DFTs-OFDM Radar using Zadoff-Chu Sequence for Radar-Communication Integration

Masahiro UMEHIRA
Faculty of Science and Technology
Nanzan University
Nagoya, Japan
umehira@nanzan-u.ac.jp

Yoshihiko TAKEUCHI
Faculty of Science and Technology
Nanzan University
Nagoya, Japan
ytakeuch@nanzan-u.ac.jp

***Abstract*— Radar-communication integration is becoming a hot topic in next generation wireless communications such as Beyond 5G/6G and wireless LAN. As Orthogonal Frequency Division Multiplexing (OFDM) based approach has been widely used for broadband mobile wireless access, OFDM based approach is desirable to support sensing functions because of the commonality of signal processing, however the OFDM based approach has several drawbacks such as high PAPR. This paper proposes Discrete Fourier Transform spreading (DFTs)-OFDM radar using Zadoff-Chu (ZC) sequence, which is Constant Amplitude Zero Auto Correlation (CAZAC) sequence, which is suitable for radar applications, as a solution for radar-communication integration. This paper describes basic design issues such as signal format and signal processing on the proposed DFTs-OFDM radar using ZC sequence. It also shows preliminary correlation detection performance of the DFTs-OFDM radar using ZC sequence by computer simulations.**

Keywords*— *DFTs-OFDM radar, Zadoff-Chu sequence, Radar-communication integration, Correlation detection

I. INTRODUCTION

Research and development of Beyond 5G (B5G) and 6G for next generation mobile communications has been carried out all over the world to achieve hyper coverage expansion, hyper sensing and hyper energy efficiency and low cost, in addition to further enhancement of eMBB (enhanced mobile broadband), ULLRC (ultra-low latency and reliability) and mMTC (massive machine type communications) in 5G [1]. Integrated sensing and communication is one of the major targets in B5G/6G to explore new applications of mobile communications such as autonomous driving and monitoring applications [2]-[5]. Sensing is also a hot topic in IEEE802.11 wireless LAN (WLAN) to explore new WiFi applications such as home security, and WiFi sensing has been standardized in IEEE802.11 TGbf [6].

As well-known, Orthogonal Frequency Division Multiplexing (OFDM) based approach has been used in various wireless mobile communication systems because of its robustness and high transmission performance in severe frequency selective fading. OFDM/Orthogonal Frequency Division Multiple Access (OFDMA) technologies have been used in combination with Multiple Input Multiple Output (MIMO) technology to achieve ultra-high spectrum efficiency in terms of bit/s/Hz, and to deploy high capacity and ultra-broadband wireless communication systems such as 4G/5G cellular systems and broadband wireless LAN, e.g. IEEE 802.11be/ax/ac.

In recent years, millimeter-wave MIMO-FMCW (Frequency Modulated Continuous Wave) radar is widely used for simultaneous detection of distance, velocity and Angle of Arrival (AoA) in Advanced Driver-Assistance Systems (ADAS) and automated driving car, in combination with camera and lidar [7]. Intelligent Transportation System (ITS) using Vehicular to X (V2X) communications is also expected to improve the efficiency and safety of transportations [8][9].

These technical trends motivate research and development of radar-communication integration technologies for co-existence of radar and wireless communications. For example, automotive radar uses 76/79GHz band to achieve high ranging resolution taking advantage of wide spectrum availability. If it becomes possible to use 76/79GHz band for both Gbps class broadband wireless communications and radar applications by radar-communication integration, spectrum efficiency will be improved, and cost of radar-communication equipment for ITS will be reduced. Radar communication integration is also promising in 60GHz WiFi because of its wideband spectrum availability.

The above-mentioned backgrounds motivate the authors to propose PMCW radar using Zadoff-Chu (ZC) sequence with ideal auto-correlation property [10]. ZC sequence is a Constant Amplitude Zero Auto Correlation (CAZAC) sequence suitable for radar applications [11]. As ZC sequence is a complex code sequence, it has not been used for radar so far [12],[13], however it is now possible to use QAM modulation for millimeter wave systems, thus ZC sequence can be used for radar. However, as MIMO-OFDM/OFDMA is widely used in mobile communication networks, OFDM-based radar seems more desirable than PMCW radar for radar-communication integration since signal processing functions for OFDM can be re-used for radar from implementation point of view. It is also important to make it possible to use millimeter wave for radar-communication integration, to take advantage of its wide spectrum availability. However, OFDM based approach has some drawbacks such as high Peak to Average Power Ratio (PAPR) which is disadvantageous for millimeter-wave systems. This is why Discrete Fourier Transform spreading-OFDM (DFTs-OFDM) is included in 5G New Radio (5G-NR) for optional use. DFTs-OFDM has an advantage of low PAPR suitable for millimeter-wave wireless systems compared with native OFDM.

Based on the above-mentioned discussions, this paper proposes a DFTs-OFDM radar using ZC sequence for radar-communication integration. The proposed DFTs-OFDM radar has advantages such as re-use of signal processing functions of OFDM/DFTs-OFDM communication and low PAPR. This paper describes basic design issues such as block diagram of radar-communication integrated device, signal format, signal processing and correlation detection for DFTs-OFDM radar, maximum detection range and range resolution in the proposed DFTs-OFDM radar. It also shows preliminary simulation results on correlation detection performance of the proposed DFTs-OFDM radar.

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II. OUTLINE OF RADAR-COMMUNICATION INTEGRATION SYSTEM BASED ON DFTS-OFDM RADAR

The proposed DFTs-OFDM radar generates radar signals and perform target detection by re-using quadrature modulator and demodulator, and Fast Fourier Transform (FFT)/Inverse FFT (IFFT) signal processing functions for OFDM communications. Furthermore, it is easy to make radar and communication co-exist in a radar-communication integrated transceiver. Figure 1 shows block diagram of DFTs-OFDM radar for radar-communication integration. Transceiver and signal processing for OFDM/DFTs-OFDM communication functions is conventional, where I/Q components are generated, D/A conversion is performed and either OFDM or DFTs-OFDM signal is transmitted. In the case of DFTs-OFDM radar, DFTs-OFDM signal modulated by ZC sequence is transmitted. On the receiver side of DFTs-OFDM radar, I/Q components of the received signal reflected from the target are detected and AD converted. Then, cross correlation of the received signal and ZC sequence is calculated, and the peak of the correlation is detected for target detection and delay time measurement. Design parameters and measurement performance of OFDM radar and FMCW radar are discussed in [12].

As shown in Fig. 1, RF transmitter and receiver including I/Q modulator and detector, and A/D and D/A for communication functions can be re-used for radar functions. Furthermore, FFT/IFFT signal processing for OFDM communication can be used for DFTs-OFDM radar as well. We assume that SW (switch) selects radar or communication function as shown here, thus either radar or communication function is enabled on time division basis.

Radar-communication integrated device transmits DFTs-OFDM radar signal, and it receives the radar signal reflected from the targets at the same time for ranging and velocity measurement. On the other hand, it transmits OFDM or DFTs-OFDM signal for communications using another assigned bandwidth and timeslot. Note that we assume each device transmits only one DFTs-OFDM radar signal to avoid high PAPR.

Figure 2 shows an example of frame structure of the proposed radar-communication integrated system using DFTs-OFDM radar. As shown here, there are two approaches, i.e., TDMA approach and TDMA/FDMA approach. In TDMA approach, a channel filter is required to extract DFTs-OFDM radar signals from the received signals. As no DFTs-OFDM radar signal is received during OFDM/ DFTs-OFDM signal time slot, FFT works as channel de-multiplexer assuming subcarrier spacing is identical. In TDMA/FDMA approach, DFTs-OFDM radar signal can be received while OFDM/ DFTs-OFDM communication signal is received. As subcarrier spacing of DFTs-OFDM radar signal and OFDM/DFTs-OFDM signal can be different, complex filter-bank to extract each radar or communication signal will be required at the receiving side to avoid inter-channel interference even though resource assignment in TDMA/FDMA approach is more flexible than TDMA approach. As complex filter-bank is not necessary, TDMA approach seems a more reasonable approach compared with TDMA/FDMA approach.

It is necessary to assign bandwidth and timeslot for DFTs-OFDM radar signal according to the required measurement performance of radar such as maximum detection range, ranging resolution, maximum detection velocity and velocity resolution just like conventional FMCW radar. Such resource assignment can be performed using conventional multiple access techniques i.e., OFDMA and CSMA-CA used in 5G NR and IEEE802.11 WLAN. Detection performance of DFTs-OFDM radar depends on ZC code sequence length, symbol rate, and correlation detection performance of DFTs-OFDM radar signal.

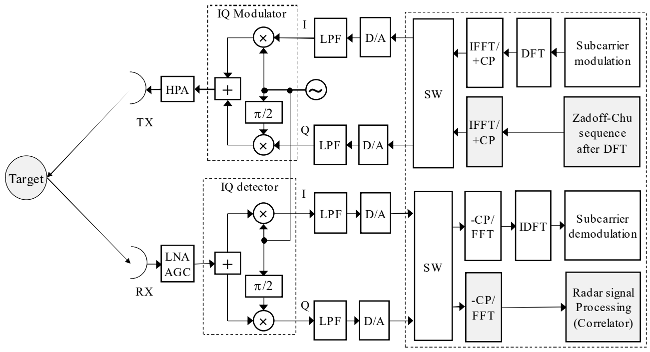
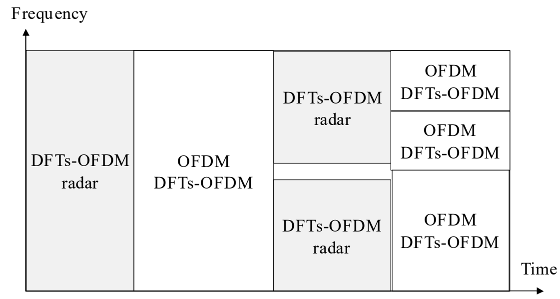
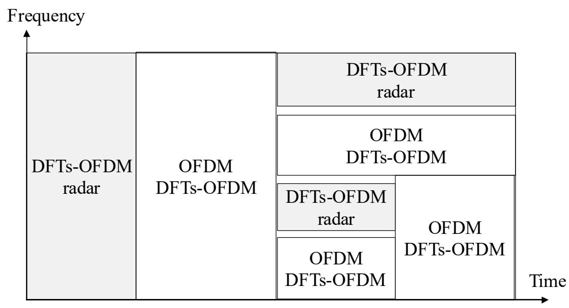


Fig. 1. Block diagram of the proposed DFTs-OFDM radar for radar-communication integration.



(1) TDMA approach.



(2) TDMA/FDMA approach.

Fig. 2. An example of frame structure of radar-communication integrated system using DFTs-OFDM radar.

III. DFTS-OFDM RADAR SIGNAL USING ZC SEQUENCE

A. *Zadoff-Chu sequence*

ZC sequence, $ZC_u(n)$ is a complex cyclic sequence with ideal auto correlation and is given by;

$$ZC_u(n) = \begin{cases} \exp\left(-j\frac{\pi u n^2}{N}\right) & : N\ even \\ \exp\left(-j\frac{\pi u n(n+1)}{N}\right) & : N\ odd \end{cases} \tag{1}$$

where N is the code length, $0 \leq n < N$, $0 < u < N$, greatest common divisor of u and N is one, and $ZC_u(n) = ZC_u(n+N)$. Most important property of ZC sequence for radar application is that it is a cyclic sequence, and it has ideal auto correlation, i.e., correlation of $ZC_u(n)$ and its cyclic shift sequence, $ZC_u(n+m)$ is zero if $m \neq 0$. Furthermore, any code length, N can be used.

As ZC sequence is a CAZAC sequence, PAPR of DFTs-OFDM signal modulated by ZC sequence is expected to be small and it has ideal auto correlation though it is not a binary sequence but a complex sequence.

B. DFTs-OFDM radar signal using ZC sequence

Figure 3 compares DFTs-OFDM radar signal and OFDM/DFTs-OFDM signal for communication. DFTs-OFDM radar signal consists of M sets of block signal modulated by ZC sequence, and cyclic prefix and cyclic postfix with length, T_{CPR} are added at the head of DFTs-OFDM radar signal and at its tail, respectively. T_C is symbol duration of ZC sequence, N is symbol length of ZC sequence, and $T_S = NT_C$ is time duration of ZC sequence. On the other hand, OFDM communication signal has a conventional signal format, i.e., cyclic prefix with length, T_{CP} is added to each OFDM or DFTs-OFDM signal with length, T_{OFDM} to avoid inter-block interference. Usually, preamble is added at the top of L sets of OFDM symbols for synchronization and channel estimation at the receiver.

Figure 4 shows DFTs-OFDM radar signal format using ZC sequence. At first, DFT spreading is performed for ZC sequence, where N point FFT is performed for $ZC_u(n)$ $(n = 0\sim N-1)$ to generate the modulation signal in frequency domain, $ZC_v(m)$ $(m = 0\sim N-1)$ for m-th OFDM subcarrier. $ZC_v(m)$ is given by:

$$ZC_v(m) = \sum_{n=0}^{N-1} ZC_u(n) \cdot \exp\left(-j\frac{2\pi mn}{N}\right). \quad (2)$$

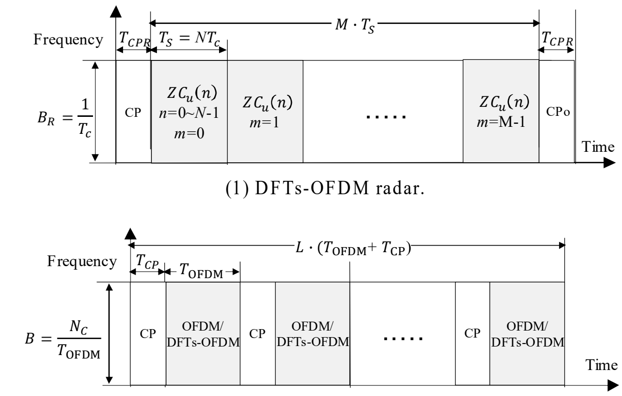
Then, $(K-N)$ point zero insertion is performed, where $K > N$. $ZC_w(k)$ after $(K-N)$ point zero insertion is given by

$$ZC_w(k) = \begin{cases} ZC_v(k) & : k = 0\sim\frac{N}{2}-1 \\ 0 & : k = \frac{N}{2}\sim K-\frac{N}{2}-1. \\ ZC_v(k-(K-N)) & : k = K-\frac{N}{2}\sim K-1 \end{cases} \quad (3)$$

K point IFFT is performed for $ZC_w(k)$ to generate DFTs-OFDM radar signal modulated by ZC sequence, $S(k)$ $(k = 0\sim K-1)$, which is given by

$$S(k) = \sum_{k=0}^{K-1} ZC_w(k) \cdot \exp\left(j\frac{2\pi km}{K}\right). \quad (4)$$

Note that the sampling frequency for $S(k)$ is K/NT_C. Time domain sampled signal, $S(k)$ passes through LPF and DFTs-OFDM signal modulated by ZC sequence, $s(t)$ with length $T_s = NT_C$ is obtained. Note that $s(t) = 0$ when $t < 0$ or $t > T_s$. As ZC sequence, $ZC_u(n)$ is a cyclic sequence, $s(t)$ is also cyclic with period of T_s, i.e., $s(t) = s(t - T_S)$.



(1) DFTs-OFDM radar.

(2) OFDM/DFTs-OFDM for communications.

Fig. 3. Comparison of DFTs-OFDM radar signal and OFDM/DFTs-OFDM signal for communication.

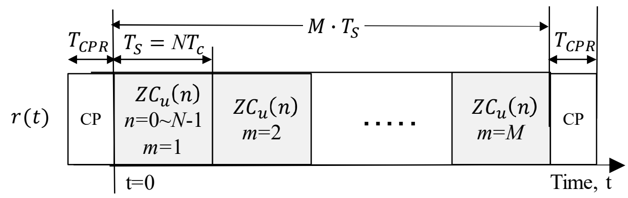


Fig. 4. DFTs-OFDM radar signal format.

Figure 4 shows DFTs-OFDM radar signal, $r(t)$ which consists of M sets of $s(t)$ to perform correlation detection, and cyclic prefix and cyclic postfix. $r(t)$ is given by

$$r(t) = s(t+T_S) + \sum_{m=0}^{M-1} s(t - mT_S) + s(t - MT_S), \quad (5)$$

where $-T_{CPR} < t < MT_S + T_{CPR}$ and $t = 0$ at the top of first ZC sequence with m=1. First term is the cyclic prefix, and the third term is the cyclic postfix. Cyclic prefix and cyclic postfix are added to maintain the cyclic property of $s(t)$ after filtering at the receiving side. M must be equal to or larger than 2 to perform correlation detection of the received signal, $r(t-\tau)$ with time delay, τ which is reflected from the target.

IV. Correlation Detection of DFTs-OFDM Radar Signal Using ZC Sequence

A. Correlation detection of DFTs-OFDM radar signals

Figure 5 shows the relationship between the transmitted DFTs-OFDM radar signal, $r(t)$ and the received signal reflected from the target, $r(t-\tau)$ with delay time, τ where $0 \leq \tau < T_S$. As shown here, we suppose $t = 0$ at the head of second ZC sequence of transmitted DFTs-OFDM signal for timing reference. The received signal $r(t-\tau)$ for $t = 0\sim T_S$ is sampled every T_C, which is given by $r(nT_c - \tau)$ $(n = 0\sim N-1)$. Then cross correlation of sampled signal, $r(nT_c - \tau)$ and k symbol shifted ZC sequence, $ZC_u(n-k)$ is calculated by the following equation:

$$X(k) = \frac{1}{N}\sum_{n=0}^{N-1} r(nT_c - \tau) {ZC_u}^*(n-k), \quad (6)$$

where $ZC_u(n) = ZC_u(n+N)$ and ${ZC_u}^*(\cdot)$ is a complex conjugate of $ZC_u(\cdot)$. Correlation $X(k)$ is calculated for $k =$

$0 \sim N-1$ and peak search of $|X(k)|$ is performed for target detection. Equation (6) indicates $|X(k)|$ shall has a peak when $\tau \cong kT_c$. For m-th block of sampled signal is given by $r(nT_c - \tau + mT_S)$ $(m = 0 \sim M-2)$. If the target is stationary, calculated cross correlation, $X(k)$ is the same for any m. Thus, we evaluate $X(k)$ for preliminary evaluation of correlation detection performance of the proposed DFTs-OFDM radar using ZC sequence. If the target moves, Doppler shift shall affect the correlation detection performance, and this remains for future study.

As ZC sequence is a cyclic sequence with cyclic period of $T_s = NT_C$, τ must be less than T_s to avoid the ambiguity of correlation detection. Thus, maximum detection range is less than $cT_s/2$ where c is the light speed. This means maximum detection range is given by the ZC sequence length, N. Regarding range resolution, it is given by $cT_c/2$ where bandwidth of radar signal, B_R is given by $1/T_c$ and subcarrier spacing of DFTs-OFDM is $1/NT_c$. This indicates flexible radar parameter setting is possible by N and T_c in the proposed DFTs-OFDM radar. M must be greater than or equal to two as shown in Fig. 5, and $(M-1)$ calculated correlation results are obtained. By integrating the calculated correlation results, SNR (Signal to Noise power Ratio) can be improved by 10 log(M) [dB], thus detection range can be extended by increasing M without increasing the radar signal output power.

B. Waveform of DFTs-OFDM radar signals using ZC sequence

We have conducted computer simulation for performance evaluation of DFTs-OFDM radar. Figure 6 shows DFTs-OFDM radar signal waveform using ZC sequence with N=128 where envelop, real part and imaginary part of DFTs-OFDM radar signals are shown. As shown here, its envelop significantly fluctuates around the center of ZC sequence, i.e. n=64. This is because DFTs-OFDM signal is almost equivalent to the PSK signals filtered by roll-off filter with roll-off factor, α=0 thus inter-symbol interference (ISI) causes this envelop fluctuation though ZC sequence is a CAZAC sequence. Thus auto-correlation property of DFTs-OFDM radar signal using ZC sequence is not ideal anymore.

C. Correlation detection performance

Figure 7 shows correlation detection performance according to delay, τ, when N=128 and N=256. Correlation according to delay is calculated using equation (6) by setting k=0. As shown here, correlation is 1 when $\tau = 0$ and it becomes zero at $\tau = nT_c (n = 1 \sim N-1)$, however correlation between $(n-1)T_c < \tau < nT_c$ is not zero. This range sidelobe is equivalent to the noise signals for another target with larger τ and smaller received power. As shown here, the range sidelobe becomes 6dB smaller at $\tau = T_s/2$ by doubling ZC sequence length, N. However, as the received power from the target becomes smaller as the target distance becomes larger. Therefore, the maximum detection range of the proposed DFTs-OFDM radar using ZC sequence should be less than half of theoretical maximum detection range, i.e. $cT_s/4$, to avoid possible large range sidelobe from the closer target to the further target.

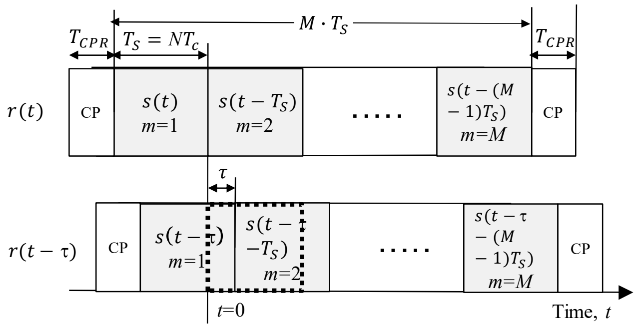


Fig. 5. Correlation detection of DFTs-OFDM radar signal.

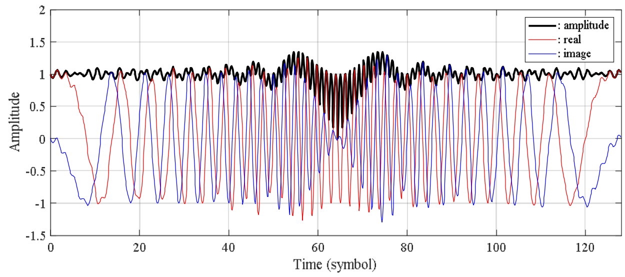


Fig. 6. Waveform of DFTs-OFDM radar signal.

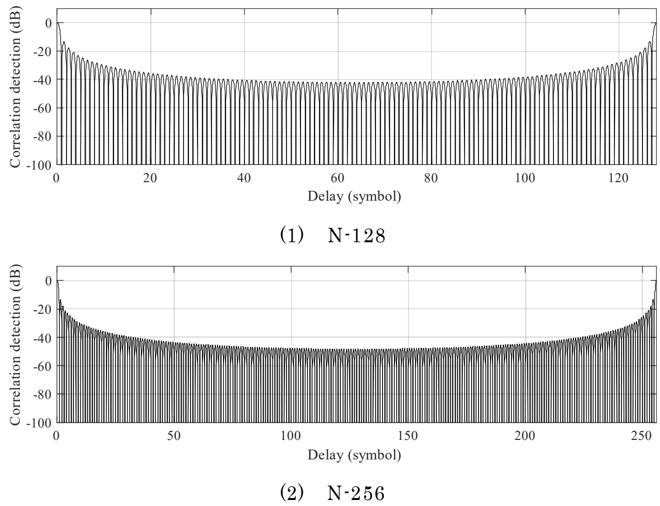


Fig. 7. Correlation detection performance according to delay when N=128 and N=256.

As described before, DFTs-OFDM radar signal is equivalent to PSK signal filtered by raised cosine roll-off filter with roll-off factor, α=0. As correlation detection performance, $X(\tau)$ according to delay is equivalent to the impulse response of the filter, thus it is given by SINC function as given by

$$X(\tau) = \frac{\sin\left(\pi(\tau/T_c)\right)}{\pi(\tau/T_c)}. \quad (7)$$

Equation (7) proves that the range sidelobe decreases by 6dB by doubling N, and it is zero at $\tau = nT_c$. Figure 8 compares theoretical correlation detection performance according to delay, $20\log(|X(\tau)|)\,[dB]$ with simulation results. The theory meets the simulation results well.

Another observation regarding correlation detection performance from equation (7) and Fig. 8 is that calculated correlation becomes less than 1 when target delay, $\tau \neq nT_c$.

As range resolution is $T_c/2$, detected correlation with $\tau = T_c/2$ decreases by 3.9dB than that with $\tau = 0$. Figure 9 shows correlation detection results according to k when N=128 and two target exists. As shown in Fig. 10 (1) when there are two targets with $\tau = 2T_c$ and $\tau = 16T_c$, no range sidelobe occurs and no decrease of detected correlation occur. However, as shown in Fig. 10 (2) when there are two targets with $\tau = 5T_c/2$ and $\tau = 33T_c/2$, detected correlation decreases by 3.9dB and large level range sidelobe occurs.

V. Conclusions

This paper proposes DFTs-OFDM radar using ZC sequence for radar-communication integration. The advantage of the proposed radar is commonality of conventional OFDM/DFTs-OFDM communications thus signal processing functions for communications such as FFT and IFFT can be re-used for radar functions. Another advantage is flexibility on radio resource assignment and design of radar measurement performance, i.e., maximum detection range and range resolution. This flexibility is originated from the fact that any ZC sequence length, N can be used and flexible bandwidth and timeslot assignment of DFTs-OFDM radar signal. Thus, the proposed radar-communication integration can accommodate various radar applications by setting ZC length and its symbol period, while spectrum efficiency is maintained.

This paper also shows preliminary correlation detection performance of DFTs-OFDM radar by computer simulations. Even though ZC sequence is a CAZAC sequence with ideal auto correlation, this paper reveals that detected correlation decreases and range sidelobe increases when $\tau \neq nT_c$ and maximum detection range should be less $cT_s/4$ to avoid the large range sidelobe from closer targets to further targets.

As the research on the proposed DFTs-OFDM radar is just on the preliminary stage, there are so many issues such as velocity detection performance and improvement of correlation detection performance remained for future study.

Acknowledgment

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References

[1] Recommendation ITU-R M.2160-0 M Series: Mobile, radiodetermination, amateur and related satellite services "Framework and overall objectives of the future development of IMT for 2030 and beyond, " (11/2023).

[2] J. A. Zhang et al., "An Overview of Signal Processing Techniques for Joint Communication and Radar Sensing," in IEEE Journal of Selected Topics in Signal Processing, vol. 15, no. 6, pp. 1295-1315, Nov. 2021, doi: 10.1109/JSTSP.2021.3113120.

[3] J. A. Zhang et al., "Enabling Joint Communication and Radar Sensing in Mobile Networks—A Survey," in IEEE Communications Surveys & Tutorials, vol. 24, no. 1, pp. 306-345, Firstquarter 2022, doi: 10.1109/COMST.2021.3122519.

[4] K. V. Mishra, M. R. Bhavani Shankar, V. Koivunen, B. Ottersten and S. A. Vorobyov, "Toward Millimeter-Wave Joint Radar Communications: A Signal Processing Perspective," in IEEE Signal Processing Magazine, vol. 36, no. 5, pp. 100-114, Sept. 2019, doi: 10.1109/MSP.2019.2913173.

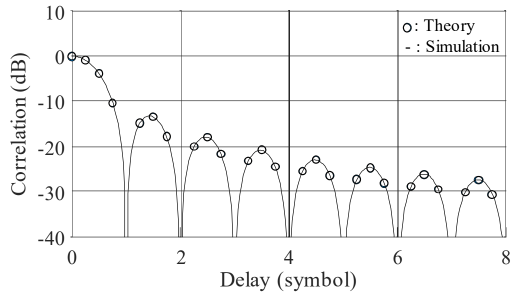
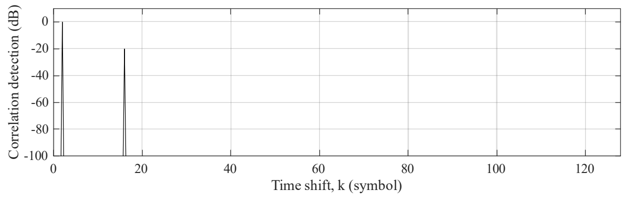
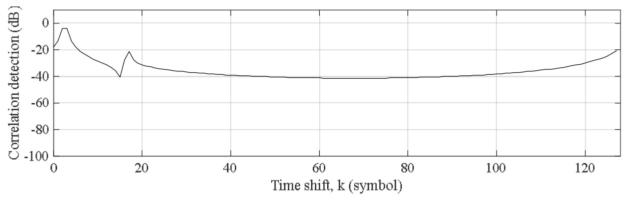


Fig. 8. Theoretical correlation detection performance according to delay with simulation results.



(1) Two targets with $\tau = 2T_c$ and $\tau = 16T_c$



(2) Two targets with $\tau = 5T_c/2$ and $\tau = 33T_c/2$.

Fig. 9. Correlation detection results according to time shift, k, when N=128 and two target exists.

[5] F. Liu, C. Masouros, A. P. Petropulu, H. Griffiths and L. Hanzo, "Joint Radar and Communication Design: Applications, State-of-the-Art, and the Road Ahead," in IEEE Transactions on Communications, vol. 68, no. 6, pp. 3834-3862, June 2020, doi: 10.1109/TCOMM.2020.2973976.

[6] C. Chen, H. Song, Q. Li, F. Meneghello, F. Restuccia and C. Cordeiro, "Wi-Fi Sensing Based on IEEE 802.11bf," in IEEE Communications Magazine, vol. 61, no. 1, pp. 121-127, January 2023, doi: 10.1109/MCOM.007.2200347.

[7] C. Waldschmidt, J. Hasch and W. Menzel, "Automotive Radar — From First Efforts to Future Systems," IEEE Journal of Microwaves, vol. 1, no. 1, pp. 135-148, winter 2021.

[8] S. Zeadally, M. A. Javed and E. B. Hamida, "Vehicular Communications for ITS: Standardization and Challenges," in IEEE Communications Standards Magazine, vol. 4, no. 1, pp. 11-17, March 2020, doi: 10.1109/MCOMSTD.001.1900044.

[9] M. H. C. Garcia et al., "A Tutorial on 5G NR V2X Communications," in IEEE Communications Surveys & Tutorials, vol. 23, no. 3, pp. 1972-2026, thirdquarter 2021, doi: 10.1109/COMST.2021.3057017.

[10] M. Umehira, K. Fujii and Y. Okumura, "Radar-Communication Integration System based on PMCW Radar using Zadoff-Chu Sequence," 2023 28th Asia Pacific Conference on Communications (APCC), Sydney, Australia, 2023, pp. 202-206, doi: 10.1109/APCC60132.2023.10460647.

[11] D. Chu, "Polyphase codes with good periodic correlation properties," IEEE Trans. Inf. Theory, vol. 18, no. 4, pp. 531–532, Jul. 1972.

[12] Johannes Fink, Friedrich K. Jondral, "Comparison of OFDM radar and chirp sequence radar," 2015 16th International Radar Symposium (IRS), 24-26 June 2015, Dresden, Germany.

[13] G. Piccinni, G. Avitabile and G. Coviello, "Narrowband distance evaluation technique for indoor positioning systems based on Zadoff-Chu sequences," 2017 IEEE 13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), 2017, pp. 1-5, doi: 10.1109/WiMOB.2017.8115766.