

Signal Reuse for Wireless Applications

This invited paper discusses current and future communications applications that may allow for efficient reuse of existing signal sources

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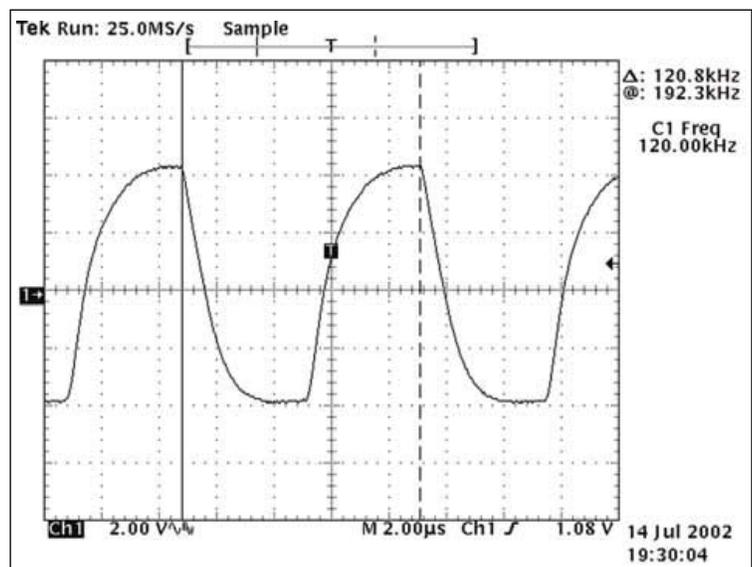
It is generally recognized that the demodulation technique providing the lowest bit error rate (BER) for any modulation type is coherent demodulation. Perfect coherent de-modulation in a receiver requires an exact replica of the transmitted signal carrier. For some modulation types, such as binary phase shift keying (BPSK), the fidelity of the carrier replica is critical to the demodulation BER. Other modulation types, such as single sideband (SSB) suppressed carrier, are more tolerant of replica carrier faults (frequency error and noise). In any case, the best BER demodulation performance is obtained when using an exact replica of the transmitter carrier in the demodulation process (phase coherent with the received signal).

Generation of a carrier at the receiver is usually done by synchronization or other processing of the received signal (squaring, phase lock loops and filtering) to produce a carrier that represents an “average” carrier for the received signal. This is only a fair representation of the true transmitted carrier. Other systems use a so-called “pilot” carrier or separately transmitted reference to better replicate the carrier at the receiver. An alternate approach is to use an existing signal available to both the transmitter and receiver as the source for the transmitter carrier and the receiver demodulation carrier.

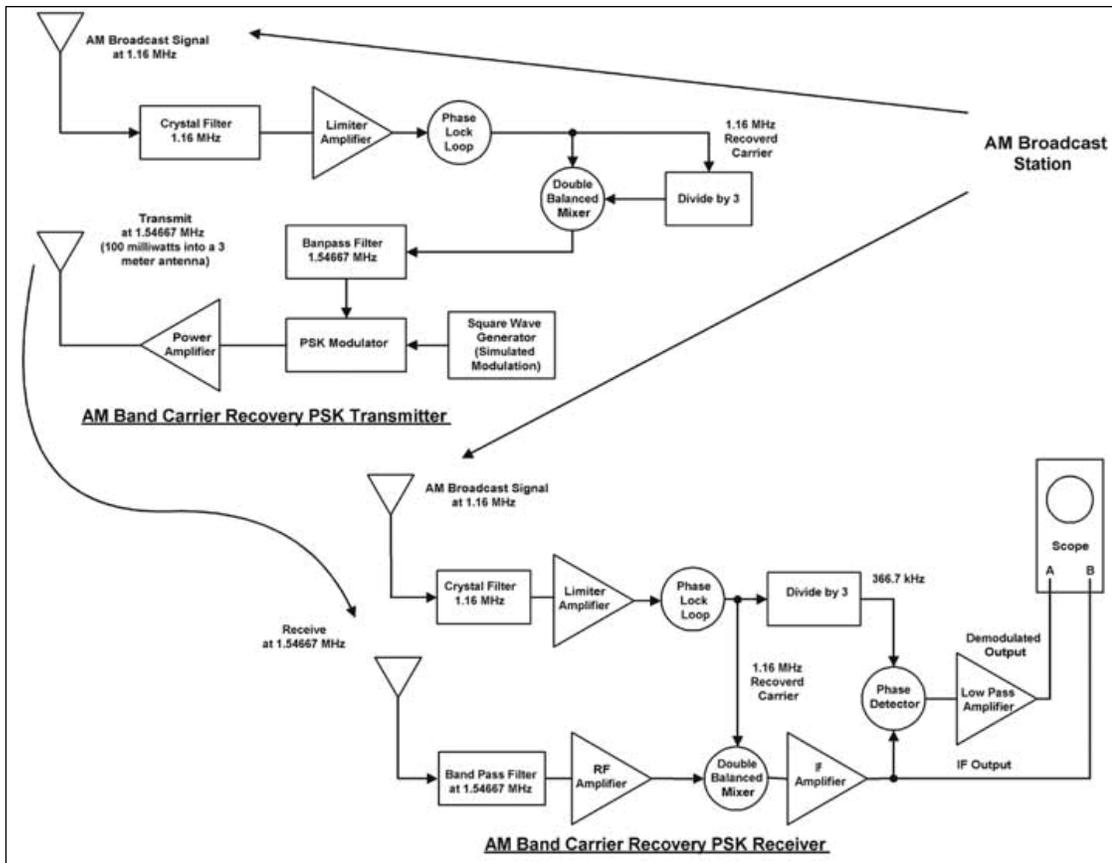
The signal source should be a stable, high-quality signal (good signal-to-noise ratio). Such signal sources might include the worldwide

global positioning system (GPS) signal, time stations (WWVB, WWV and HBG) and amplitude modulation (AM) broadcast stations. These signals are available off the air and are readily available.

A representative example of these signal types is the National Institute of Standards and Technology (NIST) station WWVB. WWVB is a 50 kilowatts AM time station with a 60 kHz carrier frequency providing an accurate frequency standard referenced to the NIST Frequency Standard. The transmitted accuracy of the WWVB carrier is normally better than 1 part in 100 billion (1×10^{-11}). Day-to-day deviations are less than 5 parts in 1000 billion (5×10^{-12}). Propagation effects are minor compared to



▲ **Figure 1. PLL output at 120 kHz using the 60 kHz WWVB signal as a reference.**



▲ **Figure 2. FCC Part 15.219 compliant phase modulated communications link using an AM broadcast station as a common reference.**

those of time stations transmitting in the low-frequency (LF) or high-frequency (HF) bands. By use of proper receiving and averaging techniques, the received frequency accuracy of WWVB signals should be nearly as good as the WWVB transmitted accuracy at most locations in the continental United States [1]. Figure 1 shows output from a phase-locked loop (PLL) locked to the WWVB signal received by a small loop antenna at a distance of approximately 900 miles.

Recently, the Southwest Research Institute™ investigated the potential for reuse of existing signals to produce the transmitted carrier and demodulation carrier reference for low rate phase modulation. The investigation included both simulations of the effects of reference errors (phase and amplitude) on the data and demonstration of wireless link performance with a common reference. It simulated the effects of noise on the link and the path to the external reference [2].

In addition to simulations, a prototype PSK link reusing an existing common reference signal was designed, assembled and demonstrated to validate the simulations. To minimize the hardware complexity, the link design was based on a low-frequency reference signal and link frequency operating under Federal Communications Commission (FCC) Part 15.219 regula-

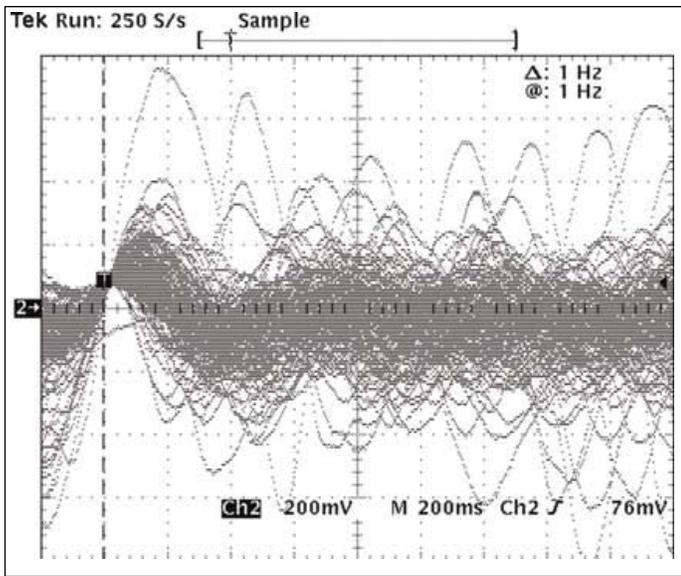
tions (unlicensed transmission in the AM broadcast band). This low frequency minimized the component cost and reduced the need for critical assembly.

The specific frequency reference selected for the prototype was an AM broadcast signal. Because AM broadcast signals require minimal processing complexity to produce a usable frequency reference, they appear very useful as short-range (less than 20 km), low-cost carrier sources. By narrow-band filtering (crystal filter with a 5 hertz, 3 dB bandwidth) the signal, a very low-noise single-frequency reference is obtained with only a few percent of

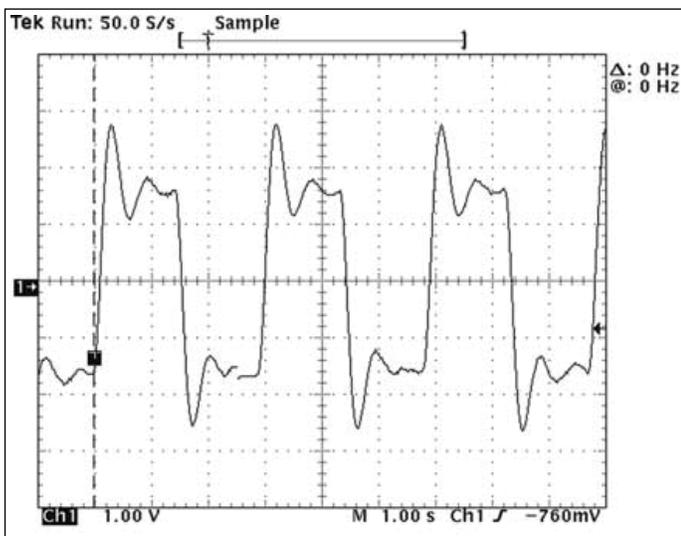
residual low-frequency AM. A limiter amplifier followed by a PLL easily removes the residual AM providing a recovered carrier with very low sideband noise.

A spectrum analysis survey of the local AM broadcast band showed several AM stations with high signal strength and good coverage in the surrounding area. Because future tests might involve extended range tests, a local station with good coverage in nearby hills was selected for the prototype link. The hill coverage may allow tests of narrow-band propagation in non-urban, low-noise areas.

The link operating frequency was also critical. The selected AM broadcast station carrier was at 1.160 MHz, which could be used as a reference for almost any frequency from LF through microwave using conventional PLL techniques. It would have been easy to translate the frequency to a harmonic or subharmonic by simple multiplication or division. Unfortunately, doing so might produce a carrier frequency in an unusable part of the radio spectrum. Also, unless the receiver circuits were extremely linear, a spectral component of the transmitted signal might jam the received AM reference signal. Therefore, a compromise was a PLL recovered carrier divided by an integer and added to the carrier frequency. The sum of the 1.16 MHz carrier added to 1.16 divid-



▲ **Figure 3. Ambient receiver noise output in a 5-hertz receiver bandwidth at 1.5467 MHz.**



▲ **Figure 4. Received signal using a common broadcast station reference.**

ed by three produced a signal at 1.54667 MHz.

The spectrum analyzer survey of the local AM broadcast band also showed that 1.54667 MHz was between FCC assigned center frequencies for local AM stations and was relatively noise free at several locations in the area. The phase-modulated transmitter block diagram is shown at the top of Figure 2.

A companion narrow-band receiver was also designed using the AM broadcast signal to produce a local oscillator for down conversion and as a phase reference for demodulation. The receiver block diagram is shown in the bottom half of Figure 2. The receiver was tested for sensitivity using a continuous-wave (CW) signal sup-

plied by a laboratory signal generator. The received level for a minimum discernible signal was -136 dBm for a receiver 3 dB bandwidth of approximately 5 hertz.

When initially tested at a transmitter-to-receiver range of 10 meters, the link did not produce a high signal-to-noise ratio (S/N) demodulated signal (square wave). Although the receiver noise floor was very low, the ambient noise level at the receiver site was much higher. Measured ambient noise level at the receiver output in the 5 hertz band using a loop antenna was a nominal 300 millivolts root-mean-square (RMS) (see Figure 3). This was more than 30 dB above the receiver noise floor. The receiver was moved to another location, which significantly reduced the received ambient noise. In the new location, at a transmitter-to-receiver range of 180 meters, the link signals were received and phase demodulated, as shown in Figure 4. Note the rise and fall time ringing on the received 0.3 hertz square waves. The receiver 5 hertz bandwidth was too narrow to handle the transmitted phase transitions.

It was very apparent that, in addition to a good propagation path, the receiver site must be selected for low ambient noise or noise reduction techniques must be used to obtain optimum S/N at a given range. In any case, the phase shift keying (PSK) prototype link successfully validated use of an AM broadcast reference for transmission and demodulation of a narrow-band phase-modulated signal.

Current applications

Others are just beginning to use existing electromagnetic signals for various applications. One of the better-known wireless applications reusing existing signals is the GPS timing signal reference for IS-95 based personal communications systems (PCS). The IS-95 standard describes a code-division multiple access (CDMA) system architecture widely used by several cellular PCS providers. IS-95 defines system time to be the same as GPS time and requires that base stations be synchronized to GPS time to less than 10 microseconds, even during periods of GPS satellite unavailability lasting up to eight hours. Consequently, each IS-95 base station incorporates a GPS receiver to synchronize their transmissions with GPS time [3].

The Air Force SILENT SENTRY radar exemplifies another rather esoteric reuse of existing signals. This radar reuses existing signals in the operating area to illuminate the target. Local television, frequency modulation (FM) radio and other very high frequency/ultra high frequency (VHF/UHF) signal sources can be used. Targets have been accurately tracked by triangulation and time of arrival to distances up to 140 miles [4].

There has also been experimentation for reuse of an existing reference signal (AM broadcast and television video) for spread spectrum applications [5]. The existing signals are used to time synchronize frequency hopping

or spreading code at the receiver and transmitter. This provides quick synchronization of the code when the code must be “time locked” at both the transmitter and receiver locations. This is an especially valuable feature for direct sequence spread spectrum (DSSS) systems having very long epoch spreading codes.

Other than precise timing or code tracking, there are only a few other acceptable methods for synchronizing DSSS codes. One of these methods is known as a transmitted reference system. A transmitted reference system uses a separate channel to transmit the spreading code from the transmitter to the receiver. This has several advantages in that there is no need for a code-sequence generator, search/tracking circuits or any of the usual code-related mechanisms of direct sequence spread spectrum communications. Since the same code is provided at the transmitter and receiver, truly random signals or noise can be used as the spreading code providing low probability of intercept (LPI).

At the receiver site, the noise can be correlated with the received modulated noise signal to produce the demodulated waveform. When a spread spectrum system must be as simple as possible, a transmitted reference may be used for acquisition, tracking or both. Both frequency hopping and direct-sequence systems are amenable to transmitted reference methods [6]. Reuse of an existing signal as a reference provides the same benefits without the need to separately transmit the reference.

Other possible applications

Our investigation of signal reuse for external frequency references has recently led to the consideration of signal reuse for other spread spectrum applications. The applications involve the generation of low LPI and low probability of detection (LPD) communications waveforms by reusing external common signals as sources of spreading codes for DSSS signals.

Some common sources for spreading code signals might include modulation from television video, AM and FM audio and direct broadcast satellite (DBS) video. Unfortunately, there are a number of problems with using modulation from these sources for LPI or LPD DSSS encoding and decoding. In addition to the problem of translating the modulation to the desired spreading waveform (spectral distribution, rate and amplitude), these signals have periodicity of modulation components such as a video-blanking signal and subcarriers. But, depending on the level of LPD or LPI required, they might still prove practical as spreading codes. Primary questions to be answered regarding the practicality of this application are the level of coherency of the code sources at widely separated points and the amount of coherency needed for acceptable data transfer.

If modulation signals prove difficult to adapt as spreading codes because of periodicity, then existing sig-

nals with true noise-like characteristics may prove more acceptable. Electromagnetic noise from a natural source common to both a transmitter and receiver should be correlatable at the receiver if they are received from a transmitter retransmitting the noise signal.

If modulation were applied to electromagnetic noise, it would appear to a receiver as noncoherent noise if the electromagnetic noise signal were not available at the receiver for demodulation (correlation). Depending on the level of coherency, it should be possible to use random noise as a spreading code for a direct sequence spread spectrum signal.

Although there are many natural sources of radio noise, few provide coherent signals at two widely separated geographic points. An exception is astronomical noise sources. The most intense astronomical source is the sun. Solar flux includes a significant amount of noise energy in the millimeter and microwave spectrum. By translating a section of the solar flux noise spectrum to a band of interest, it should be possible to transmit the modulated noise to a receiver and demodulate using the same band of translated noise. Since solar noise is essentially random, there would be no autocorrelation of the modulated noise as in conventional receivers. Such a transmitted waveform should be very difficult to detect in the presence of real noise (LPD) and reveal no information if detected (LPI).

The sun is a well-characterized celestial noise source. The sun’s effective noise temperature ranges from 10,000 to more than 300,000 K, depending on its state (quiet sun versus disturbed sun) and the frequency. Due to the small 0.5° angle subtended by the sun, the overall noise signal received from the sun is small unless highly directional antennas are used. The effective noise temperature is a function of antenna gain at each solid angle spanned. This is apparent from the following equation for total received noise temperature $T_{eff,noise}$ [7].

$$T_{eff,noise} = \frac{\int G_{ant}(\Omega)T_{noise}(\Omega)d\Omega}{\int G_{ant}(\Omega)d\Omega}$$

where:

Ω = solid angle

$G_{ant}(\Omega)$ = antenna gain

$T_{noise}(\Omega)$ = total received noise temperature

The noise N_{pl} (energy density in a 1 hertz bandwidth as a function of frequency f) due to the Planck black body radiation continuum from the sun is given by:

$$N_{pl} = \frac{(2\pi hf^3 r^2)}{\left(c^2 \left[e^{\left(\frac{hf}{kT} \right)} - 1 \right] R^2 \right)} \frac{\text{watts}}{\text{meter}^2} \text{ per hertz}$$

where:

- h = Planck's constant (6.63×10^{-34} Js)
- c = velocity of light (3×10^8 m/s)
- r = radius of the sun (6.96×10^8 m)
- k = Boltzman's constant (1.38×10^{-23} J/K)
- T = temperature (10,000 to 300,000 K at radio frequencies)
- R = distance of the noise receiver from the sun.

At low microwave frequencies (1 to 3 GHz), the solar noise power is about 1×10^{-20} watts/meter² per hertz. For an antenna of only 0.1 m², the solar noise energy received would be -180 dBW per hertz. This is 24 dB above the ambient (room temperature) noise floor of -204 dBW per hertz [8]. The ratio of received solar noise to ambient thermal noise is a strong function of the antenna gain the center frequency and the solar flux level. But, depending on the amount of coherency required, a system with a sufficient S/N for correlation with minimal receiver/antenna complexity could be possible. In addition to the sun, there are other sources of radio noise that may prove useful. For example, radio noise from Jupiter may be received using simple receivers at frequencies from 10 to 40 MHz. To reduce the incidence of undesired signals, the Jupiter signals can be received in a "quiet zone" from 25.55 to 25.67 MHz set aside by the FCC as one of the radio astronomy listening windows.

The important question for reuse of celestial signals at more than two points is the signal coherency. There has been some investigation of long baseline infrared interferometry on celestial sources showing good coherency. Unfortunately, the long baseline for interferometry (up to 110 meters) is short compared to the distances that might be considered for communication [9]. But, radio telescopes such as the very long baseline array (VLBA) have demonstrated limited coherency of astronomical signal sources at baselines of several thousands miles down to frequencies as low as 330 MHz. More research is needed for practical reuse of celestial signals for spread spectrum applications.

Conclusion

Reuse of existing signals is currently limited to only a few applications. For the most part, these applications have resulted from a need for a coherent signal at two or more locations. With the exception of radar and other single-point applications (timing, frequency calibration and phase reference for beam forming), the signal must be coherent and adequately detectable at both ends of the communications path.

For communications applications, the coherent signal is often used as a carrier source or time standard for transmission and reception. When cost is not a factor, conventional synchronization, code tracking or carrier

recovery techniques can usually meet the need. For very low data rate links operating within very narrow bandwidths, carrier frequency and long-term phase tracking are difficult to obtain at reasonable cost. Links operating with low S/N are especially susceptible to degradation when demodulated using information (carrier, timing and code) derived directly from the received signal. Also, links requiring code or timing synchronization must sacrifice data rates due to code or time acquisition. For applications where the conventional carrier regeneration methods are too complex/expensive, inefficient at low S/N or have too much acquisition overhead, reuse of external signals may be more effective.

Signal reuse is not appropriate for every wireless application, but may be a viable option for some. The requirement for additional signal paths may limit the usefulness of the method to fixed-point communications, but benefits obtained from reuse of existing signals common to both points may outweigh the limitations imposed. Table 1 (see Appendix) lists wireless applications with example reusable signals for the applications and the benefits of signal reuse. This is a partial list of current and possible applications. Many other applications may be feasible once the benefits of signal reuse are considered. ■

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Appendix

Wireless applications	Example signals suitable for reuse	Potential performance benefits
Short-range, low data rate links using all modulation types	GPS, time stations, AM broadcast and terrestrial video broadcasts demodulation and narrow bandwidth	High frequency stability at low cost, greater range through coherent
HF automatic link establishment (ALE) using all modulation types	GPS and satellite television broadcasts	Faster signal acquisition and more accurate throughput during low S/N reception
Meteor scatter using all modulation types	GPS and satellite television broadcasts	Reduced acquisition time providing higher throughput for short meteor ionization trails
Low probability of intercept (LPI) links using all modulation types	Common source modulation, solar noise and other celestial noise sources	Quasi-random signal encryption
Low probability of detection (LPD) links using all modulation types	Common source modulation, solar noise and other celestial noise sources	Noise-like signal spreading
Spread spectrum (direct sequence and frequency hopping modulation) links	Common source modulation, solar noise and other celestial noise sources	Encryption, faster signal acquisition and better low-signal synchronization
Links using orthogonal frequency division multiplexing (OFDM) modulation	GPS, time stations, AM broadcast and terrestrial video broadcasts	Tighter transmit-to-receive clock synchronization without using PLLs on pilot subcarriers
Links using time-division multiple access (TDMA) modulation	GPS, time stations, AM broadcast and terrestrial video broadcasts	Faster signal acquisition and more accurate throughput during low S/N reception
Antenna beam forming	GPS, time stations, AM broadcast and terrestrial video broadcasts	Precise phase control for widely separated transmitting antenna array elements
Passive radar	Terrestrial video, FM and AM broadcast	Wide area coverage with good resolution without the need for a dedicated transmitter

▲ **Table 1. Wireless applications with example reusable signals for the applications and benefits of signal reuse.**