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A Combined Chirp Signal Modulation Technique for Multiple Access System

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Abstract: These recent years, as the wireless communication has gained increasing attention, various kinds of wireless communication techniques have developed rapidly to get a better system performance. Chirp signal is also noticed again for the feature of low power consumption, high processing gain and low cost. However, traditional chirp signal modulation technique is not suit for multiple access, which is an important parameter to estimate a modern wireless communication system. Even in a WPAN system, the expected number of users at the same time is at least four. In this study, a form of combined chirp signal is designed to solve the multiple access problem. The cross coherence of the signal from different users is analyzed in this study. At the same time, this study also discusses the system performance in AWGN channel and 802.15.4a indoor channel, respectively. Analysis and simulation show this new combined chirp signal technique has a better BER performance as well as the multiple access capacity.

Key words: Combined chirp signal, multiple access, multi-user, multipath channel

INTRODUCTION

Indoor wireless communication has gained increasing attention over some time and its market share is growing rapidly in recent years due to its advantages over cable networks, such as mobility of users, elimination of cabling and flexibility. Many kinds of wireless communication techniques

Such as OFDM (Zhaogan *et al*., 2007) technique and UWB technique (Venkatesan and Ravichandran, 2007) has a fast development to satisfy requirements for high data rate and long distance. The use of chirp signal for wireless communication was first proposed by Winkler (1962). As a kind of spread spectrum technique, chirp signals was noticed because of its high process gain, low power consumption, anti-multipath ability and anti-Doppler effect (Gugler *et al*., 2000a). But the whole system was based on the use of the Surface Acoustic Wave (SAW) filters and could only work in the High-Frequency (HF) band (Gott and Newsome, 1971). Berni and Gregg (1973) gave a further discussion on chirp modulation and gave out a conclusion that chirp modulation is better than FSK but a little worse than PSK. In 1994, the anti-multipath ability of chirp signal under Rayleigh and Rician channel is discussed by Tsai and Chang (1994). And then some modulation methods using chirp signal was proposed which could be grouped into two categories: binary orthogonal keying (Springer *et al*., 2000) and chirp spread spectrum, combined with other modulation technology such as DPSK (Zhang and Liu, 2006; Pinkeny *et al*., 1998; Gugler *et al*., 2000b).

The multiple access chirp modulation did not get much consideration until recent years. Two main kinds of multiple access method were proposed. One method is to change the bandwidth with the same center frequency (Zhang and Liu, 2006) and the other method is to change the center frequency with the same bandwidth (Ju and Barkat, 2004). The first method has a good performance to resist single-frequency interference, but the problem is that the bandwidth is not infinity and the number of multi-users is restricted by the bandwidth and the non-orthogonality of adjacent chirp signals. The second method makes good use of the orthogonality between adjacent chirp signals in time domain, but the overlap of chirp signals in frequency domain will caused the decline of system performance. In this study, a new method of multiple access chirp modulation method is considered to combine the two methods above. Although, a similar idea was proposed by Molisch *et al*. (2007), but some differences are obviously, all the sub-chirp signals have the same center frequency and different chirp rate. However, in this study, chirp signals with both different center frequency and chirp rate are used as sub-chirp signals which can improve system capacity efficiently.

THE MULTIPLE ACCESS COMBINED CHIRP SIGNAL

Chirp spread spectrum theory: For a linear chirp signal, the instantaneous frequency varies linearly with time. The waveform can be written as:

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$$s(t)=\begin{cases} a(t)\cos(\omega_0 t+\pi\mu t^2) & -\frac{T}{2}<t<\frac{T}{2} \\ 0 & \text{elsewhere} \end{cases} \qquad (1)$$

where, T, a(t), $f_0 = \omega_0/2\pi$ and μ are the chirp duration, the envelope, the center frequency and the chirp rate, respectively. The chirp rate indicates the rate of change of the instantaneous frequency.

The impulse response of a matched filter to the signal in Eq. 1 is:

$$h(t)=\sqrt{4\mu}\cos(2\pi(f_0-\frac{\mu t^2}{2})) \quad -\frac{T}{2}<t<\frac{T}{2} \qquad (2)$$

By noting that the high frequency term ($2\omega_0$) in the result can be ignored and assuming that the envelope a(t) is a rectangular function, the output of the matched filter is:

$$g(t)=\sqrt{BT}\frac{\sin\left(\pi Bt\left(1-\frac{|t|}{T}\right)\right)}{\pi Bt}\cos\omega_0 t \qquad (3)$$

for $-T<t<T$. The envelope has its maximum at t = 0 and its first zeros at $t = \pm 1/B$. The compression aspect of pulse compression comes from the fact that while the transmitted signal is rectangular, the output of the matched filter is a sinc function with most of its energy from $-1/B \le t \le 1/B$ and the ratio of the input and output pulse is therefore given by the time-bandwidth product BT which is also known as the processing gain.

Combined chirp signal: In this study, a combined chirp signal are designed and described in Fig. 1. This new chirp signal is combined by two sub-chirp signals and the duration time of each of them is equal.

The general equation of the combined chirp signal can be written as:

$$\begin{aligned} s_{K1}(t)&=a(t)\cos(\omega_0 t+\pi\mu t^2) \\ s_{K0}(t)&=a(t)\cos(\omega_0 t-\pi\mu t^2) \end{aligned} \quad 0\le t\le T/2 \qquad (4)$$

And:

$$\begin{aligned} s'_{K1}(t)&=a(t)\cos\left(\omega_0\left(t-\frac{T}{2}\right)+K\Delta\omega\left(t-\frac{T}{2}\right)+\pi\mu'\left(t-\frac{T}{2}\right)^2\right) \\ s'_{K0}(t)&=a(t)\cos\left(\omega_0\left(t-\frac{T}{2}\right)-K\Delta\omega\left(t-\frac{T}{2}\right)-\pi\mu'\left(t-\frac{T}{2}\right)^2\right) \end{aligned} \quad T/2\le t\le T \qquad (5)$$

where, K is the user number, K = 1, 2,....., M, M is the total number of users. Δf is the frequency separation between adjacent users at t = T/2, μ_K is the chirp rate of the first half of signal duration and μ'_K is the chirp rate of the second half of signal duration. The chirp rates can be written as below:

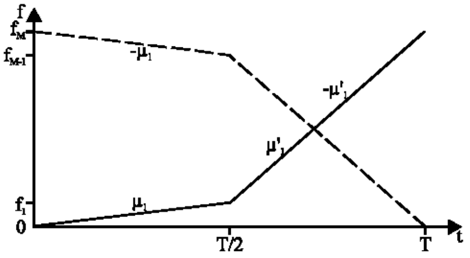

Fig. 1: The combined chirp signal form

$$\mu_K=\frac{K\Delta f}{T/2} \quad \mu_K{}'=\frac{(M-1)-k}{T/2}\Delta f \qquad (6)$$

The bandwidth of different signals is the same is described as $B = M\Delta f$, the BT product is $MT\Delta f$.

CROSS COHERENCE OF THE COMBINED CHIRP SIGNALS

The most important parameter to affect the system performance is the cross coherence ρ which is 0 in the ideal situation. Using the combined chirp signal, ρ can be calculated in three stages from special to general.

In stage 1, ρ is calculated with the same chirp rates and different signs. This situation means the case of ρ between the two binary signals of the same user. ρ can be written as:

$$\begin{aligned} \rho^1_{Ki,Kj}&=\int_0^{T/2} s_{k1}(t)s_{k0}(t)dt+\int_{T/2}^{T} s'_{k1}(t)s'_{K0}(d)dt \\ &=\frac{1}{T}\left[\int_0^{T/2}\cos\left(2\pi\mu_k t^2\right)dt+\int_{T/2}^{T}\cos\left(2\pi\mu'_k\left(t-\frac{T}{2}\right)^2+2K\Delta\omega\left(t-\frac{T}{2}\right)\right)dt\right] \end{aligned} \qquad \begin{aligned} i&=1,0 \\ j&=1,0 \\ i&\ne j \end{aligned} \qquad (7)$$

In stage 2, ρ is calculated with the different chirp rates but same signs. This situation means the case of two binary signals for different users and ρ can be written as:

$$\rho^2_{Ki,Ii}=\frac{1}{T}\left[\begin{aligned} &\int_0^{T/2}\cos\left(\pi(\mu_K-\mu_I)t^2\right)dt \\ &+\int_{T/2}^{T}\cos\left((K-I)\left(t-\frac{T}{2}\right)\Delta\omega+\pi(\mu'_K-\mu'_I)\left(t-\frac{T}{2}\right)^2\right)dt \end{aligned}\right] \qquad (8)$$

where, I = 1, 2,...... M, i = 0 or 1.

In stage 3, ρ is calculated with both different chirp rates and different signs. This situation also means the case of two binary signals for different users and can be written as:

$$\rho^3_{Ki,Ij} = \frac{1}{T}\left[\begin{array}{c} \int_0^{T/2} \cos\left(\pi(\mu_K + \mu_I)t^2\right)dt \\ + \int_{T/2}^{T} \cos\left((K+I)\left(t-\frac{T}{2}\right)\Delta\omega + \pi(\mu'_K + \mu'_I)\left(t-\frac{T}{2}\right)^2\right)dt \end{array}\right] \quad (9)$$

This form is the general form of ρ, ρ^1 and ρ^2 both can be get form it if some parameters are set specially. For example, ρ^1 can be get from Eq. 9 by making $\mu_K = \mu_1$, $\mu'_K = \mu'_1$ and $K = I$.

This cross coherence ρ can be written in a closed form in terms of Fresenel cos and sin intergrals C(x) and S(x), respectively, as:

$$\rho = gC(x) + \int_{0.5}^{\tau} \cos\left(A\tau^2 + 2B\tau + D\right)d\tau \quad (10)$$

Where:

$$g = \frac{1}{2\sqrt{(K+I)\frac{BT}{M}}}, \quad x = \sqrt{(K+I)\frac{BT}{M}}$$

And:

$$A = 2\pi(2M-K-I)\frac{BT}{M},\ B = 2\pi(K+I-M)\frac{BT}{M},\ D = \pi\left(M - \frac{3I}{2} - \frac{3K}{2}\right)\frac{BT}{M}$$

Figure 2 shows the relationship between the maximum value of cross-coherence function and the product of BT with different number of users. We can see clearly that as the number of users M increases, ρ increases too. This is caused by the multiple access interference, but we can still consider this system is quasi-orthogonal.

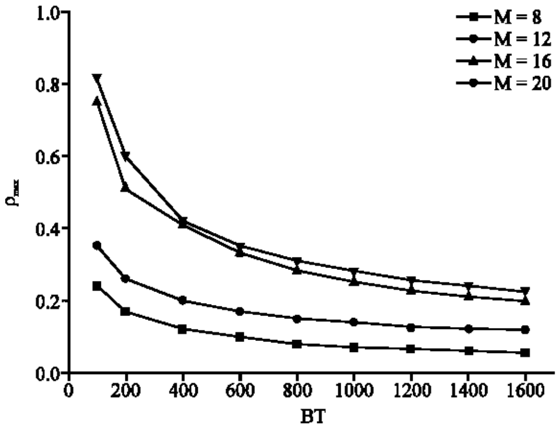

Fig. 2: The relationship between the maximum of cross coherence and BT

PERFORMANCE OF COMBINED CHIRP SIGNAL IN AWGN CHANNEL

The received signal of the Kth user in AWGN channel can be written as:

$$r(t) = s_{Ki}(t) + n(t) \quad K = 1,2,3....M,\ i = 1,0 \quad (11)$$

where, n(t) is white Gaussian noise with zero mean. The response of the Ith matched filter to the Kth user signal, s_{Kj} is:

$$r_{Ij} \mid s_{Kj}(t) = \int_0^{T_s} \left[s_{Ki}(t) + n(t)\right]s^*_{Ij}(t)dt \quad (12)$$

Which can be written in the terms of the general cross coherence as:

$$r_{Ij} \mid s_{Kj}(t) = E\rho_{Ki,Ij} + m_{Ij} \quad (13)$$

Where:

$$m_{Ij} = \int_0^{T_s} n(t)s^*_{Ij}(t)dt$$

The probability density function then can be written as:

$$P\left(r_{Kj} \mid s_{Kj}\right) = \frac{1}{(2\pi)^M |D_{IK}|^{\frac{1}{2}}}\exp\left[\frac{1}{2}\tilde{r}^T D_{IK}{}^{-1}\tilde{r}\right] \quad (14)$$

Where:

$$D_{IK} = E\left[m_{Ij}m_{Ki}\right] = \frac{N_0E}{2}\rho_{I_j,K_i} \text{ and } \tilde{r} = r_{Kj} - E\rho_{Ij,Ki}$$

Then we can get the average probability of error as follows:

- Multiple the probability of the Kth signal and the conditional probability of making an error of the Kth signal
- Sum the results over all possible values of K_i. This leads to:

$$P(\varepsilon) = \sum_{K_i=1}^{2M} P(\varepsilon \mid s_{Ki})P(s_{Ki}) = \frac{1}{2M}\sum_{K_i=1}^{2M} P(\varepsilon \mid s_{Ki}) \quad (15)$$

Also we know:

$$P(\varepsilon \mid s_{Ki}) \le \sum_{\substack{Ij=1 \\ Ij\ne Ki}}^{2M} Pe\left[r_{Ij} \ge r_{Ki} \mid s_{Ki}\right]$$

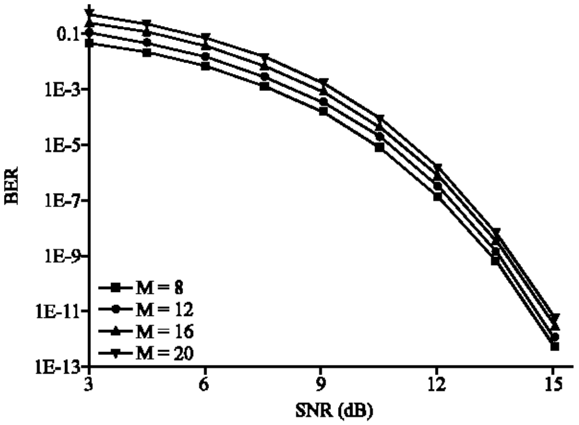

Fig. 3: BER of combined chirp signal with different numbers of user, BT = 500

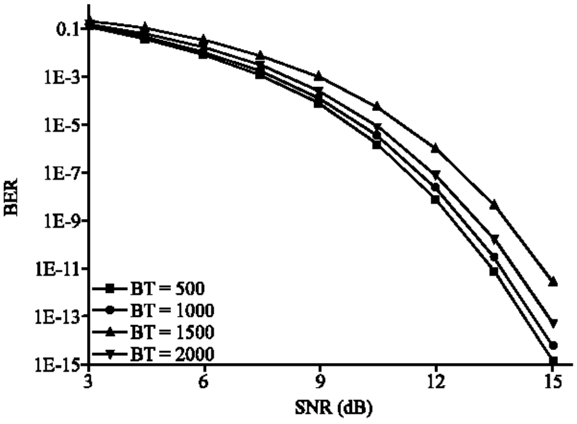

Fig. 4: BER of combined chirp signal with different BT, M = 8

then using Eq. 14, we can get:

$$P(\varepsilon) \le \frac{1}{2M} \sum_{Ki=1}^{2M} \sum_{\substack{Ij=1 \\ Ij \ne Ki}}^{2M} Pe(Ij,Ki) \tag{16}$$

In which Pe (Ij, Ki) is simply the binary error probability and can be written as:

$$Pe(Ij,Ki) = Q\left(\frac{d_{Ij,Ki}}{2}\right) \tag{17}$$

where, d is the minimum distance between two signals, defined as function of SNR and the cross coherence coefficient, as:

$$d^2_{Ij,Ki} = \frac{4E}{N_0}\left(1-\rho_{Ij,Ki}\right) \text{ and } Q(x) = \frac{1}{\sqrt{2\pi}} \int_{\pi}^{\infty} \exp\left(\frac{-u^2}{2}\right) du$$

Then we can get a final form of the probability of error of the combined chirp signals as below:

$$P(e) \le \frac{1}{2M} \sum_{Ki=1}^{2M} \sum_{\substack{Ij=1 \\ Ij \ne Ki}}^{2M} Q\left(\frac{d_{Ij},Ki}{2}\right) \tag{18}$$

Figure 3 shows the relationship between SNR (dB) and the maximum of P(e) with the number of users is 4, 8, 16 and 20, respectively and BT is 500. It can be see clearly when M increase, P (e) increases because of multiple access interference. In Fig. 4, the number of users is fixed, M = 8. In this situation, P (e) decreases while the value of BT increases. As we know, BT can be considered as the gain of system, so that means when the system has a higher system gain, a better BER performance can be obtain. However, high system gain is hard to realize for hardware, a proper BT to balance the BER performance and the system complexity is necessary. Usually, in actual system, BT = 500 is reasonable, which means the system has a 26 dB system gain compared to a DS system.

PERFORMANCE OF COMBINED CHIRP SIGNAL IN MULTIPATH CHANNEL

In this study, a 802.15.4a indoor channel model is used as the multipath channel. There are several rays in one cluster, each of them has independent fading. The impulse response of this model is:

$$h(t) = X \sum_{l=0}^{L} \sum_{k=0}^{K} a_{k,l} \delta(t - T_l - \tau_{k,l}) \exp(j\phi_{k,l}) \tag{19}$$

where, X is the amplitude gain of the channel model and follows normal distribution fading, $a_{k,l}$ is the tap weight of the kth component in the *l*-th cluster, T_l is the delay of the *l*-th cluster, $\tau_{k,l}$ is the delay of the k-th MPC relative to the *l*-th cluster arrival time T_l. The phase is $\phi_{k,l}$ uniformly distributed, i.e., for a bandpass system, the phase is taken as a uniformly distributed random variable from the range [0, 2π].

Rake receiver is a good selection for multipath channel model and is proved by Hengstler *et al.* (2002) which can get a reasonable system performance for traditional chirp signal. However, no one knows if it still works with our new combined chirp signals. Here, we choose the total chirp duration time T = 10 ns and BT = 500. MRC method is used to improve the system performance and we selected 5 rays and all rays, respectively, to calculate the BER with different SNR. Figure 5 shows the result that the more rays used for calculating, the better performance we can get. Even only

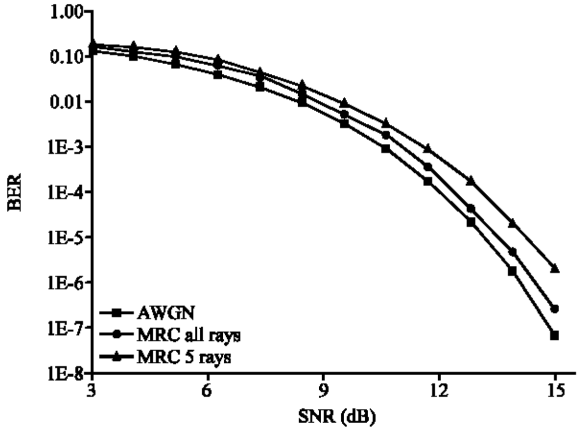

Fig. 5: The performance of Rake receiver for the combined chirp signal

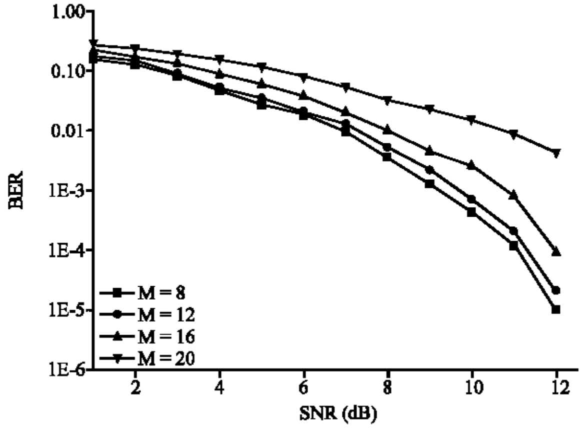

Fig. 6: The performance of combined chirp signal in multipath channel

5 rays is used to simplify the system, the BER is still in a reasonable range. That means, Rake receiver can work well with the new combined chirp signal.

Figure 6 shows the system performance with different number of users in the 802.15.4a LOS channel. The total chirp duration time T = 10 ns and BT = 500. It can be see clearly, the system performance decreases due to the increasing number of users. When M = 20, there is an obviously decline of BER compared to M = 8 (almost 500 times). That is because the cross coherence ρ increases when M increases. This kind of multiple access interference is unavoidable in chirp signal system because of the overlap of signals, but can be decreased through careful design. When, M = 20, the BER is already undesirable if other techniques are not used. So, if we want to increase the number of users, other techniquel must be considered to be applied in this system.

CONCLUSION

In this study, we proposed a new form of combined chirp signal to solve the problem of multiple access chirp modulation. The cross coherence ρ of this combined signal is presented and from the simulation, we know, if the value of BT is big enough, the orthogonality for different users can be guaranteed. Then the BER performance of this system in AWGN channel is discussed with different number of users and different value of BT, respectively. The results show that the proposed combined chirp signal is a promising multi-access technique. Then we applied this combined chirp signal in the 802.15.4a multipath channel, The results also show this form of chirp signal has a better performance to resist the affect of multipath. However, as the number of users increase, the BER performance still has an obvious decrease. Otherwise, in this study, we do not consider the frequency offset which is not easy to estimate because the sub chirp signals have different center frequency and the duration time for the signals is long. That is what we wish to do in next step.

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