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Position Location in a TDMA Network

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Introduction

Many of the communications systems being developed today for the tactical environment use some form of TDMA in order to share the communications resource among the network elements. In addition, a time dependent waveform (eg, JTIDS, Packet Radio, etc.) is often utilized to increase jam resistance. These systems require time synchronization within the network in order to be able to successfully communicate. The timing measurements necessary to provide network synchronization can be extended to provide accurate range measurements between network elements. These range measurements can be used to calculate the positions of all network elements relative to some grid which has been established by the network. The tactical value of a relative position location function is well established for providing relative nagivation, targeting, resource mapping and allocation, routing and low probability of intercept information. The availability of range measurements, which could be used for position location, and the value of position location as a tactical tool motivated the development of the position location methods described in this paper.

The method for providing a relative position location function is summarized below. As a part of the network initialization process, a relative grid is established for the network. Each element in the network will be responsible for tracking its own position relative to that grid. Accurate range measurements are obtained by accurately controlling the time of transmission (TOT) and by accurately measuring the time of arrival (TOA) of messages. The propagation delay measurement obtained from the TOT and the TOA is multiplied by the speed of propagation to obtain a range measurement. If the transmitted message contains the position of the transmitter, the range measurement can be used along with similar range measurements from other sources to calculate an estimate of the receiver's position and the current network reference time. Periodically, these estimates are used by a Kalman filter linear estimator to develop and correct a state model of the dynamics of the unit and its internal time base. The rate at which these models must be updated is a function of the mobility of the platform and its position location accuracy requirements. By using these state models, each unit can track its estimated position and an estimate of the network reference time. This information is then made available to other units for use in their position location algorithms. A hierarchical structure is used to determine which potential sources of position information should be utilized by a particular user. This structure prevents the feedback of errors which can result in an unstable condition. The remainder of the paper will provide an overview of the major concepts introduced above, will discuss some of the factors which determine accuracy, and will consider the issues associated with actually implementing a position location function.

Multilateration

Multilateration is the use of range measurements from multiple sources to determine position relative to the locations of the sources. Multilateration is suited for use in a tactical TDMA network for a variety of reasons, including:

a. It utilizes available propagation delay measurements

b. Position estimates can be calculated by each element

c. It does not require fixed references

d. It does not rely upon critical nodes.

Given the TOT and TOA of the message, an estimate of the line of sight range between the transmitter and receiver can be computed. If the received message contains the absolute or relative position of the source (transmitter), the receiver can use this information, in conjunction with the measured range and similar measurements from other sources, to estimate its position. Each range measurement defines a circle of radius R (where R = measured range) with its center at the source. According to the measurement, the receiver lies somewhere on the circle. In the horizontal case (ie, altitude assumed known) perfect range measurements from three noncolinear sources will generate three circles with a unique common intersection which is the position of the receiver. However, error-corrupted measurements will produce a set of circles with no common intersection or an incorrect common intersection. This result is illustrated in figure 1 for four sources and one receiver. Given these error-corrupted range measurements, the receiver is required to calculate a position estimate which is in some sense optimum.

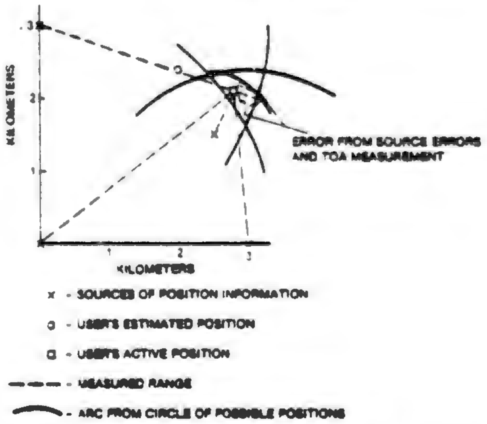

Figure 1. Multilateration Measurements for Position Location.

By linearizing the problem using a Taylor's series expansion and employing a weighted least square error criterion, this problem can be efficiently solved by a microprocessor. This method requires an initial position estimate provided by previous measurements or by an initialization algorithm which is beyond the scope of this paper. The result of the linearization can be observed in figure 2a. The ith range measurement now constrains the solution to lie on the straight line which is tangent to the circle of radius R(i) at the point where the line connecting the ith source and the estimated position intersects the circle. The weighted least square error criterion is then used to solve for an estimate. The weights take into account the relative accuracy of the position and time estimates of the sources. The variance of the error in the estimate is also calculated based on the estimated variance of each measurement. The final estimate derived from the measurements of figure 1 is illustrated in figure 2b.

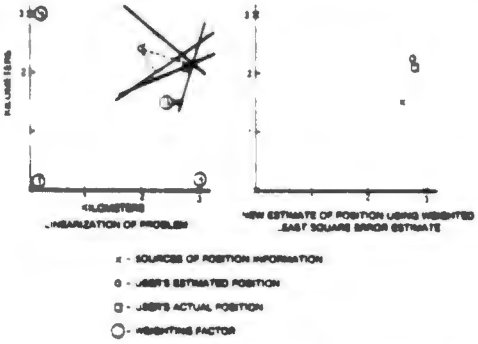

Figure 2. Linearized Solution of Multilateration Problem.

Thus, a network element provided with three range measurements of adequate quality can compute an estimate of its relative position.

Range Measurements

The accuracy and quantity of range measurements available to a unit is an important factor in the accuracy of the position location function. On the other hand, the portion of the network capacity required to support position location messages should be minimized. Thus, a range measurement technique which fulfills both of these requirements is desirable. There are two basic methods (modes) of obtaining a range measurement for position location and a clock offset measurement for time synchronization. One method, a passive mode measurement, requires only the reception of a position report from the source. The second method, an active mode measurement, requires an interrogation of the source of position information and a reply containing the information needed to calculate an active range measurement. A comparison of these two modes reveals that the selection of the measurement mode is dependent upon the operational requirements and the network environment of the unit.

In the passive mode of operation, the unit estimates its position and clock offset utilizing passively received position reports. The form of the passive mode measurement is illustrated in figure 3. By including terms to indicate the sources of error, the equation for the measurement, D, in figure 3 can be rewritten as

$$D = (\Delta t_2 + \Delta t_3) \cdot V - ER + n + m \qquad (1)$$

where

n = errors introduced by incorrect source position estimates

m = TOA measurement error.

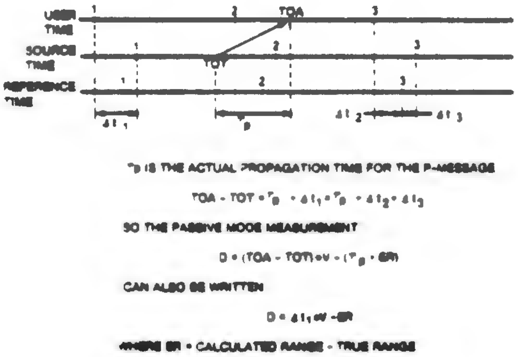

Figure 3. Passive Mode Observation.

Upon reception of similar measurements from at least three noncolinear sources, equation (1) can be linearized and an estimate of the clock offset and the error in the unit's previous position estimate can be obtained.

In the active mode of operation, a unit must interrogate the sources from which it desires to obtain position and time information. Upon reception of this interrogation, the interrogated unit replies with a position report containing the TOA of the interrogation and the position of the source at the time of the reply. The form of the active mode range measurement is illustrated in figure 4. The two transmissions of the active mode provide an independent time measurement, Dt, and an independent position error measurement, Dp. From figure 4, Dt and Dp can be written as

$$Dt = \Delta t_1 + (m2 - m1)/2 \qquad (2)$$

$$Dp = ER + (m2 + m1)/2 + n \qquad (3)$$

where

mi = ith TOA measurement error

n = errors introduced by incorrect source position estimate.

These equations show that clock offset and position errors have been decoupled in the active mode.

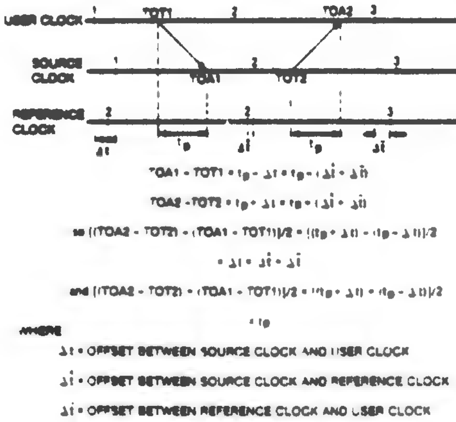

Figure 4. Active (RTT) Observation.

Analysis and simulation results indicate that the active mode range measurements produce better performance that is less dependent upon the geometry of the sources than for the passive mode case. However, there are reasons for choosing to use the passive mode at the expense of degraded performance. In an operational scenario, some units may be required to operate in a radio silent mode. At the same time, it may be important for these units to include position information in their infrequent transmissions. Such units would certainly operate in the passive mode. Another important consideration is the amount of network traffic required for position location. If network capacity is a problem and an adequate source geometry is available, then assigning some units to the passive mode can reduce the traffic requirements. Another solution to this problem is the use of a hybrid mode employing active time measurements with passive position measurements. A discussion of the hybrid mode is beyond the scope of this paper. In an attempt to satisfy accuracy requirements, capacity limitations and operational objectives, a typical network may include active mode units, passive mode units, and hybrid mode units.

Kalman Filter

In order to successfully track the clock and the position of a unit using noisy measurements and to extrapolate time and position between sets of measurements, a state model of the clock and the dynamics of the unit must be maintained. Thus, once position and time estimates have been obtained from the solution to the linearized multilateration equations, this new estimate must be combined with the previous estimates to update the state model. A Kalman filter was selected to track the state of the system. A Kalman filter provides improved performance over simpler fixed gain filters (eg α , - β tracker) and it provides the error covariance matrix necessary to implement the covariance defined hierarchy described below. The Kalman filter is defined by the state model description of the system and the error-corrupted measurements which are available for updating the model. For a ground, mobile network, a six-dimensional state vector has been demonstrated to provide an adequate state model. The six components are clock offset, clock drift rate, x-direction position, y-direction position, x-direction velocity, and y-direction velocity. This model assumes that altitude is provided from an external measurement, independently from the position location function. A variant of the above state vector would use heading and velocity in place of velocity in the x and y directions. The measurement used by the Kalman filter would be the solution to the linearized multilateration equations and its associated covariance matrix. Platforms exhibiting higher mobility, eg aircraft, would require an extended state vector and additional measurements from onboard navigation equipment in order to successfully track the platform.

Given a measurement and its variance, a Kalman filter attempts to update the state model in a way such that the trace of the covariance matrix of the state vector is minimized. The basic Kalman filter equations are summarized below:

Extrapolation

$$\underline{s}\,(\text{ext}) = A\,\underline{s}\,(\text{old})$$

$$C\,(\text{ext}) = A\,C\,(\text{old})A^T$$

Update

$$\underline{s}\,(\text{new}) = A\,\underline{s}\,(\text{old}) + K\,(\text{new})\,[\,\underline{z}\,(\text{new}) - HA\,\underline{s}\,(\text{old})]$$

$$K\,(\text{new}) = C\,(\text{ext})\,H^T\,[\,H\,C\,(\text{ext})\,H^T + R\,(\text{new})]^{-1}$$

$$C\,(\text{new}) = C\,(\text{ext}) - K\,(\text{new})\,H\,C\,(\text{ext})$$

where

$\underline{s}$ = state vector

A = state transition matrix

C = state vector error covariance matrix

K = Kalman filter gain matrix

$\underline{z}$ = measured values

H = linear transformation from $\underline{s}$ to $\underline{z}$

R = measurement error covariance matrix.

These Kalman filter equations and the multilateration measurements provide the basis for tracking the relative position of network elements.

Network Architecture

The ability of each network element to perform position location is dependent upon the existence of a common relative grid and the reception of an adequate number of useable position reports. The network structure of the position location function should perform four major tasks. Those tasks are:

a. Support time synchronization in the network

b. Establish a rectilinear coordinate grid for relative navigation

c. Ensure an adequate supply of position reports to support any unit attempting to perform position location

d. Provide for stability and robustness of the position location function.

Due to the interrelationship between time synchronization and position location, any network structure which performs the last three tasks will support time synchronization in the network. For applications where relative navigation is not required, the position location algorithms can provide time tracking only. The clock offset measurements can be provided by active mode measurements without position or by passive mode measurements with a rough position estimate.

In conjunction with the network initialization procedure, the position location network structure should define a relative rectilinear grid and, if possible, a geodetic grid. Some of the network elements are given the responsibility for establishing the grid. These elements are:

a. Master Unit (MU). An element whose relative position is defined to be the origin of the grid.

b. Relative Position Reference (RPR). An element which knows its position relative to the MU and one other RPR. These are at least two RPR's in the network. The ranges between the MU and the RPR's may be obtained through round-trip timing measurements, but some prior information must be available to obtain an unambiguous estimate of their relative positions.

c. Absolute Position Reference (APR). An element with an accurate estimate of its geodetic coordinates obtained from some source other than the position location function.

During network initialization, the MU and RPR's define a relative rectilinear grid. Given two APR's, the relative grid can be mapped onto a geodetic grid through a coordinate transformation algorithm. Once the grid is established, the loss of an MU, RPR, or APR does not disable the position location capability of the network. An alternate master unit (AMU) is designated to assume the role of the MU upon loss of the original master unit. This feature enhances the survivability of the position location function in the network.

The covariance defined hierarchy is used to select the useable sources of position information from the set of all elements within line of sight (LOS) of a particular element. Each element includes a quantized estimate of the error variances of its position and time estimates in its position report. These variances are provided by the Kalman filter of each element. The position report also contains information indicating the number of relays between that element and the MU. An element selects the sources with the most accurate position information which are closer to the MU than it. In this manner, positive feedback of errors is eliminated.

Performance Considerations

The algorithm and network architecture introduced above were the subject of an in-depth analysis to determine the accuracy of the system and its impact upon network operation. This effort utilized an analysis of the state model, a Kalman filter error sensitivity analysis program and a Monte Carlo simulation to characterize the effects of various factors upon performance. It was found that the performance of the position location function is a complex function of the update rate, the mobility of the platform, the TOA measurement accuracy, the propagation effects, the quality and topology of the sources used, and several other factors. By characterizing the individual and cumulative effects of these factors, required values for parameters, such as required update rate, required TOA estimator accuracy, etc., which will provide adequate accuracy for a given operational scenario can be determined. The impact of three of the performance factors is summarized below.

Update Rate/Platform Dynamics

A major impact of the position location function upon a network is the portion of the communications capacity of the network which must be allocated to position location. Ideally, the minimum number of position reports necessary to meet the performance goal should be used. This implies that the update rate of each unit should be as low as possible. The major factors determining the update rate are the operational accuracy requirements and the mobility of the platform. The two basic sources of error, which are a function of the update rate, are errors introduced by state extrapolation and errors caused by combining position reports received at different times into one measurement. These errors increase as the mobility of the platform increases and decrease as the update rate increases. A highly mobile platform exhibits significant acceleration and higher order derivatives of motion. These unmodeled states can cause divergence of the estimate unless they are compensated for by age weighting or similar techniques. An analysis of these errors was performed using the Kalman filter error sensitivity analysis. From these results and given the accuracy requirement, the expected dynamics of the platform, and the conditions (source error, GDOP, etc.) under which the accuracy is required, a minimum update rate can be selected. This interaction is illustrated in figure 5, where maximum update periods were selected for various platforms and performance goals.

PERFORMANCE GOAL PLATFORM	50 FT	30 FT	50 METERS	3 METERS
MAN ON FOOT	24 SEC	24 SEC.	20 SEC	40 SEC
OFF ROAD VEHICLE	6 SEC	12 SEC.	2 SEC	24 SEC
HIGHWAY VEHICLE	3 SEC .01	6 SEC .01	6 SEC 12	2 SEC 2
[illegible] HELICOPTER	1 SEC .31	1 SEC .31	1 SEC 6	4 SEC 6

ASSUMED CONDITIONS: SOURCE UNCERTAINTY = 50 FT
GDOP = 1.4
4 = 2

* INDICATES 3 DIMENSIONAL KALMAN FILTER

Figure 5. An Example of Update Rate vs. Platform Goals.

Propagation Delay Measurement

The sources of error in the propagation delay measurement include TOT errors, propagation effects, and TOA errors. The sum of all these errors can be lumped together and called the TOA measurement error. The impact of TOA measurement errors on position accuracy is a function of the mode of the unit (active or passive), the number of sources used, the dynamics of the unit, and the state model used by the Kalman filter. The effect of TOA uncertainty was characterized under various conditions using the analysis tools mentioned earlier. The uncertainty in the TOA measurement increases the uncertainty of the measurement supplied to the Kalman filter. This increases the response time of the filter, making it more difficult to track mobile platforms. The analysis indicates that a TOA of one sigma uncertainty of 100 ns may be acceptable for a slowly moving platform (eg, manpack), but the accuracy must increase as the mobility increases in order to maintain the same accuracy and update rate.

Network Topology

The topology of the network has a significant impact on the position location accuracy of the units in the network. A number of different network properties determine the configuration and quality of sources available to an individual unit. Some of these properties are listed in table 1.

Table 1. Network Properties and Source Quality.

PROPERTY	COMMENTS
Covariance defined hierarchy	Determines quality and choice of sources
Number of units in net	Effects number of sources available
Area of coverage	Effects network connectivity
Location of MU, RPR and APR	Effects source quality
Network dynamics	Effects availability and quality of sources
Network terrain	Effects network connectivity

The geometric dilution of precision (GDOP) is a measure of the errors introduced by the geometry of the sources. It is usually defined as

$$\sqrt{\sigma x^2 + \sigma y^2 / \sigma m^2} \qquad (4)$$

where

σx^2 = variance of the solution for position in the x-direction

σy^2 = variance of the solution for position in the y-direction

σm^2 = variance of the measurement error from sources.

As GDOP increases, the accuracy of a measurement decreases. GDOP is a function of the method of range measurement. The correlation between time and position errors in the passive mode accounts for much of the GDOP present in that mode. As a comparison between passive and active mode GDOP, consider the contours of equal GDOP plotted in figure 6 and figure 7. Obviously, for the source configuration of the figures, the active mode should provide better performance. This premise is borne out by the simulation results recorded in figure 8 for a unit traveling with constant velocity along the path indicated in figure 6 and figure 7.

One response of a passive mode unit with poor performance due to GDOP would be to switch to active mode operation. However, operational objectives may force some units to operate in the passive mode. In that case, it is the responsibility of the network to provide adequate sources of position information.

Implementation Issues

The impact of the position location function can be identified in three areas. These areas are: (1) network throughput, (2) hardware, and (3) software.

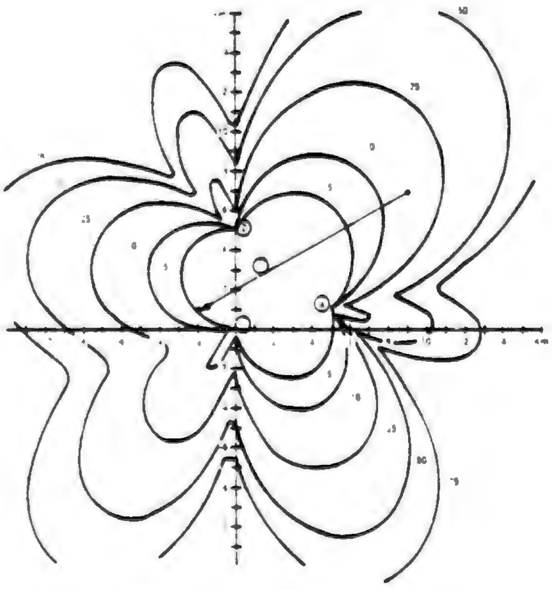

Figure 6. GDOP Contours for Basic Position Location Element (Passive).

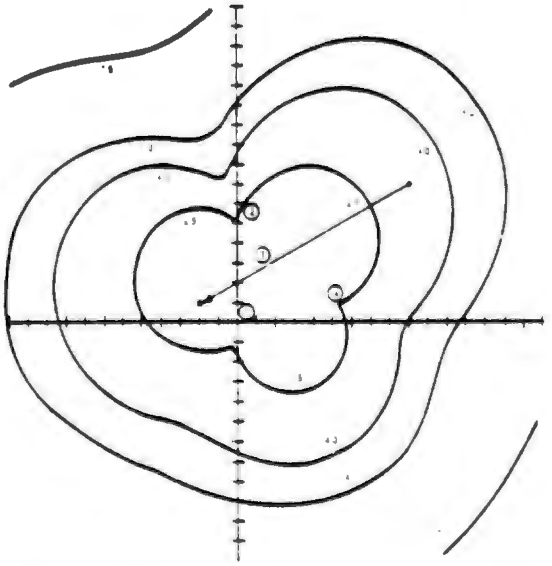

Figure 7. GDOP Contours for Basic Position Location Element (Active).

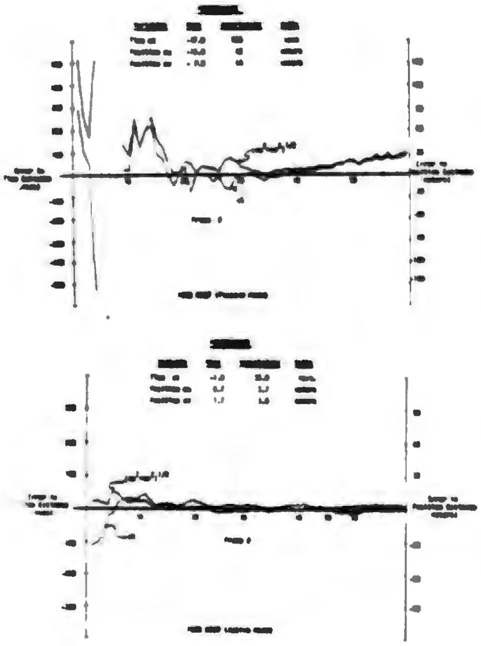

Figure 8. Simulation Results.

Throughput

The throughput or data distribution capability of the network is impacted in two ways. First, some amount of overhead traffic is introduced into the network to support the requirement for position reports. This traffic is in the form of overhead bits added to existing messages and additional messages created solely for the purpose of carrying position information. Second, some of the processing time of the unit must be used to process position information. For some networks, processing delays can become the limiting factor on throughput. Consequently, the amount of processing required for POSLOC could have an adverse effect on network throughput.

In figure 9, the average bits/sec of position information received by an average unit is plotted as a function of the number of units within LOS of that unit. This is a realistic measure of network loading because the position reports are not relayed when used solely for computing position. Several plots are included in figure 9, representing several network make-ups and position locaton strategies. The important point to note is that for less than 20 LOS units, all of the scenarios require less than 1 kb/s of position information.

The amount of processing time required by the position location algorithm can be estimated by determining the time required for the floating point operations. An estimate was done for a 16-bit processor with a hardware multiply and divide. With a 6-s update rate, approximately 3 percent of the processor's capability would be used for position location. Thus, this type of processor should be able to provide position location without seriously increasing node delay.

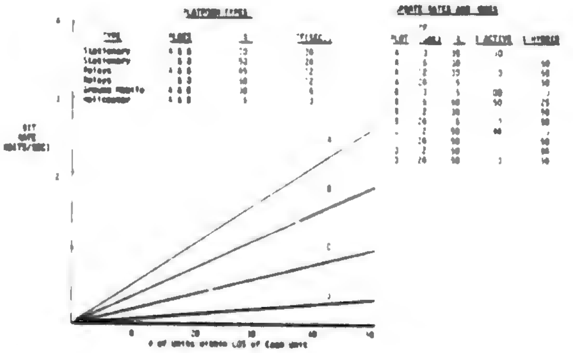

Figure 9. POSLOC Bit Rate Example.

Hardware

In general, the hardware would be impacted in the following three areas:

a. Accurate TOA estimator

b. Accurate TOT control

c. Increased memory

The TOA estimator hardware is determined by the type of waveform used. In some systems, a delay lock loop is used to track the TOA of the incoming signal. In a ground, mobile environment, it is desireable to detect the leading edge of the received multipath signal. Detection of the leading edge may require coherent averaging of the signal in order to increase the signal to noise ratio of the leading multipath component. The TOT can be controlled by retiming the signal immediately before modulation of the IF. A survey of TOA estimator and TOT control techniques indicates that the TOA estimator and TOT controller add to the complexity of the system, but their complexity is not unreasonable. An algorithm supporting two modes of operation and coordinate conversion routines could be stored in less than 8 k 16-bit words. Thus the hardware modifications required are feasible.

Software

The use of range measurements to provide time synchronization and position location requires a significant amount of software. The software tasks would include the following functions:

a. Position location algorithms
   1. Multilateration solution
   2. Kalman filter

b. Interface with the operating system

c. Creation and transmission of position reports

d. Protocols for position reports.

Conclusion

In summary, usable position accuracies can be obtained within a TDMA network. A position location algorithm utilizing multilateration and a Kalman filter linear estimator can track the position and clock offset within each network element. An analysis of this method shows that performance is a complex function of a number of factors. With the tools which have been developed for analyzing performance, the obtainable accuracy can be predicted or the parameters required to meet a performance goal can be chosen, given a particular scenario. The cost of implementing position location in terms of network throughput and hardware complexity should not be unreasonable. Consequently, position location may be a valuable, obtainable addition to a tactical data distribution network.

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