position of the reference station and at a position of the second station. The apparatus 100 is, for example, configured to determine an absolute difference of distances of points of the second hyperbola or of the second hyperboloid from the foci using the second time-difference-of-arrival
15 TDOA₂ 130.

According to an embodiment the apparatus 100 is configured to calculate the position 140 of the tag using a multiplication of the TOA 110 with a propagation speed of a signal, using a multiplication of the first time-difference-of-arrival TDOA₁ 120 with the propagation
20 speed of the signal and using a multiplication of the second time-difference-of-arrival TDOA₂ 130 with the propagation speed of the signal, based on a lateration. The propagation speed of the signal is, for example, represented by a velocity of light c_0 . The lateration is, for example, a method to determine the location of the tag, wherein the tag can be movable or stationary in space, using multiple ranges (i.e. distances) between the tag and
25 multiple spatially separated locations (i.e. stations, like the reference station, the first station and the second station).

Thus the multiplication of the TOA 110 with the propagation speed of the signal represents, for example, a distance between the reference station and the tag, the multiplication
30 of the first time-difference-of-arrival TDOA₁ 120 with the propagation speed of the signal represents, for example, a difference between a distance between the reference station and the first station and a distance between the tag and the first station and the multiplication of the second time-difference-of-arrival TDOA₂ 130 with the propagation
35 speed of the signal represents, for example, a difference between a distance between the reference station and the second station and a distance between the tag and the second station. According to an embodiment the apparatus is configured to use the information

about the absolute or relative positions of the reference station, of the first station and of the second station.

- According to an embodiment the apparatus 100 is configured to calculate the position 140 of the tag by solving an equation system according to

$$\begin{aligned} TOA \cdot c_0 &= \sqrt{(x_R - x_T)^2 + (y_R - y_T)^2}, \text{ and} \\ TDOA_i \cdot c_0 &= \sqrt{(x_T - x_{Si})^2 + (y_T - y_{Si})^2} \\ &\quad - \sqrt{(x_R - x_{Si})^2 + (y_R - y_{Si})^2} \\ &\text{and/or} \end{aligned}$$

$$\begin{aligned} TOA_n \cdot c_0 &= \sqrt{(x_{R_n} - x_T)^2 + (y_{R_n} - y_T)^2 + (z_{R_n} - z_T)^2}, \text{ and} \\ TDOA_i \cdot c_0 &= \sqrt{(x_T - x_{Si})^2 + (y_T - y_{Si})^2 + (z_T - z_{Si})^2} \\ &\quad - \sqrt{(x_{R_n} - x_{Si})^2 + (y_{R_n} - y_{Si})^2 + (z_{R_n} - z_{Si})^2}, \end{aligned}$$

- 10 wherein a position of the reference station, e.g., a 2D-position (x_R, y_R) or a 3D-position (x_R, y_R, z_R) , and a position of a station, e.g., a 2D-position (x_{Si}, y_{Si}) or a 3D-position (x_{Si}, y_{Si}, z_{Si}) , is known by the apparatus 100 and the position of the tag, e.g., a 2D-position (x_T, y_T) or a 3D-position (x_T, y_T, z_T) is calculated by the apparatus 100.
- 15 According to an embodiment the apparatus 100 is configured to obtain at least two time-difference-of-arrivals, e.g., the first time-difference-of-arrival $TDOA_1$ 120 and the second time-difference-of-arrival $TDOA_2$ 130, wherein for each TDOA a separate station is used. Thus the apparatus 100 knows, for example, the 2D-position (x_{S1}, y_{S1}) or the 3D-position (x_{S1}, y_{S1}, z_{S1}) of the first station and the 2D-position (x_{S2}, y_{S2}) or the 3D-position (x_{S2}, y_{S2}, z_{S2}) of the second station. According to an embodiment the index i , e.g., $i \in [1; N]$, wherein $N \geq 2$, represents a number of a station S_i , at which the reception time stamps describing the reception times of the two signals, one transmitted by the reference station and one transmitted by the tag, are obtained.
- 25 According to an embodiment the apparatus 100 is configured to obtain more than one time-of-arrival TOA 110, wherein for each TOA_n a separate reference station is used. Thus the apparatus 100 knows, for example, the 2D-position (x_{R_n}, y_{R_n}) or the 3D-position $(x_{R_n}, y_{R_n}, z_{R_n})$ of each reference station. According to an embodiment the Index n , e.g., $n \in [1; N]$, wherein $N \geq 1$ or $N \geq 2$, represents a number of a reference station R .

Figure 2 shows a concept of a two way ranging TWR and a shift of time stamps caused by a signal power, i.e. power or signal power level of a signal, and an error due to an antenna delay. In other words on the left of Fig. 2 an effect of the power on a determination of a time-of-arrival TOA by a station, by an external device or by an apparatus, as described, e.g., in Fig. 1, is shown. In other words on the right of Fig. 2 an effect of an offset, i.e. the antenna delay, on a determination of the time-of-arrival TOA by a station, by an external device or by an apparatus, as described, e.g., in Fig. 1, is shown.

According to an embodiment the time-of-arrival is calculated based on a transmission time stamp T_1^R 220₁ and a reception time stamp T_1^T 230₁ of a first signal 210 transmitted by the reference station 200₁ and received by the tag 200₂ and a transmission time stamp T_2^T 220₂ and a reception time stamp T_2^R 230₂ of a second signal 212 transmitted by the tag 200₂ and received by the reference station 200₁.

According to an embodiment the reference station 200₁ is the initiator. A first message 210, i.e. a first signal, is send by the reference station 200₁ at a time stamp T_1^R , i.e. a first transmission-time-stamp 220₁ of the reference station 200₁. A time stamp T_1^T , i.e. a first reception-time-stamp 230₁ of the tag 200₂ of the received message at the tag 200₂ is affected by the signal power, which cause of the time stamp by E1. In other words E1 represents a signal-power-correction 240₁ associated with a first signal power level of the first signal 210 to correct the first reception-time-stamp 230₁ of the tag 200₂. The same applies, for example, for a response message, i.e. a second signal 212 but this time at the reference station 200₁. In other words E2 represents a signal-power-correction 240₂ associated with a second signal power level of the second signal 212 to correct the first reception-time-stamp 230₂ of the reference station 200₁. It is important to note that the transmission-time-stamps T_1^R 220₁ and T_2^T 220₂ are not affected by the signal power.

On the other side does the antenna delay (A, B) 250₁, 250₂, i.e. an antenna offset, affecting all time stamps (shown on the right of Fig. 2). It is, for example, assumed that a sending delay equates the receiving delay. Without the correction would a TWR equation be $0.5 \cdot ((T_2^R - T_1^R) - (T_2^T - T_1^T))$. The time of flight, i.e. the time-of-arrival TOA, between the reference station 200₁ and the tag 200₂ with the corrections can be estimated with the following formula:

$$TOA = 0.5 \cdot ((T_2^R - T_1^R) - (T_2^T - T_1^T) - E2 - E1) - A - B.$$

The values E1 and E2 can be obtained from a signal-power-correction curve or a Data-bank of signal-power-correction values corresponding to different signal power levels, as described with respect to Fig. 8 and or Fig. 9b. It should be taken into account that the

signal power affects the tag 200₂ and the reference station 200₁ differently. Due to the signal power is a time difference $\Delta T_{1,2}^R$ 260₁ increasing and a time difference $\Delta T_{1,2}^T$ 260₂ decreasing. Due to the antenna delay is the time difference $\Delta T_{1,2}^R$ 260₁ increasing and the time difference $\Delta T_{1,2}^T$ 260₂ decreasing. A zero line for the signal power and the antenna offset are both unknown but constant, hence both values can be represented by the variable Z.

Although in Fig. 2 an effect of the signal power level of a signal (see the left of Fig. 2) and an antenna delay (see the right of Fig. 2) are shown separately, it is clear, that both errors can coexist. Thus, for example, the first transmission time stamp 220₁ of the reference station 200₁ and a first transmission time stamp 220₂ of the tag 200₂ can be corrected by an antenna-delay-correction and the first reception time stamp 230₁ of the tag 200₂ and the first reception time stamp 230₂ of the reference station 200₁ can be corrected by the antenna-delay-correction and/or by the signal-power-correction.

According to an embodiment additionally or alternatively a clock-drift-correction can be used to correct transmission time stamps 220₁ and/or 220₂ and/or to correct reception time stamps 230₁ and/or 230₂.

According to an embodiment a clock drift can be corrected by three messages. Figure 3 shows how this principle can be adapted for the two way ranging to enable a determination of a clock-drift-corrected time-of-arrival TOA. The method shown in Fig. 3 can comprise features and functionalities shown in Fig. 2, wherein in Fig. 3 additionally to the two messages 210, 212 a third message 214, i.e. a last message, is transmitted by the reference station 200₁ and received by the tag 200₂. The last message 214 is, for example, used to obtain a clock drift error $C_{1,3}^{RT} = \Delta T_{1,3}^R - \Delta T_{1,3}^T$, wherein the time difference $\Delta T_{1,3}^R$ 262₁ represents a difference between transmission time stamps 220₁ and 220₃ associated with the first signal 210 and the third signal 214 and wherein the time difference $\Delta T_{1,3}^T$ 262₂ represents a difference between reception time stamps 230₁ and 230₃ associated with the first signal 210 and the third signal 214. It can be seen that the signal power E1 has no effect on the time stamp difference $\Delta T_{1,3}^T$ 262₂. The final time of flight equation with the clock drift correction and three messages becomes, for example:

$$TOA = 0.5 \cdot \left(\Delta T_{1,2}^R - \Delta T_{1,2}^T - \frac{C_{1,3}^{RT}}{\Delta T_{1,3}^T} \cdot (\Delta T_{1,2}^T + E_1) - E_2 - E_1 \right) + Z$$

In other words the clock-drift-correction is, for example, based on a transmission time stamp T_3^R 220₃ and a reception time stamp T_3^T 230₃ related to a third signal 214 transmitted by the reference station 200₁ and received by the tag 200₂ and transmission time

stamps T_1^R 220₁ and reception time stamps T_1^T 230₁ related to a first signal 210 transmitted by the reference station 200₁ and received by the tag 200₂.

In other words the clock-drift-correction is, for example, used to correct the difference $\Delta T_{1,2}^T$ 260₂ between a first transmission time stamp T_2^T 220₂ of the tag 200₂, describing when the second signal 212 is transmitted by the tag 200₂, and a first reception time stamp T_1^T 230₁ of the tag 200₂, describing when the first signal 210 transmitted by the reference station 200₁ is received by the tag 200₂, and/or wherein a signal-power-correction E_1 240₁ correcting the first reception time stamp T_1^T 230₁ obtained at the tag 200₂ is performed.

With the corrected time measurements TOA and the propagation speed of the signal it is possible to use a lateration to obtain a position of the tag 200₂ (x_T , y_T , z_T) with respect to anchors, e.g. the reference station 200₁:

$$TOA_i \cdot c_0 = \sqrt{(x_{R_i} - x_T)^2 + (y_{R_i} - y_T)^2 + (z_{R_i} - z_T)^2} \quad 1 \leq i \leq N$$

Fig. 3 showed how the clock drift and the offset can influence the time of arrival position estimation. In Fig. 4 and Fig. 5 we show how the TOA messages 210, 212 can be used to combine TOA with TDOA and synchronize the clocks, e.g., a clock of a reference station 200₁, a clock of a tag 200₂ and clocks of different stations 202, wireless. In Fig. 4 and in Fig. 5 is exemplarily only one station N 202_N of a plurality of stations 202 shown, wherein the index N is a Number out of a range of 1 to n and wherein n is at least 2. Time difference of arrival (TDOA) requires, for example, that the clocks of the different stations are synchronous. Otherwise, an additional signal from another station at known position can be used for clock synchronization [12]. Two way ranging (TWR) based on TOA requires, for example, that both stations, e.g., the reference station 200₁ and the tag 200₂, are emitting a signal 210, 212. Therefore, one station can be used as a reference station for the clock synchronization. In Figure 5 this principal is illustrated. In other words Fig. 5 shows TOA and TDOA with clock drift correction. The effect of clock drift and the antenna delay on the TDOA can be seen in Fig. 4. The effect of a signal power level of a signal on the TDOA can be seen in Fig. 4 on the left and the effect of an offset, i.e. the antenna delay, on TDOA can be seen on the right.

Although in Fig. 4 an effect of the signal power level of a signal (see the left of Fig. 4) and an antenna delay (see the right of Fig. 4) are shown separately, it is clear, that both errors can coexist. Thus, for example, the first reception time stamp 230₄ of the station 202_N and a second reception time stamp 230₅ of the station 202_N can be corrected by the antenna-delay-correction C 250 and/or by the signal-power-correction E3 or E4.

According to an embodiment the antenna delay C 250 as shown in Fig. 4 on the right is, for example, the same for all time stamps, transmission time stamps and reception time stamps of one station and differs, for example, between two different stations. Although the antenna delay C 250 is only shown for the station 202_N it is clear, that for each station, the reference station, the tag and/or other stations an antenna delay can be determined, which can be used by the apparatus or by an external device to correct transmission and reception time stamps of the corresponding station. The antenna delay for the reference station and the tag can be seen, for example, in Fig. 2 on the right.

According to an embodiment the value E₃ 240₃ and E₄ 240₄, shown in Fig. 4 and Fig. 5, represent signal power-corrections, e.g., a predetermined value associated with an actual signal power level, associated with a correction of reception time stamps of the Station N 202_N for received signals with a first signal power level and a second signal power level. Although the signal-power-corrections are exemplarily shown for only one station 202_N it is clear, that similar signal power-corrections can be applied to reception time stamps of all stations 202.

According to an embodiment the value E₁ 240₁, shown in Fig. 5, represents a signal power-correction, e.g. a predetermined value associated with an actual signal power level, associated with a correction of reception time stamps of the tag for received signals with a first signal power level.

According to an embodiment the value E₂ 240₂, shown in Fig. 5, represents a signal power-correction, e.g. a predetermined value associated with an actual signal power level, associated with a correction of reception time stamps of the reference station for received signals with a second signal power level.

According to an embodiment the first signal 210 and the third signal 214 have a first signal power level and the second signal 212 has a second signal power level. Although E₁ 240₁ and E₃ 240₃ are associated with the same signal power level they can differ from each other, since the signal-power-correction can depend on the station receiving the signals. The same applies, for example, for E₂ 240₂ and E₄ 240₄. Reception time stamp determined by the same station, like T_1^S 230₄ and T_3^S 230₆ associated with signals 210, 214 having same signal power levels, can be corrected by the same signal-power-correction E₃ 240₃. The same applies, for example, for the time stamps T_1^T 230₁ and T_3^T 230₃ corrected by E₁ 240₁.

To determine the TOA and the TDOA, signals are transmitted between stations. In that matter, for example, a first TOA signal 210₁ is transmitted by the reference station 200₁ and received by the tag 200₂ and a second TOA signal 212₁ is transmitted by the tag 200₂ and received by the reference station 200₁ to determine the TOA. According to an embodiment a first TDOA signal 210₂ is transmitted by the reference station 200₁ and received exemplarily by the station 202_N and a second TOA signal 212₂ is transmitted by the tag 200₂ and received exemplarily by the station 202_N to determine the TDOA. According to an embodiment the first TOA signal 210₁ can be the same as the first TDOA signal 210₂ or can differ from the first TDOA signal 210₂. According to an embodiment the second TOA signal 212₁ can be the same as the second TDOA signal 212₂ or can differ from the second TDOA signal 212₂.

The two way ranging is, for example, obtained between the tag 200₂ and the reference station 200₁. The other stations 202 are passive not responding to the reference station 200₁ and/or the tag 200₂. The difference between time stamp two T_2^S 230₅ and one T_2^S 230₄ for every anchor, i.e. station 202, is different depending on the position of the reference station 200₁ and the tag 200₂ with respect to the anchor. In contrast to the TWR applications presented before, see Fig. 2 and/or Fig. 3, are the influence of the signal power and the antenna delay different for TDOA applications, see Fig. 4 and/or Fig. 5.

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It is, for example, assumed that for the TDOA application the influence of the antenna delay is the same for the time stamps T_1^S 230₄ and T_2^S 230₅, see the left of Fig. 4. Therefore is the TDOA equation, for example, independent from the antenna delay. On the other side is according to an embodiment a new offset K 310, see Fig. 5, appearing. This offset 310 represents, for example, a delay between the signal of the tag 200₂, i.e. the second signal 212, and the signal of the reference station 200₁, i.e. the first signal 210. If both stations, e.g., the reference station 200₁ and the tag 200₂, would send at the same time, this offset K 310 would be zero. Thus the TDOA can be calculated according to $TDOA = \Delta T_{1,2}^S - E_4 + E_3 + K$.

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The third message 214, shown in Fig. 5, from the reference station 200₁ is used to obtain a clock drift error $C_{1,3}^S$ according to $C_{1,3}^S = \Delta T_{1,3}^R - \Delta T_{1,3}^S$, wherein $\Delta T_{1,3}^S = T_3^S - T_1^S$ and $\Delta T_{1,3}^R = T_3^R - T_1^R$. In other words the deviation $C_{1,3}^S$ represents a difference between a difference $\Delta T_{1,3}^R$ 262₂ of transmission time stamps associated with a transmission of two signals 210, 214 having same signal power levels, transmitted by the reference station 200₁, and a difference $\Delta T_{1,3}^S$ 262₃ of reception time stamps associated with a reception of the two signals 210, 214 having same signal power levels by the station S_N 202_N. The difference $\Delta T_{1,3}^R$ 262₂, e.g., represents a difference between a second transmission time stamp

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T_3^R 220₃ of the reference station 200₁ describing when a third signal 214 is transmitted by the reference station 200₁ and a first transmission time stamp T_1^R 220₁ of the reference station 200₁ describing when a first signal 210 is transmitted by the reference station 200₁. The difference $\Delta T_{1,3}^S$ 262₃, e.g., represents a difference between a third reception time stamp T_3^S 230₆ of the station S_N describing when the third signal 214 transmitted by the reference station 200₁ is received by the station S_N and a first reception time stamp T_1^S 230₄ of the station S_N describing when the first signal 210 transmitted by the reference station 200₁ is received by the station S_N . The first signal 210 and the third signal 214 have, for example, same signal power levels. With linear interpolation of the clock drift error $C_{1,3}^S$, the TDOA equation becomes

$$TDOA = \Delta T_{1,2}^S + \left(\frac{C_{1,3}^S}{\Delta T_{1,3}^S} \cdot (\Delta T_{1,2}^S + E_3 - E_4) \right) - E_4 + E_3 + K.$$

According to an embodiment the clock-drift-correction $\frac{C_{1,3}^S}{\Delta T_{1,3}^S}$ is used to correct the difference $\Delta T_{1,2}^S$ 260₃ between the reception time stamps T_1^S 230₄ and T_2^S 230₅ obtained at a station 202 and to correct the signal-power-corrections E_3 240₃ and E_4 240₄ correcting the reception time stamps T_1^S 230₄ and T_2^S 230₅ obtained at the station 202.

This equation still depends on the offset K 310. However, this offset 310 is, for example, represented by the traveling time of the signal, i.e., of the first signal 210, from the reference station 200₁ to the tag 200₂ and the computational time 260₂ of the tag 200₂ before the signal, i.e., the second signal 212, is emitted by the tag. This offset 310 is, for example, calculated as follows:

$$K = TOA + \Delta T_{1,2}^T + \left(\frac{C_{1,3}^{RT}}{\Delta T_{1,3}^T} \cdot (\Delta T_{1,2}^T + E_1) \right) + E_1 + 2B$$

According to an embodiment the offset K 310 can be calculated using a clock-drift-correction, correcting a clock drift error $C_{1,3}^{RT}$. The deviation $C_{1,3}^{RT}$, representing the clock drift error, represents, for example, a difference between the difference $\Delta T_{1,3}^R$ 262₁ of transmission time stamps and a difference $\Delta T_{1,3}^T$ 262₂ of reception time stamps associated with a reception of the two signals 210, 214 having same signal power levels by the tag 200₂. The difference $\Delta T_{1,3}^T$ 262₂, e.g. represents a difference between a third reception time stamp T_3^T 230₃ of the tag 200₂ describing when the third signal 214 transmitted by the reference station 200₁ is received by the tag 200₂ and a first reception time stamp T_1^T 230₁ of the tag 200₂ describing when the first signal 210 transmitted by the reference station 200₁ is received by the tag 200₂.

A new TDOA equation without the offset K 310 and with all correction values becomes, for example:

$$TDOA_i = \left(\frac{C_{1,3}^{Si}}{\Delta T_{1,3}^{Si}} \cdot (\Delta T_{1,2}^{Si} + E_3 - E_4) \right) + 0.5 \cdot \left(\Delta T_{1,2}^T + \frac{C_{1,3}^{RT}}{\Delta T_{1,3}^T} \cdot (\Delta T_{1,2}^T + E_1) \right) \\ + \Delta T_{1,2}^{Si} + 0.5 \cdot \Delta T_{1,2}^R - A + B + 0.5 \cdot (E_1 - E_2) - E_4 + E_3$$

- According to an embodiment with every measurement it is now possible to obtain one TOA equation and depending on the amount of anchors, i.e. stations 202, different TDOA equations. This method allows to use a high update rate with just four stations for localization in a two dimensional space, two anchors, one reference station and one tag.

$$TOA_1 \cdot c_0 = \sqrt{(x_{R_1} - x_T)^2 + (y_{R_1} - y_T)^2}, \text{ and}$$

$$TDOA_i \cdot c_0 = \sqrt{(x_T - x_{Si})^2 + (y_T - y_{Si})^2} - \sqrt{(x_{R_1} - x_{Si})^2 + (y_{R_1} - y_{Si})^2}$$

- According to an embodiment the index i , e.g., $i \in [1;N]$, wherein $N \geq 2$, represents a number of a station 202, at which the reception time stamps describing the reception times of the two signals 210, 212, one 210 transmitted by the reference station and one 212 transmitted by the tag, are obtained.
- The TDOA equation is, according to an embodiment, not symmetrical due to the dependency on the noise of reference station one, i.e. the reference station 200₁. The selected reference station 200₁ should be the one with the lowest noise otherwise we recommend the reader to have a look in our previous publication about symmetrical TDOA equations [17].
- According to an embodiment an apparatus is configured to obtain, e.g. receive or calculate, time-difference-of-arrivals TDOA's as described according to an embodiment of Fig. 4 and/or Fig. 5.
- According to an embodiment the time-difference-of-arrivals are based on a difference $\Delta T_{1,2}^S$ 260₃ between a first reception time stamp information T_1^S 230₄ of a station 202 and a second reception time stamp information T_2^S 230₅ of the station. The first reception time stamp information T_1^S 230₄ of the station describes, for example, with respect to a clock of the station, when the station receives a first signal 210 transmitted by the reference station 200₁ and the second reception time stamp information T_2^S 230₅ of the station de-

scribes, for example, with respect to the clock of the station, when the station receives a second signal 212 transmitted by the tag 200₂.

5 The theoretical concepts can be verified by real measurements with, for example, a measurement setup as shown in Fig. 6. A two dimension position estimation can be performed with four stations, like a reference station 200₁, a tag 200₂, a first station 202₁ and a second station 202₂. Tests have been carried out, for example, with Decawave EVB DW1000. Decawave provides different message types specified for a discovery phase, ranging phase and final data transmission. A single message can vary depending on the
10 update rate and the preamble length between 190 μ s to 3.4 ms. In our position estimation algorithm, for example, the 190 μ s messages have been used, also called blink messages.

General settings for the TWR and TDOA position estimation can be a channel 2 or a
15 channel 5 of the stations, a center frequency of below 960 MHz, in the range of 3.1 GHz to 10.6 GHz, like 3993.6 MHz, or in the range of 22 GHz to 29 GHz, with a bandwidth of at least 480 MHz, like 499.2 MHz, or of at least 500 MHz. A pulse repetition frequency is, for example, 64 MHz or 16 MHz, a preamble length is of 128 or 1024 and/or a data rate can be 6.81 Mbps or 110 Kbps.

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Figure 6 and table 1 show an exemplarily constellation of the stations. Ground truth data was obtained by laser distance measurement. It is assumed that the position of the tag 200₂ with the identification (ID) two is unknown. The other stations are used to estimate the position of the tag 200₂. The station which is identified as reference station 200₁ can
25 change during the TWR positioning. In other words the first station 202₁ and the second station 202₂ can represent at some point of the measurements the reference station for TOA measurements. This is due to the fact that for TWR trilateration the distances between the tag and the other stations are, for example, obtained successively. In contrast to TDOA, where the reference station remains the same, in this example station with the
30 id one 200₁. This is also the reason why TDOA is much faster than TWR.

Tabelle 1: Position of the stations according to an embodiment

Station ID	X-Axis [m]	Y-Axis [m]
1	0	0
2	0	1.5134
3	1.27	1.643
4	1.1439	0.0385

Figure 7 shows the results for the TOA and TDOA position estimation. A mean of the TOA and TDOA differs, for example, for the x-axis in a range of 0.0001 m to 0.05 m, in a range of 0.0005 m to 0.005 m or in a range of 0.001 m to 0.03 m, like by 0.0023 m and for the y-axis in a range of 0.00001 m to 0.05 m, in a range of 0.00005 m to 0.005 m or in a range of 0.0001 m to 0.001 m, like by 0.0006 m. The small difference indicates that the assumptions of the offset and the clock drift, as presented herein, are correct. Otherwise, if the offset is calculated as the difference and not the sum for TOA the drift between the mean of TOA and TDOA would be for the x-axis in a range of 0.001 m to 1 m, in a range of 0.01 m to 0.5 m or in a range of 0.1 m to 0.2 m, like 0.17 m and for the y-axis in a range of 0.0001 m to 0.5 m, in a range of 0.001 m to 0.05 m or in a range of 0.01 m to 0.04 m, like 0.034 m. The deviation between the mean of the TOA and TDOA measurements with respect to the ground truth data is, for example, due to uncertainty of the antenna delay and the ground truth data estimation.

The following table 2 shows a standard deviation precision for the TOA and TDOA position estimation. The y-axis scattering is, for example, near most equal for both measurement principles. On the other hand according to an embodiment, the x-axis scattering for TDOA is higher compared to the TOA. This effect is, for example, due to the asymmetry of the TDOA, which is actually a fusion between TOA and TDOA. The compensation of this effect is described in an previous publication [17]. In combination with a filter it is possible to obtain highly accurate results. According to an embodiment the position of the anchors effect the tag localization, with a tag more centered with respect to the anchors is it possible to obtain better results [15].

Table 2: Precision: standard Deviation according to an embodiment

	TOA	TDOA
X-Axis [m]	0.0175	0.0479
Y-Axis [m]	0.0249	0.0256

The accuracy depends, for example, on the correct position of the anchors and the offset estimation.

Fig. 6 and Fig. 7 show explicit applications of embodiments of a herein described apparatus. It is clear that Fig. 6 and Fig. 7 show only examples and that the apparatus is not limited hereto.

Herein a method, see Fig. 1 to Fig. 9b, for clock drift, signal power dependency and antenna delay correction for time of arrival and time difference of arrival based measurements is introduced. It was shown how the wireless clock calibration for the time difference of arrival can be provided by an additional station. The corrected time of arrival and time difference of arrival measurements were combination to increase the amount of equations for the time difference of arrival position estimation.

Fig. 8 shows a schematic view of a proposed approach to determine a time stamp power correction information and/or a clock drift correction, which can be used by the inventive apparatus or an external device to calculate TOA and or TDOA. The proposed approach can represent an alternative clock drift correction. The transmitting station (TX) 200₁ is, for example, sending three signals P1 210, P2 212, and P3 214 at transmission time stamps T_1^{TX} 220₁ (T1), T_2^{TX} 220₂ (T2) and T_3^{TX} 220₃ (T3), which represent, for example, a transmission time stamp information, and a receiver 200₂ is, for example, configured to receive the three signals 210, 212 and 214 at the reception time stamps T_1^{RX} 230₁ (T1), T_2^{RX} 230₂ (T2) and T_3^{RX} 230₃ (T3), which can represent a reception time stamp information. The transmitter 200₁ can represent the reference station or optionally any other station and the receiver 200₂ can represent the tag, the first station, the second station or optionally the reference station. According to an embodiment the receiver 200₂ represents the station to be calibrated, for which the time-stamp-correction and or the signal-power-correction is determined.

A clock 300₁ of the transmitter 200₁ and a clock 300₂ of a receiver 200₂ are, for example, not synchronous. The clock 300₁ of the transmitter 200₁ can be indicated as a first clock and the clock 300₂ of the receiver 200₂ can be indicated as a second clock. If the clocks 300₁, 300₂ have no drift, then both clocks 300₁, 300₂ should have the same frequency and the difference between $\Delta T_{1,2} = T2 - T1$ should be the same for the transmitter 200₁ and the receiver 200₂ if the first signal 210 and the second signal 212 have same signal power levels, otherwise $\Delta T_{1,2}^{RX} \neq \Delta T_{1,2}^{TX}$. The same applies for $\Delta T_{1,3}$. If the clock 300₂ of the receiver

200₂ (RX), i.e. the reference station, is faster than the clock 300₁ of the transmitter station TX 200₁, then $\Delta T_{1,3}^{RX} > \Delta T_{1,3}^{TX}$ and the clock drift error equates $C_{1,2} = \Delta T_{1,2}^{RX} - \Delta T_{1,2}^{TX}$ 170₁ and/or $C_{1,3} = \Delta T_{1,3}^{RX} - \Delta T_{1,3}^{TX}$ 170₂.

- 5 According to an embodiment the receiver 200₂ (RX) and/or the transmitter station 200₁ (TX) can determine a clock-drift correction based on the clock drift error $C_{1,2}$ 170₁ and or the clock drift error $C_{1,2}$ 170₂. Alternatively the herein described apparatus is, for example, configured to obtain the transmission time stamp information T_1^{TX} 220₁ (T1), T_2^{TX} 220₂ (T2) and T_3^{TX} 220₃ (T3) from the transmitter station 200₁ (TX) and obtain the reception time stamp information T_1^{RX} 230₁ (T1), T_2^{RX} 230₂ (T2) and T_3^{RX} 230₃ (T3) from the receiver 200₂ (RX) to calculate the clock-drift correction.

The general approaches are using the integrator of the phase locked loop (PLL) to obtain a correction value. Commonly, a frequency difference between two clocks was presented by an integrator of PLL. After the warm-up time the clocks, for example, the clock 300₁ and/or the clock 300₂, reached their final frequency. The clock drift error would now increase linearly. This correction method is less suitable, due to a dependency on the signal power. Alternative methods such as symmetrical and asymmetrical double-sided two way ranging [5] are not obtaining the clock drift but using three or more messages to mean the error. According to an embodiment the apparatus is configured to use TOA and/or TDOA determined by a common method. For short measurement periods the linear clock drift error could also be assumed during the oscillator warm-up, for example, based on the herein proposed approach according to an embodiment of the present invention.

- 25 According to an embodiment, shown in Fig. 8, an apparatus for determining a time stamp power correction information, i.e. a signal-power-correction, on the basis of transmission time stamp information and reception time stamp information associated with the at least three signals 210, 212 and 214 is configured to obtain, for example, the transmission time stamp information comprising the first time stamp T_1^{TX} 220₁, the second transmission time stamp T_2^{TX} 220₂ and the transmission time stamp T_3^{TX} 220₃ and to obtain the reception time stamp information comprising the first reception time stamp T_1^{RX} 230₁, the second reception time stamp T_2^{RX} 230₂ and a third reception time stamp information T_3^{RX} 230₃. The apparatus is, for example, configured to determine the time stamp power correction information using a clock drift correction which is based on transmission time stamp information, comprising the first transmission time stamp T_1^{TX} 220₁ and the third transmission

time stamp T_3^{TX} 220₃, and reception time stamp information, comprising the first reception time stamp T_1^{RX} 230₁ and the third reception time stamp T_3^{RX} 230₃, of at least two signals, for example, the first signal 210 and the third signal 230, having same signal power levels. The first transmission time stamp information T_1^{TX} 220₁, the second transmission time stamp information T_2^{TX} 220₂ and the third transmission time stamp information T_3^{TX} 220₃ are associated with the second clock 300₂ associated with the second transceiver 200₂ and the first reception time stamp information T_1^{RX} 230₁, the second reception time stamp information T_2^{RX} 230₂ and the third reception time stamp information T_3^{RX} 230₃ are associated with the second clock 300₂

Thus the transmission time stamp information and the reception time stamp information of the first signal 210 and the third signal 214 having same signal power levels are, for example, used to determine the clock-drift-correction and the transmission time stamp information and the reception time stamp information of the first signal 210 and the second signal 212 having different signal power levels are, for example, used to determine the time stamp power correction information, i.e. the signal-power-correction.

If the first signal 210 and the third signal 214 have same signal power levels and the second signal 212 has a different signal power level the apparatus is, for example, configured to determine the clock drift correction to correct time stamps related to the second signal using time-interpolation $\frac{\Delta T_{1,2}^{TX}}{\Delta T_{1,3}^{TX}}$ of a deviation $C_{1,3}/170_1$ between a first difference $\Delta T_{1,3}^{TX}/262_1$ of transmission time stamps T_3^{TX}, T_1^{TX} associated with a transmission of the two signals 210, 214 having same signal power levels and a second difference $\Delta T_{1,3}^{RX}/262_2$ of reception time stamps T_3^{RX}, T_1^{RX} associated with a reception of the two signals 210, 214 having same signal power levels. The main idea is, that the clock drift error $C_{1,3} = \Delta T_{1,3}^{RX} - \Delta T_{1,3}^{TX} / 170_1$ can be used to correct the timestamp T_2^{TX} 220₂ with simple linear interpolation.

If the first signal 210 and the second signal 212 have same signal power levels and the third signal 214 has a different signal power level the apparatus is configured to determine the clock drift correction to correct time stamps related to the second signal 212 using time-extrapolation $\frac{\Delta T_{1,3}^{TX}}{\Delta T_{1,2}^{TX}}$ of a deviation $C_{1,2}/170_2$ between a first difference $\Delta T_{1,2}^{TX}/260_1$ of transmission time stamps T_2^{TX}, T_1^{TX} associated with a transmission of the two signals 210, 212 having same signal power levels and a second difference $\Delta T_{1,2}^{RX}/260_2$ of reception time

stamps T_2^{RX}, T_1^{RX} associated with a reception of the two signals 210, 212 having same signal power levels.

According to an embodiment the apparatus is, for example, configured to determine the clock drift correction CDC based on a deviation $C_{1,3}/170_1$ between a first difference $\Delta T_{1,3}^{TX}/262_1$ of transmission time stamps T_3^{TX}, T_1^{TX} associated with a transmission of two signals 210, 214 having same signal power levels and a second difference $\Delta T_{1,3}^{RX}/262_2$ of reception time stamps associated with a reception of the two signals having same signal power levels according to

$$CDC = -\frac{C_{1,3}}{\Delta T_{1,3}^{TX}} \cdot \Delta T_{1,2}^{TX},$$

wherein $\Delta T_{1,2}^{TX}$ is associated with a difference 260₁ of transmission time stamps of a transmission of the two signals having different signal power levels.

According to an embodiment the apparatus is configured to apply the clock drift correction to the deviation 260₁ between the first transmission time stamp information T_1^{TX} and the second transmission time stamp information T_2^{TX} to determine the time stamp power correction information. With this linear interpolation it is possible to estimate a shift of the time stamp 220₂ due to the clock drift. Additionally or alternatively the apparatus is configured to apply the clock drift correction to the deviation 260₂ between the first reception time stamp information T_1^{RX} and the second reception time stamp information T_2^{RX} to determine the time stamp power correction information.

According to an embodiment the apparatus is configured to determine the time stamp power correction information based on a deviation between a first time interval 260₁ between a transmission of two signals 210, 212 having different signal power levels and a second time interval 260₂ between a reception of the two signals 210, 212 having different signal power levels using the clock drift correction which is based on transmission time stamp information T_3^{TX}, T_1^{TX} and reception time stamp information T_3^{RX}, T_1^{RX} of at least two signals 210, 214 having same signal power levels. The first time interval 260₁ represents, for example, an optionally clock-drift-corrected deviation between the first transmission time stamp information T_1^{TX} and the second transmission time stamp information T_2^{TX} and the second time interval 260₂ represents, for example, an optionally clock-drift-corrected deviation between the first reception time stamp information T_1^{RX} and the second reception time stamp information T_2^{RX} .

According to an embodiment the deviation $C_{1,2}/170_2$ is caused by a clock drift and by the different signal power levels. Thus the apparatus can be configured to at least partially remove a contribution $\frac{C_{1,3}}{\Delta T_{1,3}^{TX}} \cdot \Delta T_{1,2}^{TX}$ caused by the clock drift from said deviation $C_{1,2}/170_2$, to thereby obtain a clock drift corrected version $C'_{1,2}$ of the deviation $C_{1,2}/170_2$. Furthermore
 5 the apparatus can be configured to provide the clock drift corrected version $C'_{1,2}$ as the time stamp power correction information or to determine the time stamp power correction information from the clock drift corrected version $C'_{1,2}$.

According to an embodiment the clock drift corrected version $C'_{1,2}$, which is, for example,
 10 associated with a power level, can be calculated according to $C'_{1,2} = C_{1,2} - \frac{C_{1,3}}{\Delta T_{1,3}^{TX}} \cdot \Delta T_{1,2}^{TX}$.

Although the calculation/determination of the clock-drift-correction and/or of the signal-power-correction is explained in Fig. 8 mainly with respect to the apparatus, it is clear, that the calculations can also or alternatively be performed by an external device and the re-
 15 sults can be received by the apparatus.

It is known that the time stamp of the DW1000 is effected by the signal power [3, 2]. Increase in signal power cause to smaller time stamps and vice versa. In Fig. 8 we have shown how a signal-power-correction curve can be obtained without additional measure-
 20 ment equipment automatically for every Decawave UWB transceiver or other transceiver or stations individually. Fig. 9a shows the correction curves for the measured vs. actual signal power and Fig. 9b shows the actual signal vs. the time stamp error.

Figure 9a shows an estimated line based on the estimated slope. The results equate the
 25 one obtained by Decawave, with the difference that in our case no additional measured equipment is required and it can be obtained individually for every station. Figure 9b illustrates the correction curve 110 with respect to the signal power. In other words Fig. 10A and Fig. 10B show final results of a herein proposed power correction, wherein Fig. 10A shows a measured signal power versus a real signal power and wherein Fig. 10B shows a
 30 correction curve representing, for example, a time stamp power correction information for different signal power levels.

According to an embodiment, the signals analyzed herein and, for example, transmitted by a transceiver and received by a transceiver as described in Fig. 1, Fig. 2, Fig. 3, Fig. 4,
 35 Fig. 5, Fig. 6, Fig. 7, Fig. 8, Fig. 9a and/or Fig. 9b are ultra-wideband signals, using ex-

tremely large frequency ranges with a bandwidth of, for example, at least 500 MHz or at least 20% of an arithmetic mean of lower and upper limit frequencies of a used frequency band. According to an embodiment the apparatus is configured to use a time of arrival and a time difference of arrival fusion for ultra-wideband indoor localization. In other words the apparatus is, for example, focused on indoor operating radio frequency (RF) based localization.

Herein a new approach is presented for wireless time difference of arrival clock synchronization for Decawave and other ultra-wideband transceivers. The presented techniques allows to fuse time of arrival and time difference of arrival measurements, without losing the advantages of each approach. The precision and accuracy of the results provided by Decawave ultra-wideband transceivers depends on three effects, the signal power, the clock drift and the antenna delay. It is shown how all the three effects can be compensated for both measurement techniques TOA and TDOA.

In our case is, for example, the synchronization signal part of the localization, without the need to know the time interval. The measurements have been provided, for example, by the Decawave EVK1000 transceivers without additional synchronization hardware. This system is able to operate in indoor environments due to the ability to deal with fading. With the herein proposed methods the signal-power-correction curve can be obtained automatically and the clock drift can be corrected for every measurement. Herein it is shown how to apply this corrections for TOA and TDOA localization.

Although some aspects have been described in the context of an apparatus, it is clear that these aspects also represent a description of the corresponding method, where a block or device corresponds to a method step or a feature of a method step. Analogously, aspects described in the context of a method step also represent a description of a corresponding block or item or feature of a corresponding apparatus.

The inventive methods can be stored on a digital storage medium or can be transmitted on a transmission medium such as a wireless transmission medium or a wired transmission medium such as the Internet.

Depending on certain implementation requirements, embodiments of the invention can be implemented in hardware or in software. The implementation can be performed using a digital storage medium, for example, a floppy disk, a DVD, a CD, a ROM, a PROM, an

EPROM, an EEPROM or a FLASH memory, having electronically readable control signals stored thereon, which cooperate (or are capable of cooperating) with a programmable computer system such that the respective method is performed.

- 5 Some embodiments according to the invention comprise a data carrier having electronically readable control signals, which are capable of cooperating with a programmable computer system, such that one of the methods described herein is performed.

10 Generally, embodiments of the present invention can be implemented as a computer program product with a program code, the program code being operative for performing one of the methods when the computer program product runs on a computer. The program code may, for example, be stored on a machine readable carrier.

15 Other embodiments comprise the computer program for performing one of the methods described herein, stored on a machine readable carrier.

In other words, an embodiment of the inventive method is, therefore, a computer program having a program code for performing one of the methods described herein, when the computer program runs on a computer.

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A further embodiment of the inventive methods is, therefore, a data carrier (or a digital storage medium, or a computer-readable medium) comprising, recorded thereon, the computer program for performing one of the methods described herein.

25 A further embodiment of the inventive method is, therefore, a data stream or a sequence of signals representing the computer program for performing one of the methods described herein. The data stream or the sequence of signals may, for example, be configured to be transferred via a data communication connection, for example, via the Internet.

30 A further embodiment comprises a processing means, for example, a computer, or a programmable logic device, configured to or adapted to perform one of the methods described herein.

35 A further embodiment comprises a computer having installed thereon the computer program for performing one of the methods described herein.

In some embodiments, a programmable logic device (for example, a field programmable gate array) may be used to perform some or all of the functionalities of the methods described herein. In some embodiments, a field programmable gate array may cooperate with a microprocessor in order to perform one of the methods described herein. Generally,
5 the methods are preferably performed by any hardware apparatus.

The above described embodiments are merely illustrative for the principles of the present invention. It is understood that modifications and variations of the arrangements and the details described herein will be apparent to others skilled in the art. It is the intent, there-
10 fore, to be limited only by the scope of the impending patent claims and not by the specific details presented by way of description and explanation of the embodiments herein.

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Claims

1. Apparatus (100) for localizing a tag (200₂), configured for:

5 obtaining a time-of-arrival of one or more signals (210, 212, 214), based on transmission-time-stamps (220₁ - 220₃) and reception-time-stamps (230₁ - 230₃) of two or more signals (210, 212, 214) send between a reference station (200₁) and a tag (200₂);

10 obtaining a first time-difference-of-arrival on the basis of a difference (260₃) between reception time stamps (230₄, 230₅) obtained at a first station (202₁) and describing reception times (230₄, 230₅) of two signals (210, 212), one transmitted by the reference station (200₁) and one transmitted by the tag (200₂), at the first station (202₁);

15 obtaining, a second time-difference-of-arrival on the basis of a difference (260₃) between reception time stamps (230₄, 230₅) obtained at a second station (202₂) and describing reception times (230₄, 230₅) of two signals (210, 212), one transmitted by the reference station (200₁) and one transmitted by the tag (200₂), at the
20 second station (202₂);

calculating a position (140) of the tag (200₂) based on the time-of-arrival and the at least two time-difference-of arrivals.

25 2. The apparatus (100) according to claim 1, wherein the apparatus (100) is configured to obtain the first time-difference-of-arrival, wherein first time-difference-of-arrival is based on a difference (260₃) between a first reception time stamp information (230₄) of the first station (202₁) and a second reception time stamp information (230₅) of the first station (202₁), and

30 wherein the apparatus (100) is configured to obtain the second time-difference-of-arrival, wherein the second time-difference-of-arrival is based on a difference (260₃) between a first reception time stamp information (230₄) of the second station (202₂) and a second reception time stamp information (230₅) of the second station
35 (202₂);

wherein the first reception time stamp information (230₄) of the first station (202₁) describes when the first station (202₁) receives a first signal (210) transmitted by the reference station (200₁),

5 wherein the second reception time stamp information (230₅) of the first station (202₁) describes when the first station (202₁) receives a second signal (212) transmitted by the tag (200₂),

10 wherein the first reception time stamp information (230₄) of the second station (202₂) describes when the second station (202₂) receives the first signal (210) transmitted by the reference station (200₁), and

15 wherein the second reception time stamp information (230₅) of the second station (202₂) describes when the second station (202₂) receives the second signal (212) transmitted by the tag (200₂).

20 3. The apparatus (100) according to claim 2, wherein the first time-difference-of-arrival is calculated using a signal-power-correction (240₃, 240₄) to correct the first reception time stamp information (230₄) of the first station (202₁) and the second reception time stamp information (230₅) of the first station (202₁); and/or

25 wherein the second time-difference-of-arrival is calculated using a signal-power-correction (240₃, 240₄) to correct the first reception time stamp information (230₄) of the second station (202₂) and the second reception time stamp information (230₅) of the second station (202₂).

30 4. The apparatus (100) according to one of the claims 1 to 3, wherein the first time-difference-of-arrival and/or the second time-difference-of-arrival is calculated using an offset (310), describing a time delay between a transmission of the two signals (210, 212), one transmitted by the reference station (200₁) and one transmitted by the tag (200₂).

35 5. The apparatus (100) according to claim 4, wherein the offset (310) is determined based on the time-of-arrival, based on a first reception-time-stamp of the tag (200₂) describing, when a first signal (210), transmitted by the reference station (200₁), is received by the tag (200₂), and based on a first transmission-time-stamp (220₂) of

the tag (200₂) describing, when a second signal (212), is transmitted by the tag (200₂), using a clock-drift-correction and/or an antenna-delay-correction (250₁, 250₂) and/or a signal-power-correction (240₁).

- 5 6. The apparatus (100) according to claim 5, wherein clock-drift-correction used for the determination of the offset (310) is based on transmission time stamps (220₃) and reception time stamps (230₃) related to a third signal (214) transmitted by the reference station (200₁) and received by the tag (200₂).

- 10 7. The apparatus (100) according to one of the claims 4 to 6, wherein the offset (310) K is determined according to

$$K = TOA + \Delta T_{1,2}^T + \left(\frac{C_{1,3}^{RT}}{\Delta T_{1,3}^T} \cdot (\Delta T_{1,2}^T + E_1) \right) + E_1 + 2B,$$

wherein the value TOA represents the time-of-arrival of the one or more signals (210, 212) transmitted between the reference station (200₁) and the tag (200₂);

15

wherein $\Delta T_{1,2}^T$ (260₂) represents a difference between a first transmission time stamp (220₂) of the tag (200₂) describing when a second signal (212) is transmitted by the tag (200₂) and a first reception time stamp (230₁) of the tag (200₂) describing when a first signal (210) transmitted by the reference station (200₁) is received by the tag (200₂);

20

wherein the deviation $C_{1,3}^{RT}$ (170₁) represents a difference between a difference (262₁) of transmission time stamps (220₁, 220₃) associated with a transmission of two signals (210, 214) having same signal power levels, transmitted by the reference station (200₁), and a difference $\Delta T_{1,3}^T$ (262₂) of reception time stamps (230₁, 230₃) associated with a reception of the two signals (210, 214) having same signal power levels by the tag (200₂);

25

wherein the value E_1 (240₁) represents a signal power-correction, associated with a correction of reception time stamps (230₁, 230₃) of the tag (200₂) for received signals (210, 214) with a first signal power level; and

30

wherein the value B (250₂) represents an antenna-delay correction related to the tag (200₂).

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8. The apparatus (100) according to one of the claims 1 to 7, wherein the first time-difference-of-arrival and the second time-difference-of-arrival are determined according to

$$TDOA_i = \Delta T_{1,2}^{Si} - E_4 + E_3 + K,$$

5 wherein the index i represents a number of a station S_i (202), at which the reception time stamps (230₄, 230₅) describing the reception times of the two signals (210, 212), one transmitted by the reference station (200₁) and one transmitted by the tag (200₂), and used to determine the difference $\Delta T_{1,2}^{Si}$ (260₃) between the reception time stamps (230₄, 230₅), are obtained;

10

wherein the value E_3 (240₃) represents a signal power-correction, associated with a correction of reception time stamps (230₄, 230₆) of the Station S_i (202) for received signals (210, 214) with a first signal power level;

15

wherein the value E_4 (240₄) represents a signal power-correction, associated with a correction of reception time stamps (230₅) of the Station S_i (202) for received signals (212) with a second signal power level; and

20

wherein the value K represents an offset (310) describing a time delay between a transmission of the two signals (210, 212), one transmitted by the reference station (200₁) and one transmitted by the tag (200₂).

9. The apparatus (100) according to one of the claims 1 to 8, wherein the first time-difference-of-arrival is calculated using a clock-drift-correction to correct the difference (260₃) between the reception time stamps (230₄, 230₅) obtained at the first station (202₁) and/or to correct signal-power-corrections (240₃, 240₄) correcting the reception time stamps (230₄, 230₅) obtained at the first station (202₁); and/or
- 25 wherein the second time-difference-of-arrival is calculated using a clock-drift-correction to correct the difference (260₃) between the reception time stamps (230₄, 230₅) obtained at the second station (202₂) and/or to correct signal-power-corrections correcting the reception time stamps (230₄, 230₅) obtained at the second station (202₂).

30

10. The apparatus (100) according to claim 9, wherein the clock-drift-correction used to calculate the first time-difference-of-arrival is based on a transmission time stamp (220₃) and a reception time stamp (230₆) related to a third signal (214)

35

transmitted by the reference station (200₁) and received by the first station (202₁) and/or

wherein the clock-drift-correction used to calculate the second time-difference-of-arrival is based on a transmission time stamp (220₃) and a reception time stamp (230₆) related to the third signal (214) transmitted by the reference station (200₁) and received by the second station (202₂).

11. The apparatus (100) according to one of the claims 1 to 10, wherein the first time-difference-of-arrival and the second time-difference-of-arrival are calculated according to

$$TDOA_i = \Delta T_{1,2}^{Si} + \left(\frac{C_{1,3}^{Si}}{\Delta T_{1,3}^{Si}} \cdot (\Delta T_{1,2}^{Si} + E_3 - E_4) \right) - E_4 + E_3 + K,$$

wherein the index i represents a number of a station Si (202), at which the reception time stamps (230₄, 230₅) describing the reception times of the two signals (210, 212), one transmitted by the reference station (200₁) and one transmitted by the tag (200₂), and used to determine the difference $\Delta T_{1,2}^{Si}$ (260₃) between the reception time stamps (230₄, 230₅), are obtained;

wherein the deviation $C_{1,3}^{Si}$ represents a difference between a difference (262₁) of transmission time stamps (220₁, 220₃) associated with a transmission of two signals (210, 214) having same signal power levels, transmitted by the reference station (200₁), and a difference $\Delta T_{1,3}^{Si}$ (262₃) of reception time stamps (230₄, 230₆) associated with a reception of the two signals (210, 214) having same signal power levels by the station Si (202);

wherein the value E₃ (240₃) represents a signal power-correction, associated with a correction of reception time stamps (230₄, 230₆) of the station Si (202) for received signals (210, 214) with a first signal power level

wherein the value E₄ (240₄) represents a signal power-correction, associated with a correction of reception time stamps of the station Si (202) for received signals with a second signal power level; and

wherein the value K represents an offset (310) describing a time delay between a transmission of the two signals, one transmitted by the reference station (200₁) and one transmitted by the tag (200₂).

12. The apparatus (100) according to one of the claims 1 to 11, wherein the first time-difference-of-arrival and the second time-difference-of-arrival are calculated according to

$$TDOA_i = \left(\frac{C_{1,3}^{Si}}{\Delta T_{1,3}^{Si}} \cdot (\Delta T_{1,2}^{Si} + E_3 - E_4) \right) + 0.5 \cdot \left(\Delta T_{1,2}^T + \frac{C_{1,3}^{RT}}{\Delta T_{1,3}^T} \cdot (\Delta T_{1,2}^T + E_1) \right) \\ + \Delta T_{1,2}^{Si} + 0.5 \cdot \Delta T_{1,2}^R - A + B + 0.5 \cdot (E_1 - E_2) - E_4 + E_3,$$

wherein the index i represents a number of a station Si (202), at which the reception time stamps (230₄, 230₅) describing the reception times of the two signals (210, 212), one transmitted by the reference station (200₁) and one transmitted by the tag (200₂), and used to determine the difference $\Delta T_{1,2}^{Si}$ between the reception time stamps (230₄, 230₅) are obtained;

wherein the deviation $C_{1,3}^{Si}$ represents a difference between a difference (262₁) of transmission time stamps (220₁, 220₃) associated with a transmission of two signals (210, 214) having same signal power levels, transmitted by the reference station (200₁), and a difference $\Delta T_{1,3}^{Si}$ (262₃) of reception time stamps (230₄, 230₆) associated with a reception of the two signals (210, 214) having same signal power levels by the station Si (202);

wherein the value E_1 (240₁) represents a signal power-correction, associated with a correction of reception time stamps (230₁, 230₃) of the tag (200₂) for received signals with a first signal power level;

wherein the value E_2 (240₂) represents a signal power-correction, associated with a correction of reception time stamps (230₂) of the reference station (200₁) for received signals with a second signal power level;

wherein the value E_3 (240₃) represents a signal power-correction, associated with a correction of reception time stamps (230₄, 230₆) of the station Si (202) for received signals with a first signal power level;

wherein the value E_4 (240₄) represents a signal power-correction, associated with a correction of reception time stamps (230₅) of the station Si (202) for received signals (212) with a second signal power level;

wherein $\Delta T_{1,2}^T$ (260₂) represents a difference between a first transmission time stamp (220₂) of the tag (200₂) describing when a second signal (212) is transmitted by the tag (200₂) and a first reception time stamp (230₁) of the tag (200₂) describing when a first signal (210) transmitted by the reference station (200₁) is received by the tag (200₂);

wherein the deviation $C_{1,3}^{RT}$ (170₁) represents a difference between a difference (262₁) of transmission time stamps (220₁, 220₃) associated with a transmission of two signals (210, 214) having same signal power levels, transmitted by the reference station (200₁), and a difference $\Delta T_{1,3}^T$ (262₂) of reception time stamps (230₁, 230₃) associated with a reception of the two signals (210, 214) having same signal power levels by the tag (200₂);

wherein $\Delta T_{1,2}^R$ (260₁) represents a difference between a first reception time stamp (230₂) of the reference station (200₁) describing when the second signal (212) transmitted by the tag (200₂) is received by the reference station (200₁) and a first transmission time stamp (220₁) of the reference station (200₁) describing when the first signal (210) is transmitted by the reference station (200₁);

wherein the value A (250₁) represents an antenna-delay correction related to the reference station (200₁); and

wherein the value B (250₂) represents an antenna-delay correction related to the tag (200₂).

13. The apparatus (100) according to one of the claims 1 to 13, wherein the time-of-arrival is calculated based on a transmission time stamp (220₁) and a reception time stamp (230₁) of a first signal (210) transmitted by the reference station (200₁) and received by the tag (200₂) and a transmission time stamp (220₂) and a reception time stamp (230₂) of a second signal (212) transmitted by the tag (200₂) and received by the reference station (200₁).

14. The apparatus (100) according to one of the claims 1 to 14, wherein the time-of-arrival TOA is calculated according to

$$TOA = 0.5 \cdot \left((T_2^R - T_1^R) - (T_2^T - T_1^T) - E_1 - E_2 \right) - A - B,$$

wherein T_1^R (220₁) represents a first transmission time stamp (220₁) of the reference station (200₁) describing when a first signal (210) is transmitted from the reference station (200₁),

5

wherein T_1^T (230₁) represents a first reception time stamp (230₁) of the tag (200₂) describing when the first signal (210) transmitted from the reference station (200₁) is received by the tag (200₂),

10

wherein T_2^T (220₂) represents a first transmission time stamp (220₂) of the tag (200₂) describing when a second signal (212) is transmitted from the tag (200₂),

wherein T_2^R (230₂) represents a first reception time stamp (230₂) of the reference station (200₁) describing when the second signal (212) transmitted from the tag (200₂) is received by the reference station (200₁),

15

wherein the value E_1 (240₁) represents a signal power-correction, associated with a correction of the first reception time stamp T_1^T (230₁) of the tag (200₂), based on a first signal power level of the first signal (210);

20

wherein the value E_2 (240₂) represents a signal power-correction, associated with a correction of the first reception time stamp (230₂) T_2^R of the reference station (200₁), based on a signal power level of the second signal (212);

25

wherein the value A (250₁) represents an antenna-delay correction related to the reference station (200₁); and

wherein the value B (250₂) represents an antenna-delay correction related to the tag (200₂).

30

15. The apparatus (100) according to one of the claims 1 to 14, wherein the clock-drift-correction used to calculate the time-of-arrival is based on a transmission time stamp (220₃) and a reception time stamp (230₃) related to a third signal (214) transmitted by the reference station (200₁) and received by the tag (200₂).

35

16. The apparatus (100) according to one of the claims 1 to 15, wherein the time-of-arrival is calculated using a clock-drift-correction to correct the difference between a first transmission time stamp (220₂) of the tag (200₂), describing when a second signal (212) is transmitted by the tag (200₂), and a first reception time stamp (230₁) of the tag (200₂), describing when a first signal (210) transmitted from the reference station (200₁) is received by the tag (200₂), and/or wherein a signal-power-correction (240₁) correcting the first reception time stamp (230₁) obtained at the tag (200₂) is performed.

17. The apparatus (100) according to one of the claims 1 to 16, wherein the time-of-arrival TOA is calculated according to

$$TOA = 0.5 \cdot \left(\Delta T_{1,2}^R - \Delta T_{1,2}^T - \frac{C_{1,3}^{RT}}{\Delta T_{1,3}^T} \cdot (\Delta T_{1,2}^T + E_1) - E_2 - E_1 \right) + Z,$$

wherein the deviation $C_{1,3}^{RT}$ (170₁) represents a difference between a difference (262₁) of transmission time stamps (220₁, 220₃) associated with a transmission of two signals (210, 214) having same signal power levels, transmitted by the reference station (200₁), and a difference $\Delta T_{1,3}^T$ (262₂) of reception time stamps (230₁, 230₃) associated with a reception of the two signals (210, 214) having same signal power levels by the tag (200₂);

wherein $\Delta T_{1,2}^R$ (260₁) represents a difference between a first reception time stamp (230₂) of the reference station (200₁) describing when the second signal (212) transmitted by the tag (200₂) is received by the reference station (200₁) and a first transmission time stamp (220₁) of the reference station (200₁) describing when the first signal (210) is transmitted by the reference station (200₁);

wherein $\Delta T_{1,2}^T$ (260₂) represents a difference between a first transmission time stamp (220₂) of the tag (200₂) describing when a second signal (212) is transmitted by the tag (200₂) and a first reception time stamp (230₁) of the tag (200₂) describing when a first signal (210) transmitted by the reference station (200₁) is received by the tag (200₂);

wherein the value E_1 (240₁) represents a signal power-correction, associated with a correction of reception time stamps (230₁, 230₃) of the tag (200₂) for received signals (230₁, 230₃) with a first signal power level;

wherein the value E_2 (240₂) represents a signal power-correction, associated with a correction of reception time stamps (230₂) of the reference station (200₁) for received signals (212) with a second signal power level; and

5 wherein Z represents a constant offset.

18. The apparatus (100) according to one of the claims 1 to 17, wherein the apparatus (100) is configured to calculate the position (140) of the tag (200₂)

10 using a distance information describing a distance between the reference station (200₁) and the tag (200₂), which is based on the time-of-arrival;

15 using a first distance difference information describing a difference between a distance between the reference station (200₁) and the first station (202₁) and a distance between the tag (200₂) and the first station (202₁), which is based on the first time-difference-of-arrival;

20 using a second distance difference information describing a difference between a distance between the reference station (200₁) and the second station (202₂), and a distance between the tag (200₂) and the second station (202₂), which is based on the second time-difference-of-arrival; and

25 using an information about positions of the reference station (200₁), of the first station (202₁) and of the second station (202₂).

19. The apparatus (100) according to one of the claims 1 to 18, wherein the apparatus (100) is configured to calculate the position (140) of the tag (200₂) using an intersection of

30 a first circle or sphere, which is determined by an information about a position of the reference station (200₁) and the time-of-arrival TOA;

35 a first hyperbola or a first hyperboloid, which is determined by an information about a position of the reference station (200₁) and of the first station (202₁) and the first time-difference-of-arrival; and

a second hyperbola or a second hyperboloid, which is determined by an information about a position of the reference station (200₁) and of the second station (202₂) and the second time-difference-of-arrival.

- 5 20. The apparatus (100) according to one of the claims 1 to 19, wherein the apparatus (100) is configured to solve a system of equations to calculate the position (140) of the tag (200₂),

10 wherein a first of the equations describes a first circle or a first sphere centered at a position of the reference station (200₁), wherein a radius of the first circle or of the first sphere is determined by the time-of-arrival;

15 wherein a second of the equations describes a first hyperbola or a first hyperboloid, foci of which are at a position of the reference station (200₁) and at a position of the first station (202₁), wherein an absolute difference of distances of points of the first hyperbola or of the first hyperboloid from the foci is determined by the first time-difference-of-arrival;

20 wherein a third of the equations describes a second hyperbola or a second hyperboloid, foci of which are at a position of the reference station (200₁) and at a position of the second station (202₂), wherein an absolute difference of distances of points of the second hyperbola or of the second hyperboloid from the foci is determined by the second time-difference-of-arrival;

- 25 21. The apparatus (100) according to one of the claims 1 to 20, wherein the apparatus (100) is configured to calculate the position (140) of the tag (200₂) using a multiplication of the time-of-arrival with a propagation speed of a signal, using a multiplication of the first time-difference-of-arrival with the propagation speed of the signal and using a multiplication of the second time-difference-of-arrival with the propagation speed of the signal, based on a lateration.
- 30

22. The apparatus (100) according to claim 21, wherein the multiplication of the time-of-arrival with a propagation speed of the signal represents a distance between the reference station (200₁) and the tag (200₂);

wherein the multiplication of the first time-difference-of-arrival with the propagation speed of the signal represents a difference between a distance between the reference station (200₁) and the first station (202₁) and a distance between the tag (200₂) and the first station (202₁); and

5

wherein the multiplication of the second time-difference-of-arrival with the propagation speed of the signal represents a difference between a distance between the reference station (200₁) and the second station (202₂) and a distance between the tag (200₂) and the second station (202₂); and

10

using an information about positions of the reference station (200₁), of the first station (202₁) and of the second station (202₂).

23. The apparatus (100) according to one of the claims 1 to 22, wherein the apparatus (100) is configured to calculate the position (140) of the tag (200₂) by solving an equation system according to

15

$$\begin{aligned} TOA \cdot c_0 &= \sqrt{(x_R - x_T)^2 + (y_R - y_T)^2}, \text{ and} \\ TDOA_i \cdot c_0 &= \sqrt{(x_T - x_{Si})^2 + (y_T - y_{Si})^2} - \sqrt{(x_R - x_{Si})^2 + (y_R - y_{Si})^2} \\ &\text{and/or} \\ TOA_n \cdot c_0 &= \sqrt{(x_{Rn} - x_T)^2 + (y_{Rn} - y_T)^2 + (z_{Rn} - z_T)^2}, \text{ and} \\ TDOA_i \cdot c_0 &= \sqrt{(x_T - x_{Si})^2 + (y_T - y_{Si})^2 + (z_T - z_{Si})^2} \\ &\quad - \sqrt{(x_{Rn} - x_{Si})^2 + (y_{Rn} - y_{Si})^2 + (z_{Rn} - z_{Si})^2} \end{aligned}$$

20

wherein the value TOA represents the time-of-arrival;

wherein the value TDOA represents the time-difference-of-arrival;

wherein the value c_0 represents a propagation speed of a signal;

25

wherein x represents a first coordinate in a 3D-space, wherein y represents a second coordinate in a 3D-space and wherein z represents a third coordinate in a 3D-space;

30

wherein the Index R indicates a reference station (200₁);

wherein the Index T indicates a tag (200₂);

wherein the Index Si indicates an i-th station (202); and

5 wherein the Index n represents a number of a reference station (200₁) R.

24. The apparatus (100) according to one of the claims 1 to 23, wherein the apparatus
(100) is configured to obtain a first transmission time stamp information (220₁) of
the reference station (200₁) describing when the reference station (200₁) transmits
10 a first signal (210) with a first signal power level, a first reception time stamp infor-
mation (230₄) of the first station (202₁) describing when the first station (202₁) re-
ceives the first signal (210) transmitted by the reference station (200₁), a first re-
ception time stamp information (230₄) of the second station (202₂) describing when
the second station (202₂) receives the first signal (210) transmitted by the refer-
15 ence station (200₁) and a first reception time stamp information (230₁) of the tag
(200₂) describing when the tag (200₂) receives the first signal (210) transmitted by
the reference station (200₁); and

wherein the apparatus (100) is configured to obtain a first transmission time stamp
20 information (220₂) of the tag (200₂) describing when the tag (200₂) transmits a sec-
ond signal (212), a second reception time stamp information (230₅) of the first sta-
tion (202₁) describing when the first station (202₁) receives the second signal (212)
transmitted by the tag (200₂), a first reception time stamp information (230₄) of the
second station (202₂) describing when the second station (202₂) receives the sec-
25 ond signal (212) transmitted by the tag (200₂) and a first reception time stamp in-
formation (230₂) of the reference station (200₁) describing when the reference sta-
tion (200₁) receives the second signal (212) transmitted by the tag (200₂); and/or

wherein the apparatus (100) is configured to obtain a second transmission time
stamp information (220₃) of the reference station (200₁) describing when the refer-
30 ence station (200₁) transmits a third signal (214) with the first signal power level, a
third reception time stamp information (230₆) of the first station (202₁) describing
when the first station (202₁) receives the third signal (214) transmitted by the refer-
ence station (200₁), a third reception time stamp information (230₆) of the second
station (202₂) describing when the second station (202₂) receives the third signal
35 (214) transmitted by the reference station (200₁) and a second reception time

stamp information (230₃) of the tag (200₂) describing when the tag (200₂) receives the third signal (214) transmitted by the reference station (200₁).

25. The apparatus (100) according to claim 24, wherein the apparatus (100) is configured to obtain a first signal-power-correction (240₁) for correcting the first reception time stamp information (230₁) of the tag (200₂) and the second reception time stamp information (230₃) of the tag (200₂) based on the first signal power level of the first and the third signal (214);

10 wherein the apparatus (100) is configured to obtain a second signal-power-correction (240₂) for correcting the first reception time stamp information (230₂) of the reference station (200₁) based on a signal power level of the second signal (212);

15 wherein the apparatus (100) is configured to obtain a third signal-power-correction (240₃) for correcting the first reception time stamp information (230₄) of the first station (202₁) and the third reception time stamp information (230₆) of the first station (202₁) based on the first signal power level of the first and the third signal (214);

20 wherein the apparatus (100) is configured to obtain a fourth signal-power-correction (240₄) for correcting the second reception time stamp information (230₅) of the first station (202₁) based on the signal power level of the second signal (212);

25 wherein the apparatus (100) is configured to obtain a fifth signal-power-correction (240₃) for correcting the first reception time stamp information (230₄) of the second station (202₂) and the third reception time stamp information (230₆) of the second station (202₂) based on the first signal power level of the first and the third signal (214);

30 wherein the apparatus (100) is configured to obtain a sixth signal-power-correction (240₄) for correcting the second reception time stamp information (230₅) of the second station (202₂) based on the signal power level of the second signal (212); and

35

wherein the apparatus (100) is configured to use the signal-power-corrections (240) in order to correct respective time stamp information.

26. The apparatus (100) according to claim 24 or claim 25, wherein the first signal-power-correction (240₁) is related to the tag (200₂), the second signal-power-correction (240₂) is related to the reference station (200₁), the third signal-power-correction (240₃) and the fourth signal-power-correction (240₄) are related to the first station (202₁) and the fifth signal-power-correction (240₅) and the sixth signal-power-correction (240₆) are related to the second station (202₂); and

wherein the first signal-power-correction (240₁), the second signal-power-correction (240₂), the third signal-power-correction (240₃), the fourth signal-power-correction (240₄), the fifth signal-power-correction (240₅) and the sixth signal-power-correction (240₆) are based on a deviation between

a first time interval (260₁) between a transmission of two signals (210, 212) having different signal power levels, wherein the first time interval (260₁) is described by a difference of transmission time stamps (220₁, 220) related to a first clock (300₁), and

a second time interval (260₂) between a reception of the two signals (210, 212) having different signal power levels by the station (202) related to the respective signal-power-correction (240₁-240₆), wherein the second time interval (260₂) is described by a difference of reception time stamps (230₁, 230) related to a second clock (300₂) representing a clock of the station (202) related to the respective signal-power-correction (240₁-240₆),

and obtained using a clock-drift-correction which is based on transmission time stamp information (220₁, 220₃) and reception time stamp information (230₁, 230₃) of at least two signals (210, 214) having same signal power levels.

27. The apparatus (100) according to one of the claims 1 to 26, wherein the apparatus (100) is configured to obtain a first antenna-delay correction value (250₁) for correcting transmission time stamps (220₁) and reception time stamps (230₂) related to the reference station (200₁);

wherein the apparatus (100) is configured to obtain a second antenna-delay correction value (250₂) for correcting transmission time stamps (220₂) and reception time stamps (230₁) related to the tag (200₂);

wherein the apparatus (100) is configured to obtain a third antenna-delay correction value (250) for correcting transmission time stamps and reception time stamps (230₄-230₆) related to the first station (202₁);

5

wherein the apparatus (100) is configured to obtain a fourth antenna-delay correction value (250) for correcting transmission time stamps and reception time stamps (230₄-230₆) related to the second station (202₂); and

10

wherein the apparatus (100) is configured to use the first antenna-delay correction value (250₁), second antenna-delay correction value (250₂), third antenna-delay correction value (250) and/or fourth antenna-delay correction value (250) to obtain the time-of-arrival, the first time-difference-of-arrival and the second time-difference-of-arrival.

15

28. The apparatus (100) according to one of the claims 1 to 27, wherein the clock-drift-correction is determined using time-interpolation or time-extrapolation of a deviation (170₁, 170₂) between

20

a first difference (260₁, 262₁) of transmission time stamps associated with a transmission of two signals having same signal power levels and

a second difference (260₂, 262₂) of reception time stamps associated with a reception of the two signals having same signal power levels,

25

wherein the first difference (260₁, 262₁) is related to a first clock (300₁) and the second difference (260₂, 262₂) is related to a second clock (300₂); and

30

wherein the apparatus (100) is configured to use the clock-drift-correction to obtain the time-of-arrival, the first time-difference-of-arrival and the second time-difference-of-arrival.

29. Method for localizing a tag, comprising:

obtaining a time-of-arrival of one or more signals, based on transmission-time-stamps and reception-time-stamps of two or more signals send between a reference station and a tag;

5 obtaining a first time-difference-of-arrival on the basis of a difference between reception time stamps obtained at a first station and describing reception times of two signals, one transmitted by the reference station and one transmitted by the tag, at the first station;

10 obtaining, a second time-difference-of-arrival on the basis of a difference between reception time stamps obtained at a second station and describing reception times of two signals, one transmitted by the reference station and one transmitted by the tag, at the second station; and

15 calculating a position of the tag based on the time-of-arrival and the at least two time-difference-of arrivals.

30. Computer program having a program code for performing, when running on a computer, a method of claim 29.

20

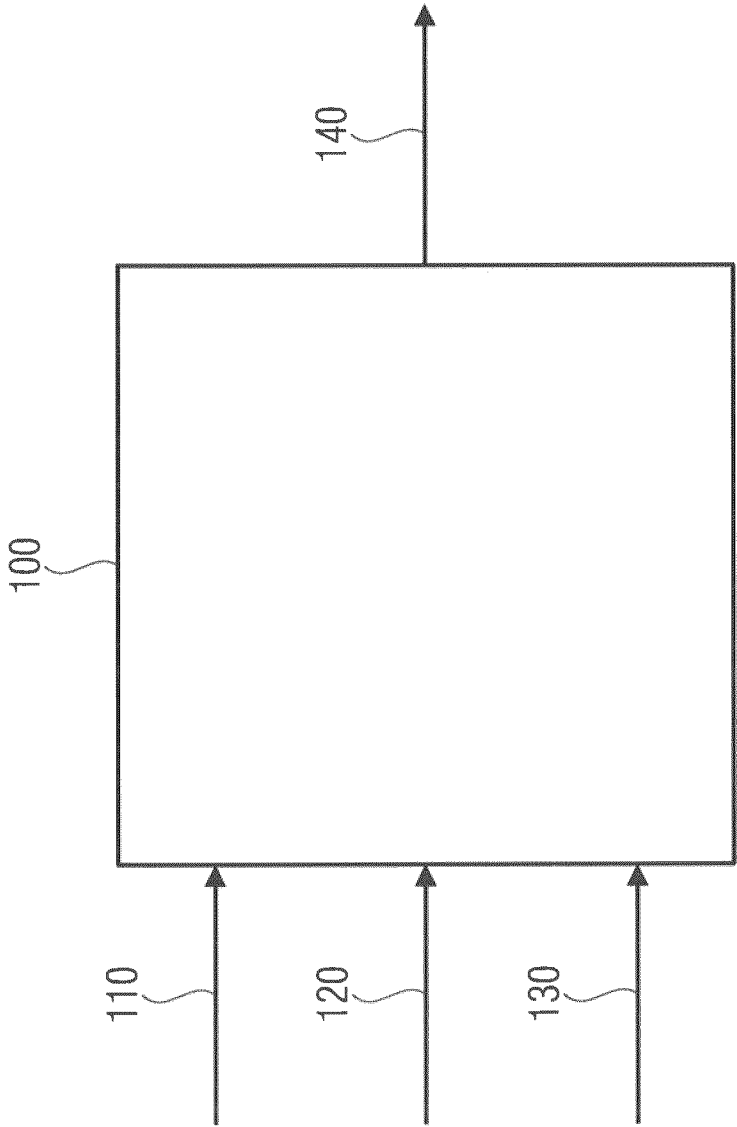


Fig. 1

2/9

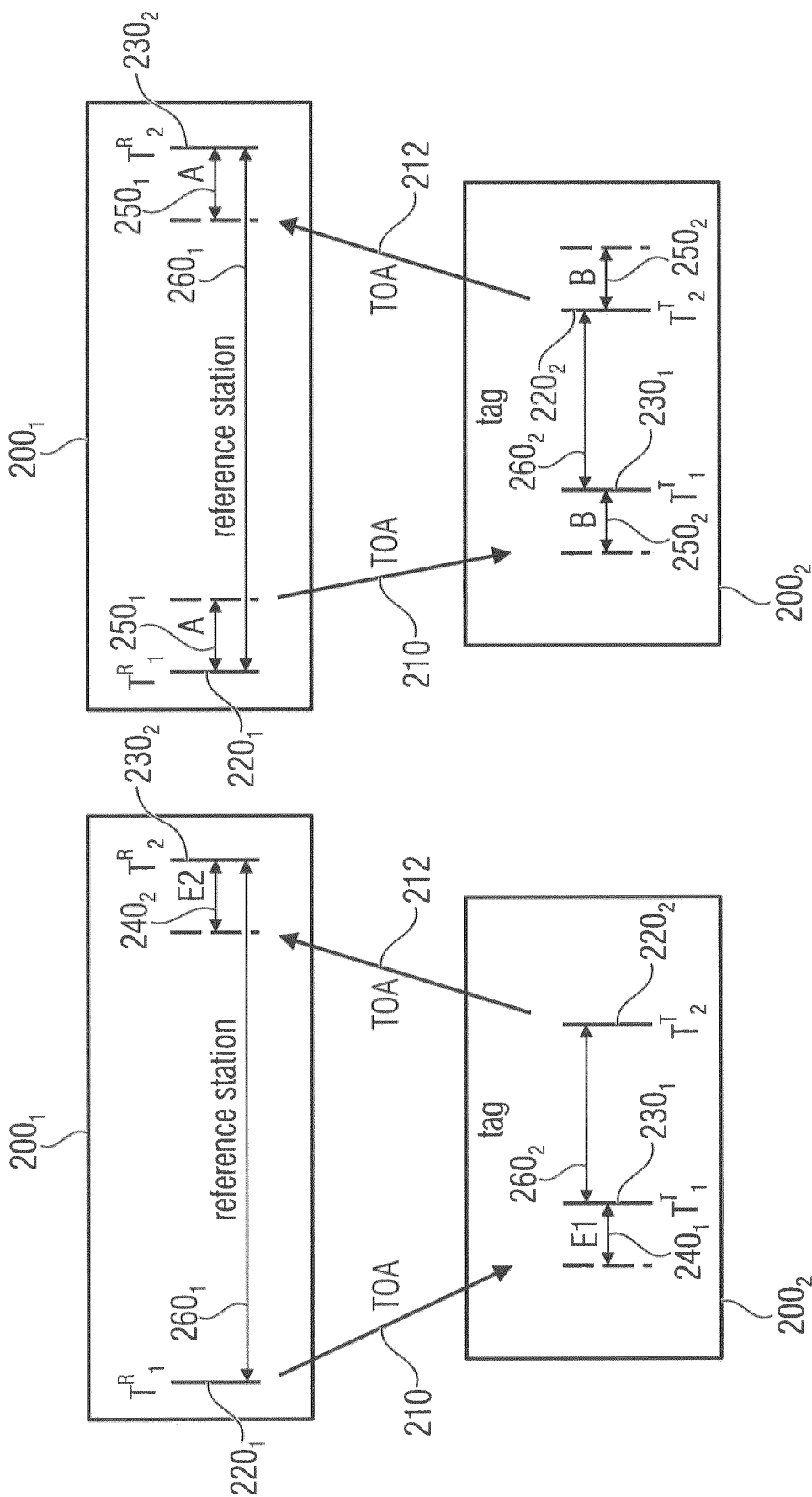


Fig. 2

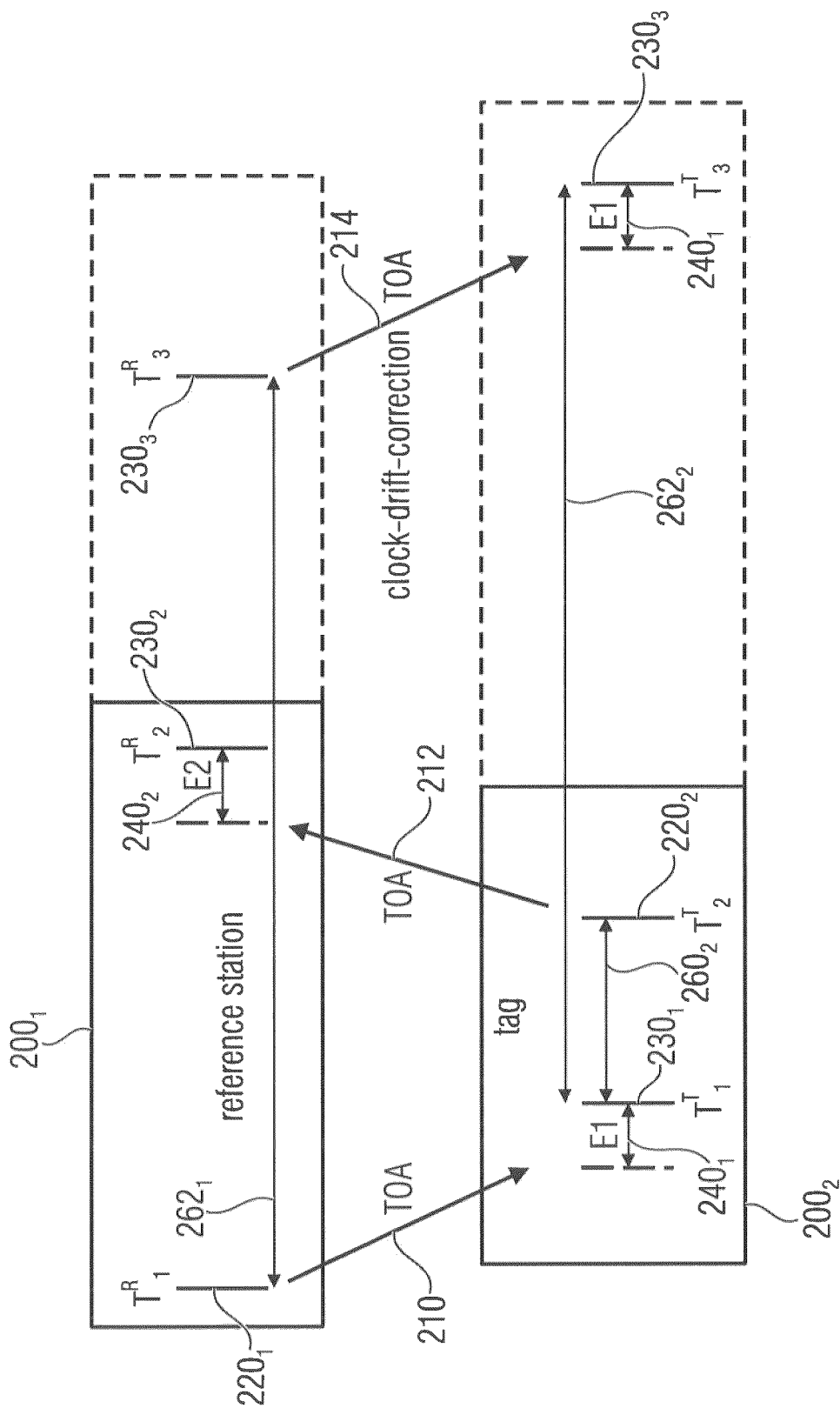


Fig. 3

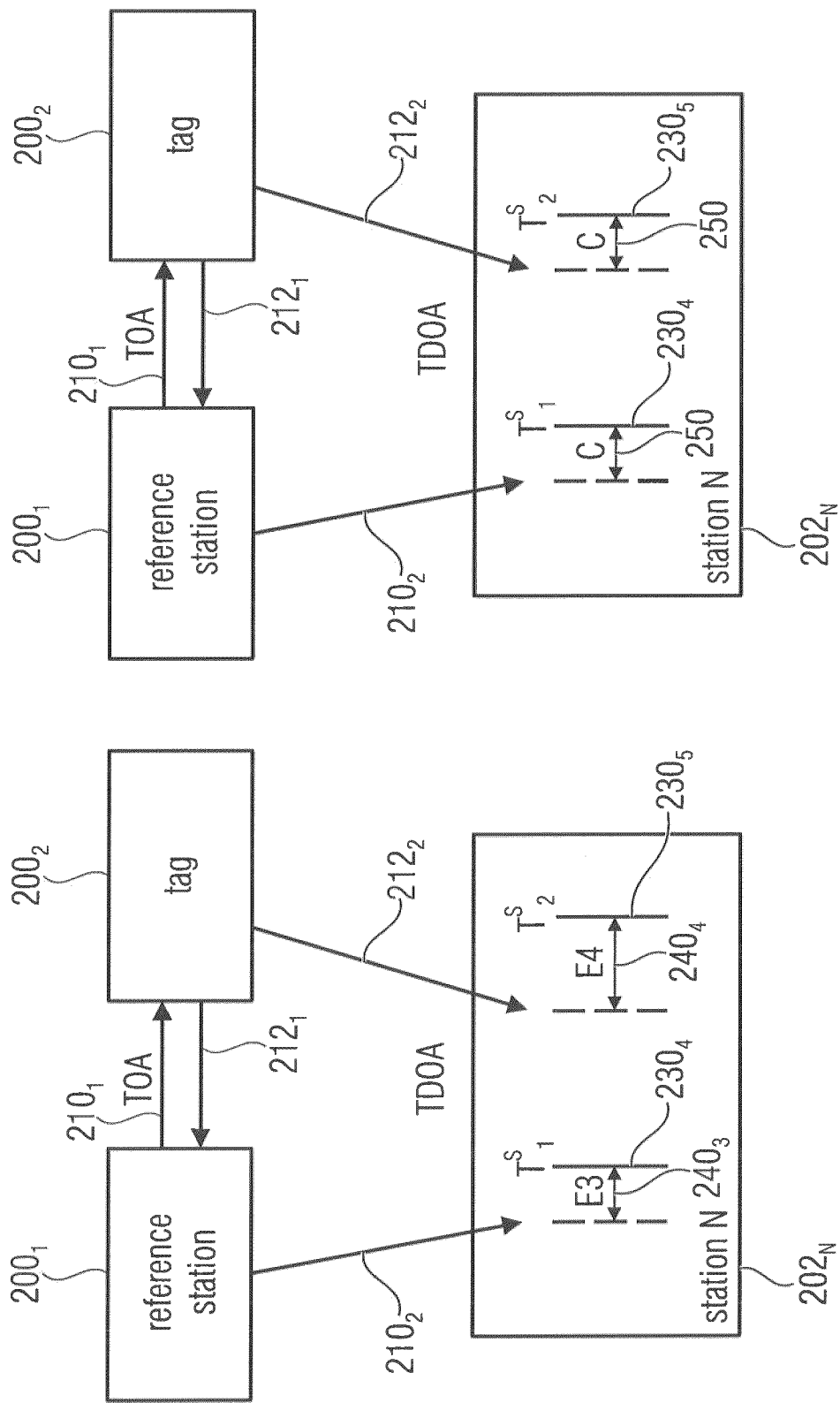


Fig. 4

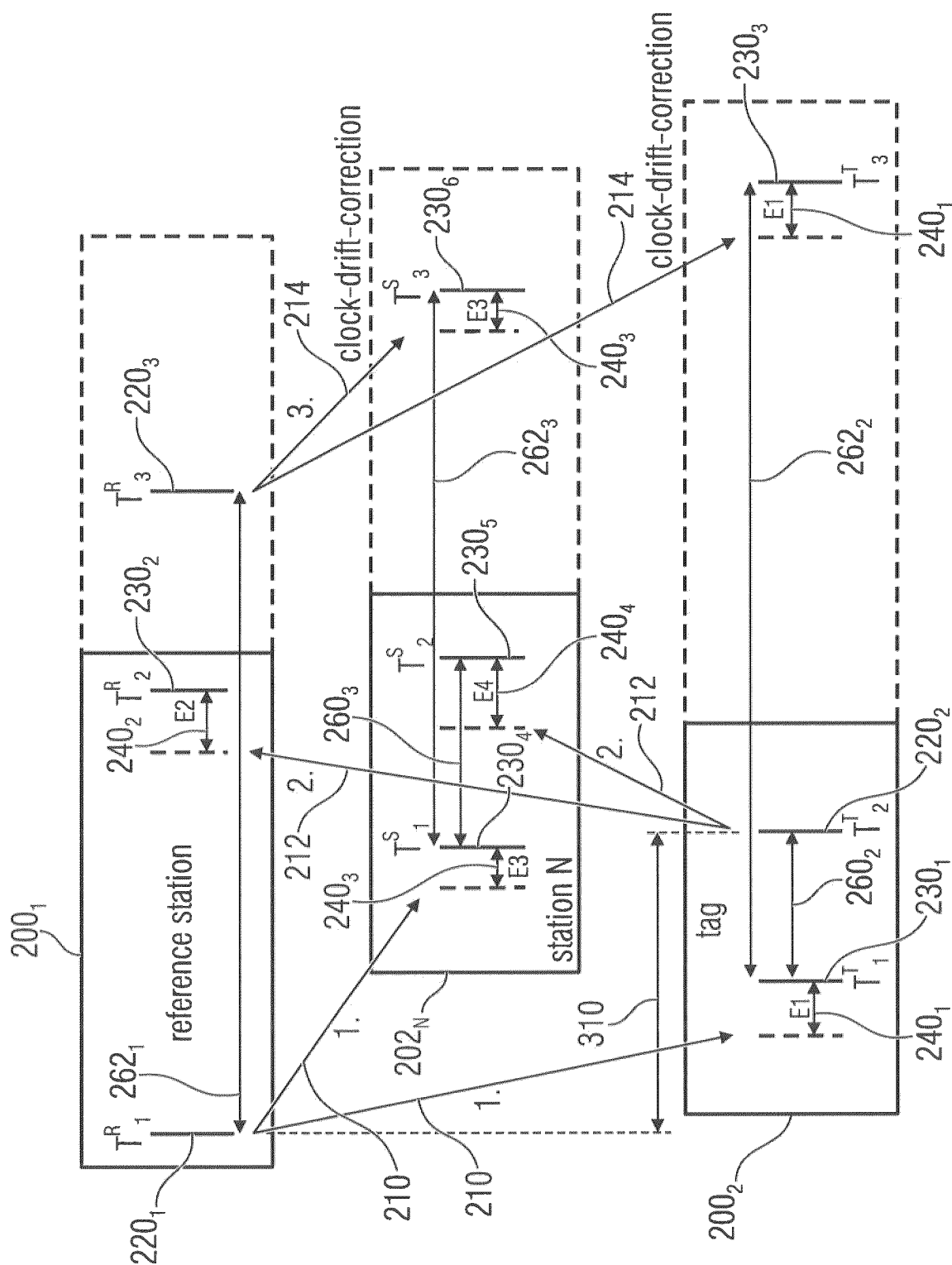
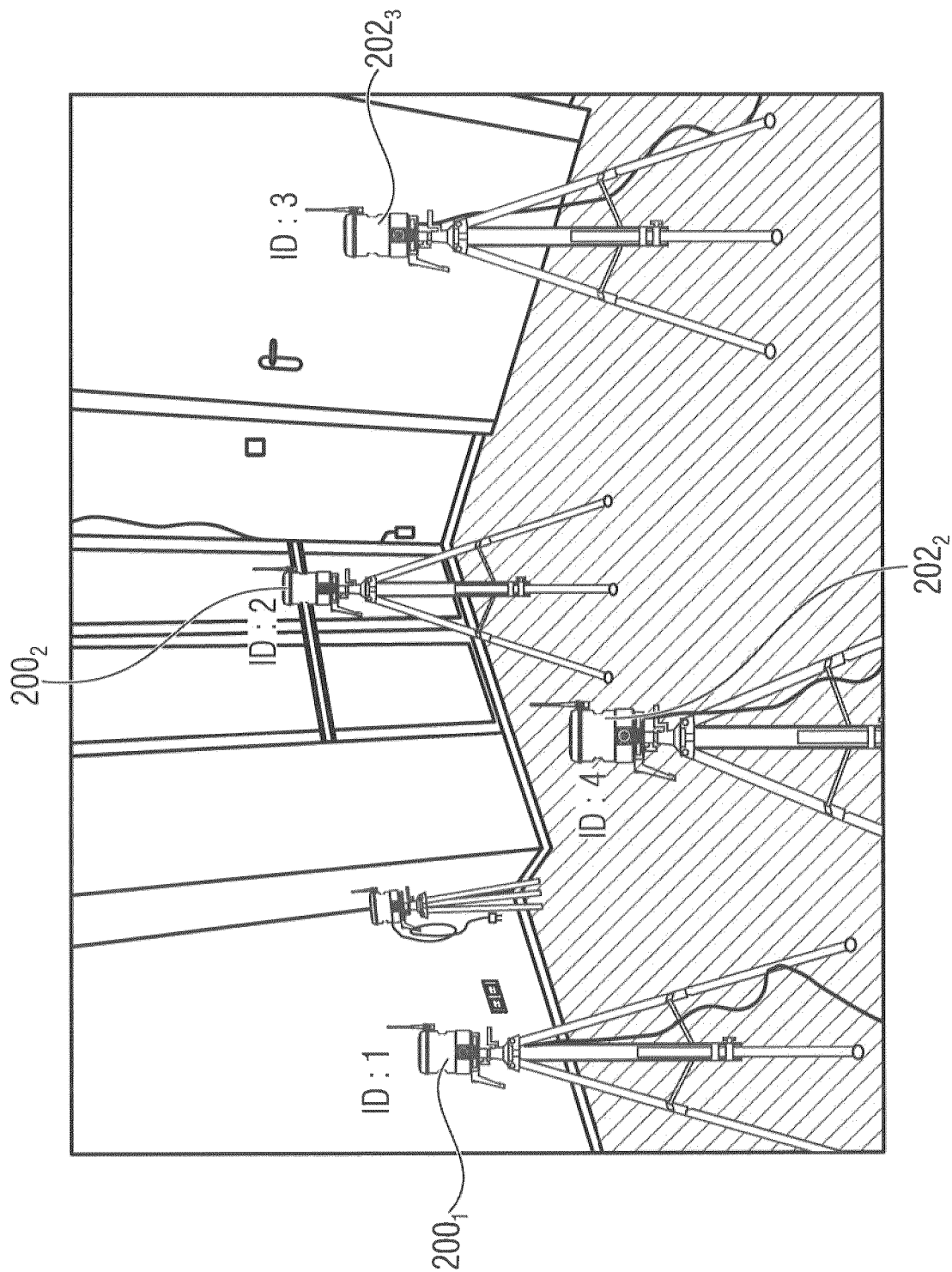


Fig. 5



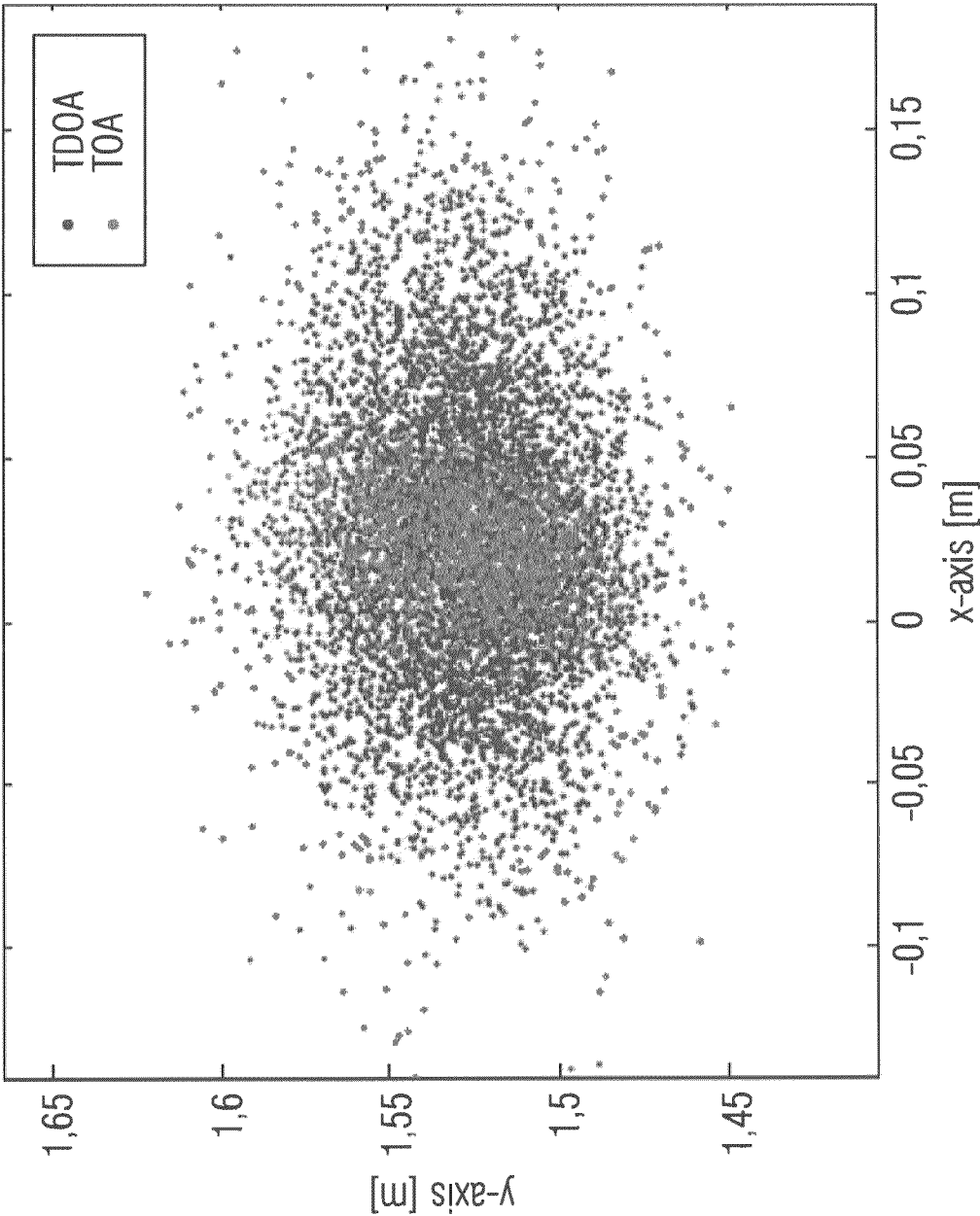


Fig. 7

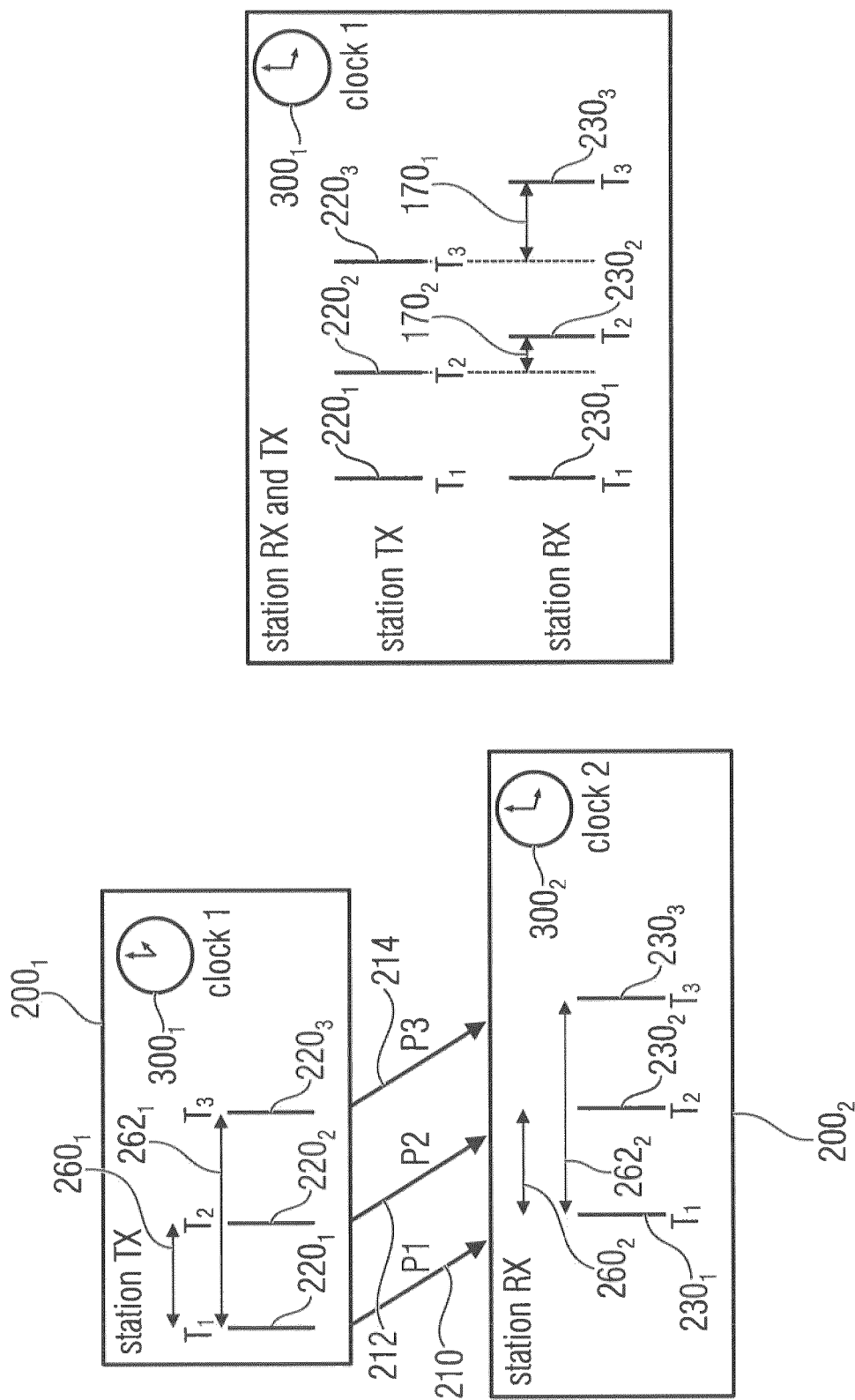


Fig. 8

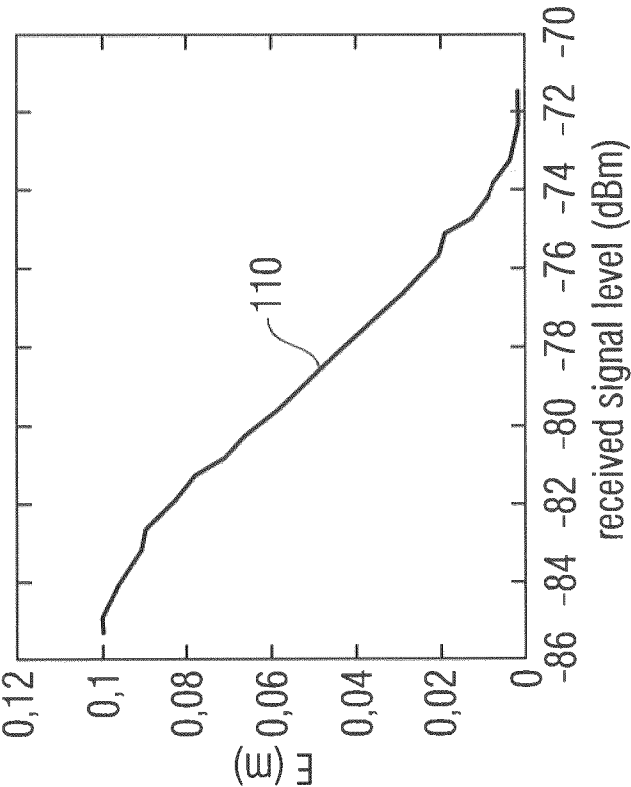


Fig. 9b

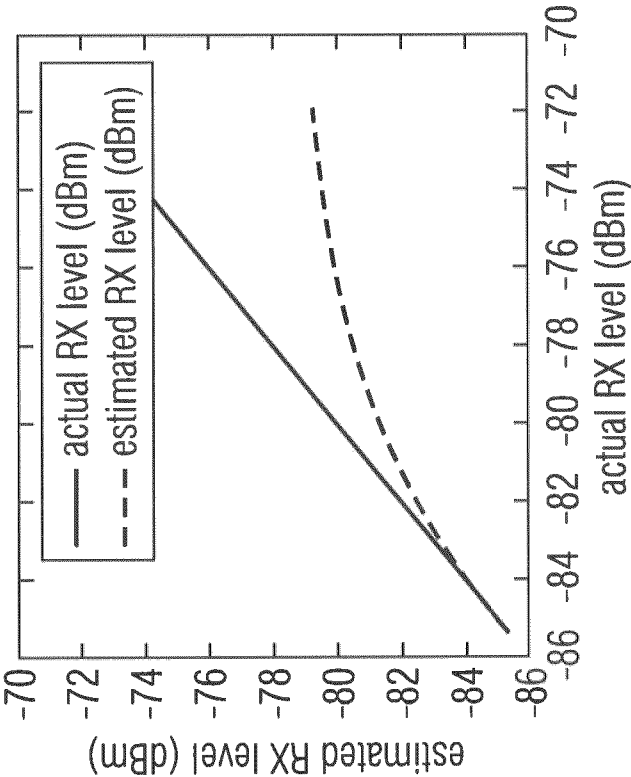


Fig. 9a

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2020/053561

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01S13/87 G01S7/40 H04W64/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01S H04W

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2015/219749 A1 (DUA PRAVEEN [US] ET AL) 6 August 2015 (2015-08-06)	1,2,4, 13, 18-24, 28-30
Y	figure 14	5,6,9,
	paragraph [0061]	10,15,
	paragraph [0067]	16,27
A	paragraph [0115]	7,8,11, 12,14
Y	----- EP 2 244 098 A1 (UNIV DUISBURG ESSEN [DE]) 27 October 2010 (2010-10-27) paragraph [0056] - paragraph [0059] ----- -/-	5,6,9, 10,15, 16,27



Further documents are listed in the continuation of Box C.



See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search

21 April 2020

Date of mailing of the international search report

29/04/2020

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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2020/053561

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2013/211780 A1 (MEADOR JAMES CHESTER [US] ET AL) 15 August 2013 (2013-08-15) paragraph [0052] - paragraph [0057] paragraph [0068] paragraph [0069] paragraph [0078] -----	1-30
A	WO 00/75681 A1 (HONEYWELL INC [US]) 14 December 2000 (2000-12-14) page 2, line 18 - line 30 figures 1,2 -----	1-30

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2020/053561

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