

A Multi-Carrier Technique for Precision Geolocation for Indoor/Multipath Environments

David Cyganski, John Orr, William R. Michalson, *Member, ION*
Electrical and Computer Engineering (ECE) Department, Worcester Polytechnic Institute (WPI)
100 Institute Road, Worcester, MA 01609
Tel: (508) 831-5448, FAX: (508) 831-5491
Email: cyganski@ece.wpi.edu

BIOGRAPHY

Dr. David Cyganski is a Professor in the ECE Department at WPI where he performs research and teaches in the areas of linear and non-linear multidimensional signal processing, communications and computer networks, and supervises the WPI Convergent Technology Center. He is an active researcher in the areas of radar imaging, automatic target recognition, machine vision and protocols for computer networks. He is a coauthor of the book *Information Technology: Inside and Outside*. Prior to joining the faculty at WPI he was an MTS at Bell Laboratories and has since held the administrative positions of Vice President of Information Systems and Vice Provost at WPI.

Dr. John A. Orr is a Professor in the ECE Department at WPI where he was department head from 1988 to 2003. Dr. Orr performed some of the earliest work on fading effects in CDMA communications systems. Dr. Orr was a member of technical staff at Bell Laboratories involved in the systems engineering of the video telephone network. More recent research interests include digital signal processing, automatic target recognition, and real-time data acquisition and processing. He is a coauthor of the book *Information Technology: Inside and Outside*. Dr. Orr is currently on sabbatical at Stanford University pursuing work in the area of GPS systems.

Dr. William Michalson is an Associate Professor in the ECE Department at WPI where he performs research and teaches in the areas of navigation, communications and computer system design, supervises the WPI Satellite Navigation Laboratory and is the Director of the WPI Bioengineering Institute's Center for Untethered Healthcare. His research focuses on the development, test, and evaluation of GPS and GPS-like navigation systems. He has been involved with navigation projects for both civilian and military applications with a special emphasis on navigation and communication techniques in indoor, underground or otherwise GPS-deprived situations. Prior to joining the faculty at WPI, Dr. Michalson spent approximately 12 years at the Raytheon

Company where he was involved with the development of embedded computers for guidance, communications and data processing systems in both spaceborne and terrestrial applications.

ABSTRACT

A novel means for precise and multipath-compatible geolocation is introduced in this paper. By applying a matrix decomposition-based multi-carrier range recovery algorithm, super-resolution location solutions can be obtained for one or more signal sources in a severe multipath environment. The technique allows separation of true source signals from multipath reflections without resort to impulsive, wideband signals. The proposed precision location signal structure is easily adapted to conform to spectral allocations and is compatible with simultaneous use for COFDM based communication. The technique is well suited for deployment as a system for precision relative location of ad hoc transceivers with respect to one another. A proof-of-concept system was constructed and experimental results are discussed.

INTRODUCTION

This paper addresses the design of signal structure and signal processing to support a system for deployable precision personnel location intended for emergency first responder activities. The problem to be solved is distinguished from the usual notion of geolocation by freedom from the need of an absolute fix with respect to an established global coordinate system as it is only the position relative to deployable reference stations that is required. Furthermore, the intended operation and solution scope is no longer global, but rather, confined to a limited area of operations. For the purposes of search, rescue and recovery operations in urban and indoor environments, such a system must have a precision on the order of 10 cm and be highly robust in the presence of multipath signals with only centimeter path length differences from the direct signal. Finally, this precision must be achieved in a way that complies with existing

spectral allocation regulations and which is compatible with existing services.

Precision and multipath immunity is usually associated with ultra wide bandwidth signals whose spectral footprint presents spectral allocation and/or inter-service interference problems. This situation is present in the extreme within the context of impulse UWB approaches. The UWB solution to the multipath problem involves the use of extremely narrow (sub-nanosecond) pulses which can be distinguished from one another on the basis of path length differences by time gating. The penalty of course is the ultra-wide bandwidth which respects no spectral allocation boundaries and can only ameliorate interference by operation at sufficiently low power levels that its contributions are on the order of the natural noise floor.

Precision indoor location presents a particularly severe version of the multipath signal problem. With the presence of very close reflectors (the person carrying the location device, the surfaces of the device itself, and nearby walls) the reflections cannot simply be time-gated away. Rather, the resulting channel becomes effectively a channel with frequency distortion over the bandwidth of the signal. That is, even the gated pulse shapes are distorted, complicating the problem of precise pulse timing estimation.

In this paper we introduce a signal structure and TDOA (time difference of arrival) recovery approach that avoids the above problems with a signal structure that is amenable to spectral assignment. This approach also takes a form that separates the notions of spatial precision and multipath immunity from those of bandwidth and temporal confinement of the pulse.

SIGNAL STRUCTURE

Consider the signal

$$s(t) = \sum_{m=0}^{M-1} A e^{j[2\pi (f_0 + m\Delta f)t + \phi_m]} \quad (1)$$

comprising M sinusoidal carriers with frequency spacing Δf and arbitrary phases ϕ_m .

If this signal is received at sentinel sites, with distances d_k from the source, giving rise to propagation delays

$\tau_k = d_k/c$, the respective received signals are given by

$$s_k(t) = \sum_{m=0}^{M-1} A_k e^{j[2\pi (f_0 + m\Delta f)(t + t_0 - \tau_{k0}) + \phi_m]} \quad (2)$$

$$= \sum_{m=0}^{M-1} A_k e^{j[2\pi \{(f_0 + m\Delta f)t - (f_0 + m\Delta f)\tau_{k0}\} + \phi_m + \psi_m]} \quad (3)$$

$$= \sum_{m=0}^{M-1} A_k e^{j[2\pi (f_0 + m\Delta f)t + \Phi_{mk}]} \quad (4)$$

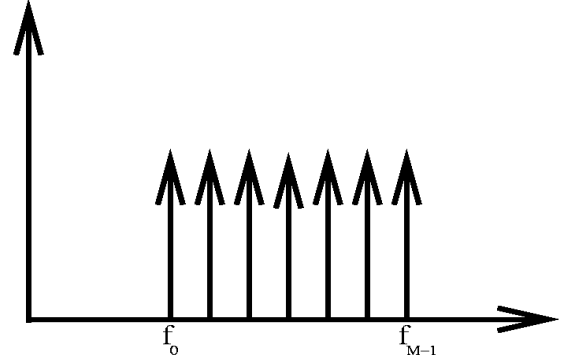


Figure 1: The simplest MC-UWB signal consists of N carriers with equal spacing and equal magnitudes.

We have assumed here that the sentinel sites have synchronized clocks, while the source clock has some unknown offset t_0 which induces the phase shift $\psi_m = 2\pi (f_0 + m\Delta f)t_0$.

Thus, the phase difference between adjacent carriers for signal $s_k(t)$ corrected for the known phases ϕ_m satisfies

$$\Delta\theta_k = \Phi_{mk} - \Phi_{m-1,k} - \phi_m + \phi_{m-1} \quad (5)$$

$$= -2\pi\Delta f\tau_{k0} + \psi_m - \psi_{m-1} \quad (6)$$

$$= -2\pi\Delta f\tau_{k0} + m\Delta\psi \quad (7)$$

modulo 2π .

Finally, from the differences of the phases obtained as above for carrier m at two sites, $\theta_{qr} = \Delta\theta_r - \Delta\theta_q$, we can recover the TDOA of the signal at those sites,

$$\Delta\tau_{qr} = \frac{-\theta_{qr}}{2\pi\Delta f} = \frac{d_2 - d_1}{c} \quad (8)$$

where c is the velocity of the wave in our medium.

Now, since our signal is periodic, with period $T = \frac{1}{\Delta f}$, the solution suffers a time (range) aliasing ambiguity. However, thanks to the limited spatial scope of the location problem we defined, by choosing Δf sufficiently small, we can make our TDOA solution unambiguous throughout a ranging cell which is defined by the locus of points within distance $R = \frac{c}{\Delta f}$ of any receiving sentinel.

MULTIPATH SOLUTION

Two carriers would be sufficient to carry out the method outlined above for recovery of TDOA information,

however, there is a great advantage to be obtained from a multicarrier signal.

If a single multipath signal were introduced into the above, each of the adjacent carrier phases would now become perturbed. While some advantage could be obtained towards recovering an estimate of the original phase difference value by an averaging of the many resulting phase difference values, an exact recovery is possible with appropriate treatment of the problem.

Consider the product of the m th Fourier coefficient of the k th direct path signal in Eq. (2),

$$S_{km} = A_k e^{j[-2\pi(f_0 + m\Delta f)\tau_{k0} + \phi_m + \psi_m]} \quad (9)$$

with the conjugate of the respective Fourier coefficient of the source model in Eq. (1),

$$S_m^* = A_k^* e^{j[\phi_m]} \quad (10)$$

which results in

$$\begin{aligned} S_{km} S_m^* &= A_k A_k^* e^{jm(-2\pi\Delta f\tau_{k0}) + \psi_m} \\ &= A_k A_k^* e^{jm[2\pi(\Delta f t_0 - \Delta f\tau_{k0})] + j2\pi\delta t} \\ &= B_k e^{j\Omega_k m}, \end{aligned}$$

where $\Omega_k = 2\pi\Delta f(t_0 - \tau_{k0})$.

These values correspond to samples of a complex sinusoid with respect to the Fourier frequency sampling index m . For a fixed Ω_k , the phases of the carriers progressively wind about zero as a function of frequency index m as shown in Fig. 2. The number of windings over the range of carriers is fixed by Ω_k , that is, by the total time offset, $\tau_{k0} - t_0$.

Discrete frequency estimation techniques can be applied to the array of coefficients defined by this equation to solve for this Fourier-index frequency Ω_k from which we easily obtain $\tau_{k0} - t_0$. Thus the TDOA between two reference receivers can again be recovered.

More importantly, by the linearity of the construction, if S_{km} consists of a linear superposition of the direct and N multipath signals with amplitudes A_{k0} and A_{kn} , $n = 1 \dots N$ and path delays τ_{k0} and τ_{kn} , $n = 1 \dots N$ respectively, then proceeding as before we obtain

$$\begin{aligned} S_{km} S_m^* &= \sum_{n=0}^N A_{kn} A_k^* e^{2\pi j(-m\Delta f\tau_{kn}) + \psi_m} \\ &= \sum_{n=0}^N B_k e^{jm\Omega_{kn}}. \end{aligned}$$

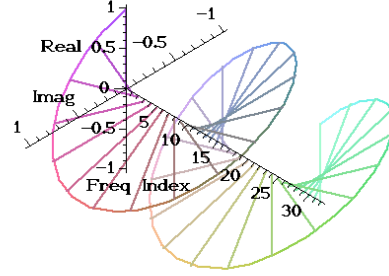


Figure 2: For a displaced source the phases of carriers wind as a function of carrier frequency index relative to the values at zero displacement.

Thus the value of the TDOA for the direct path signal and each multipath signal can be obtained by solving an estimation problem for the anharmonic frequency-index coefficient “frequencies,” Ω_{kn} of the sampled signal presented by the Fourier based construction above.

SINUSOIDAL FREQUENCY ESTIMATION

The problem of estimating the frequencies of multiple, anharmonically spaced, sinusoidal signals from a noisy linear combination has a long history with the first general method having been proposed by Prony in 1795 [1]. Today this problem is considered to be at the core of the body of analytic and computational methods known as Modern Spectral Analysis [2].

In our implementation we have chosen to apply the state space approach [3]. This method permits the exact solution (in the noiseless case) of the P sinusoidal component frequencies and amplitudes from $M > 2P$ Fourier samples. The state space method has the virtue of being a non-iterative solution that yields the desired component frequencies and amplitudes via a fixed sequence of matrix operations even in the over determined case. Furthermore, it has been shown that for increasing S/N the performance of the method rapidly approaches the Cramer-Rao bound.

Being a model-based spectral analysis method, an assumption must be made with regard to the number of sinusoidal components (that is signal paths) that are to be found. If the model involves too few, the quality of the results are compromised; if too many, certain steps in the algorithm become very poorly numerically conditioned and may fail altogether. Since the solutions can be rapidly obtained for any model order, we have found that testing increasing model orders for convergence of the dominant component parameters is not a prohibitive approach to

resolving this issue. There exists a literature with regard to estimation of the correct model order [4].

Thus, given a transmitted signal with M frequency components in its multi-carrier comb, we may extract from the M Fourier coefficients of any one receiver's signal the values of $\tau_{kn} - t_0$, representing the propagation delays (with fixed transmitter clock offset) of the direct path signal and

$$N \leq \left\lfloor \frac{M-1}{2} \right\rfloor - 1 \quad (11)$$

multipath signals. From these parameters, the TDOA between various receiver sites immediately follows.

One of the many algorithms that have been proposed for solving location from TDOA information may now be applied to this data. Because the multipath TDOAs will not be related to each other as they would be for the true source, these TDOAs will not yield true solutions (residual model errors will be large) of the transmitter location. Thus, incorrect selections of direct path delay values from among the time delay solution sets obtained by the index frequency estimation procedure above can be identified by application of the location algorithm.

However, to avoid unnecessary computation, it is desirable to be able to identify candidate direct path solutions. If the clock offset t_0 is known (as provided by an initialization procedure) then the identification of the direct path solution candidate in each reference node's solution set is quite easy: the shortest propagation delay in each set is the direct path solution. Another approach to finding the appropriate set of candidates to which to apply the location solver which does not involve initialization and/or subsequent tracking of the offset involves making the unambiguous ranging cell larger than the physical operations area such that the collection of all strong signal components fall into a clearly definable (perhaps circularly wrapped) sub-area corresponding to the operations area. Now the ordering of the solutions in this sub-region will again allow identification of the shortest path return. Both of these approaches will correctly select direct path solutions if a direct path solution was present (which can fail to be the case in the event of strong attenuation of this path.)

DEMONSTRATION

We have constructed a real-time "to scale" demonstration of a system based upon the approach described above. To allow rapid prototyping, we chose to use an acoustic signal rather than an RF signal. This allowed us to achieve the same wavelengths in an air medium with an audio signal as would match that of an EM wave with a center

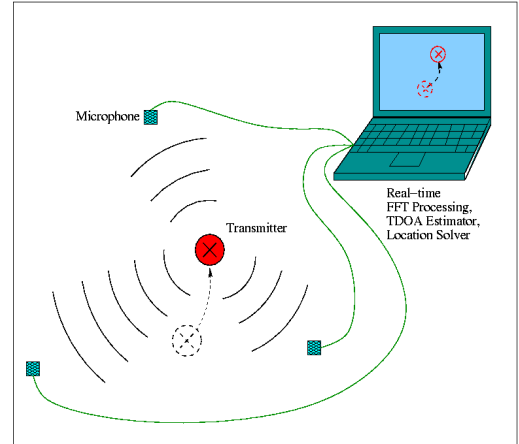


Figure 3: The demonstrator was implemented as a real-time MATLAB program executing on a laptop computer utilizing audio frequency acoustic signals with a center wavelength of 6.3cm.

frequency of 4.77 GHz and a bandwidth of 5.3 GHz. Performing this demonstration with audio frequency signals allowed us to construct a real time "software radio" realization based upon a MATLAB script executing on a general purpose laptop computer with no special signal processing or acquisition hardware beyond a PCMCIA A/D card.

The transmitted signal is generated by repeated D/A conversion of a discrete signal with 8192 samples transmitted at a clock rate of 44.1 KHz to produce a 5.38 Hz periodic wave. The signal contains 101 carriers, thus allowing propagation delays for up to 50 signal paths to be resolved. The effective carrier spacing in a parallel RF implementation would be 53 MHz and the ranging cell size is approximately 6 meters.

The signal is received at several microphones representing the reference receivers and digitized again at 44.1 KHz. Measurements in the laboratory revealed that our input S/N is approximately 8 dB, primarily due to ambient noise from the air conditioning and ventilation system. The sinusoidal components are then extracted with an 8192 point FFT and the state space method is applied to obtain the TDOA information via a MATLAB program. The TDOA values are then used to solve for the location of the transmitter via the closed-form least-squares source location estimation algorithm of Smith and Abel [5]. The real-time location results are displayed on the laptop screen.

On the laptop screen we display not just the direct path solutions of the target location but also false solutions due to multipath. Ordinarily these false solutions can be easily identified and eliminated. However, we found it instructive to display them together with an indicator of the relative strength of the signals giving rise to them as

compared to the direct path signal. This allowed us to show that the system worked correctly even in situations in which the direct path signal was small compared to one or more multipath signals.

The proof-of-concept system also demonstrated that the solution is robust in the face of severe and small-delay multipath conditions. While holding a large metal plate, that acted as a highly reflective surface, less than an inch from our transmitter, essentially unperturbed direct path solutions were still obtained.

CONCLUSIONS

The MC-UWB signal structure and modern spectral analytic solution technique offers significant advantages for the problem domain of precision personnel location relative to known sensor positions. This signal structure offers high precision location with essentially infinitesimal bandwidth thanks to its sparse line spectral content. The ability of modern spectral analysis to estimate the anharmonic components of a signal permit in this case the super-resolution solution for TDOA information from a signal despite large-amplitude multipath components.

The simple form that the mobile node takes, that of a transmitter of a single, period signal with no time synchronization requirements, immensely lowers the cost of equipping personnel and materiel as compared with systems that require complex receivers or transceivers.

The entire system is amenable to simple software radio implementation as demonstrated by our acoustic wave prototype. Since the signal structure and system implementations are one-to-one with those used for OFDM communications systems, this opens the opportunity to integrate precision location into existing OFDM systems and/or to provide OFDM communications channels in any such realization of a precision locator.

ACKNOWLEDGMENTS

The support of the National Institute of Justice of the Department of Justice is acknowledged.

REFERENCES

[1] G.R.B. Prony, "Essai experimental et analytique, etc.," Paris, J. de L'Ecole Polytechnique, vol. 1, cahier 2, pp. 24-76, 1795.

[2] Steven M. Kay, "Spectrum Analysis – A Modern Perspective," Proc. IEEE, vol. 69, no. 11, pp. 1380-1419, Nov. 1981.

[3] B.D. Rao, K.S. Arun, "Model Based Processing of Signals: A State Space Approach," Proc. IEEE, vol. 80, no. 2, pp. 283-309, Feb. 1992.

[4] J.J. Fuchs, "Estimating the number of sinusoids in additive white noise," IEEE Trans. Acoust. Speech, Signal Proc., vol. ASSP-36, pp. 1846-1853, Dec. 1988.

[5] J.O. Smith, J.S. Abel, "Closed-Form Least-Squares Source Location Estimation from Range-Difference Measurements," IEEE Trans. Acoust. Speech, Signal Proc., vol. ASSP-35, no. 12, pp. 1661-1669, Dec. 1987.