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(54) Title: CONCEPT FOR WIRELESS LOCATION USING ASYNCHRONOUS CLOCKS

(57) **Abstract:** Wireless signals are used to estimate the range differences between SUDs and each of at least 3 (for 2D positioning) or at least 4 (for 3D positioning) SNAPs. From the precise locations of the SNAPs, a computing element in the system calculates the position of the SUDs based on the ranges measured.

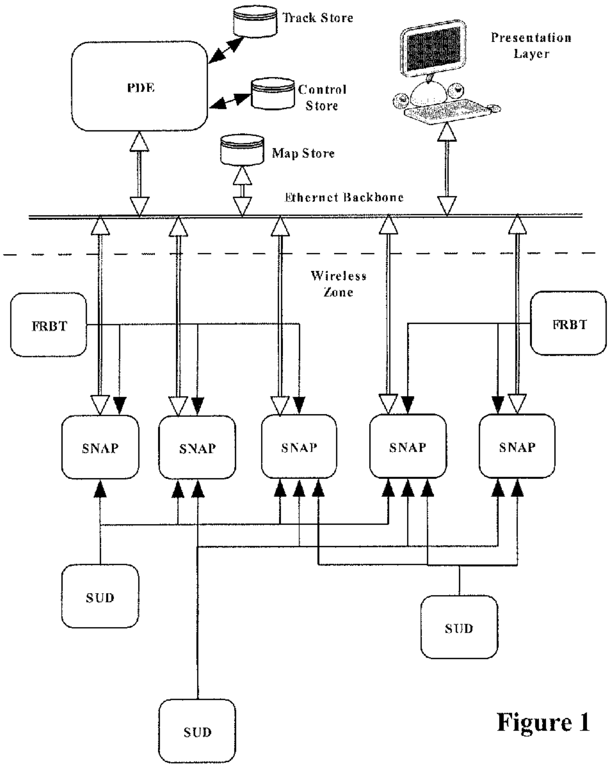

Figure 1

Subsystem Elements

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Concept for Wireless Location Using Asynchronous Clocks

Field of the Invention

This invention relates to the use of wireless ranging stations to determine the location of a wireless transmitter. The prime example considered within this specification is that of Special IEEE802.11 Wi-Fi Network Access Points (SNAPs) locating Standard IEEE802.11 Wi-Fi User Devices (SUDs). However, other examples that could use all or part of this invention include special 802.11 user devices, special cellular network base stations locating standard handsets or modems or two-way radio sets locating each other. Broadly this invention involves methods, devices and systems for locating wireless transmitters.

Background of the Invention

A range of applications for IEEE 802.11 WI-FI systems involve the need to locate SUDs with varying levels of accuracy down to 1 foot or 300mm. In order to achieve this desired accuracy, ranging techniques based on time of flight are necessary rather than ranging based on signal level. The prior art involves both techniques and also methods and apparatus for determining location based on amplitude signatures at multiple NAPs. However, none of these approaches incorporate mechanisms capable of achieving accuracy in the order of 1 foot.

Since standard User Devices are to be located it will be necessary to base the ranging on the measured times of receipt of signals from the SUDs at the Network Access Points (NAPs) and to add new measuring techniques capable of providing the desired accuracy.

Prior art for Wi-Fi positioning involves estimation of the ranges between SUDs and NAPs based on the signal powers received at the NAPs. This is necessarily a coarse ranging technique that is seriously affected by walls furniture and other obstructions causing attenuation along the signal paths. Another approach in the prior art involves storing signatures consisting of sets of amplitude measurements at multiple NAPs and correlating these signatures with location. Location is then determined by comparing the amplitude measurements from the NAPs with the signatures. This is potentially more accurate but remains a relatively coarse technique.

Ranging based on Time Of Flight has also been explored but is limited by NAP synchronization errors. One solution for the synchronization problem that has been advanced involves measuring changes in range only. Each of these measurements is a measurement of elapsed time made using a single clock. Thus it is not subject to synchronization error. This allows position to be tracked accurately once an initial location is known. However, the accurate initialization of the tracking remains problematic. Furthermore, the errors that do occur will accumulate during the tracking process.

To measure the ranges between a roving SUD and several Specially modified NAPs (SNAPs) more accurately, in order to make a precise position fix, would involve estimating the times of flight of the signals between the SNAPs and the SUD. Since the SUD must be any standard IEEE802.11 compliant device, it is not possible to obtain the times of transmission or reception of the signals from the SUDs. Prior art for the cellular application has solved this problem by measuring the Time Differences Of Arrival (TDOA) amongst a set of base stations and using these measurements to derive range differences between the handset or modem and that group of base stations. The location is then determined based on these range differences and the known locations of the base stations.

Use of TDOA for the Wi-Fi application would require synchronization of the SNAPs. The required accuracy of synchronization would have to be such that the synchronization errors did not contribute to ranging errors larger than about 300mm. This limits the allowable synchronization errors to well under 1ns which is very difficult to achieve at low cost. This accuracy requirement demands an alternative approach to location via TDOA that does not rely upon such precise synchronisation.

The system is intended to provide precise positioning for use in a wide range of applications many or indeed most of which involve indoor locations. The indoor environment complicates the synchronization problem since autonomous GPS timing cannot be used while Assisted GPS timing is both insufficiently reliable and nowhere near accurate enough. It also means that foot level positioning must be achieved in the presence of significant levels of multipath interference.

The precision required in any one application depends upon the application. In warehouse applications, 3D precision is generally required to about 1 foot. In office applications the foot accuracy is often in the horizontal plane and is less important in the vertical as long as the floor of the building is unambiguous. Achieved precision in any one application depends upon many factors, one of the most important of which is the geometry of the SNAPs.

Brief Description of the Invention

Preliminary Discussion

A WI-FI system consists of wireless NAPs at fixed locations providing access to the WLAN for roving SUDs. Wireless signals are transmitted regularly in both directions between the wireless NAPs and the SUDs using the WLAN as part of the normal operation of 802.11.

In this invention, these signals are to be used to estimate the range differences between each of the SUDs and each of at least 3 (for 2D positioning) or at least 4 (for 3D positioning) SNAPs. The differences in the times of flight of the signals are directly proportional (via the speed of light) to these range differences provided the signals travel directly from transmitting antenna to receiving antenna.

Knowing the precise locations of the SNAPs, a computing element in the system would then calculate the position of the SUDs based on the ranges measured.

Brief Description of the Drawings

Figure 1 depicts the positioning subsystem of the present invention.
Figure 2 depicts the TDOE scheme of the present invention.
Figure 3 depicts the measurement of TOF in the present invention.
Figure 4 is a block diagram for a typical de-spreading code generator in a correlation receiver incorporating a numerically controlled oscillator (NCO).

Positioning Subsystem Elements

The positioning subsystem will consist of several elements as indicated in Figure 1. The elements in the wireless zone consist of the Frequency Reference Beacon Transmitters (FRBTs) which will be described later, the SNAPs and the SUDs. The functions of these elements will be discussed in detail later in this document. The other elements needed include the Position Determining Entity (PDE), a Map database and, optionally, a Track database and a Presentation Layer. These items are usually connected directly or indirectly to the SNAPS via an Ethernet backbone or equivalent but may communicate in other ways. The key issue is that all the system elements can communicate with each other and with the SNAPS.

The PDE is typically a server or server farm with computing capability and memory capacity. The functions of the PDE are:

1. In concert with a data base, select the devices to be tracked and the frequency of tracking

2. To control the positioning process by controlling system elements where required,
3. To resolve SUD location ambiguities using supplementary information such as signal amplitude and map matching where necessary,
4. To compute cartesian position coordinates,
5. To convert cartesian position coordinates into useful map coordinates,
6. To optionally maintain track of all or selected SUDs.

A Presentation Layer may be needed depending on the nature of the application to show where the tracked objects are on a plan of the building or tracking environment.. Alternatively, locations may be supplied to the application layer on demand. Many applications may be serviced by the one PDE. Depending on capacity and demand there may be multiple PDEs. The PDE may periodically compute the locations of all or selected SUDs or may only do so on command from the application layer.

The control database would contain information on which SUDs are to be tracked and at what intervals. This information may be assembled based on queries from the application layer.

The Map database registers the locations of walls, floors and SNAPs and is essential to the operation of the PDE. The PDE might control the SNAPs in the following way. Having received a request for position of a specific SUD, the PDE would request responses from those SNAPs receiving from that PDE. Using the locations of walls floors and SNAPs from the Map database and the signal levels from the SNAPs, the PDE would then determine which floor the SUD was on and decide which SNAPs to use for positioning and how they should be paired.

The PDE would then instruct the selected SNAPs to perform measurements on signals from the selected SUD. Those SNAPs would then measure TDOEs and return these to the PDE. The PDE would then compute the required TDOAs and solve for the cartesian position coordinates of the SUD. The latter computation would typically be a least squares calculation. However, in some applications involving tracking of a moving SUD it may be desirable to track the SUD using a Kalman filter or similar algorithm. The PDE would then convert these cartesian coordinates into user-friendly map coordinates in terms of floor, room and location relative to walls and floor.

Note that, as discussed later, the PDE needs Time Of Flight (TOF) estimates for the pairs of SNAPs. These could be stored with the SNAP coordinates in the Map database. They could be obtained via regular calibrations as discussed later.

If an SUD is to be tracked continuously then the PDE may store the position data in the Track database for supply to the application layer as required. The precise operation of the major computing and data-base elements is unimportant to the innovation but the functional operation is important.

Operating Wi-Fi Environment

The operating environment will involve a mix of SUDs from many different manufacturers conforming to various substandards of IEEE 802.11 (eg 802.11A, 802.11B and 802.11G). There may also be NAPs present from other manufacturers all of which conform to some subset of the 802.11 standards. No variation from the standards is permitted as it could affect interoperability among the SUDs and the NAPs.

Also, only the SNAPs will be modified to implement the positioning system. The system must work with completely standard SUDs. However, custom users devices may of course also be used.

Primary System Requirements

The following requirements are assumed:

- If the SNAPs are synchronized wirelessly using GPS or some other wireless means, the wireless antennas will preferably be integrated into the SNAP assemblies (as opposed to external antenna(s) mounted externally to the building.) This is an important innovation to reduce the amount of cabling required with external antennae and the calibration required due to the timing delays introduced by cabling which will generally be of differing lengths and delays.

- The system is to be capable of very high positioning accuracy. Application accuracy requirements will vary but accuracy requirements down to 300mm or even better in both horizontal and vertical dimensions is envisaged for some applications.

- The system must be capable of operating within buildings including warehouses, office buildings and so on. Such buildings may have metal roofs and/or walls and may contain metal structures. There may also be very large buildings.

- The system ideally will operate with standard SUDs. That is, the system will require special features in the SNAPs only.

Preliminary Analysis of Primary Requirements

Implications of the Positioning Accuracy Requirement

To achieve accuracy of 300mm the times of flight must be estimated to within 1ns. This is an extremely tight requirement. For example, it is an order of magnitude more precise than is achieved using GPS code measurements under Line-Of-Sight (LOS) conditions.

The primary impediments to achieving the desired accuracy are:

1. The need to provide synchronization accuracy between SNAPS to better than 1ns,

2. The limitations imposed by clock resolution,
3. The fact that IEEE802.11 NAPs are not designed to measure time of arrival of signal instants and will require special receive circuitry to do this to the required accuracy, and
4. The effects of multipath interference in the indoor environment.

Synchronization Accuracy

In the scope of the invention normal 802.11 NAPs are modified to become SNAPs by the addition of circuitry and software and the circuitry will include a precise controllable clock in each SNAP. Synchronizing the SNAP clocks to 1ns accuracy is extremely difficult if not impossible using economically viable techniques although the system would work with synchronised clocks. However, estimation of elapsed times to this accuracy is definitely feasible without such synchronisation. It requires stabilization (as opposed to synchronization) of the SNAP clocks to a degree that is dependent on the elapsed time to be measured. For example, to measure a 1s time interval to 1ns accuracy requires a clock stabilized to 1 part in one billion (1ppb) for the period during which measurements are taken. This is relatively short of the order of seconds. Another way of saying this is that the accuracy of the system depends on relative stability of the clocks over short periods rather than long-term absolute stability which is more difficult and expensive to achieve. This is an important claim of this inventions (ROD> IF you agree, please add a claim)

Clock Resolution

Typical clock frequencies used to drive wireless systems run at tens of MHz. This implies clock resolution of the order of 10s of ns. This is between 1 and 2 orders of magnitude larger than the desired 1ns accuracy for measuring the time of flight. In practice, to get 1 nsec accuracy in measurement from several SNAPs, the synchronising clock needs to be accurate to a fraction of a nanosecond so that the aggregate errors do not approach the order of magnitude of that which is being measured.

Navigation and time transfer systems like GPS use similar clock frequencies. However, this problem is overcome by estimating the Time Of Transmission (TOT) to very high precision at a clock edge. The highest resolution element of the TOT is the codephase of the spreading code. The codephase of the receiver-generated replica of the spreading code can only be changed at a clock edge but can be changed to very high precision. In this way the local code can be aligned with the code of the incoming signal to extremely high precision and can be latched on any given clock edge with that same precision.

Wi-Fi systems also use spreading codes although the code lengths are much shorter being the length of 1 bit of the data. If Wi-Fi receivers were to establish and maintain code sync with the incoming signal in a similar manner to GPS receivers (ie using correlation receiver techniques) then the misalignment between the clock edges and the chip edges could be established with high precision and taken account of in the time of flight calculations. Standard 802.11 NAPs are not designed with this application in mind. Therefore supplementary receiver circuits are required.

Code Tracking Noise

Given the very demanding accuracy requirements to be aimed at, the use of correlation receiver circuitry does not guarantee that the desired accuracy will be achieved. This is especially true since the Wi-Fi spreading codes have not been chosen with precise ranging in mind. It may not be possible to reduce the code tracking noise to the necessary level. Therefore supplementary techniques may be required.

Multipath Errors

In addition, the WI-FI signals are also subject to multipath. DSSS chipping rates, for example, can be as low as 11MBPS, depending on the variant of 802.11 which means that the maximum multipath error is around 30m which is very large compared to the desired accuracy. Such large path length differences are also likely in warehousing environments in particular. Significant multipath errors are quite likely unless specific features are built into the system to mitigate them.

However, 802.11B has become the most common implementation and uses HR/DSSS with higher chipping rates. Also, unlike the situation with GPS in urban canyons and indoors, with WI-FI, the direct signal should invariably be significantly stronger than the delayed multipath signals. Hence multipath mitigation techniques in the signal processing can be very effective. Thus, if the ranges between the SUDs and the SNAPs are relatively short it should be possible to limit the effects of multipath to an acceptable degree.

Eliminating the Synchronization Problem via Time Difference Of Events

The Time Difference Of Events (TDOE) Concept

The TDOE concept is based on the idea of constructing TDOA (Time difference of arrival) measurements from a set of elapsed time measurements using a single clock to measure the elapsed time between pairs of events. The time difference between each pair of events must be measured by a sufficiently stable clock.

This scheme involves pairs of SNAPs. One of the pair receives a token from a SUD, transmits another token and and measures the elapsed time between the 2 events. Such a measurement is called a TDOE. The second token is received by a second SNAP which has also received the same token from the SUD and measures the elapsed time between those two events.

Figure 2 illustrates the concept. Rather than ranging directly between multiple SNAPs and the SUD whose position is to be determined, in this concept the differences between the ranges from several SNAPs to the SUD are measured. This is the TDOA as is used in cellular positioning. However, rather than measuring the TDOA directly, we measure TDOEs at multiple SNAPs and then compute the TDOAs from the TDOEs.

Consider one pair of SNAPs. Each SNAP latches the time of receipt of the same token (Token 1) from the SUD as T1 at AP1 and T2 at AP2. AP1 then transmits a new token (Token 2) to AP2 and latches the Time of Transmission of that token as T3. The elapsed time (T3-T1) between reception of Token 1 and transmission of Token 2 is a TDOE measurement that is available to be taken account of in the TDOA calculation. AP2 then latches the time of receipt of Token 2 (T4). Hence in AP2 we have another TDOE measurement being the elapsed time between T1 and T4. The TDOA is then calculated as:

$$\mathrm{TDOA} = (\mathrm{T4}-\mathrm{T2}) - (\mathrm{T3}-\mathrm{T1}) - \Delta\mathrm{T}$$

$$= \mathrm{TDOE2} - \mathrm{TDOE1} - \Delta\mathrm{T}$$

where ΔT is the time of flight between AP1 and AP2 which is known a-priori.

TDOA is directly proportional (via the speed of light) to the difference in ranges to the SUD of AP2 and AP1.

Note that the TDOA is calculated from TDOE measurements only. Each TDOE measurement is a measurement of elapsed time between 2 events at the same SNAP. No absolute time estimates are required and thus no synchronization is required amongst the SNAPs. This is the key difference between this scheme and a simple TDOA measurement scheme.

It is important to note that the tokens to be used are instances in the normal transmissions from the SUDs and SNAPs. No additional wireless traffic is generated for positioning purposes. The tokens could be, for example, the ends of frames. In the case of the SNAP transmissions, the tokens could be the ends of beacon frames.

It is important to note that the transmission of Token 2 from one SNAP to another does not have to be consequential upon the receipt of Token 1. It can precede it. The important thing is that the relative times are measured by stabilised highly accurate clocks that are frequency synchronised rather than time synchronised.

An alternative method of operation therefore is that the SNAPs transmit tokens to each other on a continuous and regular basis, latching the relative times of each Token until a SUD token arrives and its relative time of arrival is then latched. There is then no need to transmit another token and the same calculation can be done as above as long as the both Token 1 and Token 2 are within close enough time to each other for the accuracy of the system to be maintained. This time depends upon many factors but is likely to be of the order of a second at the current state of the art.

Clock Stabilization

The total elapsed times to be measured may be of the order of a second since normal IEEE802.11 medium access mechanisms may delay the transmission of Token 2 in the first example for some time. Hence the clock stability required is of the order of 1ppb as required to provide ranging accuracy to 300mm.

The solution to this problem is to use one or more Frequency Reference Beacon Transmitters (FRBTs) within the area where SUDs are to be tracked. In the preferred embodiment, the FRBT would transmit a suitable signal in the ISR band (for compatibility with the IEEE802.11 antennas and RF sections and to reduce the regulatory demands) but is not necessarily restricted to this band for the purposes of this patent.

One possible implementation of this signal would be a spread spectrum signal to minimise interference with the IEEE802.11 signals. However, it would be modulated with one or more highly stable frequencies which would be used to stabilize the clocks in the SNAPs via phase or frequency locking. These stable FRBT frequency references could be derived from suitable 1PPB oscillators or from GPS receivers.

These beacons could also provide time synchronization which may be of use in applications requiring less accuracy and involving special or Custom User Devices (CUDs). One important benefit would be that it would facilitate round trip ranging using much the same TDOE mechanisms. The use of round trip ranging would facilitate location calculations using fewer SNAPs (ie 3 SNAPs for 3D positioning and 2 SNAPs for 2D positioning (albeit with ambiguity)). A master-slave beacon concept could also be employed in which there is only one source of time and frequency references with repeaters extending its range if required.

Measuring the Time of Flight Between SNAPs

The time of flight between 2 SNAPs is required for the TDOA calculation as indicated earlier. It can be estimated based on the locations of the 2 SNAPs or it can be measured as indicated in Figure 3. AP2 transmits Token 1 to AP1 and latches the time of transmission as T5. AP1 latches the time of receipt of Token 1 as T6 and later transmits Token 2 back to AP1. It also latches the time of transmission of Token 2 as T3. AP2 then latches the time of receipt of Token 2 as T4. The time of flight between the 2 SNAPs is then computed as:

$$\Delta T = (T4-T5) - (T3-T6)) / 2$$

$$= (TDOE4 - TDOE3)/2.$$

Again, this is computed from TDOE measurements.

Combining TDOA and TOF Measurements

The measurements in Figure 2 and Figure 3 can be combined leading to the following TDOA calculation:

$$\mathrm{TDOA} = ((T4+T5)/2 - T2) - ((T3+T6)/2 - T1)$$

This calculation involves 3 event times latched at each of the two SNAPs rather than one measurement of elapsed time between two events. However, the clock synchronization error between the 2 SNAPs still cancels out yielding an accurate TDOA measurement.

Note also that the order of events is not important. In particular, T3 may occur before T1 and T3 may occur before T6.

Operation Without Dedicated Communication Between SNAPs

Rather than having the SNAPs transmitting extra messages to each other, the SNAPs can simply listen to the beacon frames transmitted by each other. These are transmitted at regular intervals as part of the standard IEEE802.11 protocols. If the combined TDOA/TOF scheme is used then the nearest pair of beacon events to any SUD reception event could be reported along with the reception event.

Overcoming Clock Precision and Spreading Code Tracking Limitations

Preliminary Discussion

The latched times of transmission and times of receipt referred to in the above sections will necessarily be latched at a clock edge. Transmission token events will typically but not necessarily occur at clock edges but reception token events generally will not. This can be overcome by estimating the misalignment between the incoming code chip edge representing the token and the nearest following clock edge at which the token receipt time is latched. The following is one possible implementation of a method of measuring time of receipt with one form of code. Other equivalent methods are available using a combination of hardware and software, the key innovation being the accurate determination of the time differences between nominated parts of the message.

Use of Codephase Latching

Figure 4 is a block diagram for a typical de-spreading code generator in a correlation receiver incorporating a numerically controlled oscillator (NCO). This form of de-spreading code generation may not be employed in a conventional NAP but could be employed in the SNAPs in one version of this concept. The NCO is made up of the code frequency register and the sub-chip accumulator. At each clock edge the accumulator adds the value held in the code frequency register to its own contents. The carry from the accumulator clocks the code generator at the chipping rate. Hence the code frequency register determines the chipping rate. The larger its contents, the more frequently the chip counter counts.

However, the chip counter always updates at a clock edge. Hence the code frequency is only maintained on average. Also, the phase of the code generator is controlled to align it with the phase of the incoming signal by manipulating the code frequency. Hence the value in the code frequency register will vary from the nominal value representing the code frequency in order to adjust the codephase alignment with the incoming signal.

Now the state of the code generator (the codephase) can be latched at any time into the codephase register. The bits of the codephase that were latched from the sub-chip accumulator then represent the fraction of a chip since the last chip edge at the latching instant. If this value is M and the nominal value in the code frequency register is N then the fraction of a clock cycle since the last chip edge is given by:

$$\text{Clock Cycles} = M/N.$$

Note that, in general, this value may be greater than 1.0 since there will generally be multiple clock cycles per chip. However, if we latch the codephase coincident with the carry then this value will represent the fraction of a clock cycle since the last chip edge. If the latching occurred at a token reception event then this number represents the fraction of a clock cycle that the token event occurred before the event time was latched. Hence this fraction of a clock cycle can be subtracted from the latched event time to give the precise event time.

The Pseudo-Token (PT) Concept

Any code tracking noise will show up in the sub-chip adjustments to the token receipt times and will thus contribute to the ranging error. One approach to reducing these random ranging errors is to employ averaging. For example, averaging over a hundred measurements will reduce the RMS ranging error by a factor of 10.

Rather than performing hundreds of complete measurements, it is more convenient to introduce the concept of a Pseudo-Token (PT). Instead of latching the times of transmission or reception of a single instant in the signal we latch the times of transmission or reception of many instants. For example, rather than latching the end of a frame we latch the ends of all the data bits in the last fragment of a frame to be transmitted or received. We then take the average of these and this represents the time associated with the corresponding PT event.

Provided the same PT is used at both ends of the transmission, the effect is the same as measuring the time associated with a token event but the accuracy is much higher.

The errors introduced through noisy code tracking will be improved in this way. However, it is important to recognize that code tracking biases will not be improved.

Working with PTs

The TDOEs associated with PTs are used in the estimation of TDOA in the same way that TDOEs associated with tokens are used. Tokens 1 to 6 can simply be replaced by PTs 1 to 6 in the above descriptions in order to see how the PTs are used.

It is important to understand that PT1 and PT2 in those descriptions can relate to different fragments of completely different frames. They can even be different lengths. It is only necessary for the transmission times and the reception times of the same PTs to be used in the calculation. Thus PT2 can relate to a beacon frame while PT1 can be any convenient frame transmitted from the SUD.

Implementing PT Event Latching

The averaging of hundreds of times associated with hundreds of token events to produce a single time associated with a PT event could result in a significant software load and an undesirable complication. However, this could be facilitated in hardware by incorporating a hardware accumulator that adds the new time to its contents at each event and is cleared at the start of the last fragment of each frame. Dividing the accumulated value at the end of the frame by the number of bits in the last fragment would yield the time associated with the PT event. This is very similar to the way in which the accumulators in NCOs operate as described earlier.

Managing The Process

In reporting event times to the PDE the SNAPs need a way of identifying the events to which they refer. The events could be identified via the signal source (for examples: SNAP 36 or SUD 531), the frame number and whether the event was a transmission event or a reception event.

Care will need to be taken, in some cases, to limit the level of traffic over the ethernet backbone between the PDE and the SNAPs. In a large system and with many SUDs to locate and, possibly, to maintain track of, care should be taken to reduce unnecessarily detailed control of the process by the PDE. However, this may lead to a large amount of ethernet traffic reporting event times to the PDE.

For example, the SNAPs could simply report every event. These would include reception of ends of frames from SUDs and transmission and reception of the ends of beacon frames. The PDE would choose groups of event times yielding desired TDOA measurements. This would result in a large number of ethernet transactions and a large amount of data for the PDE to manage and to process.

Alternatively, the PDE could command each SNAP in near real time as to which sources it should report events for and even which frame numbers to report events on. That would lead to a large amount of Ethernet traffic simply to manage the process along with a nearly impossible task for the PDE in keeping track of all wireless transactions.

Clearly some compromise between these two extremes will be required and the optimal compromise will depend on the application. Once an initial location of a SUD to be tracked is known, the PDE may choose to limit the number of SNAPs reporting its transactions to those closest to its last known location. The PDE could also time division multiplex the system operation across zones thereby limiting the volume of ethernet traffic and its own processing load.

Overall, it is expected that at a system level, each SUD and any custom devices to be tracked, will have allocated a scan frequency. For example lap-tops might be scanned and tracked every minute while desk-tops every hour. This allocation would be advised to the relevant SNAPs which would then throw away irrelevant data to unload the Ethernet traffic. Time division multiplexing of operation would be useful here. For example, each group of SNAPs around an SUD that is being tracked would be given a time slot by the PDE in which to track that SUD and would ignore it at other times. If the object starts to move and requires more frequent tracking, then the PDE could uprate the tracking frequency of the relevant SNAPs as well as activate SNAPs in adjacent areas where the SUD might enter.

Determining Location

The range between a SUD and a SNAP is a non-linear function of the locations of those two entities. Thus equations can be constructed relating the ranges of multiple SNAPs to their locations and that of the SUD to be located. A location solution algorithm can be derived by linearizing those equations via differentiation and then differencing them to obtain range difference equations. Three range difference equations involving the three coordinates of one SUD location can be solved to determine that location. The most obvious approach is to express the set of equations in matrix terms and to solve the problem via matrix inversion.

In the preferred embodiment, the locations are all expressed in cartesian coordinates and a more sophisticated equation is set up in which the covariances of the measurement errors and of the location uncertainties are used to weight the measurements. The solution is still performed by matrix inversion but the solution is now an optimal least squares solution. The primary advantage of this approach is that more than 3 sets of range difference measurements can be utilized to obtain an improved solution taking account of the varying reliability of the measurements. The latter would depend on signal strength, for example.

In a tracking application where a SUD location is to be updated frequently, this least squares solution process can be formulated as a Kalman filter in which the history of the SUDs motion is taken into account and its dynamic characteristics can also be modelled. Such an algorithm can also be enhanced in various ways to reject or otherwise mitigate multipath effects based on the probability of the measurements.

The accuracy of location depends upon the position of the SNAPs and is degraded when they are co-planar. This is a typical situation in an office where all the SNAPs might be located on a ceiling. In this situation, horizontal positioning can be very accurate but vertical may not. Other techniques, such as signal strength are then important to determine the floor on which the SUD is located and to distinguish between SNAP tracking where the SNAPs are on different floors and the floors and ceilings are relatively transparent to signals.

This is generally not a serious problem in offices where vertical location beyond the determination of which floor the object is on, is largely irrelevant. In warehouses with pallet stacking as an example, vertical position may be important and SNAPs will generally be arranged in a 3 dimensional matrix and not made co-planar so as to achieve the required accuracy.

Degraded Modes

Degraded Configurations

There may be times when the network design is not well controlled or where there are adverse constraints on the placement of antennas. This may limit the number of SNAPs that can receive from devices in a particular area. It is desirable to be able to provide some location information under these conditions even if the full accuracy is not achievable.

Degraded Modes of Operation

The following degraded modes of operation are envisaged:

1. The location is computed with poor DOP resulting in poorer accuracy than desired.

2. The measurements are subject to high multipath distortion resulting in poorer accuracy than desired.

3. Only 2 SNAPs are able to range the SUD. Ranging is performed via TDOA using beacon synchronization rather than TDOE and signal amplitude is used to help resolve the inherent 2-D ambiguity and to locate the SUD to a floor. This results in poorer accuracy.

4. The SNAPs cannot listen to each other and ranging is performed via TDOA using beacon synchronization rather than TDOE. In this case amplitude may be used to improve the accuracy by initially locating the SUD to a region. This results in poorer accuracy.

5. Only 1 SNAP is able to range the SUD which is only located to a region. Amplitude may also be used to assist with this.

Claims

We claim:

1. A wireless system for determining the location of a wireless transmitter to a desired precision comprising a plurality of wireless ranging stations that measure times of arrival of signal instants using clocks that are imprecisely synchronized or not synchronized at all.

2. The system of claim 1 in which the said ranging stations also transmit signals and measure the times of transmission and reception of instants in those signals and use those measurements along with the measured reception times of the previously said signal instants from the said transmitter to determine time differences of arrival of the said signals from the said transmitter with the desired precision.

3. The system of claim 2 in which the said ranging stations are used in pairs to measure pair-wise differences in times of arrival of the said signal instants from the said transmitter and use these differences to compute the location of the said transmitter to the desired precision.

4. The system of claim 3 in which the said clocks in the said ranging stations are stabilized by locking them in frequency or phase to a reference received from one or more beacon transmitters.

5. The system of claim 4 in which the said ranging stations report the measured time differences of arrival to a position determining entity which computes the location of the said transmitter.

6. The system of claim 5 in which many of the said transmitters are located and tracked concurrently using an array of the said ranging stations.

7. The system of claim 6 in which the said position determining entity also controls the operation of the said ranging stations by allocating regions of the said array to time slots and the said ranging stations only report times of transmission or receipt that fall within their allocated time slots.

8. The system of claim 7 in which the said transmitters are IEEE802.11 Wi-Fi user devices.

9. The system of claim 8 in which the said ranging stations are specially modified IEEE802.11 network access points.

10. The system of claim 9 in which the said modifications incorporate a separate receiver baseband that utilises correlation receiver technology involving the use of a numerically controlled direct synthesis oscillator and codephase latching to overcome the limitations of clock granularity in measuring times of receipt.

11. The system of claim 10 in which the said receiver baseband is able to receive from multiple channels and frequencies concurrently or in close enough sequence to facilitate reception from nearby network access points.

12. The system of claim 8 in which the said signal instants are specific points in message frames such as the ends of the frames.

13. The system of claim 9 in which the said transmissions from the network access points are beacon frames.

14. The system of claim 7 in which the said beacon transmitters also encode synchronization data into their signals and this synchronization data is used to synchronize the said ranging stations so that ranging can be performed with reduced accuracy when there would otherwise be too few said ranging stations that are able to receive from the said transmitter or that can receive from each other.

15. The system of claim 13 in which the times of transmission and receipt of the said beacon frames are measured by the said network access points whenever they are received but the only such measurements reported are those closest to when the ends of frames from the said user devices are received.

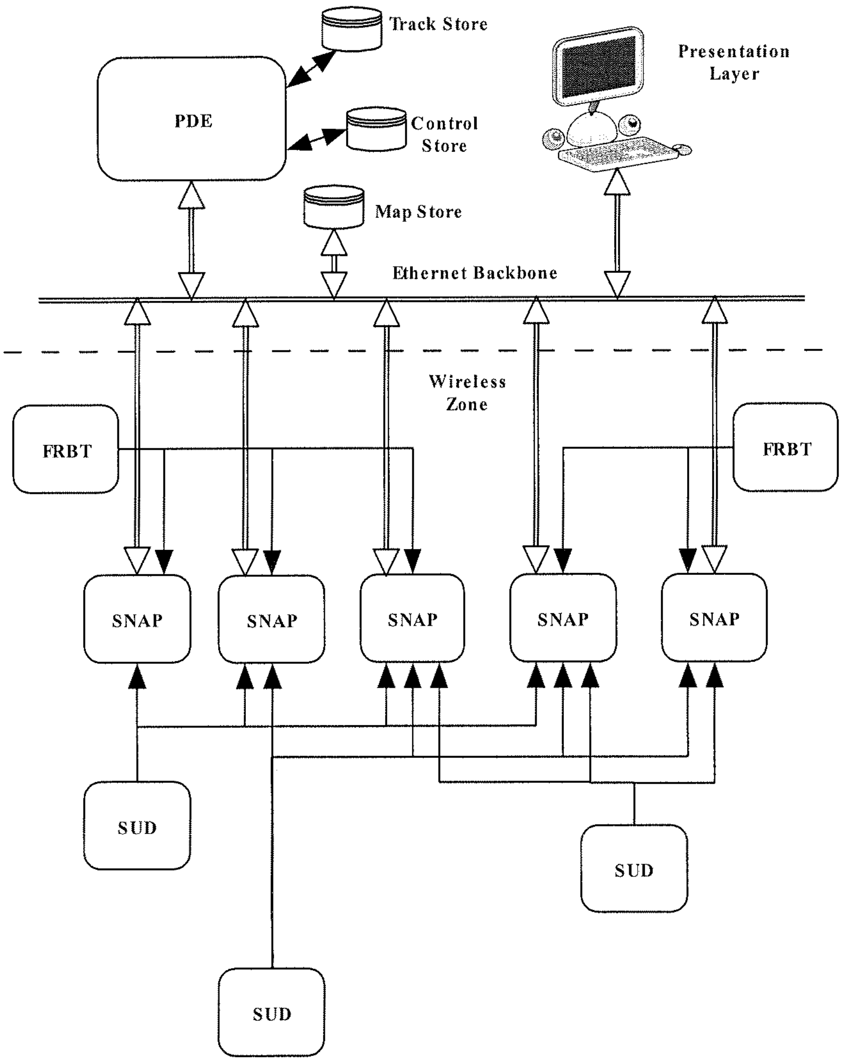

Figure 1– Subsystem Elements

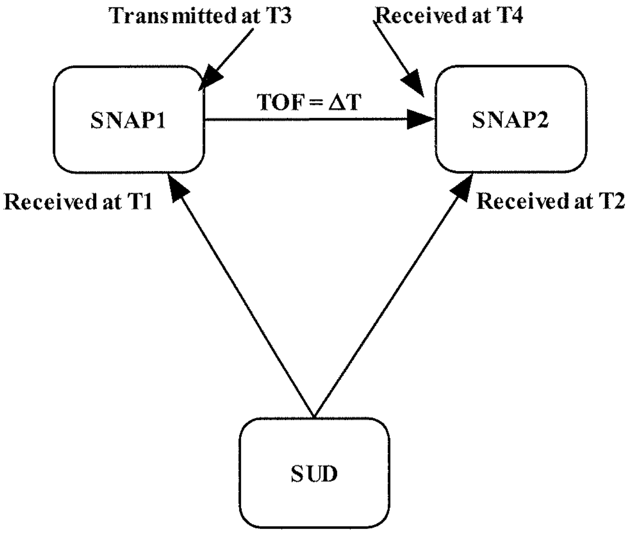

Figure 2 – TDOE Scheme

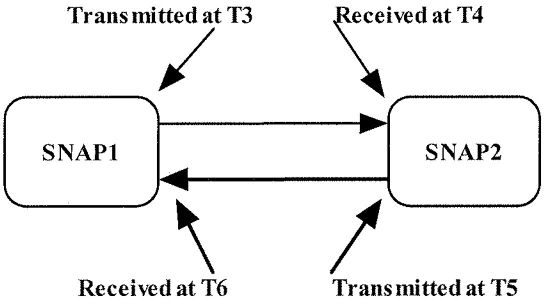

Figure 3 – Measuring TOF

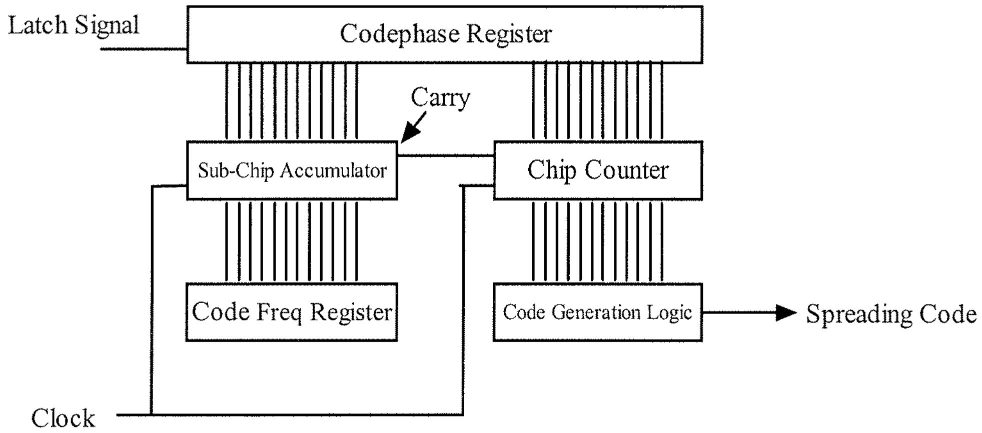

Figure 4 – Code Gen Block Diagram

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2008/061262

A. CLASSIFICATION OF SUBJECT MATTER

H04Q 7/38(2006.01)i, H04L 12/28(2006.01)i

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)
IPC 8 : H04Q 7/38, H04L 12/28

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean Utility models and applications for Utility Models since 1975
Japanese Utility models and applications for Utility Models since 1975

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKIPASS(KIPO internal) "location, determination, TOA, ranging, synchronization"

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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A	US 2004-0002344 A1 (Moeglein, Mark et al.) 01 Jan. 2004 See abstract, figures 2,10, claims 1-9, and paragraphs [0037]-[0046], [0070]	1-15
A	US 2005-0037775 A1 (Moeglein, Mark et al.) 17 Feb. 2005 See abstract, figures 4,6, claims 1-15, and paragraphs [0010]-[0014], [0041]-[0044], [0052]-[0054]	1-15
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☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search 26 AUGUST 2008 (26.08.2008)	Date of mailing of the international search report **26 AUGUST 2008 (26.08.2008)**
Name and mailing address of the ISA/KR Korean Intellectual Property Office Government Complex-Daejeon, 139 Seonsa-ro, Seo-gu, Daejeon 302-701, Republic of Korea Facsimile No. 82-42-472-7140	Authorized officer KIM, Kwang Sik Telephone No. 82-42-481-8355

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Information on patent family members

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