Impulse Radio: How It Works

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Abstract— **Impulse radio, a form of ultra-wide bandwidth (UWB) spread-spectrum signaling, has properties that make it a viable candidate for short-range communications in dense multipath environments. This letter describes the characteristics of impulse radio using a modulation format that can be supported by currently available impulse signal technology and gives analytical estimates of its multiple-access capability under ideal multiple-access channel conditions.**

Index Terms—**Impulse radio, spread-spectrum multiple access, time hopping, ultra-wideband radio.**

I. A RATIONALE FOR IMPULSE RADIO

IMPULSE RADIO communicates with baseband pulses of very short duration, typically on the order of a nanosecond, thereby spreading the energy of the radio signal very thinly from near dc to a few gigahertz. When this pulse is applied to an appropriately designed antenna, the pulse propagates with distortion. The antennas behave as filters, and even in free space, a differentiation of the pulse occurs as the wave radiates.

Impulse radios, operating in the highly populated frequency range below a few gigahertz, must contend with a variety of interfering signals, and also must insure that they do not interfere with narrow-band radio systems operating in dedicated bands. These requirements necessitate the use of spread-spectrum techniques. A simple means for spreading the spectrum of these ultra-wide bandwidth (UWB) low-duty-cycle pulse trains is time hopping, with data modulation accomplished by additional pulse position modulation at the rate of many pulses per data symbol.

There must be a real payoff in the use of impulse radio to tackle the difficult problem of coexistence with a myriad of other radio systems. Multipath resolution down to a nanosecond in differential path delay (equivalently down to a differential path length of 1 ft) leads to an elimination of significant multipath fading. This may considerably reduce fading margins in link budgets and may allow low transmission power operation. Due to its significant bandwidth, an impulse radio-based multiple-access system may accommodate many users, even in multipath environments. Carrierless (baseband) transmission suggests that an impulse radio may be manufactured inexpensively.

The same qualities that make this radio attractive also provide the design challenges. Regulatory considerations over such a wide bandwidth will limit the radiated power, ultra-fine time resolution will increase sync acquisition times and may require additional correlators to capture adequate signal energy, full mobility will exacerbate power control needs in multiple-access networks, etc.

II. MULTIPLE-ACCESS TECHNIQUES

A. Time-Hopping Format Using Impulses

A typical time-hopping format employed by an impulse radio in which the kth transmitter's output signal is

$$s_{\mathrm{tr}}^{(k)}(t^{(k)}) = \sum_{j=-\infty}^{\infty} w_{\mathrm{tr}}(t^{(k)} - jT_f - c_j^{(k)}T_c - \delta d_{\lfloor j/N_s \rfloor}^{(k)}) \tag{1}$$

where $t^{(k)}$ is the kth transmitter's clock time and T_f is the *pulse repetition time*. The transmitted pulse waveform $w_{\mathrm{tr}}(t)$ is referred to as a *monocycle*.

To eliminate catastrophic collisions due to multiple access, each user (indexed by k) is assigned a distinctive time-shift pattern $\{c_j^{(k)}\}$ called a *time-hopping sequence*. This provides an additional time shift of $c_j^{(k)}T_c$ seconds to jth monocycle in the pulse train, where T_c is the duration of addressable time delay bins. For a fixed T_f, the *symbol rate* R_s determines the number N_s of monocycles that are modulated by a given binary symbol via $R_s = (1/N_sT_f)$ s^{-1}. The modulation index δ can be chosen to optimize performance.

For performance prediction purposes, the data sequence $\{d_j^{(k)}\}_{j=-\infty}^{\infty}$ is modeled as a wide-sense stationary random process composed of equally likely symbols. A pulse position data modulation is considered here in which it is assumed that the data stream is balanced so that the clock tracking loop S-curve can maintain a stable tracking point. With more complicated schemes, pulse shift balance can be achieved in each symbol time.

B. The Multiple-Access Channel

When N_u users are active in the multiple-access system, the composite received signal at the output of the receiver's antenna is modeled as

$$r(t) = \sum_{k=1}^{N_u} A_k s_{\mathrm{rec}}^{(k)}(t - \tau_k) + n(t) \tag{2}$$

Manuscript received August 25, 1997. This work was supported in part by the Joint Services Electronics Program under Contract F49620-94-0022, and in part by the Integrated Media Systems Center, a National Science Foundation Engineering Research Center, with additional support from the Annenberg Center for Communication at the University of Southern California , and by the California Trade and Commerce Agency. The associate editor coordinating the review of this letter and approving it for publication was Prof. Y. Bar-Ness.

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Publisher Item Identifier S 1089-7798(98)01915-2.

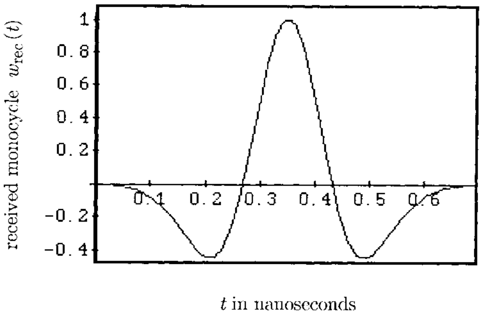

Fig. 1. A typical ideal received monocycle $w_{\text{rec}}(t)$ at the output of the antenna subsystem as a function of time in nanoseconds.

in which A_k represents the amplitude of the signal received from the kth transmitter. The random variable τ_k represents the time asynchronism between the clock of transmitter k and the receiver, and $n(t)$ represents other nonmonocycle interferences (e.g., receiver noise) present at the correlator input.

The number of transmitters N_u on the air and the signal amplitudes A_k are assumed to be constant during the data symbol interval. The propagation of the signals from each transmitter to the receiver is assumed to be ideal, each signal undergoing only a constant attenuation and delay. The antenna/propagation system modifies the shape of the transmitted monocycle $w_{\text{tr}}(t)$ to $w_{\text{rec}}(t)$ at its output. An idealized received monocycle shape $w_{\text{rec}}(t)$ for a free-space channel model is shown in Fig. 1. This channel model ignores multipath, dispersive effects, etc.

III. Impulse Radio Receiver Signal Processing

The optimum receiver for a single bit of a binary modulated impulse radio signal in additive white Gaussian noise (AWGN) is a correlation receiver [1], which implements

$$\text{“decide } d_0^{(1)} = 0\text{”} \Longleftrightarrow$$

$$\underbrace{\sum_{j=0}^{N_s-1} \overbrace{\int_{\tau_1+jT_f}^{\tau_1+(j+1)T_f} r(u,t)v(t-\tau_1-jT_f-c_j^{(1)}T_c)\,dt}^{\text{pulse correlator output } \triangleq\, \alpha_j(u)}}_{\text{test statistic } \triangleq\, \alpha(u)}$$

$$> 0 \tag{3}$$

where $v(t) \triangleq w_{\text{rec}}(t) - w_{\text{rec}}(t-\delta)$.

The optimal detection in a multiuser environment, with knowledge of all time-hopping sequences, leads to complex receiver designs [2]. However, if the number of users is large and no such multiuser detector is feasible, then it is reasonable to approximate the combined effect of the other users' dehopped interfering signals as a Gaussian random process [3]. Hence, the single-link reception algorithm (3) is used here as a theoretically tractable receiver model, amenable as well to practical implementations.

The test statistic α in (3) consists of summing the N_s correlations α_j of the correlator's template signal $v(t)$ at various time shifts with the received signal $r(t)$. The signal processing corresponding to this decision rule in (3) is shown in Fig. 2.

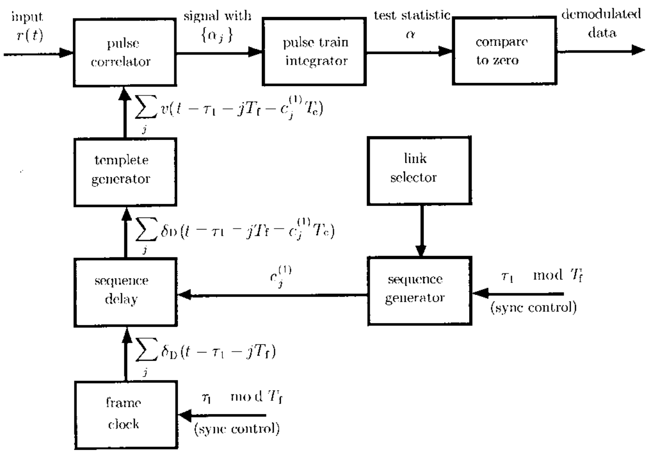

Fig. 2. Receiver block diagram for the reception of the first user's signal. Clock pulses are denoted by Dirac delta functions $\delta_D(\cdot)$.

IV. Multiple-Access Performance

Using the approach of [4], the multiple-access performance of impulse radio is evaluated using randomly selected time-hopping sequences. Let us suppose that a specified signal-to-noise ratio SNR_{spec} must be maintained for the link to satisfy a performance specification, i.e., bit-error rate (BER). Under the assumption of perfect power control, the number of users that the multiple-access impulse radio system can support on an aggregate AWGN channel for a given data rate is shown in [5] to be

$$N_u(\Delta P) = \lfloor M^{-1}\,\text{SNR}_{\text{spec}}^{-1}\{1-10^{-(\Delta P/10)}\}\rfloor + 1 \tag{4}$$

where M is the modulation coefficient. The parameter ΔP is the fractional increase in required power (in units of decibels) to maintain its signal-to-noise ratio at a level SNR_{spec} in its receiver in the presence of multiple-access interference caused by $Nu - 1$ other users.

Note that (4) is a monotonically increasing function of ΔP. Therefore,

$$\begin{aligned} N_u(\Delta P) &\leq \lim_{\Delta P\to\infty} N_u(\Delta P) \\ &= \lfloor M^{-1}\,\text{SNR}_{\text{spec}}^{-1}\rfloor + 1 \triangleq N_{\max}. \end{aligned} \tag{5}$$

Hence, for a specified BER based on SNR_{spec}, there are upper bounds on the number of users (for a given modulation rate) that cannot be exceeded by impulse radio multiuser communications systems using single-user detectors.

V. A Performance Evaluation Example

The performance of the impulse radio receiver in a multiple-access environment is evaluated using a specific example. The duration of a single symbol used in this example is $T_s = N_sT_f$. The modulation parameter δ in (1), which affects the shape of the template signal $v(t)$, affects performance implicitly only through the coefficient M. For the monocycle waveform of Fig. 1 which we will use in this example, the optimum choice of δ is 0.156 ns. Choosing $\delta = 0.156$ ns and $T_f = 100$ ns, the quantity M^{-1} is calculated to be 2.63×10^5 for a data rate $R_s = 19.2$ kb/s.

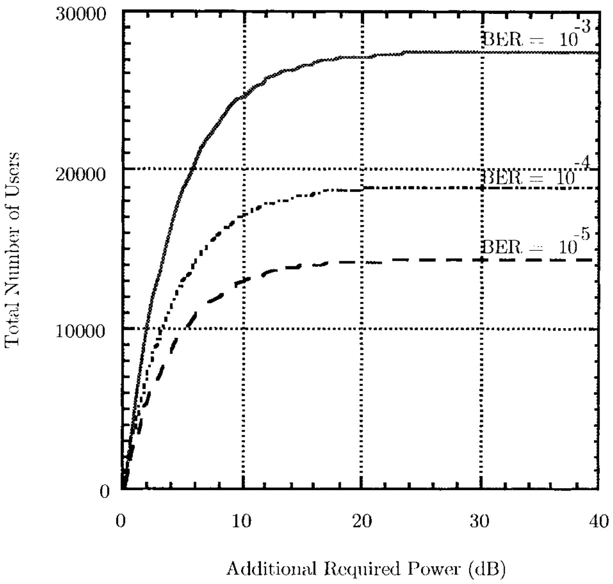

Fig. 3. Total number of users versus additional required power (decibels) for the impulse radio example. Ideal power control is assumed at the receiver. Three different BER performance levels with the data rate set at 19.2 kb/s are considered.

The number of users versus additional required power ΔP for multiple-access operation with ideal power control is plotted for typical BER's in Fig. 3 for this example. To maintain BER of 10^{-3}, 10^{-4}, and 10^{-5} in a communications system with no error control coding, $\mathrm{SNR}_{\mathrm{spec}}$ must be 12.8, 14.4, and 15.6 dB, respectively. Note that the number of users increases rapidly as ΔP increases from 0 to 10 dB. However, this improvement becomes gradual as ΔP increases from 10 to 20 dB. Beyond this point, only negligible improvement can be made as ΔP increases and N_u approaches $N_{\max}$. In practice, impulse radios are expected to operate in regions where the increase in the number of users as a function of ΔP is rapid. The values of $N_{\max}$ is calculated to be 27488, 19017, and 14426 for BER's of 10^{-3}, 10^{-4}, and 10^{-5}, respectively, and these are the asymptotic values on the curves in Fig. 3.

VI. COMMENTS ON SEQUENCE DESIGN

The above performance evaluation is based on average results for randomly selected time-hopping sequence designs. In reality, some sort of pseudonoise generator must provide both transmitter and receiver with a previously agreed upon time-hopping sequence for each communication link. Techniques for providing sets of sequences with good Hamming correlation are well known [6] and may be adapted to the time-hopping application to provide quasi-orthogonal signaling schemes.

The ability of the receiver to reject narrowband interference and the ability of the transmitter to avoid interfering with other radio systems depends on the power spectral density (PSD) of the time-hopped monocycle pulse trains. For a given periodic pseudorandom time-hopping sequence $\{c_j^{(k)}\}$, the PSD of $s_{\rm tr}^{(k)}(t^{(k)})$ in the absence of data modulation can be computed as

$$S_{\rm tr}(f) = \frac{1}{T_p^2}|W(f)|^2 C(f) \sum_{k=-\infty}^{\infty} \delta_D(f - k/T_p) \qquad (6)$$

where

$$C(f) = \left| \sum_{n=0}^{N_p-1} \exp\{-j2\pi f(nT_f + c_n^{(k)}T_c)\} \right|^2 . \qquad (7)$$

Notice that the delta functions which compose the line spectral density are now separated by the reciprocal of one period $(1/T_p)$ of the pseudorandomly time-hopped signal. This narrower spectral line spacing provides an opportunity to spread the power more evenly across the band and to minimize the amount of power that any single spectral line can represent. The addition of nontrivial data modulation on the signal will further smooth this line spectral density as a function of frequency.

The envelope of the lines in the spectral density has two frequency-dependent factors, namely $|W(f)|^2$ and $C(f)$, the latter being time-hopping sequence dependent. Note that when T_f is a integer multiple of $T_c, C(f)$ is periodic in f with period $1/T_c$, so attempts to influence one portion of the frequency spectrum by sequence design will have an effect on other portions of the spectrum. There may be an opportunity to make $C(f)$ better than approximately flat as a function of frequency, e.g., make $C(f) \approx 1/|W(f)|^2$ over a specified interval.

There may be some lines in the power spectral density that cannot be reduced by time-hopping sequence design. For example, suppose that $T_f/T_c = m'/n'$, where m' and n' are relatively prime integers. Then $C(f) = N_p^2$ for all frequencies f that are integer multiples of n'/T_c, and lines exist in $S_{\rm tr}(f)$ at these frequencies. The heights of these spectral lines are independent of the time-hopping sequence and can only be influenced by the energy spectrum $|W(f)|^2$ of the monocycle waveform.

VII. A CLOSING COMMENT

The potential of impulse radio to solve difficult indoor mobile communication problems is apparent because of its fine multipath resolution capability. As with most systems that push the capabilities of current technology, we believe that impulse radio eventually will become a practical solution to these problems.

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