NON-GNSS RADIO FREQUENCY NAVIGATION

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ABSTRACT

There are many situations in which Global Navigation Satellite Systems (GNSS) such as the Global Positioning System (GPS) cannot provide adequate navigation performance (such as indoors or in urban canyons). This paper describes the technical challenges of non-GNSS radio frequency navigation, with particular emphasis on signals of opportunity (i.e., signals that are intended for purposes other than navigation). Advantages and disadvantages of signal of opportunity navigation are described, along with the dominant issues that must be dealt with in order to make such systems a practical reality.

Index Terms— Navigation, Signals of Opportunity

1. INTRODUCTION

Over the past couple of decades, there have been a number of trends that have driven the desire to improve our ability to navigate in all environments. Previously, the primary desire was to navigate single, stand-alone systems (such as a car), but now, the desire is increasingly to have simultaneous navigation awareness of multiple interdependent systems (such as a traffic notification system in a car). Previously, navigation capability could not always be counted on, but increasingly navigation is considered to be an assumed infrastructure (like knowing the lights will come on when you turn on the light switch). Previously, navigation accuracy of 5-10 m seemed almost extravagant when other worldwide navigation options prior to GPS (namely, Omega [1] and stand-alone inertial) had accuracies more on the order of 1-2 km. Now, many applications require meter or sub-meter level accuracy (such as precision agriculture). Previously, due to cost, power, and size constraints, it was generally only feasible to know where the "big things" are (such as airplanes). Now, navigation is desired on more and more, smaller and smaller objects (such as cell phones).

While GPS has been the driving factor behind most of these trends, there are limitations to GPS that have become more evident over time as we have increasingly come to rely on navigation. This motivates the need for non-GPS (or, more generally, non-GNSS) navigation technologies.

2. ALTERNATIVE NAVIGATION TECHNIQUES

There are at least three categories of non-GNSS navigation approaches:

- **Image/lidar/Doppler/DR aiding of inertial.** These techniques attempt to use an inertial system, but constrain the drift by incorporating another source or sources of aiding. Such systems are typically self-contained. Examples include image-aided inertial navigation [2], lidar-aided inertial navigation [3], and pedometry-based DR-aiding of inertial [4].
- **Beacon-based navigation (including pseudolites).** If the GPS signal is not adequate for navigation in a particular environment, it is possible to transmit an additional signal or signals that are specifically designed for navigation purposes. Examples of beacon-based navigation systems for indoor navigation can be found in [5] and [6].
- **Navigation using signals of opportunity (SoOP).** Signals of opportunity, as defined in this paper, are radio frequency (RF) signals that are not intended for navigation. Examples from previous research include digital television [7], analog television [8], and AM radio [9], [10].

This paper is focused on the third category: navigation using signals of opportunity.

3. REASONS TO USE SIGNALS OF OPPORTUNITY

There are many SoOP available for navigation. There is potential for incredible signal diversity, in both direction and frequency, when using signals of opportunity. Depending on the location, there can be dozens of potential SoOP signals. There are some locations where there many not be many SoOP available, but such signals are much more plentiful in typical urban environments (where the navigation gap is).

SoOP can be relatively high power and are able to penetrate buildings. This concept can be exemplified by comparing GPS received signal power to a typical FM radio station.

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A GPS satellite transmits at 282W effective isotropic radiated power (EIRP) from a distance of approximately 20,000 km (if the satellite is directly above the receiver). In contrast, consider an FM radio station with an effective radiated power of 50,000W at a distance of 20 km. The combined difference in radiated power and path loss means that the FM radio station will have over 82 dbW/m^2 more received power density (i.e., a received power density that is 1.8×10^8 W/m^2 higher than that of GPS). This is much more power margin available to penetrate walls and buildings.

No infrastructure is required to transmit the signals. SoOP are already being transmitted for other purposes (by definition), so they are essentially "free" to the navigation user. There is no need to set up transmitters in order to navigate using signals of opportunity.

Advances in radio technology are making navigation using SoOP more feasible. Relatively recent improvements in radio technology have made it more reasonable to consider building a radio that receives and processes data simultaneously from many different signals. For example, there are more examples of software-defined cognitive radios that are able to quickly switch frequencies as needed to avoid interference (usually for communication purposes) [11]. These are the type of capabilities that would be important for a practical SoOP radio.

All of the reasons stated above indicate why navigation using SoOP is promising; however, this is not the complete picture. There are some very real difficulties in this approach, and these are described in the next section.

4. CHALLENGES OF USING SIGNALS OF OPPORTUNITY

SoOP are not optimized for navigation. Unlike GPS and other signals transmitted for the purposes of navigation, SoOP are usually not designed with navigation in mind. One of the most important factors is timing. In order to use the time of arrival to determine position, the transmission time must be known. However, most communication systems are not time-synchronized to an accuracy of several nanoseconds (like GPS), which would be required in order to navigate without an additional reference receiver.

Availability varies by location. Signals of opportunity are not uniformly available throughout the world. While many signals of opportunity tend to exist in urban areas, the exact nature of these signals can vary between various countries, due to different broadcasting and communication standards.

Transmitter locations must be known. In order to navigate using signals of opportunity, the locations of the transmitters must be known. (If the transmitter is far from both the mobile receiver and a reference receiver, then just the direction of the transmitter is required.)

There are challenges in building reasonable SoOP navigation radios. One of the advantages of signals of opportunity is that there are a wide variety of signals in different frequency bands. However, for a radio to receive a wide variety of signals, it must have 1) a wideband antenna, 2) a wide bandwidth front-end, and 3) adequate signal processing to handle the wide bandwidth front end data (high sample rates, etc.), all of which are costly. For example, a radio that tracks a single television channel only needs to be able to process a signal with a 10 MHz bandwidth. However, if a radio is to simultaneously track many television signals, then it must be able to process signals between 45.25 MHz (the low end of the broadcast VHF signals) and 801.25 MHz (the high end of the broadcast UHF band).

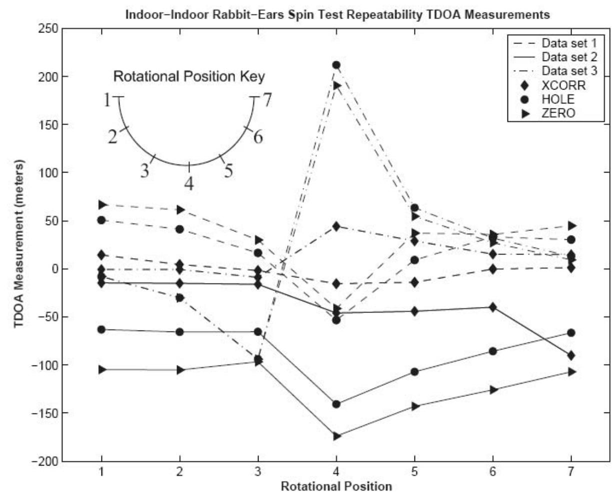

Fig. 1. Variation in analog television TDOA measurement as a function of rotational position for indoor, short-baseline test using "rabbit ears" antennas.

Multipath and non line-of-sight (NLOS) problems are significant. When considering indoor or heavy urban environments, it is likely that many of the RF signals that can be tracked by a receiver will be reflected or scattered signals rather than direct signals. This causes a significant problem for navigation, where it is the *timing* of the signal that is most important. A good example of the impact of multipath can be seen in Fig. 1, which shows short-baseline TDOA measurements generated from analog television signals in an indoor environment using "rabbit-ears" antennas. Three different data sets were collected at different times but in the same location, and three different TDOA measurement formation methods were applied (represented as XCORR, HOLE, and ZERO in the figure). More details of the methods can be found in [8]. The large variation in TDOA measurements observed when the antenna was simply rotated is strongly suggestive of multipath effects, which would vary as the antenna gain pattern changes relative to the environment. While multipath is perhaps the greatest challenge with using SoOP for navigation, it should be noted that the multipath problem is faced by any other system (such as beacon navigation sys-

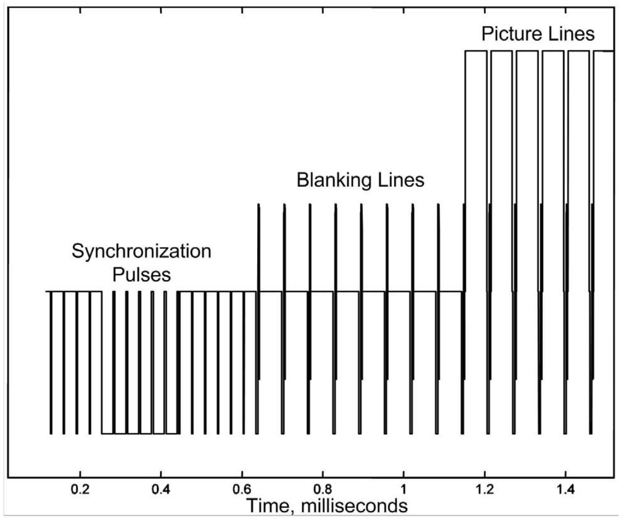

Fig. 2. Synchronization pulses and blanking lines for analog television signal [8].

tems) that uses RF-based signals for position determination.

5. TDOA MEASUREMENT FORMATION

TDOA measurements are typically formed in one of two ways. The first method is to perform a direct cross-correlation between samples from the reference receiver and samples from the mobile receiver. The time offset corresponding with the peak of this cross-correlation is then the TDOA measurement, indicating the delay at which the signal most closely correlates between the two receivers. One advantage of this direct cross-correlation technique is that the exact signal structure does not need to be known in order to obtain the TDOA measurement. This may be particularly useful in the SoOP case, because the user has no control over the signals being transmitted. For example, an encrypted signal can still be used to determine a TDOA measurement, even if the encryption prohibits extracting the information out of the signal. The primary disadvantage of the direct cross-correlation technique is that it requires significant bandwidth over the backchannel to move the raw samples from the reference to the mobile receiver, because the raw samples are taken at a very high sampling rate. (At an absolute minimum, the sample rate should be at least twice the front end bandwidth to avoid aliasing).

The second way to form a TDOA measurement is to separately detect signal "features" in each receiver, and then share only the time at which those features were detected. For example, Fig. 2 shows the synchronization pulses that occur at the beginning of each frame for typical analog television transmissions. (At the beginning of each frame, the electron beam starts at the top of the screen and starts scanning downward). These pulses are a "feature" which can be observed and timed by a receiver. The reference receiver can determine the start time of this pulse sequence and send that start time to the mobile receiver through the backchannel communications link. The mobile receiver measures its own start time for its own synchronization pulses and differences it with the reference receiver start time to form the TDOA measurement. This same concept can be applied with any type of signal that has known measurable features in the time domain. This approach requires minimal backchannel communications bandwidth, because only measurement time is passed (rather than the raw samples as in the direct cross-correlation case).

Consider a system which consists of a SoOP transmitter and reference receiver at known locations and a mobile receiver at an unknown location. Each receiver forms an estimate (measurement) of the time of arrival of a particular feature in the signal

$$\begin{aligned} \hat{t}_r &= t_r + \delta t_{c_r} \\ \hat{t}_m &= t_m + \delta t_{c_m} \end{aligned} \tag{1}$$

where $\hat{t}_r$ and $\hat{t}_m$ are the time of arrival measurements at the reference and mobile receivers, t_r and t_m are the true time of arrivals, and δt_{c_r} and δt_{c_m} are the receiver clock errors at the time of measurement. A TDOA measurement is formed as

$$\Delta\hat{t}_{mr} = \hat{t}_m - \hat{t}_r = t_m - t_r + \delta t_{c_m} - \delta t_{c_r} = t_m - t_r + \delta t_{c_{mr}} \tag{2}$$

The difference between true receive times can be related to ranges as

$$t_m - t_r = \frac{r_m - r_r}{c} \tag{3}$$

where c is the signal velocity (nominally the speed of light), and r_m and r_r are the ranges between the transmitter and the mobile and reference receivers, respectively. By combining equations (2) and (3), it can be shown that

$$c\,\Delta\hat{t}_{mr} + r_r = r_m + \delta t_{c_{mr}}. \tag{4}$$

The left side of the equation consists of the TDOA measurement and r_r (a known quantity). By adding in the r_r term, the TDOA measurement has been converted into what is normally called a "pseudorange" measurement within the GPS community, consisting of the true range plus a term due to the receiver clock error. The benefits of converting the TDOA measurement in this way is that all of the techniques used for determining position using GPS measurements can be directly applied in the TDOA case. Additionally, the concept of dilution of precision (DOP), which characterizes the impact of measurement geometry on solution accuracy, can also be used when this conversion is used.

6. AMBIGUITY RESOLUTION

For people familiar with navigation technology, "ambiguity resolution" often refers to the need to resolve the integer ambiguities in GPS carrier-phase measurements in order to obtain the highest level of accuracy for GPS. When using SoOP, there can sometimes be ambiguities in the TDOA measurements as well, which when there are parts of the signal of opportunity that repeat in time. Equation (1) can be amended to include the effects of these ambiguities as follows:

$$\begin{aligned}\hat{t}_r &= t_r + K_r t_{amb} + \delta t_{c_r} \\ \hat{t}_m &= t_m + K_m t_{amb} + \delta t_{c_m}\end{aligned} \tag{5}$$

where t_{amb} is the repeat interval, and K_r and K_r are integers.

For example, for the analog television signal shown in Fig. 2, the synchronization pulses occur at the beginning of each frame. Each synchronization pulse sequence repeats at a rate of 30 Hz (t_{amb} = 1/30 sec) This means that, if the synchronization sequence at the rover was off by once period compared to the subsequent synchronization sequence at the base (reference), then there would be an ambiguity error of 1/30th of a second, which is equivalent to approximately 10,000 km. In this case, the TDOA measurement would be approximately 10,000 km off from the correct value. It is easy to correct for this large of an ambiguity, because usually there is at least some rough idea of where the receiver is located, and all that's important is to know this approximate location more precisely than the ambiguity. For analog television, simply assuming that one is within reasonable range of the transmission tower would suffice.

The problem is more difficult for other signals of opportunity, however. Consider AM radio, which consists of an amplitude-modulated sinusoidal carrier signal. Because the AM signal is primarily dominated by a fixed-frequency carrier, there is a significant amount of replication, even with the varying amplitude. As a result, it is possible to associate one carrier cycle in the rover with another carrier cycle in the base receiver, resulting in an ambiguity error in the TDOA measurement. AM radio has wavelengths between approximately 175-575 m, so it may not be possible to know an initial position precisely enough to determine the ambiguity error directly, as in the television case. In this case, ambiguity resolution techniques similar to those used by GPS may need to be employed. Note that, for a static roving receiver, there is no geometry change when using fixed TDOA measurements, so the benefits of geometry change experienced with GPS (due to the moving satellites) will not be experienced with SoOP.

7. CONCLUSION

Navigating in indoor and highly urban locations is a "navigation gap" where GPS cannot currently perform, and the use of signals of opportunity is one potential way to fill that navigation gap. There is a wide diversity of signals available, and many are transmitted at a power much higher than GPS, enhancing the ability to penetrate into buildings. There are still significant challenges to the use of signals of opportunity for navigation, however, including hardware design issues and multipath/NLOS mitigation.

8. DISCLAIMER

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