A Method for Identifying Simultaneously-Transmitted Signals from Different Transmit Antennas in Multi-Antenna Channel Sounding Experiments

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Abstract

A method is described for identifying simultaneous signals from different transmit antennas in multi-antenna sounders. Multiple orthogonal signals are produced from one pseudorandom code by using it to modulate RF carriers at pre-calculated offset frequencies. Although their frequency spectra are interleaved, the spectral lines from different transmitters are separable by Fourier transform at the receiver output. Since there is a one-to-one relationship between the length of the signal required for Fourier analysis and the number of orthogonal sounding signals, any arbitrary number of such signals can be generated, but Doppler spreads limit the number that can be employed with acceptable isolation among them.

1. Introduction

For double directional channel sounding, one must identify the signal transmitted from each of multiple transmit antennas. Techniques for this include: switching both receive (Rx) and transmit (Tx) antennas, switching at the Tx while receiving with a multi-channel Rx, transmission of the same code from different antennas with delay offsets, using Loosely Synchronous (LS) codes, and using Modified LS (MLS) codes. So-called FDM sounding techniques, which are similar, but not identical to the one reported here have also been proposed. Switching requires Tx/Rx synchronisation and involves delays that limit mobile station (ms) speeds, as do delay offset techniques. Multi-channel receivers are practical only in chirp systems, where recorded data have narrow bandwidths [1]. LS and modified LS codes need to have very long sequences, resulting in low energy efficiency [2, 3] and require slow ms speeds. FDM sounders that have previously been reported [4, 5] have limited instantaneous bandwidth, and would require inordinate Tx powers on outdoor channels due to the absence of processing gains.

Sounding signal code lengths must be short to measure fast changes in channel characteristics, and sounding signals from different Tx antennas must have little or no correlation. These requirements can be met by benefiting from the excellent auto-correlation properties of PN codes but avoiding their high cross-correlations by using them to produce Frequency-Orthogonal PN (FOPN) sounding signals, as described in the following.

2. Generation of Frequency-Orthogonal PN (FOPN) Sounding Signals

PN codes have unique patterns that guaranty very low auto-correlation for nonzero lags. Their autocorrelations can be written as:

$$R(m) \quad = \sum_{n=0}^{N-1} p(n)p(n+m) = \begin{cases} N & when\, m = 0 \\ \varepsilon/_{N} & when\, m \neq 0 \end{cases} \tag{1}$$

where:
m signifies lag; *p(n)* represents the PN code and *N* is the code length.

The constant auto-correlation term $\varepsilon/_{N}$ is very low, even for fairly short codes. This good characteristic can be imparted to multiple orthogonal sounding signals generated using the same PN code, as follows.

Let $p(n)$ be a PN code with length N and let $p_{rep}(n)$ to be the sequence resulting from repeating $p(n)$ M times, such that $p_{rep}(n)$ has a length of NM. Its Fourier transform can be shown to be:

$$P_{REP}(k) = \sum_{n=0}^{N-1} p_{rep}(n).e^{\frac{-j2\pi nk}{NM}} + \sum_{n=0}^{N-1} p_{rep}(n+N).e^{\frac{-j2\pi(n+N)k}{NM}} + \ldots .+ \sum_{n=0}^{N-1} p_{rep}\big(n+N(M-1)\big).e^{\frac{-j2\pi(n+N(M-1))k}{NM}} \quad (2)$$

$$= \sum_{n=0}^{N-1} p(n).e^{\frac{-j2\pi nk}{NM}}.\left\{e^{\frac{-j2\pi k.(0)}{M}} + e^{\frac{-j2\pi k.(1)}{M}} + \ldots\ldots\ldots .. + e^{\frac{-j2\pi k.(M-1)}{M}}\right\} \quad (3)$$

$$= \begin{cases} M.\sum_{n=0}^{N-1} p(n).e^{\frac{-j2\pi nk}{NM}} & if\ k\ is\ a\ multiple\ of\ M \\ 0 & elsewhere \end{cases} \quad (4)$$

It is clear from equation (4) that only every Mth spectral line of $P_{REP}(k)$ is non-zero. This allows the generation of M FOPN signals with interleaved spectral lines by multiplying $p_{rep}(n)$ with complex exponentials:

$$\mathrm{FOPN}_{k'}(\mathrm{n}) = p(n)e^{\frac{-j2\pi nk'}{NM}} \qquad \mathrm{k}' = 0,1,..,M-1. \quad (5)$$

If each of M antenna elements at the Tx emits a different FOPN signal, Fourier processing at the sounder receiver output thus allows separation of the spectral lines of the M different sounding signals. An advantage over other techniques is that the 100% duty cycle inherent with this scheme results in high energy efficiency.

An anticipated problem, however, is that on mobile channels, Doppler smearing of the energy in different spectral lines could degrade the isolation between signals from different transmitters. Monte-Carlo simulations were therefore conducted to study the effects of Doppler spread on signal correlations at the receiver output. Doppler shift was modelled as a zero-mean random variable that is uniformly distributed in the interval $[-x.df,+x.df]$, where df is the separation between FOPN signal centre frequencies and x varied from 0 to 0.5. For each of 1000 realisations of the received signal resulting from the transmission of one of four FOPN signals, up to 20 multipath components, each having a randomly-chosen Doppler shift within a specified range of Doppler spread were summed. The result was then cross correlated with a reference sequence for the "desired" FOPN signal, and the mean of the resulting correlation coefficients was plotted as a function of Doppler spread. For each realisation the cross correlation of the received signal with reference sequences for the other 3 FOPN signals was also plotted. Results are shown in Fig. 1, where it can be seen that for a post-correlation receive SNR of about 10 dB, correlation characteristics are affected by less than 10% with respect to ideal until Doppler spreads reach about 0.45*df*. In a practical sounding system with 4 Tx antennas and a 25 Mchps PN sequence length of 255 chips, df = 24.5 kHz. Doppler spreads of 45% of this value at 2 GHz translate to ms speeds that significantly exceed those used for channel sounding in urban environments. This makes the proposed method, with 4 FOPN signals, robust to Doppler phenomena. However, Doppler spread becomes increasingly more significant in deteriorating the isolation between FOPN signals as their number increases, since df decreases accordingly.

3. Measurements

The above-described method was used to implement a 4-antenna sounder Tx in which the 4 FOPN sounding signals were generated from a single 25 Mchps 255 chip PN signal. Each of 4 replicas of the PN signal was modulated onto an RF carrier at a nominal frequency of 2.25 GHz, plus an offset frequency equal to a consecutive multiple of one quarter of the spacing between spectral lines of the PN code, or 24.51 kHz.

Fig. 2 shows results from off-air measurements made when the Tx and Rx were stationary inside in a large garage, with the Tx array and a single monopole Rx antenna about 3 m apart. Each of the 4 subplots shows cross correlations between the received signal and previously recorded back-to-back system reference sequences at each offset frequency when selected Tx antennas were active. It can be seen in subplot (a) and (b) that the desired signal produces a cross correlation result with low sidelobes, while the signals from the inactive Tx antennas are just noise. Fig. 2 (c) shows a combination with 3 Tx antennas active in which there is some response on the inactive channel, but this is 20 dB down. Various multiple antenna results showed such unwanted signals. Reasons for this are under study, and could be related to implementation. Fig. 2(d) shows results when all 4 transmit antennas were active. It is clear from this figure that the four estimated impulse response functions are almost identical, as one would expect, since the Tx antenna element spacings were only half a wavelength. Differences are the result of the vector addition of multipath signals within the delay resolution of the system, and the fact that input powers to the different antenna elements varied over a range of 3 dB.

4. Conclusions

The impulse response between a receiver and each of multiple antenna elements at a Tx array can be estimated using signals herein referred to as FOPN sounding signals. Such signals are frequency shifted versions of the same PN sequence and have interleaved frequency spectra, but the spectral energy of each can be isolated through Fourier analysis of a sampled version of the received signal with an appropriate number of samples. Advantages over techniques that involve Tx and Rx antenna switching include: simplicity, robustness as a result of the absence of a requirement for Tx/Rx synchronisation, and the ability to sound from all Tx antennas simultaneously thus avoiding switching delays and enabling greater ms speeds. Advantages over LS and MLS coded systems include a 100% duty cycle. For a reasonable number of Tx antennas and practical PN sequence lengths, the required frequency offsets are such that the system is robust to Doppler spreads associated with practical urban vehicle speeds. Phase noise is another source of possible degradation that has yet to be investigated. However, it is anticipated that phase noise limitations on the proposed system will be found to be no more severe than those for any system used for angle of departure estimation. Back-to-back as well as initial static off-air measurements have shown that the proposed system can be easily implemented, and functions as required in allowing the identification of sounding signals from specified Tx antennas.

5. References

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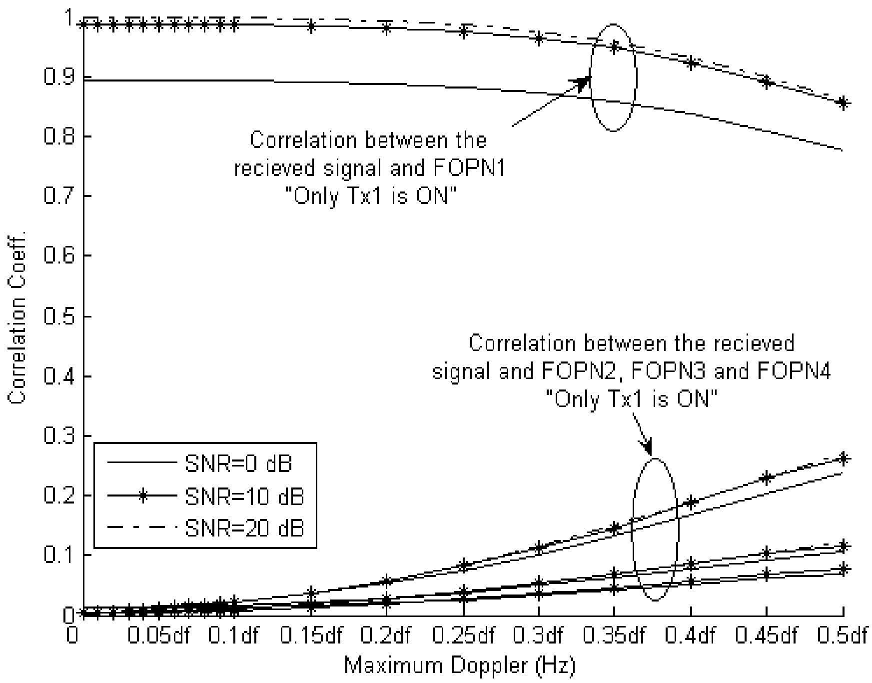

Fig. 1. Degradation in correlation characteristics as a function of Doppler spread.

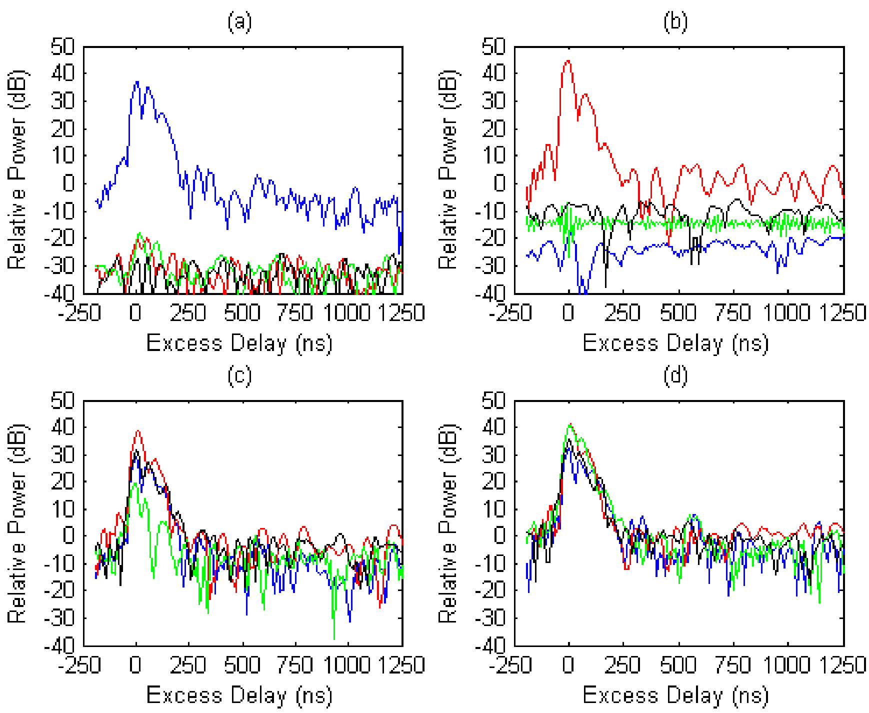

Fig. 2. Off-air impulse response estimates: (a) Tx ant 1 active only, (b) Tx ant 2 active only,(c) Tx ant 1,Tx ant 2, and Tx ant 3 active, (d) All transmit antennas active (blue: ant 1, red: ant 2, green: ant 3, black: ant 4).