Application of Radio Navigation Technology to Advanced Automatic Train Control

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Abstract — Communication devices and network techniques are combined in a radio system under development to satisfy safety critical, operational requirements for train location and control in railroad and transit applications. Spread spectrum radios, installed on-board trains, at wayside locations, and at control stations, participate in a synchronous, time slotted network enabling location determination in conjunction with reliable transfer of control information.

I. INTRODUCTION

Congestion in our contemporary urban traffic ways has resulted in significant losses in productivity and major increases in vehicle pollution emissions. For example, traffic delays in Texas cost the traveling public an estimated five billion dollars a year. Similarly, the 1990 Clean Air Act Amendments designated many metropolitan areas, such as Los Angeles and Houston, as non-attainment areas [1]. Such congestion and its attendant costs can be reduced by both improvements in traffic management and changes to alternative modes of transportation thus yielding a balanced and automated intermodal transportation system [2, 3].

In this context, advanced public transportation systems must increase capacity over existing infrastructure without sacrificing reliability or safety. Improving the effectiveness of a rail mass transit system means minimizing the intervals between two successive consists (trains) on the same track.

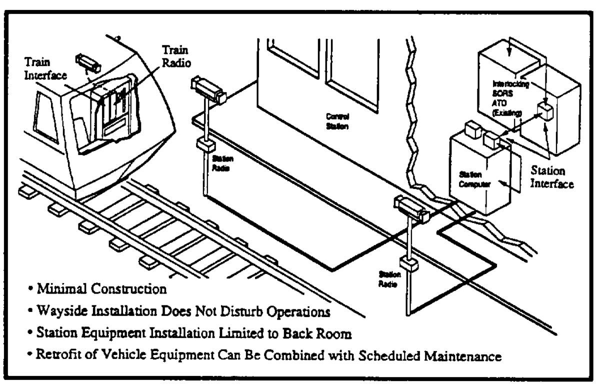

Figure 1. System Elements.

Inherent in this control process is the accurate, real-time position location of all consists under conditions with high ambient interference. To satisfy these resolution requirements, conventional detection and signalling methods require placement of sensors and communication devices at short intervals along the tracks resulting in expensive installation and maintenance costs. This paper presents an adaptation of military vehicle location and communication technology to the problem of real-time train tracking and control. High resolution position determination and reliable transfer of command information can be achieved along elevated, at-grade, and in-tunnel tracks using spread spectrum radios placed at quarter mile to one mile intervals. This *integrated cooperative ranging and communications approach* can replace or complement existing train signalling approaches as illustrated in Figure 1.

II. TRAIN CONTROL ARCHITECTURE

Railroad and public transit control systems in general and BART in particular are based on a distributed control architecture in which the entire transportation corridor is divided into control areas. Within each control area, a local control station independently both directs all routine train movements and is responsible for insuring system safety. Each control station performs a series of hand shakes with its neighbors before allowing a train to enter or leave the adjacent control area.

The primary purpose of the central control center is to schedule trains and respond to problems. The control center cannot grant any safety critical functions, but may request the local control station to do so in the course of its normal activities. It also responds to problems and failures as they occur by dispatching maintenance crews.

At the local control station level, the track is divided into control zones. Each zone is further divided into blocks. A train obtains permission to enter a block only after the local control station determines that it is safe for the train to enter that block. Between interlockings, the train separation may be as close as one block. Shorter trains and greater traffic density have necessitated higher position resolution and hence shorter block sizes in the transit industry.

While this technology has since evolved, train control systems are still based on track circuits to detect trains, control algorithms to assure train separation with adequate stopping distance, and interlockings to prevent conflicts between indicated routes and actual track switch settings [4].

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III. HEADWAY MINIMIZATION PROBLEM

For a mass transit system, each station has a maximum number of cars which can be accommodated at existing platforms. Each car also has a practical limit to the number of people which it can carry. Hence, improving the effectiveness of the transit system by increasing capacity without adding infrastructure consequently implies minimizing the headway (interval) between two successive consists on a track. Such traffic demand results from ridership on a given line and/or merging of separate lines. In BART, such peak traffic demand results from three separate lines merging to cross into San Francisco through the trans-bay tube.

In transit systems, the speed information the local control station sends to the train are called speed codes. The onboard train control system reads the speed codes and then sends the proper motor or braking control information to the rest of the train to affect the proper response. Speed codes are used to set safe top speeds and to safely slow or stop trains because of lower speed limits or obstructions. They are also used for scheduling purposes.

The selection of safe speed codes are based on very conservative assumptions regarding the distance required to stop a train [5, 6, 7]. Worst case stackups of components tolerances and reaction times are assumed per Figure 3. These assumptions are so conservative that sending a "stop" or 0 mph command to a train traveling at high speeds would cause normal trains to stop significantly shorter than the rare worst case train. To minimize this effect, a descending sequence of speed commands are transmitted via the track circuits under and ahead of the moving train, thus forming a speed command profile that the train would be commanded to follow to achieve a stop. This approach, although necessary with fixed block system, has two major drawbacks. First, because normal trains brake harder than a worst case train, the commanded speed is reached earlier than is necessary and the train is required to speed maintain for some distance before the next lower speed command is received. This has the effect of reducing the train's average speed as well as consuming energy that would not be necessary if the train were to brake continuously to a stop. Second, because train position resolution is limited by the locations of fixed block boundaries and the blocks are generally quite long, the ability to shorten headways becomes limited by block lengths. Figure 4 shows a train whose tail car is barely in Block 4T, but the following train must stop short of Block

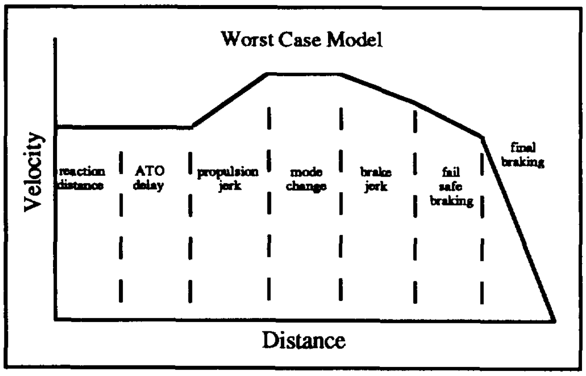


Figure 2. Speed Profile Model.

4T. Minimum train spacing, which means minimum headways, is achieved when the block length goes to zero.

Reducing the block lengths by adding more blocks can become : a) prohibitively expensive at a cost of $30,000 per block, b) a serious reliability problem due to the increased amount of equipment, and c) an operationally crippling installation on existing systems due to the amount of track side work. Alternatively, attempts to determine train position within a track circuit have not proven feasible [8].

To circumvent the limitations of fixed block systems, the railroad and transit communities in general and BART in particular are interested in moving block train control systems that do not rely upon fixed block train detection . In response to such interests, several systems using radio frequency (RF) communication technologies are currently in development worldwide. These systems are generally being developed with onboard equipment that enables trains to determine positions by sensing widely spaced fixed markers along the track and counting wheel revolutions. Trains transmit location data to a station computer which uses this information to compute and return commands to the trains which enable trains to run faster and closer together while utilizing less tractive energy. The system presented in this paper provides moving block control using spread spectrum military position location radios. This approach has the advantage that trains are located anywhere in the system without first having to move them past and subsequently detect a wayside marker.

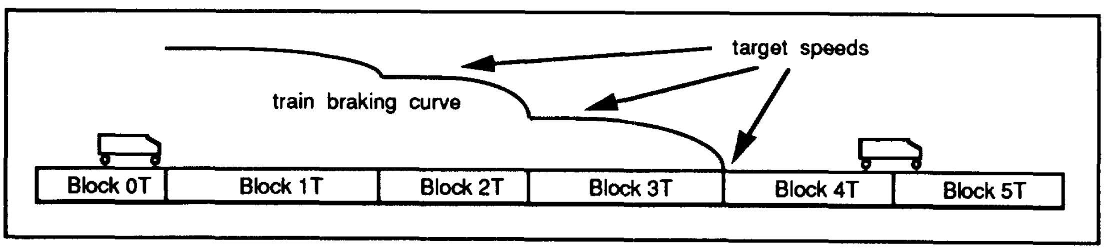


Figure 3. Fixed Block Occupancy and a Corresponding Train Speed.

IV. TRAIN TRACKING BY RADIO NAVIGATION

Communication devices and network techniques are combined to perform the safety-critical, train tracking and control communication functions in rail transit applications. On-board and trackside radios participate in a synchronous, time-slotted communication network providing contentionless and highly responsive access to all participants. Secure, validated, and error protected communication links provide reliable and redundant transfer of information among train, trackside, and control station radios. Spread spectrum communication techniques enable range measurements between all participants [10, 11, 12]. These data links relay train range measurements to control stations and relay commands from the control stations to the trains using far higher data rates than inductive loop or other conventional methods. High resolution location is determined along elevated, at-grade, and in-tunnel tracks using sparse device placement.

Spread spectrum radios are installed in the lead and tail cars of each consist. This provides redundant communications and permits independent location of both front and rear of each train. Each control station has two radios, one at each end of the station. Radios are also strategically placed along the trackside so that each front and rear radio in any train at any location along either track is within RF line of sight of at least two wayside radios. The trackside locations are also selected so that each wayside radio communicates with at least two radios uptrack and downtrack. This provides multiple opportunities for tracking and control.

Control messages are relayed outward from the control station, bucket brigade style, by the trackside radios to the train radios. The train radios receive the control messages and during demodulation measure their range from the transmitting trackside radio. Train radios transmit data messages containing their status and measured ranges. The trackside radios receive the data messages and, again as part of the demodulation process, measure their ranges from the transmitting train radio. All this status and range data is relayed inward to the control station, bucket brigade style, by the trackside radios. A control station uses these multiple range reports and the known locations of the trackside radios to determine each train's position along the track. Safe speed codes are chosen for each train and the overall process then repeats. In this manner, train and trackside radios participate in cooperative range measurements based on each other's normal data communications. Hence, this integrated ranging does not require a special, separate process.

V. NETWORK ARCHITECTURE

The network architecture is a partitioned set of control communities. Each control zone has its own synchronized communications network thereby maintaining the distributed control architecture of transit systems. As shown in Figure 4, the wayside, train, and control station radio sets together form a time division multiple access (TDMA) network. Participants are uniquely assigned one or more time slots. Inherent in a TDMA system is the requirement that all participant radio sets are synchronized to common time reference. All control zone nets are also synchronized to the same time to facilitate train transfer through transition zones.

Wayside radios always remain under control of specific control stations, but train radios belong to the control station that governs the control zone in which it currently resides. A moving train then enters and exits several control zones. Train radios are automatically given new network assignments as they transition between control zones. Dynamic allocation of train time slots in a control zone permits each zone network to accommodate the maximum number of trains. The number of control zones is not limited.

The network is organized around a half second frame. The network will normally deliver four range reports for each train to the control station every frame. Positions are then calculated and speed codes delivered back to each train within a half second. With 256 time slots per frame, the network supports 20 trains on each side of each station.

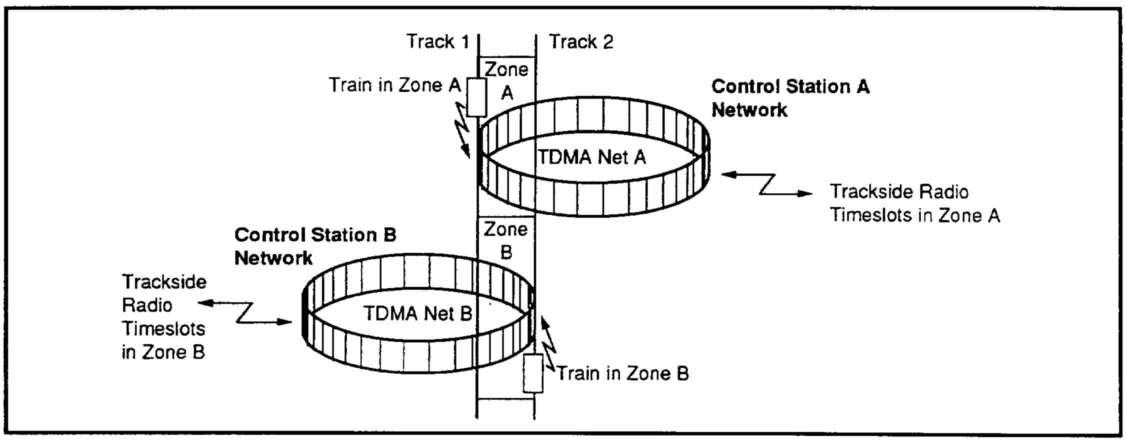


Figure 4. Synchronized Time Division Multiple Access (TDMA) Networks.

VI. DATA BUS ARCHITECTURE

The network has five categories of data distribution: (1) network synchronization and control, (2) outbound commands from the control station radio to the wayside and train radios, (3) train transmissions, (4) inbound range reports from wayside radios to control station radios, and (5) transition zone communications. Since the network supports an essentially linear physical configuration, the time slots are organized into two full duplex relay data buses on each side of each station as shown in Figure 5.

Each bus has a balanced data capacity in the two directions. Each of the data buses is allocated 120 time slots per second in each direction, for a total of 240 time slots per second for each data bus. The time slots are interleaved for the in-bound and outbound directions. Timeslots are also interleaved for the A and B buses

Messages flow 'down' the bus during odd time slots and flow 'up' the bus during even time slots. When a data message is transferred from one radio to another in a time slot, that message is relayed down the bus two time slots later. This process is repeated in odd time slots down the bus. Every eight time slots this process restarts from the same radio. Therefore, there are two data messages "moving" down the bus, eight time slots apart. Since they are only transferred on odd time slots, the repeat period is four odd time slots. This repeat distance, corresponding to four radios, is called a moving 'window'. This window structure allows time slots to be 'reused' without any interference.

Due to the two data buses and two directions on each bus, and given the repeat period of eight time slots for one bus, there would be a 16 time slot repeat period between a radio's successive transmissions on the same bus. However, every 16th time slot is reserved for special purposes, such as network acquisition, and thus the typical spacing between successive transmissions by the same radio in the same direction on the same data bus is 17 time slots. Thus, each half second frame has 15 windows in each direction on each bus, yielding a maximum control station capacity of 60 outbound plus 60 inbound messages per frame for each control station. This readily supports up to 20 trains plus reserve for network and inter-station coordination.

Each wayside radio set is normally assigned to participate on 2 buses. These must be one "A" and one "B" bus. These are usually for the same control station, except for the transition zones, where each assignment is for a different adjacent control station. All wayside radios relay all messages on their assigned buses. A control station always sends a message in every outbound opportunity. Thus each wayside radio normally transmits every 33 msec on each outbound bus. Including the two buses, each wayside radio typically transmits outbound 30 times per frame.

Each train radio is assigned to repetitively and synchronously initiate an inbound message once per second on each bus. Hence, each train initiates four report messages per second. Each train radio also listens for signals from four consecutive wayside radios for each bus. These may be the same or different wayside radios for each bus.

Also, all radios send extra reports in response to one time commands. This "interrogate-transpond" feature is integrated into the data bus architecture and used to collect extra reports or to make up for an occasional missed report.

Each transition zone will have two wayside radio sets which have one bus assignment for each of the two adjacent control stations. In general, one wayside radio would have sufficient area coverage, but the second wayside radio provides redundant coverage. These transition zone wayside radios assure that a train in or near the transition zone will be able to have range and status reports delivered to both control stations. Also, these wayside radios perform a store and forward function for data exchange between the adjacent stations. This station to station data exchange is highly desirable for early warning of approaching trains and for synchronously coordinated hand-off of train responsibility.

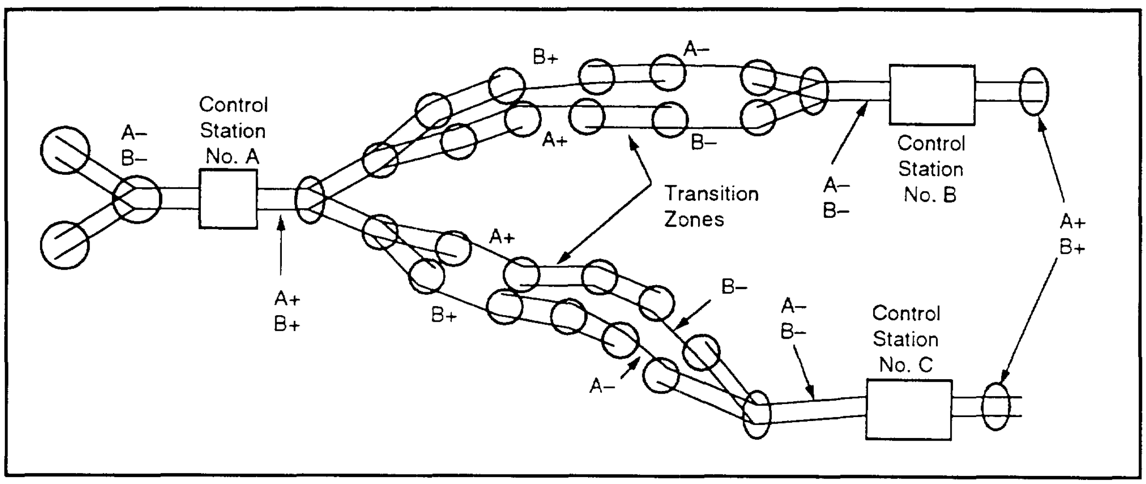


Figure 5. Data Bus Architecture Including Divergencies and Transition Zones.

VII. MAINTAINING NETWORK SYNCHRONIZATION

All control zone TDMA networks must be in time synchronization with each other. For ease of startup, several of the wayside radio sets are equipped with a Global Positioning System (GPS) module. Using GPS as an external reference is a straightforward method for synchronizing many elements in a geographically dispersed system. Many parts of the network can be built outward from multiple starting points with proper synchronization at the interfaces. Each radio will align its internal clock time offset and frequency drift to GPS. If the GPS signals are lost, the radio sets will still maintain synchronization with each other using a battle-proven, mutual synchronization algorithm.

Each radio has a crystal oscillator for maintaining its own time base. As an artifact of the manufacturing tolerances for hardware components, each crystal oscillator has a slightly different resonant frequency (approximately one part in one million), so, over time, the time bases and hence the start of time slots in different radios drift slightly relative to each other as shown in Figure 6. Left uncorrected, this drifting would cause inaccuracies in the range measurement. By combining two time of arrival (TOA) measurements in close proximity, the instantaneous drift is zero and the long term drift is determined. This longer term drift, which is relative between two radios, is called offset and continually corrected for during normal network operations.

As shown in Figure 7, each wayside radio set automatically listens to three previous wayside or station radios in each direction. The wayside radios monitor for link reliability and TOA measurement consistency. About four times per frame, each radio sends out a net synchronization message. All receiving radios reports their filtered TOA measurements to their adjacent radios. Each radio uses the two-way TOA measurements to calculate its clock offset relative to each of its adjacent radios. Each radio weighs their offsets from their adjacent radios based on its measurement's quality and its distance from a GPS timing source. If the weighted average of these calculated offsets is greater than 0.2 microseconds, then this radio corrects its clock frequency by about 0.02 microseconds per second until its clock timing is tightly synchronized.

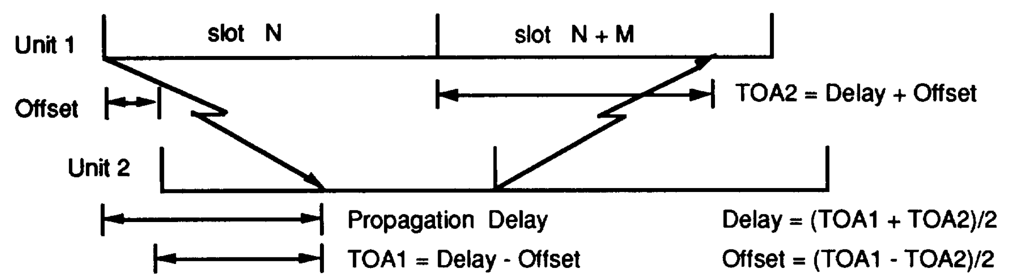
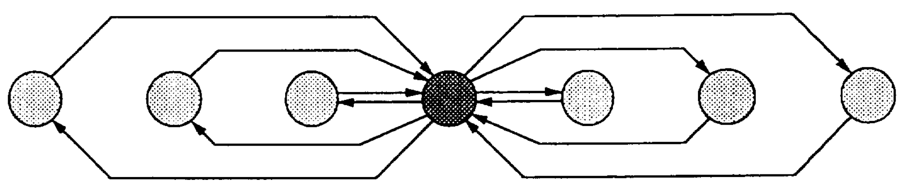


Figure 6. Deriving Clock Offset and Range based on Time of Arrival (TOA) Measurements.

1) Each Radio Receives and Filters TOA Measurements from up to 3 Upstream Radios and from up to 3 Downstream Radios



2) Each Radio Sends Filtered TOA Measurements to up to 3 Upstream Radios and to up to 3 Downstream Radios

3) Each Radio Calculates Clock Offsets and Corrects its Own Clock to Minimize Errors

Figure 7. Maintaining Synchronization Along the Data Bus.

VIII. TRACKING PERFORMANCE

The train tracking algorithms are derived from position location algorithms developed for battlefield location and tracking systems. Examples are PLRS and EPLRS [13, 14]. These systems automatically calculate and report to commanders the three-dimensional locations of all manpack, vehicle, and airborne units in the forward battlefield areas. The train tracking problem is essentially a linear version of this multi-dimensional battlefield problem.

With only one transmission per time slot, relative ranges between units can be measured by elapsed time of routine communications within this time-ordered, synchronous network. Since the ranging does not require a separate process and mutual ranging results in overall position location, this approach is integrated cooperative ranging and communications. Ranging between all radios in the network, but mainly between train and wayside radios, is possible using a spread spectrum modulation for each individual transmission. In a direct sequence, spread spectrum communication system, a wideband spreading signal is modulated onto a lower rate data signal. By synchronizing to the higher rate transmissions, time demarcations are established. Elapsed time equates to distance from the transmitter. For instance, at sea level, radio propagation speed is 0.98356 feet per nanosecond. Higher spreading rates yield more accurate resolution. A combination of 5 MHz spreading rate and 16 times over sampling in the receiver correlators yield a range resolution of 12 feet on any one individual TOA measurement.

Time demarcations in the ranging process are refined continually during the course of reception. Course spread spectrum chip boundaries are determined during the message acquisition process. At the preamble end, synchronization is to half of a chip, or 100 nanoseconds. At the end of the time refine buffer, synchronization is to one-quarter chip, or 50 nanoseconds. Timing corrections continue throughout message reception, so that at the message's end, synchronization is to the nearest sixteenth of a chip, or 12.5 nanoseconds. The TOA measurement is then actually a measurement from the end of message reception to the end of the time slot, which is directly proportional to range delay.

Wayside and train radios use TOA measurements on their messages to form a range measurement from a wayside radio to a train. Per Figure 6, the paired TOAs average out any offset and drift in the respective time basis of the two radios, so that each range measurement has a precision of 6 feet. In practice, multiple TOA measurements are averaged in each direction and paired to form a range. Since the location of the wayside radio is accurately known from a surveyed installation, the range measurement is added to the known trackside location to get an estimate of the train's position. Any one estimate is typically accurate to within 6 feet. Furthermore, the tracking algorithms at the control station combine several range measurements from several different wayside radios to calculate the position of each train's lead and tail cars. These position estimates are further refined using a predictive corrective tracking filter.

The algorithms required for train position location are not as complex as those required for battlefield applications because several key locations are already known to high precision. The actual train track and the wayside radio locations are both at surveyed positions which serve as reference points. This information can be used to greatly simplify the generic location algorithms per Figure 8.

The train tracking filter employs a simplified version of the discrete Kalman filter, which requires that in addition to estimates of position an velocity, an error covariance matrix reflecting the quality (uncertainty) of these estimates is computed. In this manner, the source of information is assigned a proper degree of importance. The resultant filters can also be termed adaptive corrective filters [15, 16].

Any very poor measurement leaves the train's position uncertainty unchanged or even increased while a low range measurement uncertainty combined with a high train position uncertainty reduces the train's position uncertainty for that measurement. For train tracking, the wayside radios have position uncertainty much less than for the measurements (essentially zero). Together, the TOA measurement averaging, the ongoing quality indicators on the position location reports, and the predictive corrective filters will yield a typical real time position location accuracy of 3 feet.

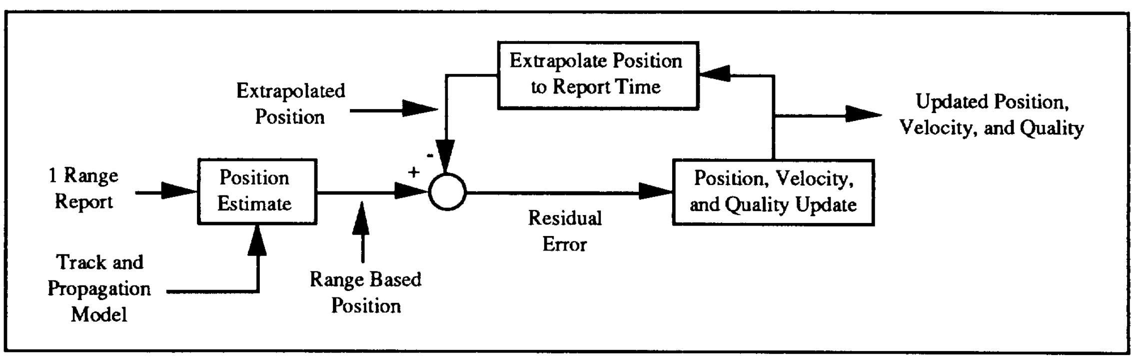


Figure 8. Tracking Algorithm.

IX. DESCRIPTION OF THE RADIO SET

The spread spectrum radio for consist tracking and control is derived from the rugged, battlefield PLRS and EPLRS radios [13, 14]. Their modular construction facilitates adapting these radios to other radio-location applications. As a derivative of militarized equipment, this transit radio is fully qualified to climatic and dynamic environments that meet or exceed the ruggedized train operational environment. This radio has seven major modules as shown in Figure 9.

The converter amplifier assembly provides frequency conversion, transmit power amplification to 1 watt, and low noise receive amplification of the 2.4 GHz waveform. During transmission, the CPSM signal is converted using a single mix approach with a low noise oscillator. This phase locked oscillator uses the temperature compensated crystal oscillator (TCXO) system reference combined with a low-noise, high-Q, 2.005 GHz resonator. During reception, low noise figure and group delay are provided by monolithic microwave amplifiers and maximal bandwidth filters.

The IF assembly performs the intermediate frequency conversion, amplification, and signal filtering. During transmission, the digital output of the signal processor is modulated onto the spread spectrum CPSM carrier. During reception, this module performs 2-bit analog-to-digital conversion of the incoming signal for subsequent processing by the signal processor. This assembly also contains the stable TCXO time base, a multi-channel frequency synthesizer, and local oscillators. Mean time between failure (MTBF) of this module exceeds 45,000 hours.

The signal processor function performs preamble detection & generation, interleaving & de-interleaving, error control encoding, error correction & detection, spread spectrum PN generation, data correlation, time & phase adjustments, and time-of-arrival measurements for position determination. MTBF of this module exceeds 140,000 hours.

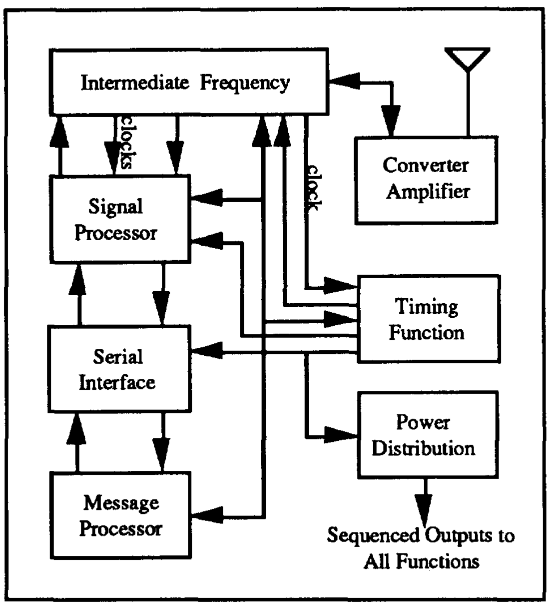


Figure 9. Radio Functional Block Diagram.

The message processor module contains a low power, complementary metal oxide semiconductor (CMOS) microprocessor that is the radio's central controller. All processes within the radio are controlled jointly with the message processor as master and the timing function as slave. Also, the message processor generates, verifies, composes, decodes, interprets, and reacts to the network message catalog. System messages are exchanged with the serial interface module. MTBF of this module exceeds 140,000 hours.

The timing function generates all time slot sequencing signals used within the radio. Control signals are enabled and disabled per the instructions of the message processor.

The serial interface module exchanges data with an ATO on-board a train or a speed-code selection computer at a control station. The serial interface module also has the extended 32 bit cyclic redundancy check (CRC) circuitry.

The power distribution function contains the power supplies, regulators, power line filters, and power switching circuitry needed to power all other radio functions. MTBF of this module exceeds 180,000 hours.

Since 1985, Hughes has participated with the Army in the development of four very high speed integrated circuit (VHSIC) modules for the EPLRS radio set. These modules perform (31,19) Reed Solomon error correction, 512 chip preamble correlation, general signal processing, and channel I/O functions. These modules increase message throughput and have built-in testing with fifty percent less parts thereby improving reliability while lowering power consumption.

In August 1992, joint engineering tests were conducted by Hughes Aircraft Company and the Bay Area Rapid Transit District. These tests demonstrated that existing military time division multiple access spread spectrum radios could successfully resolve the positions of consists to within 15 feet circular error probability. Robust communications leading to accurate position location functionality were achieved in urban, rural, and aerial settings. However, as predicted, propagation in the various tunnels was not successful. Per Figure 10, the 420-450 MHz operating frequency band of the PLRS and EPLRS radios is the frequency band which experiences the most transmission loss in train occupied tunnels [17]. These measurements reflect the significant impact of a train's presence on radio propagation in a tunnel. Experience shows that below 150 MHz, the transmission phenomenon in tunnels is attenuated free space propagation, whereas above 150 MHz the transmission phenomenon in tunnels is waveguide propagation. However, at 5 GHz, ribbed tunnel walls cause wave scatter, so overall tunnels favor communications using intermediate frequencies.

Selection of an operating frequency for the data link involves many issues. In particular, the frequency selection must support the data link architecture, including waveform modulation, error correction codes, and network protocols. This architecture uses radio-location to resolve train placement and the system waveform uses spread spectrum modu-

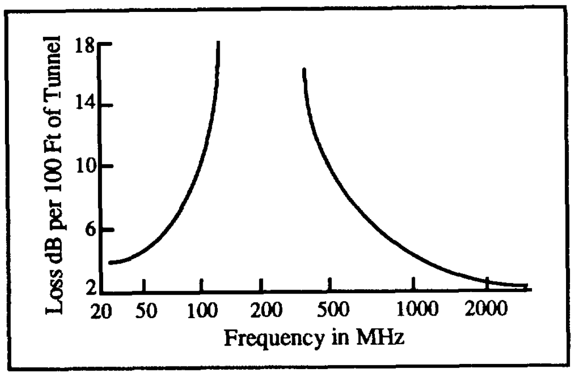


Figure 10. Radio Frequency (RF) Transmission Loss in Train Occupied Tunnels [17].

lation to obtain the resolution accuracy. Under Federal Communications Commission (FCC) ruling 15.247, three frequency bands are currently reserved for spread spectrum communications — 902-928 MHz, 2.4-2.485 GHz, and 5.725-5.865 GHz. The United States also has the 420-450 MHz band reserved for radio-location. Based on the spread spectrum frequency band requirement, excess path loss at higher frequencies in urban areas, excess indigenous noise at low frequencies in urban areas, and excess transmission loss at both high and low frequencies in tunnels, the 2.4-2.485 GHz band was selected as the recommended operational frequency band. To provide experimental confirmation of this analytical choice, after modifying several radios with frequency converter assemblies, extensive propagation tests were conducted by Hughes in the various BART tunnels during February 1993. Results demonstrated 99.9% data throughput reliability and 15 feet circular error probability for position location. Hence, these tests confirmed that 2.4 GHz is the proper overall operational frequency band.

X. CONCLUSIONS

The described train tracking and control system uses wireless methods and sparse device placement to improve the effectiveness of existing rail transit infrastructure. This system has many advantages over conventional train signalling and control systems. This approach enables faster response times, has higher data rates, does not require physical contact with the train, uses minimal devices wayside, functions in tunnels, maintains accuracy along curves, does not require system shut down to perform maintenance, uses readily available hardware components, and is less sensitive to noise interference. This system can be either an independent replacement or an overlay of existing signalling systems for continuous tracking and redundant communications. While derived from proven military technology, this approach is radical for the transit industry and is currently under consideration by the Advanced Research Project Agency (ARPA) for the Technology Reinvestment Project (TRP) in the vehicle technology category.

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