A Signals of Opportunity Based Cooperative Navigation Network

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Abstract—With the advent of advanced wireless standards has come the ability to address more sophisticated problems. One such issue is to provide robust navigation in challenging environments. Our approach to develop a signals of opportunity (SoOP) based cooperative navigation network that has the potential to provide improved performance and extend coverage under a variety of difficult conditions from jamming to multipath fading. Under the premise that GPS is not always available, we employ SoOP as the core of this radionavigation system. A critical advantage of signals of opportunity is that they are more abundant and of significantly higher received signal power than other GNSS signals. There are many signals that are available but not all meet the requirements of robust navigation. Of particular importance are digital television (DTV), AM radio, and 3G cellular signals. Our basic premise is to implement these signals to provide geolocation capability using time difference of arrival (TDOA) which requires cooperation among users. We extend these concepts further to the development of a cooperative network that can be used to provide coverage to users outside the range of the navigation signals. We also demonstrate that cooperation can be used to mitigate the effects of multipath fading and provide simulation results.

I. INTRODUCTION

The issues in obtaining robust navigation capabilities using GPS have been well documented over the past few decades. Numerous impediments to GPS accuracy exist that range from lack of sufficient received signal power to penetrate buildings, susceptibility to multipath fading, jamming, etc. To compensate for these issues, mitigation techniques such as differential GPS (DGPS) and assisted GPS (AGPS) have been developed to provide improvements under specific conditions. AGPS has been particularly helpful in outdoor environments for cellular mobile devices that have limited computational capability. However, these approaches do not address the fundamental problems related to the aforementioned issues. More recent navigation systems have been studied that do not rely on GPS. Instead the goal is to improve the accuracy of navigation systems by employing signals of opportunity (SoOP). These signals are not navigation-specific. They are radiofrequency (RF) signals used for communication purposes that originate from the many wireless systems that are in place today. As we present in this paper, there are many advantages to using SoOP that include higher received signal power and diversity in the signal space.

While the investigation of SoOP for navigation applications is a fairly new field, important research has been done regarding the various signals that can be employed. One of the earliest attempts and using SoOP was with relation to AM radio. It was shown in [1] that AM radio has some advantageous properties but is susceptible to multiple sources of interference from overhead power lines to ground wave propagation. It also is subject to integer ambiguity. Algorithms to resolve integer ambiguity have been addressed by a number of authors [2], [3]. To avoid issues related to AM radio, other signals have been investigated. One of the goals has been to find a signal that is of sufficient bandwidth to allow for improved accuracy while not having the integer ambiguity problems that plague lower bandwidth systems. Consequently, digital television (DTV) has met that requirement [4], [5]. The main difficulty arises from the fact that in many locations the majority of DTV transmitters are co-located. Therefore, using a combination of AM and DTV has been studied [6], [7]. One component of this research is that we extend this research area by investing the potential use of cellular signals as SoOP.

The next step is to advance the state-of-the-art by developing a cooperative network that allows for accurate positioning by utilizing a large number of nodes in combination with SoOP. The core capability of the cooperative network is that each node has the ability to not only receive SoOP from selected towers but also to generate navigation signals that can be utilized by other users in the network. In this way, both global and local positioning is possible. Global positioning is provided by the known locations of the SoOP. By contrast, local positioning enables signals generated via the...
cooperative network. Extending coverage with a cooperative network provides for positioning to users outside of the range of the SoOP. This concept is illustrated in Fig. 1.

In addition to extending coverage beyond the coverage area of the SoOP, we can use the network to extend coverage inward. In this scenario, the network can be viewed as a multiresolution solution to the navigation problem which has the potential to be used for multipath fading mitigation. Multipath is a topic that we address in this work. A multiresolution solution to robust navigation involves a coarse estimate with SoOP and a finer estimate with the cooperative network.

The challenges in developing this cooperative network are complex. Innovation at various levels is needed. We summarize some of the issues below:

1) Physical layer design - mitigation of fading and interference
2) Algorithmic design - information sharing and performance optimization
3) Mobile device design - HW/SW that supports required functionality
4) Communications systems design - multiple access and other system issues

The goal of this paper is to provide insight into the challenges and results that we have found to date. Specifically, we will discuss the SoOP that we have investigated and the tradeoffs in making the different choices for signals to be employed. We also describe issues and challenges related to the cooperative network in moving forward. Additionally, we describe multipath fading on our chosen signals of opportunity and our approach to mitigation. Simulation results are presented in order to quantify the navigation potential for the signals that we have investigated to this point.

The rest of this paper is organized as follows. Navigation with SoOP is discussed in Sec. II. The TDOA navigation model is described in Sec. III. Our cooperative navigation network is presented in Sec. IV. Simulation results are presented in Sec. V. Finally, concluding remarks and future research work are given in Sec. VI.

II. NAVIGATION WITH SIGNALS OF OPPORTUNITY

Wireless networks and their associated signals are plentiful and occupy the frequency spectrum from tens of kilohertz (such as the case of AM radio) to tens of gigahertz (for recent high-speed multimedia). However, the far majority of signals within this range are not sufficient for robust navigation. Frequencies at the upper range are subject to greater path loss. They are generally used for systems requiring small ranges, such as home multimedia systems. Frequencies at the low end of the spectrum propagate over larger distances but may be easily interfered with, such as the case of AM radio, or the bandwidth for digital systems is too small for accurate positioning. Likewise, an important feature is to have signals that have a periodic aspect to them so that the receiver can lock more easily.

Our choice of high-data rate signals that cover a large geographic area, and meet power requirements, are cellular signals. These signals are plentiful and provided by many different service providers. The air interfaces vary depending upon the particular network. Today’s 3G cellular data standards include 3GPP’s wideband CDMA (WCDMA) and 3GPP2’s CDMA2000. Both of these standards are CDMA-based with high data rates that provides for more accurate navigation. Future cellular standards promise even high transmission. The main two are IEEE’s WiMAX (802.16e) and 3GPP’s Long Term Evolution (LTE).

Cellular signals in both the 900 MHz and 1900 MHz bands and digital television signals in the 700 MHz band have two main benefits: sufficient transmit power and number of stations to cover a wide area, and a symbol (or chip) rate that is fast enough to accommodate a high degree of accuracy. These wide area signals have significant advantages over local area signals such as WiFi (IEEE 802.11g/n) and ultrawideband (UWB).

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In the next section, we describe our TDOA-based navigation system that utilizes these signals and their corresponding issues.

We present important digital signals that we initially investigated in Table I. The table demonstrates the achievable timing errors in an additive white gaussian noise (AWGN) channel. Two receiver power levels are examined: receiver sensitivity, and at an SNR of 10 dB. These results demonstrate the effect of bandwidth on the timing error. This bandwidth effect on timing error for GPS signals was shown in [8]. Here we have quantified the effect on a 2G cellular system (GSM) with a 3G cellular system (WCDMA). Our initial goal was to employ GSM since it is a very widely deployed technology. However, as the table demonstrates the rate was too low to allow for accurate positioning. Hence, we moved on to more recent technologies. With WiMAX and LTE, there is the possibility for even greater accuracy in the future.

This list is not all inclusive as it does not include satellite and other signals. We are most interested in ground-based signals with sufficient power and thereby coverage. From a signaling point-of-view, digital television signals are the best choice. They are wideband signals with enough power to cover a wide geographic area. As we have stated, the problem is that the broadcast towers in most cities lack geographic diversity. As an example in Los Angeles, essentially all of the towers are atop Mount Wilson. Similarly in Chicago, the towers are located on tall buildings in the downtown area. Consequently, other signals are needed to augment DTV and AM radio. There are digital AM radio signals that are transmitted in adjacent frequency bands. However, it was found that the symbol rate was too low for accurate positioning.

<table>
<thead>
<tr>
<th>SYSTEMS</th>
<th>fc (MHz)</th>
<th>Rate (Mips)</th>
<th>BW (MHz)</th>
<th>δt (sens.)</th>
<th>δt (10 dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTV</td>
<td>700</td>
<td>10.76</td>
<td>5.38</td>
<td>&lt;0.1</td>
<td>0.41</td>
</tr>
<tr>
<td>WCDMA</td>
<td>1900</td>
<td>3.84*</td>
<td>3.84</td>
<td>30.4</td>
<td>1.4</td>
</tr>
<tr>
<td>GSM</td>
<td>1900</td>
<td>0.271</td>
<td>0.16</td>
<td>28</td>
<td>25</td>
</tr>
</tbody>
</table>

*Mcips per second.

TABLE I

List of digital signals of opportunity.
While cellular signals have the signal power and coverage that is needed for robust navigation, one main challenge is the reuse aspect as is shown in Fig. 2. Because our system utilizes TDOA, multiple users are needed for each station to remove the transmitter clock bias. In this case, this requires that at least two users are resident in a given cell or that multiple users can receive the signals from a particular cell. Clearly, if the user is outside the cell, the distance is greater and the received SNR will be lower. We are currently investigating this challenge as a part of our system design.

III. NAVIGATION SYSTEM MODEL

For a synchronous navigation system, we begin with the pseudorange for the $m^{th}$ mobile device from the $k^{th}$ signal source or station. For the station-to-mobile range $r(\cdot)$, this is expressed as

$$\rho_m^{(k)}(t) = r^{(k)}(t, t - \tau) + c(\delta t_m(t) - \delta t^{(k)}(t - \tau)) + \varepsilon_m^{(k)}(t),$$

where $\tau$ is the delay from when the signal was sent from the station to the time it was received at the mobile, $\delta t_m(t)$ and $\delta t^{(k)}(t)$ are the mobile and station clock offsets respectively, $\varepsilon_m^{(k)}(t)$ is a nuisance parameter related to the noisy environment, and $c$ is the speed of light. Dropping the time dependence and incorporating the speed of light into the clock bias of both the mobile and station, (1) is rewritten as

$$\rho_m^{(k)} = ||\mathbf{x}_m - \mathbf{x}^{(k)}|| + b_m - b^{(k)} + \varepsilon_m^{(k)},$$

where $\mathbf{x}$ is the two-dimensional position coordinates vector. (Note that we use boldface for vectors.) Assuming the nuisance term is small, there are four unknowns in (1): two position terms and two clock bias terms. In GPS the clock bias term of the satellites are continually adjusted and can therefore be ignored. Thus there would be three corresponding unknowns that require two more signal sources to solve the set of pseudorange equations. With SoOP, this approach does not apply. Each new station adds an additional clock bias term. Therefore a different approach is required.

To remove one the uncertainty of the station clock bias’ requires measurements from two different locations. This can be done in two ways. One method is to employ a station at a known location that measures and estimates the clock bias and transmits this information to individual subscribers. Resolving the unknowns in this manner requires fixed infrastructure. The other approach, the basis of our current research, is to have individual users derive their pseudoranges and share them via the cooperative network.

To remove the station clock bias, we define the pseudorange difference between mobile $i$ and $j$ relative to station $k$ as

$$\delta \rho_i^{(k)} = \rho_i^{(k)} - \rho_j^{(k)} = ||\mathbf{x}_i - \mathbf{x}^{(k)}|| - ||\mathbf{x}_j - \mathbf{x}^{(k)}|| + b_i - b_j + \varepsilon_{ij}^{(k)}.$$  

The differential pseudorange is defined as

$$\delta \rho_i = \mathbf{G}_i \delta \mathbf{z}_i + \varepsilon_i,$$

where $\mathbf{G}_i$ is the geometry matrix of the form

$$\begin{bmatrix} (-\mathbf{1}^{(1)})^\intercal & 1 \\ \vdots & \vdots \\ (-\mathbf{1}^{(k)})^\intercal & 1 \end{bmatrix}$$

and $\mathbf{1}^{(i)}$ is the normalized vector from user $i$ to station $k$ that is derived from the user $i$’s estimated position. Combining these differentials for all stations into a single set of equations yields

$$\delta \mathbf{d} = [\mathbf{G}_i - \mathbf{G}_j] \begin{bmatrix} \delta \mathbf{z}_i \\ \delta \mathbf{z}_j \end{bmatrix} + \varepsilon_i - \varepsilon_j = \mathbf{G}_{ij} \delta \mathbf{z}_{ij} + \varepsilon_{ij}.$$  

This set of equations can be written in the standard form as

$$\delta \mathbf{d} = \begin{bmatrix} \mathbf{G}_i - \mathbf{G}_j \end{bmatrix} \begin{bmatrix} \delta \mathbf{z}_i \\ \delta \mathbf{z}_j \end{bmatrix} + \varepsilon_i - \varepsilon_j = \mathbf{G}_{ij} \delta \mathbf{z}_{ij} + \varepsilon_{ij}.$$  

To remove the station clock bias, we define the pseudorange difference between mobile $i$ and $j$ relative to station $k$ as

$$\delta \rho_i^{(k)} = \rho_i^{(k)} - \rho_j^{(k)}$$

The equations in (1) and (2) are non-linear and require an iterative solution. This is a convex optimization problem that is solved with a gradient-based search. For GPS, a detailed description of the derivation can be found in [8]. Here we describe the equations and how they relate to our system.

The differential pseudorange is defined as

$$\delta \rho_i^{(k)} = \rho_i^{(k)} - \rho_0^{(k)}$$

where $\rho_0^{(k)}$ is the pseudorange estimate for user $i$ relative to station $k$ that is derived from the user $i$’s estimated position. Combining these differentials for all stations into a single set of equations yields

$$\delta \mathbf{d} = \begin{bmatrix} \mathbf{G}_i - \mathbf{G}_j \end{bmatrix} \begin{bmatrix} \delta \mathbf{z}_i \\ \delta \mathbf{z}_j \end{bmatrix} + \varepsilon_i - \varepsilon_j = \mathbf{G}_{ij} \delta \mathbf{z}_{ij} + \varepsilon_{ij}.$$  

The solution to this generic least-squares estimation problem is

$$\delta \mathbf{z}_{ij} = (\mathbf{G}'_{ij} \mathbf{G}_{ij})^{-1} \mathbf{G}'_{ij} \delta \mathbf{d}.$$  

The difficulty with this approach is that the column-space of $\mathbf{G}_{ij}$ is linearly-dependent. The reason can be understood by examining the columns of $\mathbf{G}_i$ and $\mathbf{G}_j$ above. Specifically the last column of each matrix is all ones. Combining them into $\mathbf{G}_{ij}$ yields a matrix that has two identical columns. Linear dependence is the result.

From a system perspective, this means that the individual clock bias’ cannot be estimated. Fortunately this is not an issue since the system only depends upon the time difference...
of arrival between the two mobiles. The absolute time is not critical. Consequently, (3) can be rewritten as

\[
\delta d = \begin{bmatrix}
-1^{(1)}, & -1^{(1)} & 1 \\
\vdots & \vdots & \vdots \\
-1^{(K)}, & -1^{(K)} & 1
\end{bmatrix}
\begin{bmatrix}
\delta x_i \\
\delta x_j \\
\delta b_i - \delta b_j
\end{bmatrix}
+ \epsilon_{ij}.
\]

Then in equation form

\[
\delta d = \tilde{G}_{ij} \delta z_{ij} + \epsilon_{ij}.
\]

With this new form the generic least-squares estimation problem can be solved as \( \delta \tilde{z}_{ij} = (\tilde{G}_{ij}^\dagger \tilde{G}_{ij})^{-1} \tilde{G}_{ij}^\dagger \delta d \).

There are important differences in the multiuser scenario. Specifically, care must be taken to ensure that the iterative solution converges. Generally for GPS, this is not a problem since the user is far from the signal sources which ensures that \( G_{ij} \) is non-singular to working precision. Step size is not important. However in a multiuser environment this is not necessarily the case. Therefore an adaptive step size is needed. We have used Armijo’s rule [9] to ensure that convergence occurs. It should also be noted that if two users have the same normalized vector to a particular station system defined in (3) will be linearly dependent. Clearly with more stations available, this is less likely to be a problem with SoOP.

IV. COOPERATIVE NETWORK

To this point the focus has been on the development of a multiuser TDOA navigation system. In a traditional TDOA system, a fixed base station is employed to estimate parameters such as timing and frequency offsets. These are subsequently provided to subscribers, via a wired or wireless connection, so that they can obtain their position. There are systems in place today that function in this manner. That is not the problem that we have chosen to solve. Instead our concept is to have the individual subscribers estimate the parameters of the particular stations and provide them to other users via a cooperative network.

There are many ways to build a cooperative navigation network if the intent is to simply share information. Today’s 3G network provides ample opportunity to share information across the network. Of course, a major challenge in this regard is supporting real-time navigation. Cellular networks are not optimal in terms of this type of networking. Delays through the network can be high especially as the number of users increases. Since a TDOA navigation system relies on the sharing of information in a timely manner, better choices are needed. We believe that the best choice is by developing the cooperative network as a mobile ad-hoc network.

There are many potential candidates that range from Bluetooth to Zigbee to WiFi to WiMAX. For short-range communication between only two users Bluetooth or Zigbee may suffice. However, they were not intended for multiuser communication. The bit rate is not the only consideration in this cooperative network. Also at issue is the multiple access technology. The system must not be targeted to a smaller defined number of users but rather scalable so that it supports the needs of a larger number of ad hoc users.

Multiple access is provided by both WiFi and WiMAX. Both are OFDM-based systems which ensures that they are more resilient to multipath effects, at least for communication purposes. However, their multiple access strategies are very different. WiFi uses time-division multiple access (TDMA). In this manner, each user is allocated all carrier frequencies for the entire OFDM symbol. Thus all sharing of the channel occurs in the time-domain. WiMAX uses orthogonal frequency division multiple access (OFDMA). Here users are allocated both timeslots and a subset of frequencies. This is more advantageous from a cellular perspective since frequency reuse can be accommodated with carriers instead of separate frequency bands as is done today. We note that LTE is also a possibility and is very similar to WiMAX. However one drawback at this time, since the standard is more recent, is a lack of availability of hardware. Thus, we have chosen to focus on WiFi and WiMAX.

A. Nodes as Beacons

Ultimately when a subscriber derives its position, it would be beneficial for that device to have the opportunity to act as a node in the navigation network. That is one of the core capabilities illustrated in Fig. 1. A main reason that we have avoided using fixed infrastructure as the communication network is that estimation of the position of one user relative to another with that signal is not possible. With a fixed infrastructure all communication is directed through the base stations. Therefore the only way to ensure that nodes can derive their position from one another is through direct communication. With the air interfaces that we described in the last section, this is possible.

The navigation signals from one node to another are basically beacons. But the key advantage is that these navigation signals can be derived from the communication signals of the cooperative network. This is the same approach that has been taken with SoOP. Namely, taking existing communication signals and using them for navigational purposes.

For the cooperative network with WiMAX as an example, the standard supports scalable bandwidth from 1.25 to 20 MHz. Based on a simple comparison with Table I, we should expect very good accuracy. Of course, there are many issues that must be addressed. In particular, which waveform should be used for navigation and how should it be multiplexed in the information signals must be addressed. WiMAX has up to 2048 orthogonal carriers so there are many degrees of freedom.

But there are some additional problems that must be addressed. Multiple access for a multiuser network is of critical importance, especially for ad-hoc networks. Likewise, interference and power control present challenges at the physical layer. One of the most important problems is multipath fading.

B. Fading Mitigation

One of the major causes of the degradation in navigation performance comes from signal fading. This can manifest itself
as a loss in SNR which ultimately leads to poor performance in physical layer issues such as in timing and frequency estimation. If the fading is too severe, it will cause the receiver to lose lock and the acquisition process must begin again. Not only does this reduce the system availability but it also requires the receiver to draw more power. This is a major issue since it has effects on the battery life of the mobile device.

Fading can come from multiple sources that include attenuation through structures such as walls and other objects, or it can occur as a result of multipath. Multipath can be partitioned into two groups: slow fading and fast fading. Slow fading occurs as the signal interferes over long distances. On the other hand fast, or carrier, fading occurs at shorter distances and is due to carriers adding destructively from many directions.

Cellular signals near the 1 GHz band and signals at higher carrier frequencies are particularly susceptible due to the short wavelength, such as 30 cm for a 1 GHz carrier. Clearly, as a user moves through the multipath field, they will experience periods of severely low signal power which can cause the receiver to lose lock. There have been number of fading models developed [10], [11] to quantify these effects. For cellular applications, 3GPP has specified fading models for GSM [12] and for WCDMA [13].

To alleviate this problem for communication systems, researchers have developed many different methods. These include OFDM-based waveform design, equalizers, diversity techniques, and coding algorithms that involve interleaving and multiple input multiple output (MIMO). But there is one important difference between communication and navigation systems. For communication systems delays induced by reflections are not of importance. The goal of an equalizer is not to remove absolute delay but to remove relative delay among the reflected signals. This is not true for a navigation system. Absolute delay directly affects the RMS error. An example is a receive signal from single reflected signal in a communication system. Equalization would not be required since there is zero delay spread. Clearly, that is not true for a navigation system. Thus a different approach is needed.

The diversity that is the core of our cooperative network may provide a solution. A simple example is as follows:

1) user A determines their position in a faded environment and informs the network
2) user B determines their position in a non-faded environment
3) user B measures user A position relative to itself
4) user B finds an error between its estimate and that provided by user A

This is a simple example but does demonstrate that with cooperation it is possible to determine whether errors due to fading are present. It is much more difficult to determine a users’ coordinates without cooperation since the algorithms that have been developed to combat fading are targeted towards communication, not necessarily navigation.

Finally, it must be noted that fading can be more severe with SoOP as compared to GPS since a line-of-sight signal may not exist as it generally does from satellite systems. That is why fading mitigation is a critical aspect of next-generation navigation systems. This research field is wide open.

V. SIMULATION RESULTS

We provide simulation results that describe the progress of our system development to date. The results presented in this section are related to the SoOP that we have investigated in our research. As this paper is an overall description of research in which we are currently involved, we have not included many specific details. As an example, it is not possible to simply take the symbol rate and bandwidth and compute the timing error. The signals that we have investigated contain specific frame and burst patterns that we have been able to utilize. These results correspond to those specific signals and format.

Fig. 3. WCDMA timing error.

The timing estimate for WCDMA was calculated on the 256 chip P-SCH (primary synchronization channel). The chip rate is 3.84 Mcps and spans 66.67 μsecs. The simulation was conducted at four samples per symbol and interpolated to 256 samples/symbol to obtain one ns of resolution. The timing was extracted by finding the time offset of the highest peak of the cross correlation of the received waveform with noise to the ideal received waveform on a single sync interval basis for 1000 trials. The average of the absolute error of 1000 trials per SNR value was computed on plotted in Fig. 3. The SNR is calculated using a matched root raised cosine filter and allows for conversion to input signal to noise density using this factor and noise figure. Also shown in the figure is the probability of synchronization on a single slot where the sync is successful if the event timing error is less than chip. In a real receiver if the error exceeds chip then the protocol messages would not be successfully decoded and synchronization must be retried.

The accuracy of time estimation for the DTV signal was determined via simulation for AWGN channel and is shown in Fig. 4. The timing estimate was calculated on the DTV four symbol synchronization word, the 511 symbol PN code, and the three 63 symbol PN codes for a total of 704 symbols. These symbols are transmitted at 10.76 MHz rate and span 65.43 μsecs. The simulation was conducted at four samples per symbol and interpolated to 128 samples/symbol to obtain greater than 1 ns of resolution. This was also repeated for

217
residual frequency error at the receiver of 100 Hz which may exist in a typical receiver. The SNR is calculated for a vestigial sideband (VSB) bandwidth of 5.38 MHz. The falsing threshold is set where the synchronization probability is 1 for SNR greater than the threshold.

The time estimate for GSM was calculated on the 64 bit SCH signal extended training bits on a single synchronzation interval These symbols are transmitted at 270.833 KHz rate and span 236.3 μsecs. The simulation was conducted at eight samples per symbol and interpolated to 2048 samples/symbol to obtain 1.8 ns of resolution. The SNR is calculated in an intermediate frequency (IF) filter with a noise bandwidth of 72 kHz.

VI. CONCLUSION AND FUTURE WORK

In this research, we have presented a SoOP-based cooperative navigation system. The system does not require base stations or other fixed infrastructure other than the SoOP. Our proposed system performs all navigation functions on the mobile subscriber devices and shares information with other users to allow for robust navigation. We have presented timing error estimates for three different SoOP: WCDMA, DTV, and GSM.

The system that we have proposed is sophisticated and requires various levels of innovation from mobile device design, physical layer algorithms, multiple access protocols, and more. As we move forward with our research, we will address these issues. Cooperative navigation is an exciting field and contains many possibilities for future research.

REFERENCES