DESIGN AND TEST RESULTS OF A SOFTWARE DEFINED RADIO FOR INDOOR NAVIGATION

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ABSTRACT

NAVSYS has developed a Software Defined Radio (SDR) test-bed with the capability of navigating inside of buildings. This test-bed combines Global Positioning System (GPS), wireless communications, and Time-of-Arrival (TOA) “Pseudolite” technology to provide location indoors for applications such as first responders, warfighters, and location-based services.

The system uses network assistance over a wireless 802.11 link to enhance GPS and TOA in low-signal and degraded-signal environments (e.g. tunnels, buildings, under tree canopy, and within proximity to RF transmissions). The network assistance information includes differential pseudorange, ephemeris, and navigation data bit aiding. Each system node is capable of navigating using GPS and can switch over to TOA in areas where GPS reception is impossible using strategically located TOA transmitter nodes. The design incorporates a frequency flexible transceiver.

Since the system is based on an SDR architecture, it is easily upgraded for additional capabilities including inertial integration and mesh enhancements using wireless and TOA. In addition, the system can leverage silicon economics and Moore’s Law as new computing technologies evolve to further reduce size, weight, and power.

This paper presents the design and operational results of the SDR indoor navigation test bed.

1. INTRODUCTION

A Software Defined Radio (SDR) provides a flexible architecture that allows the same radio components to be reconfigured to perform different functions. NAVSYS has developed an SDR that includes the capability to operate both as a Global Positioning System (GPS) receiver and also as a 900 MHz transceiver operating within the Industrial, Scientific and Medical (ISM) band. Since both the GPS and communications functions reside within common radio hardware, this positioning and communications (POSCOMM) device can use the GPS and communications functionality to provide a positioning capability that leverages both the GPS derived pseudorange and carrier phase observations and also Time-Of-Arrival (TOA) observations derived from the communications channel. The design of the POSCOMM Software Defined Radio is described in this paper.

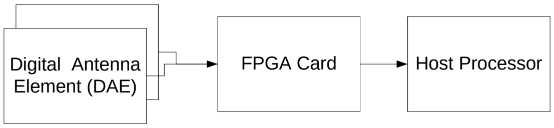

Figure 1 Software Defined Radio Architecture

The POSCOMM SDRs are designed to operate in a networked architecture, as shown in Figure 2, where “Master” units are designated as transmitters to provide TOA augmented navigation to “Slave” units operating as receivers in a GPS-denied urban environment. The Master units transmit a TOA message that includes a pseudorandom sequence from which the time of arrival at the Slave unit can be precisely determined. A message is also sent including the precise time of transmission of the TOA message and the precise location of the Master unit based on the GPS observations. The time-of-arrival differenced with the time-of-transmission provides the Slave unit with a pseudorange observation from each of the Master units’ locations. This can be used to solve for the position of the Slave either using the TOA updates alone or using a combination of both the GPS and TOA observations.

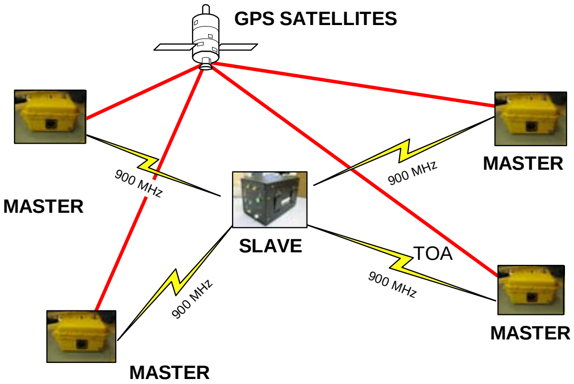

Figure 2 POSCOMM TOA NETWORK[1]

2. POSCOMM SOFTWARE DEFINED RADIO

The POSCOMM GPS/TOA navigation solution was implemented using NAVSYS' Software Defined Radio test bed shown in Figure 3[2.] This has been developed using a modular PC/104 configuration to facilitate rapid prototyping and testing of SDR software applications to support advanced positioning and communications functions. Previously, this SDR has been used for demonstrating a Software GPS Receiver (SGR) Application Programming Interface (API)[3], network assisted GPS operation using the military P(Y) code GPS signals[4], and also integrated GPS/inertial operation including Ultra-Tightly-Coupled (UTC) GPS/inertial tracking[5].

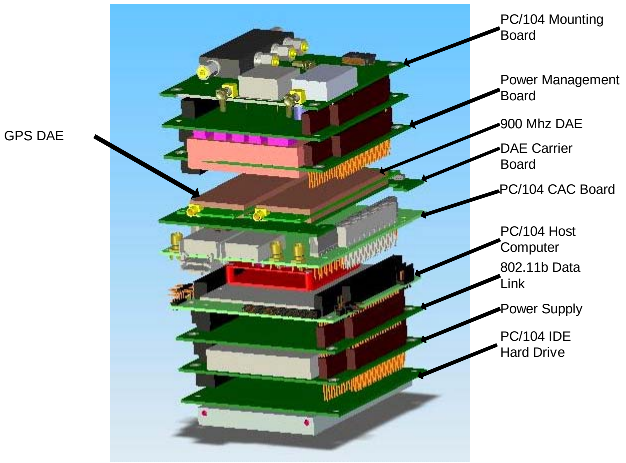

Figure 3 POSCOMM SDR Components

Figure 4 POSCOMM SDR

The POSCOMM SDR system is based on low-cost, commercial-off-the-shelf (COTS) hardware and software. The hardware can use any PC-based environment including desktop, laptop, PC/104, or CompactPCI form factors. Signal processing is performed by a Xilinx Spartan-3 Field Programmable Gate Array (FPGA) card and a Pentium-class CPU. The software is portable and developed for real-time flavors of Windows and Linux operating systems. An SCA-based XML schema is used for system configuration.

Received RF signals for both GPS and TOA are converted to digital signals using Digital Antenna Elements (DAEs). The DAEs have a small 1"x4" size and can be easily modified for alternate frequencies and sampling rates. The DAE is responsible for RF down-conversion and up-conversion as well as high-speed A/D and D/A sampling. Each DAE uses a common sample clock and phase-locked reference local oscillator assuring a coherent sampling environment for all transmitted and received signals.

The POSCOMM SDR PC/104 stack shown in Figure 3 is packaged in the enclosure shown in Figure 4 and includes the following main components.

- **GPS Digital Antenna Element**. This is used to receive and track the GPS signals.
- **GPS 900 MHz Digital Antenna Element**. This includes a 900 MHz receive and transmit channel that is used for either broadcasting or receiving the TOA-aided data. This could also be configured for use in communicating between the POSCOMM units. 900 MHz was selected as this lies in the unlicensed ISM band. The DAE transceiver can be configured though to work at other frequencies.
- **802.11b Data Link**. This was used to provide the inter-unit communications link during this phase of testing.
- **PC/104 CAC Card**. This is a NAVSYS designed card that includes three Spartan FPGAs and a PCI interface to the Host Computer. This interfaces directly with the DAE receive and transmit channels through an adapter board, as shown in Figure 5.
- **Host Computer**, Hard Drive and Power Supply. These are COTS components that include a PC/104 form-factor Pentium-M Single Board Computer, power supply and 80 GByte Hard Drive

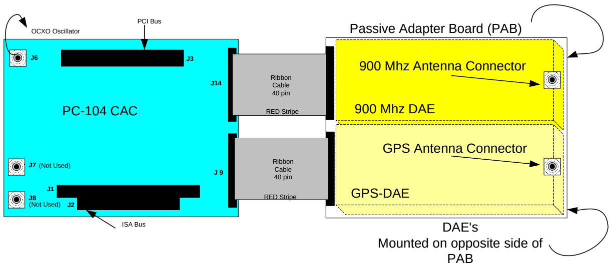

Figure 5 PC/104 CAC to DAE Interfaces

3. POSCOMM SDR OPERATION

The POSCOMM SDRs are configured through software to operate as either a Master (Transmit) or Slave (Receiver) mode of TOA operation.

Master units are required to be tracking at least one GPS satellite to allow the time of the TOA transmission to be synchronized precisely with GPS time. These units send TOA Assistance messages across the network which tells the Slave units what TOA observations are available for use in aided navigation and also provide the location of the Master units that are providing the TOA aiding.

Slave units will default to GPS tracking if satellites are in view, but are not required to track any GPS satellites for them to operate. At start-up, they initialize time across the network using Network Time Protocol (NTP). On receipt of the TOA Assistance messages from the Master units, the Slave unit will then initiate tracking of the TOA observations which will be used, in combination with any observed GPS satellites, to compute the aided navigation solution.

The GPS/TOA solution accuracy is a function of the following components which are addressed in the POSCOMM SDR design and described in the following sections of this paper.

- Accuracy of the GPS time and position mark at the Master unit.
- Geometry provided by the TOA observations.
- Accuracy of the TOA observations

Table 1 TOA Acknowledge Message

Field Name	Units	Description
Time	Week secs	GPS time of week of first TOA being transmitted
PRN		ID of PRN code
Period	ms	Interval between TOA signals
Duration	ms	Duration of TOA ranging signal
Freq	MHz	RF Frequency of TOA signal

4. TOA TRANSMISSIONS

The SDR architecture allows for a variety of different waveforms to be used to provide TOA assistance. The key feature of the POSCOMM SDR approach is that the design of the SDR DAEs and firmware allows the timing of the TOA transmission to be precisely locked in time to the received GPS signals. For the POSCOMM testing, we implemented a combined Code-Division Multiple Access (CDMA), Time-Division Multiple Access (TDMA), and Frequency-Division (FDMA) approach for sharing the spectrum between the multiple Master Units providing TOA assistance. This provides maximum flexibility in configuring the POSCOMM TOA assistance network to optimize performance and share limited bandwidth for both positioning and communications functionality. The CDMA, TDMA and FDMA parameters that specify the TOA signal characteristics are all defined using configuration parameters and are defined in the TOA ACK Message sent by the Master Units (see Table 1).

5. GEOMETRY OF TOA-AIDED SOLUTION

The horizontal and vertical accuracy of a GPS TOA-aided solution is a function of the TOA dilution of precision (DOP) scaled by the TOA observation accuracy. The worst-case performance occurs when no GPS satellites can be tracked and only TOA observations are available for navigation.

If only ground-based TOA transmitters are used, then the 3-D TOA solution is indeterminate and the DOP approaches infinity (Figure 6). If altitude-aiding is used, for example from a baro-altimeter, then a 3-D solution can be calculated. Figure 7 shows the simulated dilution of precision with 4 transmitters located around a 3-story building where HDOP<1 and VDOP<1.

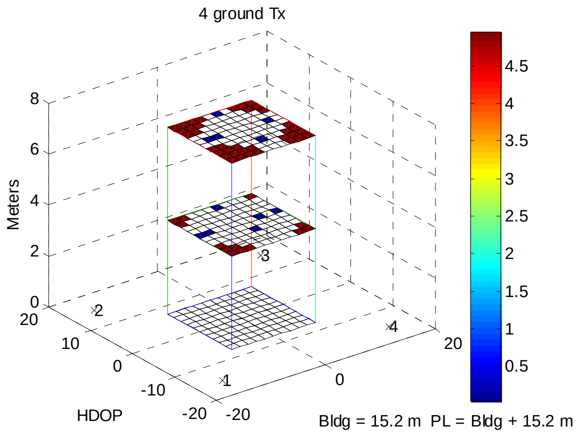

Figure 6 HDOP with 4 Ground-Based Transmitters

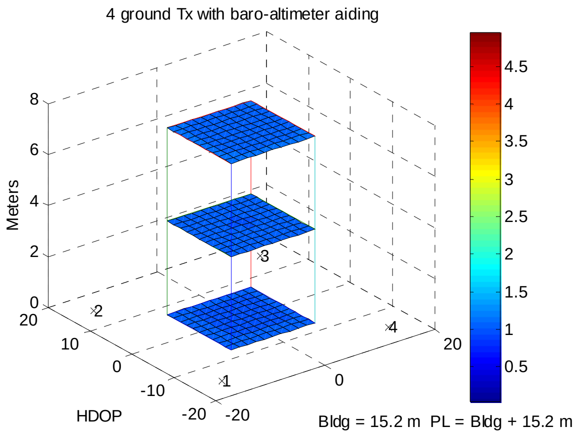

Figure 7 HDOP with 4 Ground-based Transmitters and Altitude-aiding

6. TOA OBSERVATIONS

The accuracy of the TOA observations is a function of the waveform characteristics, the tracking loops employed and the environment. The main challenge faced for the TOA ranging signal design is to provide robust and accurate performance in the presence of multipath.

To evaluate the multipath environment and the ability of the TOA tracking loops to handle these errors, four Master units were set up around the NAVSYS building shown in Figure 8 with the test layout shown in Figure 9. Test results were collected from units operating both outside the building, where GPS could be used as a truth reference, and inside the building. In both cases, the TOA signals were passing through multiple different types of construction. The west end of the building is metal construction while the center and east end is brick construction.

A maximum likelihood estimation (MLE) algorithm is used to estimate the TOA from the correlation results generated from the 900 MHz received signal correlated with the modulated PRN code. The algorithm detects the peak of the correlation from the closest in signal detected. This will result in detecting the correlation peak of the signal from the direct path from the transmitter rather than a multipath signal that arrived from an indirect path. Figure 10 shows the correlation results from four transmitters when the receiver has a direct line-of-sight to the transmitters. All four signals have a strong detected correlation peak with a received RF signal of around -16 dBm. Figure 11 and Figure 12 show the correlation results from signals received through the NAVSYS building. In these cases, the building can significantly attenuate the received signal power and also strong multipath signals are present, which appear as peaks showing to the left of the direct signal peak. The MLE algorithm used to perform the TOA tracking detects the closest peak in each case shown.

Figure 8 NAVSYS Building (Southwest View)

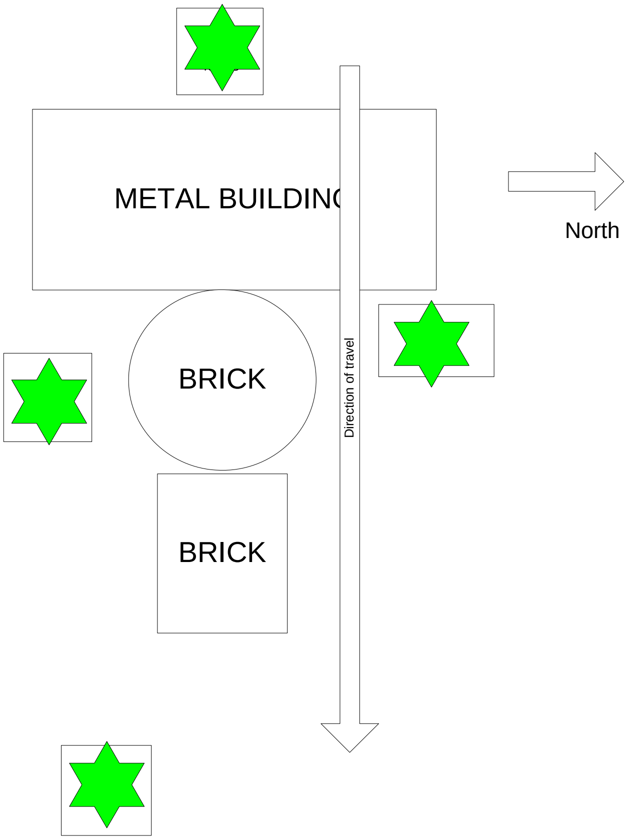

Figure 9 Indoor Test Pseudolite Layout

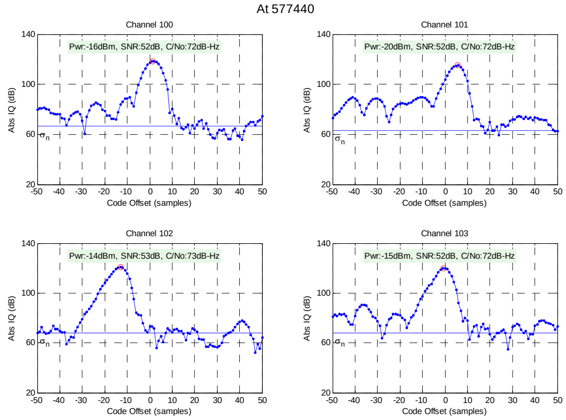

Figure 10 MLE Estimation of Shortest TOA Pseudorange (outdoor testing)

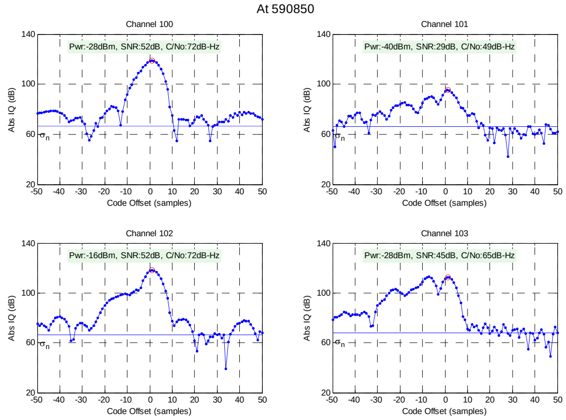

Figure 11 MLE Estimation of Shortest TOA Pseudorange (indoor testing)

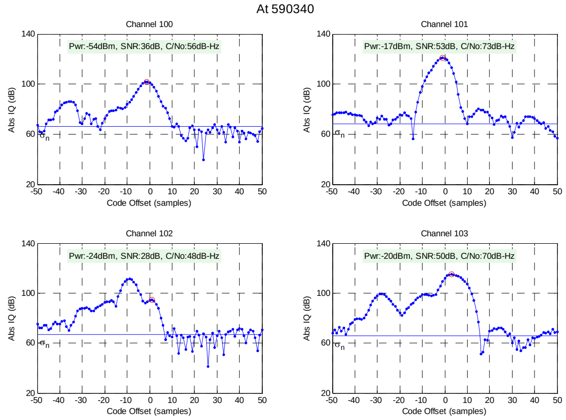

Figure 12 MLE Estimation of Shortest TOA Pseudorange (indoor testing)

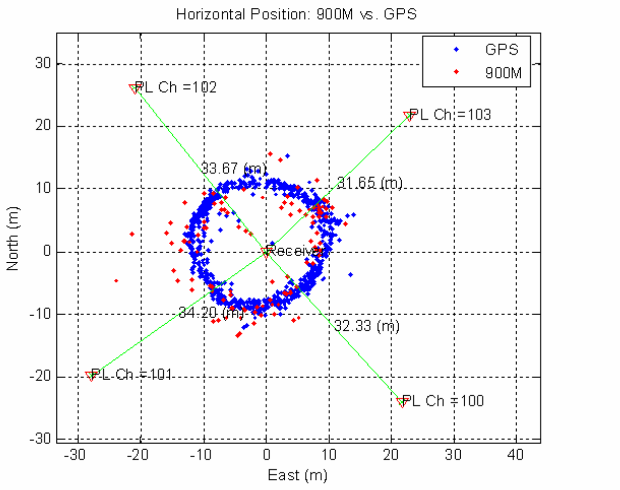

Figure 13 TOA Navigation Solution

7. TOA-AIDED NAVIGATION TEST DATA

The TOA observations were processed and compared with GPS as truth data to analyze the performance of a TOA navigation solution. The results are shown in Figure 13. The POSCOMM navigation solution computed from four TOA observations agreed with the GPS truth solution to within 5 meters except for a few excursions. Further improvements are being added to the design of the Master and Slave POSCOMM SDRs to improve on the accuracy of these initial results. In the next phase of the project, we will also be integrating a MEMS IMU with the POSCOMM SDR to assist in filtering and tracking the TOA observations.

8. CONCLUSION

The POSCOMM units are being developed to provide a robust urban navigation solution that can provide precise positioning inside buildings where the GPS signals cannot be received. Military applications for this technology include improved military operations in urban terrain (MOUT). Commercial applications include firefighters as well as other first responders. Rex Systems Incorporated has expanded on the basic POSCOMM positioning capabilities provided by NAVSYS and is partnering with NAVSYS to develop the First Responder System shown in Figure 14. This project will give firefighters, police officers and emergency officials an electronic vest and eyepieces that will provide their commanders with their location and their vital signs, as well as real-time video of their surroundings.

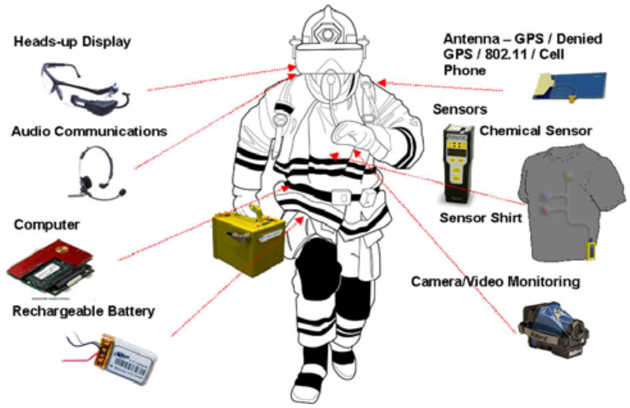

Figure 14 First Responder[6]

The initial tracking and positioning results shown in this paper show the capability provided by the POSCOMM SDR to augment GPS signal tracking in the challenging urban environment with TOA aiding from an alternative RF source. This technology offers the capability to provide access to GPS-like quality of service both outside and inside buildings.

9. ACKNOWLEDGMENTS

The authors would like to acknowledge the support of CERDEC, STTC, and Rex Systems Incorporated who have provided funding to support the development of this technology.

10. REFERENCES

[1] Systems shown from Rex Systems Incorporated First Responder Program
[2] A. Brown, Y. Lu, and J. Nordlie, “Integrated GPS/TOA Navigation using a Positioning and Communication Software Defined Radio,” Proceedings of ION GNSS 2005, Long Beach, California, September 2005.
[3] F. Carpenter, S. Srikanteswara, and A. Brown, “Software Defined Radio Test Bed For Integrated Communications And Navigation Applications,” Proceedings of 2004 Software Defined Radio Technical Conference, Phoenix, Arizona Nov. 2004
[4] A. Brown and P. Olson, “Urban/Indoor Navigation using Network Assisted GPS”, Proceedings of ION 61st Annual Meeting, Cambridge, Massachusetts, June 2005
[5] A. Brown and Y. Lu, “Performance Test Results of an Integrated GPS/MEMS Inertial Navigation Package,” Proceedings of ION GNSS 2004, Long Beach, California, September. 2004
[6] First Responder System being developed by Rex Systems Incorporated