Comparisons of Analog and Digital Impulse Radio for Wireless Multiple-Access Communications

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Abstract— Attractive features of time-hopping spread-spectrum multiple access systems employing impulse signal technology are outlined and emerging design issues are described. Performance of such communications systems in terms of multiple-access capability is estimated for both analog and digital data modulation formats under ideal multiple access channel conditions.

I. INTRODUCTION TO IMPULSE RADIO SYSTEMS

THE term wideband, as applied to communication systems, can have different meanings. When applied to conventional systems, it refers to the data modulation bandwidth. In that case, the more wideband a system is, the higher its data transmission rate. In this paper, a spread-spectrum system [1], [2] is described in which the transmitted signal, even in the absence of data modulation, occupies an extremely large bandwidth. In this case, with a fixed data modulation rate, as the transmitted signal bandwidth increases, the signal may become more covert because its power density is lower, may have higher immunity to the effects of interference, and may have improved time-of-arrival resolution.

The spread-spectrum radio system described here is unique in another regard: It does not use sinusoidal carriers to raise the signal to a frequency band in which signals propagate well, but instead communicates with a time-hopping baseband signal composed of subnanosecond pulses (referred to as monocycles). Since its bandwidth ranges from near d.c. to several GHz, this impulse radio signal undergoes distortions in the propagation process, even in very benign propagation environments. On the other hand, the fact that an impulse radio system operates in the lowest possible frequency band that supports its wide transmission bandwidth, means that this radio has the best chance of penetrating materials that tend to become more opaque at higher frequencies.

Finally it should be noted that the use of signals with GHz bandwidths implies that multipath is resolvable down to path differentials on the order of a nanosecond or less, i.e., down to path length differentials on the order of a foot or less. This significantly reduces fading effects, even in indoor environments, and the resulting reduction of fading margins in link power budgets leads to reduced transmission power requirements.

The modulation format described in this paper can be supported by current technology. The receiver processing and performance predictions, for both analog and digital data modulation formats, are considered under ideal multiple access channel conditions. Real indoor channel measurements and their implications for Rake receiver design [3], [4], [5], [6] will be discussed in a sequel.

II. SYSTEM MODEL

A. Time-Hopping Format Using Impulses

A typical time-hopping format employed by an impulse radio in which the $k$th transmitter's output signal $s_{tr}^{(k)}(u,t^{(k)})$ is given by

$$s_{tr}^{(k)}(u,t^{(k)}) = \sum_{j=-\infty}^{\infty} \omega_{tr}(t^{(k)} - jT_t - c_j^{(k)}(u))T_c - d_j^{(k)}(u),$$

where $t^{(k)}$ is the transmitter's clock time, and $\omega_{tr}(t)$ represents the transmitted monocyte waveform that nominally begins at time zero on the transmitter's clock.

The frame time or pulse repetition time $T_t$ typically may be a hundred to a thousand times the monocyte width, resulting a signal with a very low duty cycle. To eliminate catastrophic collisions in multiple accessing, each user (indexed by $k$) is assigned a distinct pulse shift pattern $\{c_j^{(k)}(u)\}$, called a time-hopping sequence, which provides an additional time shift to each pulse in the pulse train. The $j$th monocyte undergoes an additional shift of $c_j^{(k)}(u)/T_c$ seconds, where $T_c$ is the duration of addressable time delay bin. The addressable time-hopping duration is strictly less than the frame time since a short time interval is required to read the output of a monocyte correlator and to reset the correlator.

The sequence $\{d_j^{(k)}(u)\}_{j=-\infty}^{\infty}$ is a sample sequence from a wide-sense stationary random process $d^{(k)}(u,t)$, with samples taken at a rate of $T_t^{-1}$. Both analog and digital modulation formats are described in this paper. For the analog impulse radio, analog subcarrier signaling is considered where stabilization of tracking S-curve of the clock control loops can be accomplished with relatively simple receiver
design. This signaling format is of particular interest for low power or miniaturized applications. For the digital impulse radio, a pulse position data modulation is considered. For simplicity, 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 $r(u, t)$ at the output of this receiver’s antenna is modeled as

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

in which $A_k$ models the attenuation over the propagation path of the signal, $s_{rec}^{(k)}(u, t - \tau_k(u))$, received from the $k$th transmitter. The random variable $\tau_k(u)$ represents the time asynchronisms between the clocks of transmitter $k$ and the receiver and $n(u, t)$ represents other non-monocycle interference (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 modifies the shape of the transmitted monocycle $w_{tr}(t)$ to $w_{rec}(t)$ at the output of the receiver’s antenna. A typical received pulse shape $w_{rec}(t)$ is shown in figure 1. This channel model ignores multipath, dispersive effects, etc.

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

III. THE ANALOG IMPULSE RADIO MULTIPLE ACCESS RECEIVER

A. Signal Processing for the AIRMA Receiver

A simplified model describing a portion of the analog impulse radio multiple access (AIRMA) receiver is shown in figure 2. A more comprehensive description of the AIRMA receiver can be found in [7] where detailed calculations of the mathematical structure at various locations of the AIRMA receiver are made. The results are summarized along with important assumptions that were made during the calculations.

Fig. 2. Simplified model of the analog impulse radio multiple access receiver front end.

It is assumed that the receiver is locked-on to the transmission from the first user so that it achieves both clock and time-hopping sequence synchronization for that transmitted signal. Under the assumption of perfect signal reconstruction, the subcarrier filter output signal is evaluated in [8] as

$$z^{(1)}(u, t) = A_1 \tilde{R}_w(d^{(1)}(u, t - \gamma)) \approx \tilde{R}(0) d^{(1)}(u, t - \gamma'), \quad (1)$$

where $\tilde{R}_w(\tau)$ is the cross-correlation function of the received monocycle $w_{rec}(t)$ and template generator output $w_{cor}(t)$. The quantity $\tilde{R}(0)$ represents the slope of $\tilde{R}(t)$ at $t = 0$, and $\gamma'$ accounts for propagation and processing delays. The latter approximation in (1) is valid when the data modulation $d^{(1)}(u, t)$ is constrained to be within the linear region of the $\tilde{R}(\cdot)$ function. Figure 3 shows exact and approximate expressions for the cross-correlation function $\tilde{R}_w(\tau)$ for the typical received waveform given in figure 1.

Fig. 3. Cross-correlation $\tilde{R}_w(\tau)$ between the received waveform and pulse correlator waveform. Also shown is the linear approximation of this cross-correlation function.

B. Signal-to-Noise Ratio of the AIRMA Receiver

Under the assumption of independent receiver noise samples, independent interference sources, and using random sequence selection, the $N_u$-user signal-to-noise ratio at the output of the subcarrier filter is calculated in [8], as

$$SNR_{out}(N_u) = \frac{A_1^2 R_{subcar}(0)}{2BT \sigma_n^2 + 2BT \sigma_{self}^2 \sum_{k=2}^{N_u} A_k^2}. \quad (2)$$

where $R_{subcar}(0)$ is the correlation function of the process $\tilde{R}_w(d^{(1)}(u, t))$ evaluated at zero shift. The parameter $B$ is
a one-sided noise equivalent bandwidth of the subcarrier filter and $\sigma_n^2$ is the variance of the receiver noise samples at the correlator output. The quantity $\sigma_{self}^2$ is defined to be
\[
\sigma_{self}^2 \triangleq T_f^{-1} \int_{-\infty}^{\infty} \left[ \int_{-\infty}^{\infty} w_{rec}(t + \zeta)w_{cor}(t) \right]^2 d\zeta.
\]

IV. THE DIGITAL IMPULSE RADIO MULTIPLE ACCESS RECEIVER

A. Signal Processing for the DIRMA Receiver

The objective of the digital impulse radio multiple access (DIRMA) receiver is to determine a reasonable model for the signal processing necessary to demodulate one symbol of the transmission from the first transmitter with binary modulation. Specifically, $D_j^{(k)}(u) = \delta D_{(j/N_s)}^{(k)}$ where the data sequence $\{D_j^{(k)}(u)\}_{j=0}^{\infty}$ is a binary (0 or 1) symbol stream that conveys information in some form, and $N_s$ is the number of monochromes per transmitted symbol. Here the notation $[x]$ denotes the integer part of $x$. As with the analog impulse radio, it is assumed that the receiver has perfectly achieved both clock and sequence synchronization for the signal transmitted by the first transmitter.

The optimal detection in a multi-user environment leads to complex receiver designs [9], [10]. However, if the number of users is large and no such multi-user detector is feasible, then it is reasonable to approximate the combined effect of the other users as a Gaussian random process [11], [7]. In this case, the optimum receiver is the correlation receiver [12], [13], which can be reduced to
\[
\text{"decide } d_0^{(1)} = 0 \text{" } \iff \text{ pulse correlator output } \triangleq \alpha(u) = \sum_{j=0}^{N_s-1} \int_{\tau_1 + jT_f}^{\tau_1 + (j+1)T_f} r(u, t)u(t - \tau_1 - jT_f - c_1^{(1)}T_c)dt > 0
\]

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

While the assumptions that make the rule in (4) optimal are not strictly valid, this decision rule will be used in the following to evaluate the performance of DIRMA receiver as a simple suboptimal means of making decisions because it is theoretically simple and suggests practical implementations. The statistic $\alpha(u)$ in (4) consists of summing the $N_s$ correlations of the correlator's template signal $v(t)$ at various time shifts with the received signal $r(u, t)$. The signal processing corresponding to the decision rule in (4) is shown in figure 4. A graph of the template signal is shown in figure 5 using the typical received waveform given in figure 1.

B. Signal-to-Noise Ratio of the DIRMA Receiver

The DIRMA receiver output signal-to-noise ratio is calculated in [11] as
\[
SNR_{out}(N_u) = \frac{(N_s A_1 m_p)^2}{\sigma_{rec}^2 + N_s \sigma_n^2 \sum_{k=2}^{N_u} A_k^2}, \quad (4)
\]

where $\sigma_{rec}^2$ is the variance of the receiver noise component at the pulse train integrator output. The parameters $m_p$ and $\sigma_n^2$ are defined to be
\[
m_p = \int_{-\infty}^{\infty} w_{rec}(x - \delta)v(x)dx, \quad \text{and}
\]
\[
\sigma_n^2 = T_f^{-1} \int_{-\infty}^{\infty} \left[ \int_{-\infty}^{\infty} w_{rec}(x - s)v(x)dx \right]^2 ds,
\]

respectively.

V. PERFORMANCE MEASURES OF MULTIPLE ACCESS SYSTEMS

In this section, the interpretations of $N_u$-user signal-to-noise ratio derived in the previous sections will be made and related to the performance of the impulse radio in terms of multiple access capacity (MAC). Multiple access capacity is defined as the number of users that a multi-user communication system can support for a given level of uncoded bit error probability performance, data rate, and other modulation parameters.

The similarity of structure of the $SNR_{out}(N_u)$ for AIRMA and DIRMA receivers given in (2) and (4), sug-
gests a generalized expression of the form

$$SNR_{out}(N_u) = \left\{SNR_{out}^{-1}(1) + M \sum_{k=2}^{N_u} \left( \frac{A_k}{A_1} \right)^2 \right\}^{-1},$$

where the parameter $M$ for AIRMA and DIRMA receivers are given respectively by

$$M_{AIRMA}^{-1} = \frac{R_{subcar}(0)}{2BT\sigma_{self}^2}, \quad \text{and} \quad M_{DIRMA}^{-1} = \frac{N_{m_p^2}}{\sigma_e^2}. \quad (5)$$

The $SNR_{out}(N_u)$ can be interpreted as the required signal-to-noise ratio at the receiver demodulator to achieve a specified average bit error probability in the presence of the other $N_u - 1$ users. If only user 1 was active, then there would be no multiple access interference and the signal-to-noise ratio at the input of the receiver demodulator would increase to $SNR_{out}(1)$. In this case the bit error probability would be clearly reduced from the specified value by as much as several orders of magnitude. Therefore the ratio of $SNR_{out}(1)$ to $SNR_{out}(N_u)$ represents the fractional increase in every transmitter’s power required to maintain its signal-to-noise ratio, at a level equivalent to $SNR_{out}(1)$ in its receiver, in the presence of multiple access interference caused by $N_u - 1$ other users. Therefore it is convenient to define the fractional increase in required power (in units of dB) as $\Delta P = 10 \log_{10} (SNR_{out}(1)/SNR_{out}(N_u))$.

Under the assumption of perfect power control, the number of users that multi-user communication system can support for a given data rate is shown in [8] to be

$$N_u(\Delta P) = \left[ M^{-1}SNR_{out}^{-1}(N_u) \left\{1 - 10^{-\left(\Delta P/10\right)}\right\} \right] + 1,$$

which is a monotonically increasing function of $\Delta P$. Therefore

$$N_u(\Delta P) \leq \lim_{\Delta P \to \infty} N_u(\Delta P) = \left[ M^{-1}SNR_{out}^{-1}(N_u) \right] + 1 \equiv N_{max}. \quad (6)$$

This result states that the number of users at a specified bit error rate (BER) can not be larger than $N_{max}$, no matter how large the power of each user’s signal is. In other words, when the number of active users is more than $N_{max}$, then the receiver can not maintain the specified level of performance regardless of the additional available power. Similar results for direct sequence code division multiple-access system can be found in [14].

VI. PERFORMANCE EVALUATION OF MULTIPLE ACCESS SYSTEMS

The performance of the impulse radio multiple access receiver is evaluated using the two specific examples of modulation schemes given in the following. A duration of the single symbol used in these examples is $T_s = N_sT_y$. For a fixed frame (pulse repetition) time $T_y$, the symbol rate $R_s$ determines the number $N_s$ of monocytes that are modulated by a given binary symbol, via the equation $R_s = \frac{1}{T_s} = \frac{N_s}{T_y}$ sec$^{-1}$.

A. AIRMA Receiver Example

As an example for AIRMA receivers with analog sub-carrier signaling, consider the frequency shift keyed (FSK) data modulation with,

$$d^{(k)}(u,t) = K \sum_n \left[ T_0 \left( t - nT_s \right) \cos(2\pi(f_c + \Delta f_n(u))t + \theta(u)) \right].$$

The scaling constant $K$ is chosen such that the data modulation levels are small enough that $d^{(k)}(u)$ always falls in the linear region and the approximation in (1) is reasonable. The random variable $\theta(u)$ is uniformly distributed on the interval $[\pi, -\pi)$. In the case of binary FSK, the carrier frequency $f_c$ is shifted by $\Delta f_n(u) = f_0$ or $\Delta f_n(u) = f_1$ depending upon whether the $n^{th}$ data symbol is zero or one, respectively. For AIRMA receivers detecting analog FSK modulation with $K = 0.025$, $T_m = 0.2877$ ns, $T_y = 100$ ns, and the data rate $R_s = 19.2$ kbps, $M_{AIRMA}^{-1}$ is evaluated numerically as $4.63 \times 10^4$. In this calculation, the subcarrier filter bandwidth is set as $2B = 1/T_y$.

B. DIRMA Receiver Example

As an example for DIRMA receivers with digital modulation, consider the binary pulse position modulation (BPPM). In DIRMA receivers the modulation parameter $\delta$, which affects the shape of the template signal $v(t)$, appears only in $m_p$ and $\sigma_e^2$ implicitly, and can be adjusted to maximize $SNR_{out}(N_u)$ under various conditions. When the receiver noise dominates the multiple-access noise, e.g., when there is only one user or when there is a strong external interferer, then it can be shown that the optimum choice of modulation parameter is that which maximizes $|m_p|$, namely $\delta \approx 0.156$. On the other hand, when the receiver noise is negligible and $SNR_{out}(1)$ is nearly infinite, then the optimum choice of $\delta$, suggested by (4), is that which maximizes $|m_p|/\sigma_e$, namely $\delta \approx 0.144$. Little is lost in choosing either of these values, and $\delta$ is chosen to be $\delta = 0.156$ ns. When $\delta = 0.156$ and $T_y = 100$ ns, then $m_p = -0.1746$ and $\sigma_e^2 = 0.006045$. In this case, the unitless constant that is required for calculating $M_{DIRMA}^{-1}$ in (5) is $m_p^2/\sigma_e^2 \approx 504$. With the above choice of $\delta$, $T_m = 0.2877$ ns, and $R_s = 19.2$ kbps, the parameter $M_{DIRMA}^{-1}$ is calculated to be $2.63 \times 10^5$.

C. Performance Evaluation

The number of users versus additional required power for AIRMA and DIRMA receivers are plotted in figure 6 for general BERs [9] for typical BERs. To maintain BER of $10^{-3}$, $10^{-4}$, and $10^{-5}$ in a communications system with no error control coding, $SNR_{out}(N_u)$ must be 12.8 dB, 14.4 dB, and 15.6 dB respectively. These curves are plotted using the parameters described in previous section. Note that the number of users increase rapidly as the $\Delta P$ increases from 0 to 10 dB. However, this improvement becomes gradual as $\Delta P$ increases from 10 to 20 dB. After this point, only negligible improvement can be made as $\Delta P$ increases and finally reaches $N_{max}$. In practice, impulse radios are expected to operate in regions where the increase in the number of
users as a function of $\Delta P$ is rapid. It can be seen that the performance of DIRMA receivers in terms of multiple access capacity can be better than AIRMA receiver by more than a factor of 5. Furthermore, figure 6 quantitatively provides the trade-off between the number of additional users and the additional power required to maintain the respective BER. The value of $N_{\text{max}}$ for AIRMA is calculated to be 4846, 3353, and 2544 for BERs of $10^{-3}$, $10^{-4}$, and $10^{-5}$. Similarly $N_{\text{max}}$ for DIRMA is calculated to be 27488, 19017, and 14426 for BERs of $10^{-3}$, $10^{-4}$, and $10^{-5}$. The significance of (7) is also clear from figure 6, in that the number of users are less than $N_{\text{max}}$.

Fig. 6. Total number of users versus additional required power (dB) for AIRMA and DIRMA receivers. This figure is plotted for three different performance levels with the data rate of 19.2 Kbps.

VII. CONCLUSION

A Comparison of AIRMA and DIRMA receivers are made in terms of multiple access capacity under ideal propagation conditions. It is shown that each of the expressions for these two receivers have identical structure with the exception of the constant $M$ which depends specifically on modulations parameters. The multiple access capacity is shown to initially increase rapidly as additional required power increases. However these improvements become gradual after a certain point and finally reach the limits which are referred to as maximum multiple access capacity. It is demonstrated that the performance of DIRMA receivers can be better than AIRMA receivers by more than a factor of 5. This can be attributed to the fact that the AIRMA receiver's subcarrier power is limited by the linear region of the cross correlation function between the received monocyte waveform and the template generator output; where as the modulation parameter $\delta$ is optimized for the DIRMA receiver to maximize the signal-to-noise ratio. The results obtained in this paper are quite general and quantitatively provide the trade-off for system design issues.

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REFERENCES