Literature Review of Spread Spectrum Signaling: Performance, Applications and Implementation

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Abstract —In this paper, we will review spread spectrum signaling techniques in terms of performance, applications and implementation. Specifically, we focus on direct sequence spread spectrum signaling and CDMA, as the most important applications of spread spectrum signaling techniques, analyzing them in details. With a number of theoretical derivations and simulations, their mathematical characteristics, merits and drawbacks can be revealed. By reading this paper, the readers are expected to have a broad understanding of spread spectrum signaling as well as of direct sequence spread spectrum signaling and CDMA.

Index Terms—Spread spectrum signaling, direct sequence spread spectrum signaling, CDMA, performance analysis

I. Introduction

With the development of modern society, higher and higher data demands and requirements of communication systems are proposed [1]–[6]. However, with conventional modulation and coding schemes, it is difficult and sometimes even impossible to satisfy these needs and requirements [7]. Therefore, some more advanced transmission techniques utilizing Orthogonal Frequency-Division Multiplexing (OFDM) are growing, in response to said conditions and demands. [8]-[10]. Other than OFDM, Spread spectrum signaling is one of the most commonly used, and promising technique of advanced communications. More specifically, it is a signaling scheme which employs a very large transmission bandwidth, in comparison with its data rate [7]. The sacrifice of bandwidth is a trade-off for lower transmitter power, confidentiality and security [11]. Code Division Multiple Access (CDMA) is therefore the most frequent implementation of spread spectrum signaling [12]. All these aforementioned merits and characteristics cannot be achieved by conventional transmission techniques and thus spread spectrum signaling holds a major position in the research of contemporary communication engineering [12]-[15]. For further investigation, we review and analyze spread spectrum signaling in detail.

Manuscript received June 8, 2015; revised December 8, 2015.
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doi:10.12720/jcm.10.12.932-938

This paper is organized in a logical sequence. In Section II, we present the fundamentals of spread spectrum signaling and interpret a number of commonly used concepts. Then, we detail the direct sequence spread spectrum signaling and CDMA in Sections III and IV, respectively. Finally, the paper
is concluded in Section V.

II. Fundamental Concepts and Merits of Spread Spectrum Signaling

Spread spectrum signals are characterized as the signals mwhose required bandwidth W is far larger than their data rate R [7]. We can define the bandwidth expansion to measure this characteristic [7]

$$B_e = \frac{W}{R} = \frac{T_b}{T_c} \tag{1}$$

where T_b is the reciprocal of R; T_c is the reciprocal of W, called chip interval.

Normally, for spread spectrum signals, $B_e \gg 1$ and should be an integer for practical systems [7]. As we have learned from literature review [16]-[18], we realize bandwidth is very precious and could cost billions of dollars [19]. Hence, we need to investigate why such a bandwidth-inefficient technique is worth implementing and how it can be used to improve the performance of a communication system. Briefly speaking, by utilizing a large amount of bandwidth, the immunity against a variety of interference can be improved significantly and high reliability is obtained [7]. This is crucial for some special communication channels used for rescue, military purposes and other emergencies [20]-[22]. Also, since the bandwidth is large enough, the corresponding transmitter power can be reduced, which is more energyefficient and suited to be implemented for some special occasions when a strict transmitter power limit is placed [23]. Additionally, along with the low power characteristic, the security may also be improved, since the truncation of spread spectrum signals behaves like noise in the band-limited receivers and cannot be deliberately intercepted and jammed without the a priori knowledge of the spread spectrum signaling scheme [7]. Therefore, this kind of signals is characterized as a low-probability-of-intercept (LPI) signal [24].

The principle of the immunity against intersymbol interference (ISI) brought by spread spectrum signaling can be explained as follows. Even though multiple transmitters share the common bandwidth, they use different coding schemes to encode their information and thus only the intended receivers can decode the corresponding received signals. Therefore, signals encoded by other codes are indistinguishable and discarded [25]. By this way, the ISI can be minimized. Normally, because the codes employed for spreading sequences, are a series of different pseudorandom patterns, this technique is called CDMA, which is the most commonly used application of spread spectrum signaling [26].

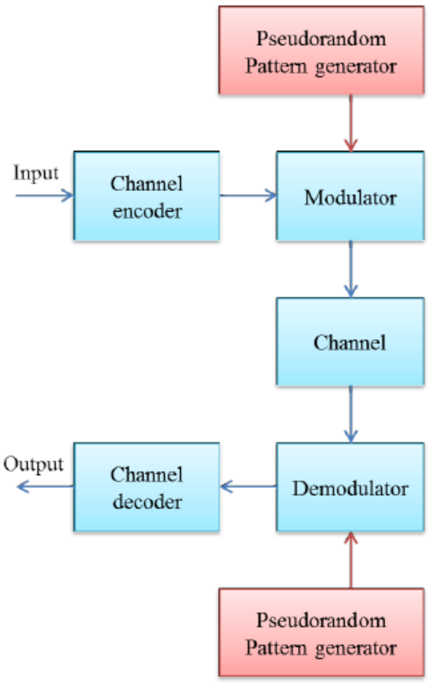

Fig. 1. Block diagram of spread spectrum digital communication system [7].

Now let us focus on the spread spectrum digital communication system. A typical model of spread spectrum digital communication is presented in Fig. 1. The two pseudorandom pattern generators denoted in red in this figure have to be identical and thus they can generate the identical pseudorandom or pseudonoise (PN) sequences. The received signals can only be successfully detected and interpreted when the pseudonoise (PN) sequences generated at the transmitter and the receiver are identical. From this point, it should be noticed that synchronization is rather important, because it guarantees identical PN sequences generation [27]–[29]. Moreover, even when the PN sequences are known to both transmitter and receiver, without proper synchronization, they still cannot match each other and therefore cannot be used to demodulate the received signals [30]. Generally, synchronization in spread spectrum digital communication system is achieved by transmitting an easily distinguishable and fixed pseudorandom bit pattern from the transmitter to the receiver before data transmission [31]. Alternatively, cyclic prefix and postfix insertions can also be used to achieve this goal [32], [33]. Other than these, more advanced and novel techniques relevant to spread spectrum digital communication system design and optimization are proposed in recent years. In [34], an implementation scheme of a typical spread spectrum digital communication system using field programmable gate array (FPGA) and Pseudo-Chaotic Sequences (PCS) are outlined; correlation delay shift keying is combined with conventional spread spectrum technique in [35]. Also, high-bit rate Barker code, Hybrid Spread-Spectrum (HSS) system and optimal jamming strategies are preliminarily analyzed in recent years, which are worth further investigating [36]–[38].

III. Direct Sequence Spread Spectrum Signaling

A. Generation and Receiving of Direct Sequence Spread Spectrum Signals

According to (1), if B_e is an integer, we can use the notation $L_c = B_e$ and thus have

$$L_c = \frac{T_b}{T_c} \tag{2}$$

More specifically, let us take binary PSK as an example. T_b is the transmission time of an information bit and T_c is the duration of a basic pulse, termed the chip. In this sense, L_c can be viewed as the number of chips in a transmission interval of a single bit. The chips are produced by a PN sequence. The relation among these variables can be clearly shown in Fig. 2. Therefore, from this figure, this procedure is equivalent to encoding k-bit information sequence into a (n, k) codeword, where $n = kL_c$.

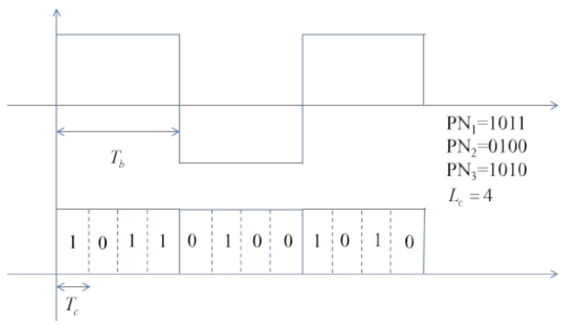

Fig. 2. Relationship between information pulses and chips produced by PN sequences.

This procedure can be accomplished by [7]

$$a_i = b_i \oplus c_i \tag{3}$$

where $\{a_i\}$ represents the ith modulo-2 summation; $\{b_i\}$ represents the ith bit of PN sequence; $\{c_i\}$ represents the ith bit of information sequence from the source encoder.

Then $\{a_i\}$ can be mapped to a sequence of basic binary PSK pulses and becomes the transmitted signal.

The specification of the basic pulse is arbitrary as long as it is reasonable, and by convention, the generic binary PSK pulse can be expressed by [7]

$$g_i(t) = \begin{cases} g(t - iT_c), & a_i = 0 \\ -g(t - iT_c), & a_i = 1 \end{cases} \tag{4}$$

Equivalently, we can also express the binary PSK pulse by

$$g_i(t) = (2b_i - 1)(2c_i - 1)g(t - iT_c) \tag{5}$$

The equivalence can be proved by Table I.

TABLE I: VALUES OF B_i, C_i, A_i AND $(2b_i - 1)(2c_i - 1)$

b_i	c_i	a_i	$(2b_i - 1)(2c_i - 1)$
0	0	0	1
0	1	1	-1
1	0	1	-1
1	1	0	1

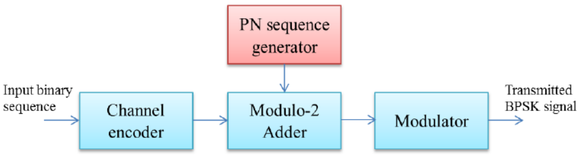

Fig. 3. Block diagram of the transmission of direct sequence spread spectrum signals.

Overall, the block diagram of this transmission procedure can be illustrated in Fig. 3. Considering the additive white Gaussian noise (AWGN) channel without attenuation and fading, the received equivalent low-pass signal is

$$r_i(t) = g_i(t) + z(t) = (2b_i - 1)(2c_i - 1)g(t - iT_c) + z(t) \tag{6}$$

where *z*(*t*) is the low-pass equivalent noise. If the chip-rate clocks can be synchronized perfectly, the identical PN sequence can be regenerated in the receiving end, i.e. fbig is known to the receiver. Also, the basic pulse g(t) is manipulated and known to both the transmitter and the receiver. Therefore, we may apply the demodulator shown in Fig. 4 to remove the effect of the PN sequence and obtain the corresponding demodulated symbols. In this case, the demodulated symbol y_i can be expressed as

$$y_i = (2b_i - 1)^2(2c_i - 1)\left[\int_0^{T_c} g(t - iT_c)g^*(t)\mathrm{d}t\right]_{t=iT_c} + v_i \tag{7}$$

where $v_i = \mathrm{Re}\left\{\int_0^{T_c} g^*(t)z[t + (i-1)T_c]\right\}$ is the noise term added by the demodulator.

It can be easily proved by traversing method that $\forall b_i \in \{0,1\}, \exists (2b_i - 1)^2 \equiv 1$. Therefore, the effect of the PN sequence can be removed and (7) can be simplified to

$$y_i = (2c_i - 1)\left[\int_0^{T_c} g(t - iT_c)g^*(t)\mathrm{d}t\right]_{t=iT_c} + v_i \tag{8}$$

Equivalently, to reduce the deviation of sampling time, we can also employ the demodulator shown in Fig. 5 and the demodulated symbol is completely the same as given in (7). More concisely, if we implement a matched filter, we can obtain the identical demodulated symbols by a simpler demodulator shown in the Fig. 6.

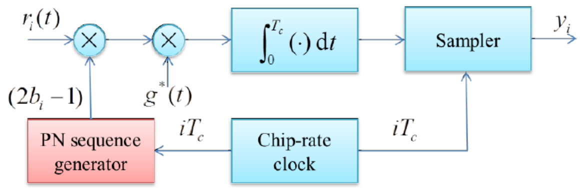

Fig. 4. Block diagram of the demodulator of direct sequence spread spectrum signals [7].

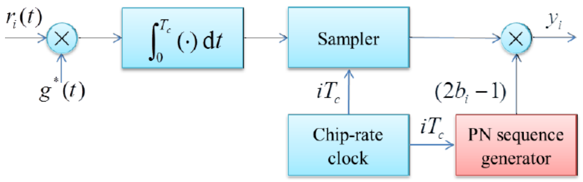

Fig. 5. Block diagram of the demodulator of direct sequence spread spectrum signals with an alternative structure [7].

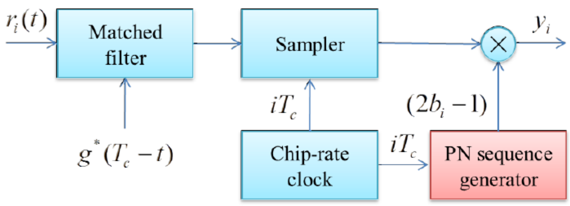

Fig. 6. Block diagram of the demodulator of direct sequence spread spectrum signals with a matched filter [7].

B. *Detection and Error Performance Analysis*

As we discussed in the previous paragraphs, because we modulate a block of k-bit information sequence, we need at least $M = 2^k$ modulated signals to represent the complete set of the k-bit information sequences [7]. Also, because a (*n*, *k*) coding scheme is employed, we will have *M* distinct codewords with *n* bits. Therefore, the correlation metrics of each codeword, where $i \in \{1, 2, \ldots, M\}$, given the demodulated symbol y_j, where $j \in \{1, 2, \ldots, n\}$, can be expressed by

$$CM_i = \sum_{j=1}^{n}(2c_{ij} - 1)y_j \tag{9}$$

By soft-decision decoding scheme [7], the index of the transmitted signal can be determined as

$$i_t = \arg\max_i CM_i \tag{10}$$

Now, we can focus on more details of the detection of direct sequence spread spectrum signals. Without loss of generality, assume an all-zero codeword is transmitted, i.e.

$$c_1 = \underbrace{\{0, 0, \ldots, 0\}}_{n} \tag{11}$$

Then, by (9), we have

$$CM_i = \begin{cases} 2n\mathcal{E}_c - \sum_{j=1}^{n}(2b_j - 1)v_j, & i = 1 \\ 2n\mathcal{E}_c\left(1 - \frac{2w_i}{n}\right) + \sum_{j=1}^{n}(2c_{ij} - 1)(2b_j - 1)v_j, & i \neq 1 \end{cases} \tag{12}$$

where $\mathcal{E}_c$ is the energy of each chip; w_i is the weight of the ith codeword.

Therefore, we can define the condition of correct detection infra

$$\forall i \in \{2, 3, \ldots, M\},$$
$$\exists D_i = CM_1 - CM_i = 4\mathcal{E}_c w_i - 2\sum_{j=1}^{n} c_{ij}(2b_j - 1)v_j > 0 \quad (13)$$

If the condition given in (13) cannot be satisfied, a detection error will occur. Now let us focus on the analysis of error probability. From (13), it is evident that there are two random variables which will determine the value of D_i and other parameters are stipulated and fixed. On average, we have

$$E[D_i] = 4\mathcal{E}_c w_i - 2\sum_{j=1}^{n} c_{ij}(2E[b_j] - 1)E[v_j] \quad (14)$$

Because the bits of the PN sequence can be viewed as binomial distributed random variables and the Gaussian variables are still Gaussian-distributed after being processed by linear operations [39], we can have

$$E[b_j] = 0.5 \quad (15)$$

and

$$E[v_j] = 0 \quad (16)$$

Hence, (14) can be simplified to

$$E[D_i] = 4\mathcal{E}_c w_i \quad (17)$$

Assume the band-limited power spectral density of the noise is [7]

$$S_{zz} = \begin{cases} 2J_0, & f \in [-\frac{W}{2}, \frac{W}{2}] \\ 0, & \text{otherwise} \end{cases} \quad (18)$$

Therefore, by basic probability theory [40], we can prove the variance of the difference D_i is

$$\mathrm{Var}[D_i] = 8\mathcal{E}_c J_0 w_i \quad (19)$$

According to the average and variance obtained above, by the definition of a Gaussian variable and its statistical properties, we can figure out the distribution of difference D_i

$$D_i \sim N(4\mathcal{E}_c w_i, 8\mathcal{E}_c J_0 w_i) = \frac{1}{4\sqrt{\pi \mathcal{E}_c J_0 w_i}} e^{-\frac{(D_i - 4\mathcal{E}_c w_i)^2}{16\mathcal{E}_c J_0 w_i}} \quad (20)$$

Consequently, according to (13), the error probability can be expressed by

$$\begin{aligned} P_e(i) &= \int_{-\infty}^{0} \frac{1}{4\sqrt{\pi \mathcal{E}_c J_0 w_i}} e^{-\frac{(D_i - 4\mathcal{E}_c w_i)^2}{16\mathcal{E}_c J_0 w_i}} \mathrm{d}D_i \\ &= Q\left(\sqrt{\frac{2\mathcal{E}_c w_i}{J_0}}\right) \end{aligned} \quad (21)$$

In order to figure out the relationship between the normalized signal-to-noise ratio (SNR) per information bit γ_b and error probability $P_e(i)$, we first need to clarify the relationship between the energy per chip $\mathcal{E}_c$ and the energy per information bit $\mathcal{E}_b$. According to the (n, k) coding scheme, it is easy to derive

$$\mathcal{E}_c = \frac{k}{n}\mathcal{E}_b \quad (22)$$

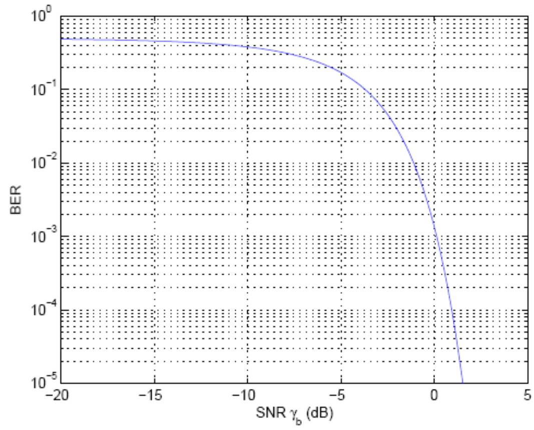

Fig. 7. Error probability variation with the normalized SNR of BPSK modulated direct sequence spread spectrum signals.

Substituting (22) and $\gamma_b = \frac{\mathcal{E}_b}{J_0}$ into (21) yields

$$P_e(i) = Q\left(\sqrt{\frac{2k\mathcal{E}_b w_i}{nJ_0}}\right) = Q\left(\sqrt{\frac{2kw_i\gamma_b}{n}}\right) \quad (23)$$

Assuming (7, 3) coding scheme is employed and the average $E[w_i] = 3.5$, we can simulate the relationship given in (23) and plot the result in Fig. 7. From this figure, it is very clear that with only a small amount of transmitter power, a rather low error probability can be accomplished. This advantageous property provides a high power efficiency and a low detectability of the transmitted signal. Therefore, the required transmitter power can be reduced; while the confidentiality and security are improved.

IV. CODE DIVISION MULTIPLE ACCESS

As we can see from previous subsections, if and only if the identical PN sequences are generated at both transmitter and receiver, the received signals can be demodulated and detected. Otherwise, due to the low transmitter power property of spread spectrum signals, if the PN sequences are different at the transmitting and receiving ends, the received signals cannot be demodulated and are treated as noise. Intuitively, this shows that we can design several, distinct, PN sequences and transmit signals spread with these PN sequences simultaneously, receive them in parallel at the receiver with less mutual interference, provided the number of simultaneously transmitted signals is small and the PN sequences are mutually orthogonal. It can be mathematically proved that the maximum number of simultaneous transmitted signals is [7]

$$N_{\max} = \frac{4WP_{av}kd_{\min}}{RnQ^{-1}\left(\frac{P_e}{M}\right)} \quad (24)$$

where $P_{av} = \frac{\mathcal{E}_b}{T_b}$ is the average transmitter power of each signal; d_{min} is the Hamming distance; $Q^{-1}(\cdot)$ is the inverse function of the tail probability function of the standard normal distribution.

If the number of simultaneous transmitted signals exceeds this upper bound, reliable communication using CDMA cannot be guaranteed.

Another key issue of CDMA is that the PN sequences used to encode for different users should be mutually orthogonal, i.e. $\forall i, j \in \{1, 2, \ldots, N_{\max}\}$, we have

$$\mathrm{PN}_i \mathrm{PN}_j^T \begin{cases} \neq 0, & i = j \\ = 0, & i \neq j \end{cases} \tag{25}$$

The easiest way to generate these satisfactory PN sequences is to apply Walsh code and Hadamard matrix [41]. The matrix of Walsh code is given by a 2×2 matrix w_2 [42].

$$\mathbf{w}_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \tag{26}$$

Then, in order to generate 2^k, we can use the recurrence relation given by Hadamard matrix infra

$$\begin{cases} \mathbf{w}_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, & k = 1 \\ \mathbf{w}_{2^k} = \begin{bmatrix} \mathbf{w}_{2^{k-1}} & \mathbf{w}_{2^{k-1}} \\ \mathbf{w}_{2^{k-1}} & -\mathbf{w}_{2^{k-1}} \end{bmatrix}, & k \in \{2, 3, \ldots, N_{\max}\} \end{cases} \tag{27}$$

Then, each row of the matrix is a PN sequence, mutually orthogonal with sequences generated by the other 2^k-1 rows.

For demonstration purposes, and without loss of generality, we take the simultaneous CDMA signals transmitted by two users as an example. Assume user 1 transmits sequence *a* and user 2 transmits sequence *b*. Processed by the two mutual orthogonal PN sequences produced by w_2, the final transmitted signals of user 1 and user 2 are

$$s_1 = a\mathbf{w}_2(1) = a[1\ 1] \tag{28}$$

and

$$s_2 = b\mathbf{w}_2(2) = b[1\ \ -1] \tag{29}$$

Because s_1 and s_2 are transmitted simultaneously, ignoring the different propagating delays, details of signal detection and noise elimination, we can have the perfect superposed signal at the receiving end

$$\mathbf{r} = a\mathbf{w}_2(1) + b\mathbf{w}_2(2) = a[1\ 1] + b[1\ \ -1] \tag{30}$$

As we assumed before, the PN sequence generator is perfectly synchronized and the identical PN sequences are regenerated at the receiver, i.e w_2 is known to the receiver. Hence, to recover the transmitted signals from user 1 and 2, the receiver can apply the replicas of both PN sequences and obtain

$$\hat{a} = \mathbf{r}\mathbf{w}_2^T(1) = 2a \tag{31}$$

and

$$\hat{b} = \mathbf{r}\mathbf{w}_2^T(2) = 2b \tag{32}$$

Then, using simple scaling, the transmitted signals from both users can be separated and obtained without mutual interference.

V. Conclusion

In conclusion, we have reviewed and presented the fundamentals of spread spectrum signaling techniques in terms of performance, applications and implementation. With a number of mathematical derivations and simulations, its mathematical models, merits and drawbacks are explained and analyzed in greater detail. Meanwhile, a series of issues related to the implementations of these techniques were also addressed. By reading this paper, the readers are expected to have a broad understanding of spread spectrum signaling for further investigation purpose and know how to implement the relevant techniques in practice. Meanwhile, we also hope that this paper can trigger the further investigations pertaining to spread spectrum signaling, especially the combinations of this technique with other advanced hardware/software tools.

References

[1] Z. X. Ma, M. Zhang, S. Shaham, S. P. Dang, and J. Hart, “Literature review of the communication technology and signal processing methodology based on the smart grid,” *Applied Mechanics and Materials*, vol. 719, pp. 436–442, 2015.

[2] I. Rpke, T. H. Christensen, and J. O. Jensen, “Information and communication technologies a new round of household electrification,” *Energy Policy*, vol. 38, no. 4, pp. 1764 – 1773, 2010.

[3] Y. Park, J. Ha, S. Kuk, H. Kim, C. J. Liang, and J. Ko, “A feasibility study and development framework design for realizing smartphone based vehicular networking systems,” *IEEE Transactions on Mobile Computing*, vol. 13, no. 11, pp. 2431–2444, Nov. 2014.

[4] C. C. Huang, P. Y. Lee, and P. Y. Chen, “Implementation of a smartphone based portable doppler flowmeter,” in *Proc. IEEE International Ultrasonics Symposium*, Oct. 2011, pp. 1056–1059.

[5] A. Rahmati and L. Zhong, “Studying smartphone usage: Lessons from a four-month field study,” *IEEE Transactions on Mobile Computing*, vol. 12, no. 7, pp. 1417–1427, July 2013.

[6] M. Sauter, *3G, 4G and Beyond: Bringing Networks, Devices and the Web Together*, Wiley, 2012.

[7] J. Proakis and M. Salehi, *Digital Communications*, McGraw-Hill Education, 2007.

[8] S. Dang, J. P. Coon, and D. Simmons, “Combined bulk/per-tone relay selection in two-hop OFDM systems,” *Wireless Communications Letters*, IEEE, 2015 (under review).

[9] Z. Ma, A. Gholamzadeh, B. Tang, S. Dang, and S. Yang, “Matlab based simulation of the efficiency of the complex ofdm on power line communication technology,” in *Proc. Fourth International Conference on Instrumentation and Measurement, Computer, Communication and Control*, Sept. 2014, pp. 374–378.

[10] S. Dang, J. P. Coon, and D. Simmons, “Combined bulk and per-tone relay selection in super dense wireless networks,” in *Proc. IEEE ICC*, London, United Kingdom, Jun. 2015.

[11] Q. Ding, *A Story of Wireless Communication*, Posts and Telecom Press, 2010.

[12] P. Baier, "A critical review of CDMA," in Proc. *IEEE 46th Vehicular Technology Conference*, Apr. 1996, vol. 1, pp. 6–10.

[13] H. V. Poor and L. A. Rusch, "Narrowband interference suppression in spread spectrum cdma," *IEEE Personal Communications Magazine*, vol. 1, no. 3, pp. 14–27, 1994.

[14] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *Communications Surveys Tutorials*, vol. 11, no. 1, pp. 116–130, First 2009.

[15] D. Koulakiotis and A. Aghvami, "Data detection techniques for ds/cdma mobile systems: A review," *Personal Communications*, vol. 7, no. 3, pp. 24–34, Jun. 2000.

[16] J. Kim, A. Marathe, G. Pei, S. Saha, B. Subbiah, and A. Vullikanti, "Analysis of policy instruments for enhanced competition in spectrum auction," in *Proc. IEEE International Symposium on Dynamic Spectrum Access Networks*, Oct. 2012, pp. 89–96.

[17] S. Gandhi, C. Buragohain, L. Cao, H. Zheng, and S. Suri, "A general framework for wireless spectrum auctions," in *Proc. 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks*, April 2007, pp. 22–33.

[18] S. Greenstein, "The revolution in spectrum allocation," *IEEE Micro*, vol. 29, no. 3, pp. 4–6, May 2009.

[19] X. Geng and A. Whinston, "Profiting from value-added wireless services," *Computer*, vol. 34, no. 8, pp. 87–89, Aug. 2001.

[20] S. Tabrizi, M. Miller, and J. Lee, "Cdma cellular system capacity in the military environment," in *Proc. MILCOM 97*, Nov. 1997, pp. 1163–1167.

[21] K. Bhargav and R. Singhal, "Zigbee based vanets for accident rescue missions in 3G WCDMA networks," in *Proc. IEEE Global Humanitarian Technology Conference: South Asia Satellite*, Aug. 2013, pp. 310–313.

[22] D. Jang, S. Choi, and T. Park, "Development of collapse-sensing phone for emergency positioning system," in *Proc. Sixth International Conference on Information Technology: New Generations*, April 2009, pp. 1649–1652.

[23] X. Duan, Z. Niu, and J. Zheng, "Downlink transmit power minimization in power-controlled multimedia CDMA systems," in *Proc. 13th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Sept. 2002, pp. 1102–1106.

[24] A. Denk, "Detection and jamming low probability of intercept (LPI) radars," Ph.D. dissertation, Monterey California. Naval Postgraduate School, 2006.

[25] D. So, *Lecture Notes of Digital Mobile Communications*, The University of Manchester, 2014.

[26] H. H. Chen, "On next generation CDMA technology for future wireless networking," in *Proc. IEEE Global Telecommunications Conference Workshops*, Nov. 2004, pp. 120–129.

[27] E. K. Lee, J. Cadd, T. L. Fulghum, and R. S. Babayi, "System and method for bit timing synchronization in an adaptive direct sequence CDMA communication system," United States Patent 5359624, Mar. 1994.

[28] C. E. Wheatley Lii and E. G. Tiedemann Jr, "Mobile station assisted timing synchronization in a CDMA communication system," Feb. 1999.

[29] S. Kuno, T. Yamazato, M. Katayama, and A. Ogawa, "A study on quasi-synchronous CDMA based on selected PN signature sequences," in *Proc. IEEE Third International Symposium on Spread Spectrum Techniques and Applications*, Jul. 1994, vol. 2, pp. 479–483.

[30] M. Sunay and P. J. McLane, "Sensitivity of a DS CDMA system with long PN sequences to synchronization errors," in *Proc. IEEE International Conference on Communications*, Jun. 1995, pp. 1029–1035.

[31] Y. J. Song, "Optimal frame synchronization property of pilot bit pattern in compressed mode," in *Proc. IEEE International Symposium on Information Theory*, June 2003, pp. 417.

[32] A. Purwoko and A. Hassan, "A time synchronization scheme for quasisynchronous up-link of MC-CDMA systems," in *Proc. 3rd IEEE International Symposium on Signal Processing and Information Technology*, Dec. 2003, pp. 371–374.

[33] Y. Wen and F. Danilo-Lemoine, "A novel postfix synchronization method for ofdm systems," in *Proc. IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications*, Sept. 2007, pp. 1–5.

[34] R. Nawkhare, A. Tripathi, and P. Pokle, "Ds-ss communication system using pseudo chaotic sequences generator," in *Proc. International Conference on Communication Systems and Network Technologies*, April 2013, pp. 78–82.

[35] J. H. Lee and H. G. Ryu, "Wireless information security improvement with chaotic high order modulation," in *Proc. 12th Annual IEEE Consumer Communications and Networking Conference*, Jan. 2015, pp. 347–350.

[36] S. Latif, M. Kamran, F. Masoud, and M. Sohaib, "Improving dsss transmission security using barker code along binary compliments (cbc12-dsss)," in *Proc. International Conference on Emerging Technologies*, Oct. 2012, pp. 1–5.

[37] M. Olama, S. Smith, T. Kuruganti, and X. Ma, "Performance study of hybrid DS/FFH spread-spectrum systems in the presence of frequency selective fading and multiple-access interference," in *Proc. IEEE International Workshop Technical Committee on Communications Quality and Reliability*, May 2012, pp. 1–5.

[38] S. Amuru and R. Buehrer, "Optimal jamming strategies in digital communications x2014; impact of modulation," in *Proc. IEEE Global Communications Conference*, Dec. 2014, pp. 1619–1624.

[39] Z. Sheng, *Probability and Statistics*, Beijing, China: Higher Education Press, 2008.

[40] C. Grinstead and J. Snell, *Introduction to Probability*, ser. 2nd ed. American Mathematical Society, 1997.

[41] E. Dinan and B. Jabbari, "Spreading codes for direct sequence cdma and wideband CDMA cellular networks," *IEEE Communications Magazine*, vol. 36, no. 9, pp. 48–54, Sep. 1998.

[42] T. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. Upper Saddle River, NJ, USA: Prentice Hall PTR, 2001.

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