Scientia Iranica D (2015) 22(3), 1061–1067

SCIENTIA IRANICA

Sharif University of Technology
Scientia Iranica
Transactions D: Computer Science & Engineering and Electrical Engineering
www.scientiairanica.com

A robust acoustic signal for smartphone-based indoor ranging and positioning

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Received 8 March 2014; received in revised form 29 June 2014; accepted 3 February 2015

KEYWORDS
Acoustic signal;
Indoor positioning;
Smartphone;
Pseudo-random code;
Cross-correlation.

Abstract. The acoustic signal is an important medium in communication, damage and leakage detection, etc., and, in recent years, for use in wireless sensor network positioning. With the development of mobile communication technology, smartphone-based indoor positioning by acoustic signals becomes possible. In an indoor environment, however, acoustic signals are interfered with by environmental noise and multipath effects. Moreover, when multiple users position simultaneously, acoustic signals interfere with each other. In order to eliminate various forms of interference, in this paper, we design a robust acoustic signal for smartphone-based indoor positioning. The signal is generated using pseudo-random codes; gold sequences, to modulate a 6 kHz cosine wave. It is detected through its auto-correlation properties in the receiver. The designed acoustic signal can resist various noises with its excellent cross-correlation characteristic. We conduct experiments on real smartphones and the results show that the signals can work well in the presence of forms of interference.

1. Introduction

Acoustic signals are an important medium in observation and measurement. They have been widely used in communication and target localization [1-3], and, in recent years, they have also become an important means for object localization in indoor environments. There have been some indoor positioning solutions based on acoustic signals, and some special positioning systems have been developed [4-9]. With the development of mobile communication technology, smartphones have become more powerful and intelligent, rendering the use of acoustic signals for smartphone-based indoor positioning possible.

Now that all smartphones are equipped with loudspeakers and microphones, the sending and receiving of acoustic signals do not require additional components. However, there are still some issues that need to be addressed: (1) The frequency range of the acoustic signal must meet the processing requirements of the smartphones; (2) Acoustic signals are susceptible to environmental noise; (3) Multipath effects aroused by walls, office furniture etc. in indoor environments also have an impact on acoustic signals; (4) In a crowded area, acoustic signals will interfere with each other when multiple smartphones conduct simultaneous positioning.

Liu et al. put forward an acoustic signal with equally distributed energy between 16 and 20 kHz for indoor positioning of smartphones [10,11]. In

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the scheme, the receiver first conducts filtering and, then, records the arrival time of signals using the *sequential change-point detection method*. Ranging and positioning are achieved through the flying time and speed of acoustic signals [10], but, the frequency of the acoustic signal in this method is so high that only a few smartphones can meet the frequency. In other words, an acoustic signal is not universally feasible. In addition, when multiple smartphones are positioning simultaneously, the acoustic signals will interfere with each other, leading to a failure in the detection of their arrival time. Peng et al. suggested using a linear frequency modulated signal between 2 and 6 kHz for indoor positioning of smartphones [12]. In the receiver, the arrival time is identified using the auto-correlation property of the signal. In this method, filtering is not necessary and the detection process of the signal is simplified. But, since the signals are not labeled, acoustic signals will also not differentiate from each other when multiple smartphones conduct positioning simultaneously.

In this paper, we design a robust acoustic signal for smartphone-based indoor positioning. The signal is generated by Gold sequences modulating the cosine wave. During smartphone-based indoor positioning using this kind of signal, the signal arrival time at the receiver is determined by the auto-correlation property of the signal. According to mobile communication theory, signals modulated by some pseudo-random sequences possess excellent immunity from environmental noise and the multipath effect [13-16]. Besides, we have also assigned different pseudo-random sequences to different signals, and thus, the signals have no impact on each other if the cross-correlation property of the pseudo-random sequences is excellent [17-22].

In the following sections, we discuss the various interferences with acoustic signals in the indoor environment, and compare the correlation properties of m sequences and Gold sequences; two of the most common pseudo-random codes in communication [23,24]. Gold sequences are chosen for their better cross-correlation property and almost the same auto-correlation property as m sequences. Then, we design the length and code width of the Gold sequences, in accordance with the working frequency of smartphone loudspeakers and microphones, and generate acoustic signals through Binary Phase Shift Keying (BPSK) modulation. Finally, we analyze the performance of the acoustic signals and conduct experiments on Android smartphones to validate the anti-interference ability of the acoustic signal.

2. Interference in indoor positioning

In the indoor environment, acoustic signals will be affected by various forms of environmental noise. Meanwhile, walls, office equipment, and furniture can lead to a multipath effect. Furthermore, in crowded areas, when multiple users are positioning simultaneously, the acoustic signals will interfere with each other.

2.1. Environmental noise

Environmental noise comes mainly from computers, copiers, air conditioners, and elevators, as well as sounds from radios, music, footsteps, talking, etc. Besides, acoustic signals can be affected by vehicle noise and wind sound transmitted into the room through windows.

Filtering is the most common approach of eliminating noise. If the acoustic signal is designed with a frequency different from the noise, then the receiver will be able to remove the noise by filtering. This approach is adopted in [10,11]. Nevertheless, only a few high-end smartphones can meet the processing requirements, as the frequencies of the acoustic signals surpass 15 kHz under such an approach. For most smartphones, the acoustic signals processed by microphones and loudspeakers will be seriously distorted when their frequencies are higher than 10 kHz [12]. Therefore, the spectrum of an ideal acoustic signal should be lower than 10 kHz.

2.2. Multipath effect

The multipath effect occurs when walls, bookshelves, and other office equipment reflect acoustic signals, resulting in the overlapping of signals as the same acoustic signal arrives at the receiver through different paths. Obviously, the signal takes the shortest time to arrive at the receiver when it travels along line-of-sight. According to the communication theory [18], signals with statistical characteristics of white noise can overcome the influence of the multipath effect.

2.3. Interference between acoustic signals

Interference between acoustic signals arises when multiple users are positioning simultaneously in a crowded area. The interference is illustrated in Figure 1.

Suppose that smartphone A sends C an acoustic signal at time T_0, and the signal arrives at time T_A.

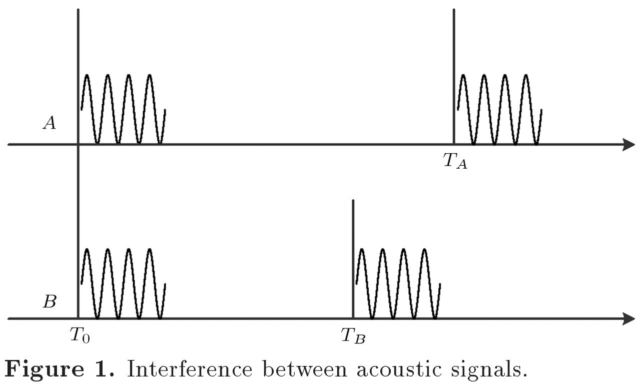

Figure 1. Interference between acoustic signals.

Meanwhile, B sends out an acoustic signal and the signal is received by C at time T_B, which is before T_A. C will not be able to distinguish between the signals, because the signals are not labelled.

Based on the above analysis, we know that an ideal acoustic signal should conform to the processing requirements of the loudspeakers and microphones of smartphones, and also overcome the influence of environmental noise, the multipath effect, and the interference of signals.

3. Acoustic signal design

The steps of smartphone-based indoor positioning using acoustic signals are as follows. First, calculate the distance between different smartphones by multiplying the flying time and the speed of the acoustic signal; then, localize the smartphones by applying certain algorithms [25-27]. In the process, whether or not the smartphone can accurately determine the flying time of the signal is crucially important. The signal frequency, duration, and detection method all have an impact on signal detection.

3.1. Frequency and duration of signal

The major function of smartphones is communication. According to the design standard, the loudspeakers and microphones of the smartphones should be able to react accurately to voices ranging from 1 to 10 kHz. Therefore, the frequencies of acoustic signals used for indoor positioning should be lower than 10 kHz. The duration can be dozens of milliseconds, in view of rapid positioning time. In fact, when adopting the pseudo-random sequence modulation to generate an acoustic signal, the frequency and duration of the acoustic signal are related. Assuming that the code width of the pseudo-random sequences is T_C, and the sequence length is N, then, the bandwidth of the power spectrum of the pseudo-random sequences is determined by T_C. The one-sided bandwidth, B, is determined by the following formula [18]:

$$B = \frac{1}{T_c}. \tag{1}$$

The duration of the signals is determined by the length of the pseudo-random sequences:

$$t = NT_c. \tag{2}$$

Based on Eqs. (1) and (2), we can choose pseudo-random sequences of 127 bits with code width T_c = 0.5 ms. The corresponding one-sided bandwidth of the pseudo-random sequences will be 2 kHz. From the perspective of spectrum, the result of the modulation is to move the spectrum of the pseudo-random sequences to the carrier frequency. Therefore, the frequency of the cosine wave can be selected at 6 kHz.

3.2. Signal generation

We select BPSK modulation, the most common and simplest way in communication, as the modulation method. The selection of the pseudo-random sequences is mainly based on the following requirements [18]:

1. The pseudo-random sequences should have good auto-correlation properties and excellent cross-correlation properties between sequences of the same family (the cross-correlation function value should be equal to zero or as low as possible).
2. The sequences should be easy to generate, process, and control.

There are many kinds of pseudo-random sequences in communication, such as Kasami codes, Barker codes, Golay sequences, m sequences, Gold sequences, etc., among which Gold sequences and m sequences are two of the most common. m sequences have outstanding auto-correlation properties, but poor cross-correlation properties; only some sequences have low cross-correlation values. Gold sequences are the result of modulo-2 addition of two m sequences with the same length (a pair of m sequences which have the lowest cross-correlation function value). Changing the relative displacements of every two m sequences will result in a new Gold sequence. Compared with m sequences, Gold sequences have both outstanding auto-correlation and cross-correlation properties. In addition, with the increase in grade, Gold sequences greatly outnumber m sequences of the same grade. Figure 2 shows the comparison between auto-correlation function values of any m sequence and any Gold sequence of 127 bits, and Figure 3 shows the comparison between cross-correlation function values of any two m sequences and any two Gold sequences of 127 bits.

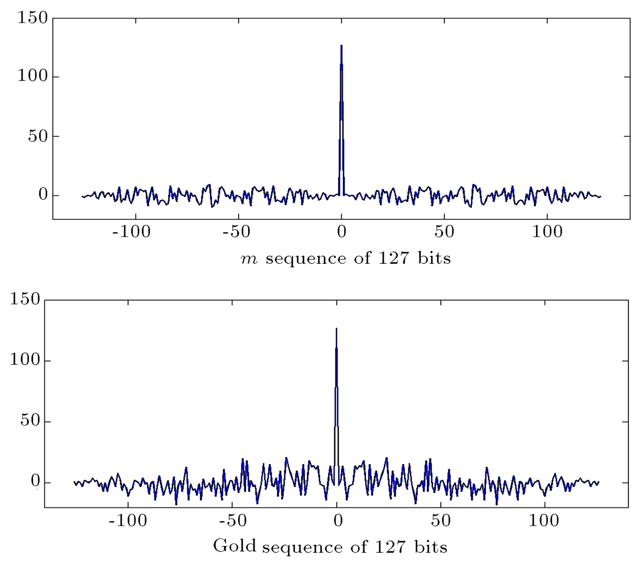

Figure 2. Comparison of auto-correlation function values of any m sequence and any Gold sequence of 127 bits.

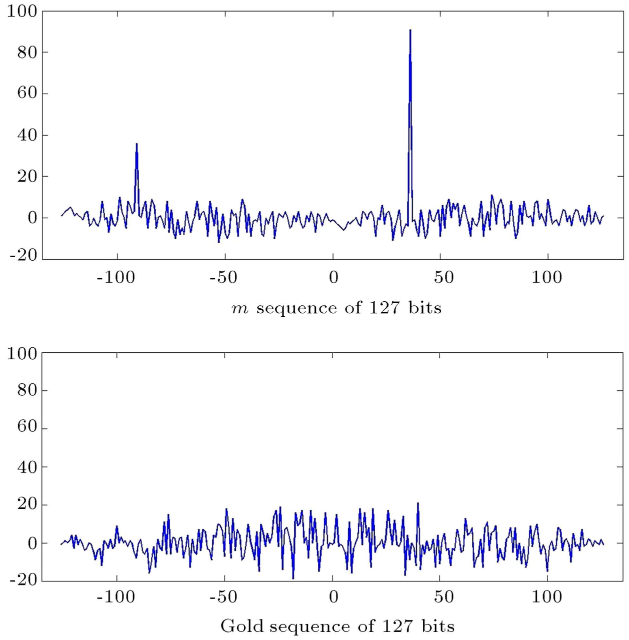

Figure 3. Comparison of cross-correlation function values of any two m sequences and any two Gold sequences of 127 bits.

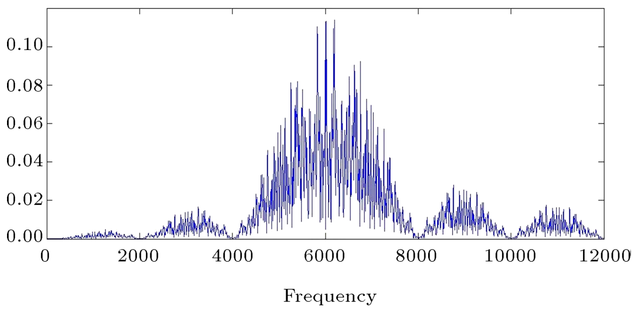

Figure 4. Spectrum of 6 kHz cosine wave modulated by a Gold sequence of 127 bits.

From Figure 2, we can see that the auto-correlation function values of both m sequences and Gold sequences are considerably high at the beginning. However, in Figure 3, the cross-correlation function values of m sequences are sharp at some points, while the cross-correlation function values of Gold sequences remain relatively low at all points. Therefore, the anti-interference ability of the acoustic signal modulated by Gold sequences is better than that of the signal modulated by m sequences.

We modulate a 6 kHz cosine wave with a Gold sequence of 127 bits. The signal spectrum is shown in Figure 4.

Figure 4 demonstrates that the modulation moves the spectrum of Gold sequence to 6 kHz. The bandwidth of the signal is between 4 and 8 kHz (the first zero points) and, therefore, conforms to the processing requirements of the loudspeakers and microphones of smartphones.

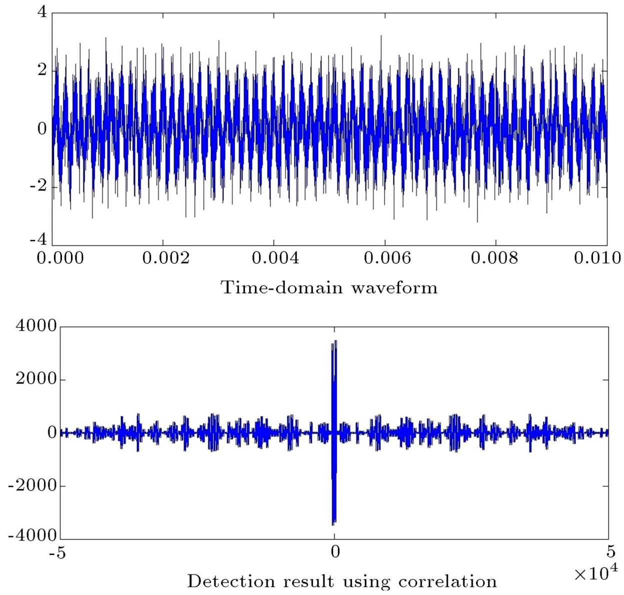

Figure 5. Time-domain waveform and detecting result of the acoustic signal superposed with 3 dB white noise.

3.3. Signal analysis

Figure 5 illustrates the simulation result of the detection of an acoustic signal superposed with white noise (SNR = 3 dB). The result shows that at the starting point of the signal, there is a sharp auto-correlation function value based on which the signal arrival time could be determined.

Next, we overlap an acoustic signal with another one modulated by a different Gold sequence, and superimpose a white noise of 3 dB on them. The time domain chart, the spectrum chart and the detection result of the signal are illustrated in Figure 6, which proves that the excellent correlation properties of the signal ensures the accurate detection of arrival time, even under the interference of strong noise and other acoustic signals.

4. Experiments and discussions

We conduct experiments to evaluate the performance of the acoustic signals designed in this paper. Experiments are performed in a rectangular room of fifty square meters. The room is located on the 5th floor. Computers, printers, desks, bookshelves and air-conditioners are arranged along the walls in the room. There are two windows on the north wall. Three smartphones used in the experiments, all equipped with Android OS, are Coolpad 7260, HTC G 7, and Samsung I 9000, marked as A, B and C, respectively. C acts as an interference source, A runs Android OS 2.3, with 512 MB RAM and a Snapdragon MSM7227T 800 MHz processor, and B runs Android OS 2.2 with 576 MB RAM and a Snapdragon QSD8250 1024 MHz processor.

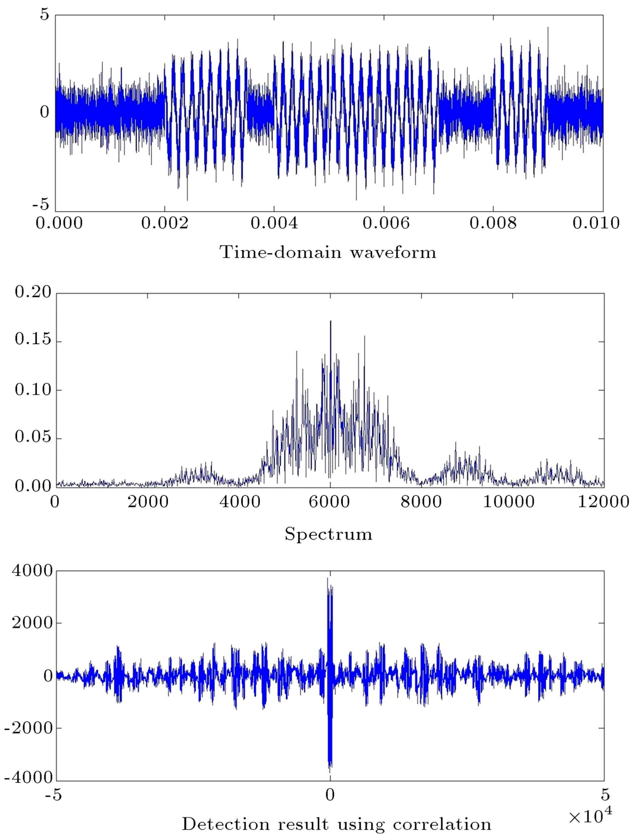

Figure 6. Time-domain waveform, spectrum and detecting result of the acoustic signal superposed with 3 dB white noise and under the interference of other acoustic signal.

The steps for the experiments are as follows. We put A and B at the center of the room, with a distance of 3 meters between them, and start the recording function of A and B to record acoustic signals. Then, we let A send out an acoustic signal and, after an interval, let B send out another acoustic signal. Meanwhile, C is repetitively sending acoustic signals to interfere with A and B. Besides, a laptop is constantly playing music to make noise. The acoustic signals sent by A, B and C are modulated by different Gold sequences. After completing the recording in A and B, we use the original signals of A and B, by means of correlation, to detect the starting points of the recorded signals in A and B. Assuming that the interval between two recorded acoustic signals in A is t_A, and that in B is t_B, then, the distance between A and B is as follows [12]:

$$d = c.\left|t_A - t_B\right|. \tag{3}$$

In Eq. (3), c (340 m/s) is the speed of the acoustic signal in air. Both A and B use a sampling rate of 44.1 kHz to process acoustic signals. Considering the inertia of the loudspeaker [12], we have sent a short 6 kHz cosine wave to activate the loudspeaker before sending acoustic signals.

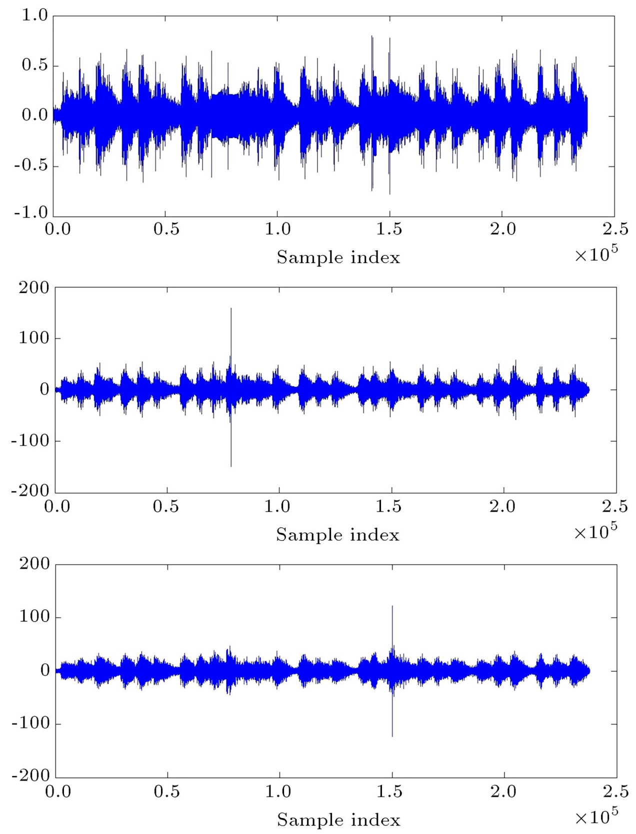

Figure 7. Time-domain waveform and detecting result of acoustic signals in smartphone A.

Table 1. Result of 6 experiments.

Index	Result (m)	Error
1	2.78	7.2%
2	2.70	10.1%
3	2.71	9.7%
4	2.70	10.1%
5	2.71	9.7%
6	2.71	9.8%

The detection method of signals is the same in A and B. The result of one experiment on A is shown in Figure 7.

Six experiments are conducted, based on Eq. (3), and the ranging results are illustrated in Table 1.

As indicated by the results, if we calculate the distance, based directly on the detection results of the signal arrival time, there will be an error of about 10%. The errors mainly result from three reasons:

1. There is a distance between the loudspeaker and microphone of the smartphones;
2. The real speed of the acoustic signal is not precisely measured during the experiments;
3. The distance between A and B cannot be as accurate as 3 meters during the experiments.

If we take these factors into consideration, the ranging accuracy will be significantly improved after we optimize the results. What, however, is of concern in this paper, is the anti-interference ability of the acoustic signals, not how to improve positioning accuracy. In fact, some measures to improve ranging accuracy have been discussed in [10-12]. We will not further discuss the errors. The experiments validate the excellent performance of the designed acoustic signals under strong noise and interference.

5. Conclusions

We have designed a kind of acoustic signal for smartphone-based indoor ranging and positioning. The acoustic signals are generated by adopting the pseudo-random codes; Gold sequences of 127 bits, with a code width of 0.5 ms, to directly modulate a 6 kHz cosine wave. The bandwidth of the acoustic signals after modulation is between 4 and 8 kHz, which meets the processing requirements of the microphones and loudspeakers of smartphones. The receiver detects the signal's arrival time using the auto-correlation property of the signals. Since Gold sequences have statistical characteristics of white noise, as well as outstanding auto-correlation and cross-correlation properties, the receiver can accurately detect the arrival time of the signal, even under various forms of interference. Our experiments validate the excellent anti-interference performance of the designed acoustic signals. It should be noted that we do not claim Gold sequences are the only pseudo-random codes that can be used to generate acoustic signals. There may be other pseudo-random codes that are also applicable.

References

1. Stojanovic, M. "Recent advances in high-speed underwater acoustic communications", *IEEE J. Oceanic Eng.*, **21**(2), pp. 125-136 (1996).
2. Pompili, D., Melodia, T. and Akyildiz, I.F. "A cdma-based medium access control for underwater acoustic sensor networks", *IEEE Trans. Wireless Commun.*, **8**(4), pp. 1899-1909 (2009).
3. Zhang, G. and Dong, H. "Experimental assessment of a multicarrier underwater acoustic communication system", *Applied Acoustics*, **72**(12), pp. 953-961 (2011).
4. Mandal, A., Lopes, C.V., Givargis T., Haghighat A., Jurdak R. and Baldi P. "Beep: 3d indoor positioning using audible sound", *2nd IEEE Consumer Communications and Networking Conference* (2005).
5. Sertatıl, C., Altınkaya, M.A. and Raoof, K. "A novel acoustic indoor localization system employing cdma", *Digital Signal Processing*, **22**(3), pp. 506-517 (2012).
6. Koyuncu, H. and Yang, S.H. "A survey of indoor positioning and object locating systems", *IJCSNS International Journal of Computer Science and Network Security*, **10**(5), pp. 121-128 (2010).
7. Minami, M., Fukuju, Y., Hirasawa, K., Yokoyama, S., Mizumachi, M., Morikawa, H. and Aoyama, T. "Dolphin: A practical approach for implementing a fully distributed indoor ultrasonic positioning system", *Ubicomp 2004: Ubiquitous Computing*, Springer, pp. 347-365. (2004).
8. Priyantha, N.B., *The Cricket Indoor Location System*, Massachusetts Institute of Technology (2005).
9. Hazas, M. and Hopper, A. "Broadband ultrasonic location systems for improved indoor positioning", *IEEE Trans. Mob. Comput.*, **5**(5), pp. 536-547 (2006).
10. Liu, H., Gan, Y., Yang, J., Sidhom, S., Wang, Y., Chen Y. and Ye, F. "Push the limit of WiFi based localization for smartphones", *ACM 18th Annual International Conference on Mobile Computing and Networking* (2012).
11. Yang, J., Sidhom, S., Chandrasekaran, G., Vu, T., Liu, H., Cecan, N., Chen, Y., Gruteser, M. and Martin, R.P. "Sensing driver phone use with acoustic ranging through car speakers", *IEEE Trans. Mob. Comput.*, **11**(9), pp. 1426-1440 (2012).
12. Peng, C., Shen, G. and Zhang, Y. "Beepbeep: A high-accuracy acoustic-based system for ranging and localization using cots devices", *ACM Transactions on Embedded Computing Systems (TECS)*, **11**(1), pp. 4:1-4:29 (2012).
13. Pursley, M.B. and Sarwate, D.V. "Performance evaluation for phase-coded spread-spectrum multiple-access communication. Ii-code sequence analysis", *IEEE Trans. Commun.*, **25**, pp. 800-803 (1977).
14. Geraniotis, E.A. and Pursley, M.B. "Error probability for direct-sequence spread-spectrum multiple-access communications -Part ii: Approximations", *IEEE Trans. Commun.*, **30**(5), pp. 985-995 (1982).
15. Sourour, E.A. and Gupta, S.C. "Direct-sequence spread-spectrum parallel acquisition in a fading mobile channel", *IEEE Trans. Commun.*, **38**(7), pp. 992-998 (1990).
16. Kim, C.-J., Lee, H.-J. and Lee, H.-S. "Adaptive acquisition of PN sequences for DSSS communications", *IEEE Trans. Commun.*, **46**(8), pp. 993-996 (1998).
17. Lee, W.C. "Overview of cellular cdma", *IEEE Trans. Veh. Technol.*, **40**(2), pp. 291-302 (1991).
18. Viterbi, A.J., *Cdma: Principles of Spread Spectrum Communication*, Addison Wesley Longman Publishing Co., Inc. (1995).
19. Moshavi, S. "Multi-user detection for ds-cdma communications", *IEEE Commun. Mag.*, **34**(10), pp. 124-136 (1996).

20. Lee, J.S. and Miller, L.E., *Cdma Systems Engineering Handbook*, Artech House, Inc. (1998).

21. Chandra, A. and Chattopadhyay, S. "Performance analysis of small set orthogonal kasami codes in cdma system under multi-path scenario", *The IUP Journal of Electrical & Electronics Engineering*, **4**(4), pp. 7-21 (2011).

22. Steiner, A., Lupu, V., Katz, U. and Shamai, S. "The spectral efficiency of successive cancellation with linear multiuser detection for randomly spread cdma", *IEEE Trans. Inf. Theory*, **58**(5), pp. 2850-2873 (2012).

23. Dinan, E.H. and Jabbari, B. "Spreading codes for direct sequence cdma and wideband cdma cellular networks", *IEEE Commun. Mag.*, **36**(9), pp. 48-54 (1998).

24. Sarwate, D.V. and Pursley, M.B. "Crosscorrelation properties of pseudorandom and related sequences", *Proc. IEEE*, **68**(5), pp. 593-619 (1980).

25. Liu, H., Darabi, H., Banerjee P. and Liu, J. "Survey of wireless indoor positioning techniques and systems", *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, **37**(6), pp. 1067-1080 (2007).

26. Alsindi, N.A., Pahlavan, K., Alavi, B. and Li, X. "A novel cooperative localization algorithm for indoor sensor networks", *17th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications* (2006).

27. Seco, F., Jimenez, A., Prieto, C., Roa, J. and Koutsou, K. "A survey of mathematical methods for indoor localization", *IEEE International Symposium on Intelligent Signal Processing*, pp. 9-14 (2009).

Biographies

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