ISAC-Motivated Interference Elimination in Wireless Communication Networks: A Pulse Compression Approach

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***Abstract*—Motivated by the robustness of frequency modulation continuous wave (FMCW) radar to interference and the potential application in integrated sensing and communications (ISAC), a novel scheme of interference elimination in wireless communication networks is proposed. In the proposed scheme, pulse compression, supported by the modulation over a wideband waveform instead of the traditional sinusoidal carrier, is employed to compress the continuous-wave signal into peaky pulses. Then, with a large probability, an interference with a time offset significantly different from the travel time of legitimate communication signal can be eliminated. The isolation and elimination of interference can also be interpreted as the decomposition of multiple amplitude modulation (AM) signals over the frequency domain. Both the single- and multiple-carrier cases are taken into account. An interference diversity approach, employing co-prime symbol periods, is proposed to minimize the impact of hard collision that cannot be eliminated. Numerical simulations are carried out to demonstrate the validity of proposed schemes.**

I. Introduction

Interference management is one of the major tasks in wireless communication networks. A strong interference at a receiver may substantially impair the legitimate signal. Various methodologies have been proposed for interference management: in 4G and 5G cellular systems using orthogonal frequency division multiplexing (OFDM) [1], interference is made marginal by orthogonal scheduling for the intra-cell case, while the inter-cell interference is averaged via frequency hopping to avoid long-term strong collision. These require a centralized scheduler. In ad hoc networks without a center, distributed scheduling is needed for minimizing the damage caused by interference. Besides these interference management approaches in the MAC layer, interference can be addressed in the physical layer, which is known as the Multiuser Detection [2] and resurrected in recent years, in the name of non-orthogonal multiple access (NOMA) [3]. In the physical layer, interference can be reduced either using vector signaling (e.g., the spreading code in code-division multiple access (CDMA)), which requires multiple codes, or interference cancellation, which needs the capability of decoding the signals of other users.

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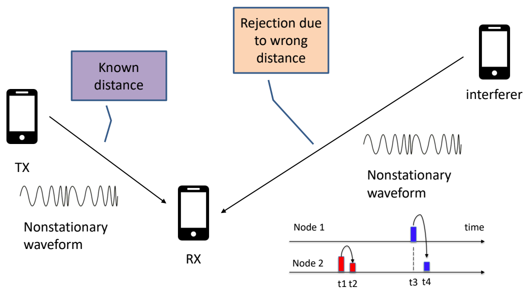

Fig. 1: Interference elimination based on distance

In this paper, we propose a novel approach for eliminating interference, based on the capability of sensing in communication networks. It neither relies on the separation using different codes (therefore, the signals of all users may lie in the same 1-dimensional subspace), nor uses successive interference cancellation (therefore, it does not need the information of modulation/coding schemes of other users). It is motivated by our research on integrated sensing and communications (ISAC), in which we carried out experiments on the robustness to interference in radar sensing [4]. Our discovery is that most of the interference between two TI mmWave frequency modulation continuous wave (FMCW) radar sets, antennas pointing to each other, is automatically eliminated by the radar receivers, to our surprise. The detailed reason for the robustness to interference in FMCW radar will be clarified later in this paper. A simple explanation is that, with a large probability, an interference of FMCW signal results in abnormal estimation of the distance, thus being eliminated due to the stretch processing structure of radio frequency (RF) circuits in FMCW radars [5].

A similar mechanism to the interference elimination in ISAC or radar systems can be transplanted to wireless communication networks. We assume that each node in the communication network is capable of sensing neighboring nodes; e.g., estimating the distance. This is readily to be achieved by ISAC, in which the same waveform is used

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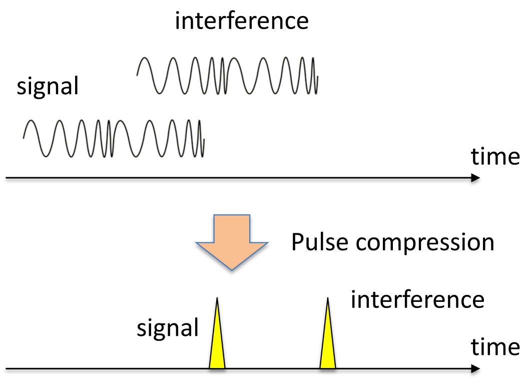

Fig. 2: Illustration of pulse compression and interference isolation

for both communications (in the forward propagation) and sensing (in the backward propagation upon reflections). As illustrated in Fig, 1, the receiver knows the distance to the transmitter based on radar sensing in ISAC. When an interference arrives, with the same waveform, the bi-static distance estimation corresponding to the time offset is significantly different from the known distance, with a large probability, thus being illegitimate and then eliminated.

Despite the simple idea, the major challenge is how to automatically eliminate the interference in the signal processing even when the legitimate signal is overlapped with the interference in the time domain. As illustrated in Fig. 2, it is highly possible that the legitimate communication signal is overlapped with an interference, since the duty cycle of communication systems is usually much higher than pulse radar systems. To isolate the overlapping signals, we propose to use the technique of pulse compression [6], which was originally proposed in the area of radar sensing and can compress continuous-wave signals into narrow pulses. Essentially, in both communications and radar, pulse compression can help to retrieve timing information, as narrow pulses do. This approach can also be interpreted in the frequency domain using harmonics isolation, as will be detailed in this paper.

Note that sensing is essential for the proposed interference elimination scheme, not only for obtaining the distance information. Moreover, non-stationary waveforms (such as the frequency-modulated waveforms in FMCW radar) are needed for the pulse compression and the retrieval of timing information. The proposed scheme cannot be realized in traditional communication networks, in which the waveform is traditional sinusoidal functions that retain little timing information. Instead, the proposed interference elimination scheme requires substantial bandwidth for the pulse compression and ranging. However, a good news is that the large bandwidth has been allocated for sensing in ISAC, thus being a free lunch for the proposed scheme of interference elimination. Therefore, the proposed interference elimination scheme also provides a substantial motivation for the development of ISAC.

The remainder of this paper is organized as follows. The existing studies related to this paper are briefed in Section II. The mechanism of interference rejection in FMCW radar is explained in Section III, which provides a motivation to our proposed algorithms. The system model is introduced in Section IV. Then, the proposed scheme of interference elimination in communication signals, based on sensing waveforms, is detailed in Section V. An interference diversity approach is proposed in Section VI, to handle interference that cannot be eliminated. Finally, numerical results and conclusions are provided in Sections VII and VIII, respectively.

II. Related Works

There have been many studies on managing interference in communication networks. In OFDM signaling of 4G and 5G systems, a scheduler endeavors to allocate non-overlapping time-frequency resource blocks to different users [1] for orthogonal transmissions, while different scheduling algorithms can be applied [7]. In CDMA signaling in 3G systems, the interference is mitigated in a ‘softer’ manner by using spreading codes and multiuser detection [2]. When the codebooks of different users are public, it is also possible to allow ’hard collisions’ among the users by letting them transmit in the same 1-dimensional space and then carrying out successive interference cancellation [8]. There are much less researches on the interference in radar sensing networks, while it is attracting more studies in recent years [9]–[12] due the wide employment of radar sets on vehicles. In ISAC, there have been studies using non-orthogonal multiple access (NOMA) to address interference mitigation in [13], [14]. Most of these studies assume synchronous transmissions at different users and do not consider physical processes such as signal propagation time or Doppler shift due to mobility, while our paper is based on the asynchrony and different signal propagation times. The impact of interference on the ISAC network performance metrics has been evaluated in [15].

III. Motivation from FMCW Radar

In this section, we introduce the mechanism of FMCW radar and explain the motivation for interference elimination in communication networks. The signal transmitted by an FMCW radar is a chirp, which is given by $s(t) = A\cos(\theta(t) + \theta_0)$, where θ is the phase and equals the integration of instantaneous frequency $f(t)$, and θ_0 is the initial phase. In FMCW radar, the frequency is linearly frequency-modulated, namely $f(t) = St + f_0$, where t is the time starting at the beginning of each pulse, S is the chirp rate and f_0 is the initial frequency. The received reflection is then given by $y(t) = gs(t-\tau)$, where g is the path loss and τ is the roundtrip time.

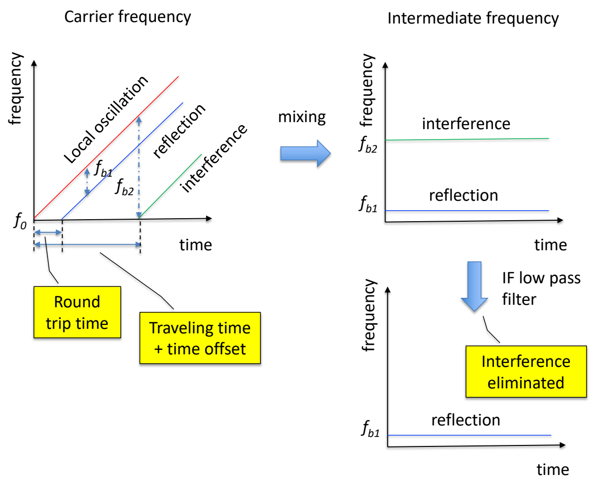

Fig. 3: Mechanism of FMCW Interference Elimination

For the purpose of radar ranging, the received reflected signal $y(t)$ is mixed with a local oscillator, as illustrated in Fig. 3, whose output is proportional to

$$o(t) \propto \underbrace{\cos\left(2\pi S\tau t - \pi S\tau^2 + 2\pi f_0\tau\right)}_{\text{beat signal: freq. = input freq. - local freq.}} + \underbrace{\cos\left(\pi S(t-\tau)^2 + 2\pi f_0(t-\tau) + \pi St^2 + 2\pi f_0 t + 2\theta_0\right)}_{\text{high frequency, removed by IF filter}}. \quad (1)$$

The second term in (1), which is of high frequency, is filtered out by an intermediate frequency (IF) filter. The first term has the beat frequency $S\tau$. By estimating the beat frequency $S\tau$ (e.g., by finding the peak in the Discrete Fourier Transform (DFT) of the IF filter output), the radar receiver obtains an estimation of τ and thus the range.

When an FMCW receiver is interfered by another FMCW pulse of the same chirp rate S, the output of the IF filter, subsequent to the mixer, is given by

$$o'(t) = A_1 \underbrace{\cos\left(2\pi S\tau t + \theta\right)}_{\text{legitimate signal}} + A_2 \underbrace{\cos\left(2\pi S\tau' t + \theta'\right)}_{\text{interference}}, \quad (2)$$

where A_1 and A_2 are the amplitudes, θ and θ' are the corresponding phases, and τ' is the time offset between the starting time of legitimate signal and the arrival time of the interference. In typical situations, τ is very small due to the light speed of signal, while τ' is significantly larger due to the asynchronous transmissions of transmitters. Hence, a low-pass filter in the IF can effectively remove the second term (interference) in (2), due to the large value of frequency $S\tau'$.

In summary, FMCW radar can eliminate most interference due to the following reasons, which can be learned from in the context of communications:

- FMCW radar can isolate signals and interference with significantly different time offsets.
- The capability of signal isolation is due to the large bandwidth for the waveform that can compress the continuous-time signal into peaks in the time domain.

In the subsequent sections, we will leverage the above principles for the application in communication signals.

IV. System Model

In this section, we introduce the system model of communication signals, for both the single-carrier and multiple-carrier cases.

A. Single Carrier

We assume the following transmitted signal for communications:

$$s(t) = \sum_{n=-\infty}^{\infty} I_n x(t - nT_p) e^{-j2\pi f_c t}, \quad (3)$$

where T_p is the symbol period, I_n is the information symbol, f_c is the carrier frequency, x is the deterministic baseband waveform, and $x(t-nT_s)e^{-j2\pi f_c t}$ can be considered as the carrier for I_n. For simplicity, we assume that x is real-valued. We further assume that the support of waveform x is $[0, T_s]$, where $T_s < T_p$. Moreover, we assume that $T_p - T_s$ is greater than the maximum travel time of signal to the receiver. In traditional communication systems, $x = 1$ and the carrier is a sinusoidal function, which is of theoretically zero bandwidth, or x is a narrow-band waveform (e.g., raised cosine function) for pulse shaping, in contrast to the wide-band waveforms in this paper. In this paper, we consider non-constant function for x, which consumes substantial bandwidth and thus endows the capability of pulse compression. Upon a significant reflector, the received reflected signal is then given by $gs(t-\tau)$, where τ is the signal travel time from the transmitter to the receiver and g is the channel amplitude gain. The total available bandwidth is denoted by W.

B. Multiple Carriers

We can extend the single carrier case to multiple carriers:

$$s(t) = \sum_{n=-\infty}^{\infty} \sum_{m=1}^{M} I_{mn} x(t - nT_s) e^{-j2\pi(f_c + (m-1)\delta f)t}, \quad (4)$$

where M is the number of subcarriers while δf is the frequency spacing, and the total bandwidth $W = M\delta f$.

V. Interference Elimination

In this section, we propose a scheme of interference elimination, motivated by that of FMCW radar and ISAC, in wireless communication networks.

A. Single Carrier

We first consider the case of single carrier. The multiple-arrier case is a natural extension.

1) Time Domain Isolation: We fix one ISAC transceiver and focus on a single communication symbol period starting from time 0. The impact of the next communication symbol is omitted due to the guard time $T_p - T_s$. A mixer with local oscillation of frequency f_c is used to down convert the frequency to the baseband. We assume that matched filter is used for the signal reception, whose impulse response is given by

$$h(t) = x(T_s - t). \tag{5}$$

Then, the output of the matched filter, given the arrival of the signal $s(t-\tau)$, is given by

$$\begin{aligned} y(t) &= g\int_0^t s(u-\tau)h(t-u)du \\ &= I_0 g\int_0^t x(u-\tau)x(T_s-t+u)du \\ &= I_0 g\int_0^{t-\tau} x(\nu)x(v+(T_s+\tau-t))dv \\ &= I_0 g r_x(t-(T_s+\tau)), \end{aligned} \tag{6}$$

where r_x is the autocorrelation function of function x. When the waveform x has a large bandwidth and is well designed (with small sidelobes), we have

$$|y(T_s+\tau)| = |I_0 g|r_x(0) \gg |I_0|r_x(t-(T_s+\tau)) = |y(t)|, \tag{7}$$

when $t \neq T_s + \tau$. Therefore, a peak is reached at the matched filter output at time $t = T_s + \tau$. This procedure is essentially the pulse compression in radar receivers [6], since the continuous-wave signal is compressed into a peaky mainlobe with substantially lower sidelobes.

When an interference is sent at time t_I and spends travel time τ_I to reach the victim communication receiver, the corresponding output of the matched filter is given by

$$y_I(t) = g_I I_I r_x(t-(T_s+t_I+\tau_I)) \tag{8}$$

where g_I is the channel gain of the interference, and I_I is the communication symbol in the interference. It reaches the peak at time $T_s + \tau_I + \tau_I$.

Then, we endeavor to eliminate the interference using the pulse compression in the following two cases:

- Unknown transmitter position: When the transmitter position is unknown and thus the travel time τ is also unknown in advance, we set a maximum travel time $\tau_{\max}$ (thus the maximal communication distance) and consider only the matched filter output in $[T_s, T_s+\tau_{\max}]$. In this case, only the interference satisfying the following condition is not eliminated:

$$0 < t_I + \tau_I < \tau_{\max}. \tag{9}$$

- Known transmitter position: When the position of the transmitter is known (e.g., in ISAC networks), the travel time τ is also known. Therefore, the reception time window at the receiver can be set to $[T_s+\tau-\delta\tau, T_s+\tau+\delta\tau]$, where $\delta\tau$ characterizes the uncertainty in the estimation of τ. In this case, only the interference satisfying the following condition is not eliminated:

$$\tau - \delta\tau < t_I + \tau_I < \tau + \delta\tau. \tag{10}$$

Actually, even if the position of the transmitter position is unknown, the value of τ may still be implicitly known, if the transmitter and receiver are well time synchronized.

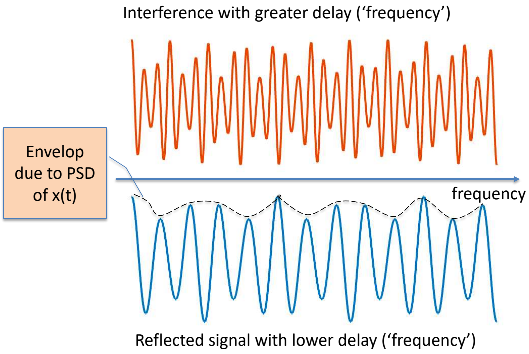

Fig. 4: Harmonics decomposition due to different time offsets

2) Frequency Domain Decomposition: We can also interpret the above interference elimination approach in the frequency domain. We notice that the frequency response of the matched filter is given by

$$\begin{aligned} H(j\omega) &= e^{-jT_s\omega}X(-\omega) \\ &= e^{-jT_s\omega}X^*(\omega), \end{aligned} \tag{11}$$

where the second equality is due to the assumption of real-valued waveforms.

Then, the frequency spectrum of matched filter output, given the reflected signal, is given by

$$Y(j\omega) = gIe^{-j(T_s+\tau)\omega}|X(j\omega)|^2, \tag{12}$$

which is a complex sinusoid $e^{-j(T_s+\tau)\omega}$ with 'frequency' $T_s - \tau$ in the frequency domain, modulated by the power spectral density (PSD) $|X(j\omega)|^2$ of the waveform. Similarly, the spectrum of the matched filter output, given the interference of starting time t_I and travel time t_I, is given by

$$Y_I(j\omega) = gIe^{-j(T_s+t_I+\tau_I)\omega}|X(j\omega)|^2. \tag{13}$$

Therefore, we can consider the spectra of the matched filter output corresponding to legitimate reflection and interference as two amplitude modulation (AM) signals in the frequency domain. To separate them, we require that

- The 'carrier frequencies' $T_s + \tau$ and $T_s + t_I + \tau_I$ be well separated, namely τ and $t_I + \tau_I$ are significantly different.

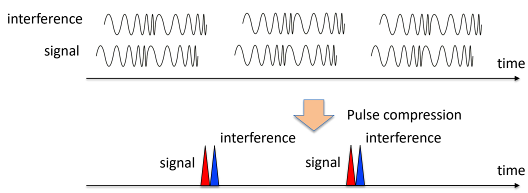

Fig. 5: Interference that cannot be eliminated

- The 'bandwidth' of the AM signals, which is determined by the variations of the PSD, needs to be sufficiently small; namely the PSD of waveform x needs to be sufficiently flat.

B. Multiple Carriers

For the case of multiple carriers, such as OFDM, we can use the above scheme of interference elimination over multiple carriers. In more details, we divide the subcarriers into L groups, where L divides M, such that each group has $N=\frac{M}{L}$ subcarriers and thus a bandwidth of $\frac{W}{L}$. Within one symbol period, the signal sent is given by

$$\begin{aligned} s(t) &= \sum_{l=1}^{L} I_l \sum_{n=1}^{N} x_{ln} e^{-j2\pi(f_0+((l-1)N+n)\delta f)t} \\ &= \sum_{m=1}^{M} I_{\lceil \frac{m}{L} \rceil} x_{\lceil \frac{m}{L} \rceil, mod(m,L)} e^{-j2\pi(f_0+(m-1)\delta f)t}, \quad (14) \end{aligned}$$

where I_l is the l-th communication symbol, and x_{ln} is the spreading code in the frequency domain. Note that we can design the spreading code in the time domain first (e.g, the Chu-Zadoff code) and then obtain x_{ln} using inverse DFT (IDFT). Obviously, we can use the standard OFDM modulation scheme for the transmitter. At the receiver, the standard demodulation scheme of OFDM can be employed to estimate $\{I_l x_{ln}\}_{n=1,\ldots,N}$ for each group l. Then, it is converted to the time domain for the application of matched filter, thus eliminating the interference using the same algorithm as the single-carrier case, for each group of subcarriers.

VI. Interference Diversity

In this section, we discuss the possible situation when the interference cannot be eliminated; namely (9) or (10) does not hold, which is of nonzero probability, as illustrated in Fig. 5. Since the timing of each transmitter does not change and the position (thus the signal travel time) of transmitter changes slowly, the hard collision cannot be eliminated for a long period of time, thus causing the outage of communications. To alleviate such a situation, we propose a simple solution, in which different transmitters use different values for the symbol repetition period T_p. A comparison is given in Fig. 6. In Fig. 6 (a) where both transmitters use the same value of T_p, the time offset keeps constant and thus the interference continues, while the pulses gradually depart from each other when they have different values of T_p, as illustrated in Fig. 6 (b). Suppose the interference elimination is governed by (10). Then after at most $\left\lceil \frac{2\delta\tau}{\Delta T_p} \right\rceil$ pulses, the interference will be eliminated, where ΔT_p is the difference between the symbol periods of the transmitters. Note that such an asynchronous approach for avoiding long-term interference is also adopted in aviation navigation systems using distance measuring equipment (DME) [16].

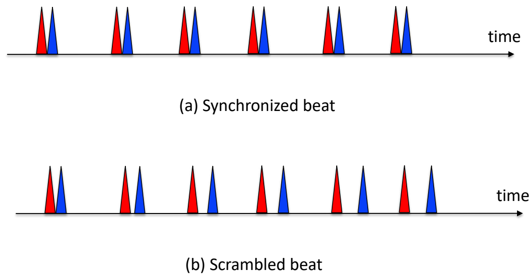

Fig. 6: Comparison between synchronous and scrambled beats

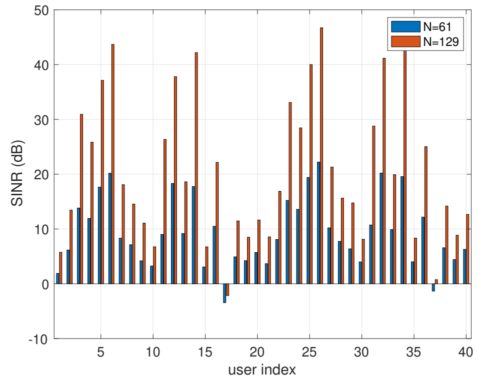

Fig. 7: Comparison of SINR when $N=61$ and $N=129$.

VII. Numerical Results

In this section, we carry out numerical simulations to demonstrate the validity of the proposed approach of interference elimination.

In the simulation for Fig. 7, we randomly drop 20 pairs of transmitter and receiver within a 200m by 200m square. The maximum communication distance is 50 meters. The bandwidth is set to 500MHz. Each transmitter randomly generates data packets, with a probability of 0.5 per time slot, whose period equals $\frac{N}{W}$, where N is the waveform length. The noise power is set such as the average SNR is 20dB. The average SINRs (in dB scale) of the 20 links are plotted in Fig. 7, for the cases of $N=129$ and $N=61$. The Golomb code is used for genearating the waveform. We observe that the larger spread gain N results in substantially

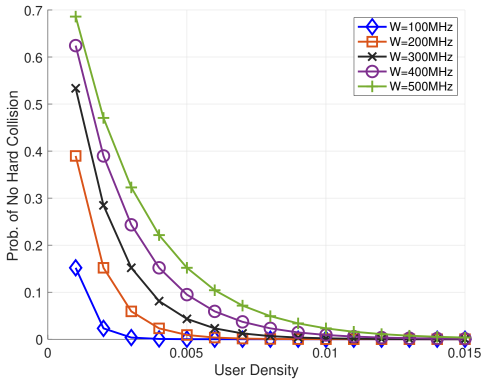

Fig. 8: Probability of no hard collision.

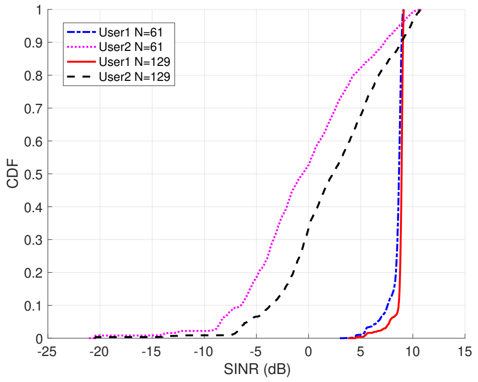

Fig. 9: CDF of SINR of individual users.

higher SINR, at the cost of larger bandwidth. However, in ISAC, the bandwidth for sensing is inherent and a free lunch for the proposed scheme.

In Fig. 8, we plotted the probability of no hard collision (almost identical arrival time). We assume that the distance between the transmitter and receiver is 50m. Other possible transmitters, as the source of interference, are distributed as a spatial Poisson process. We plotted the probability of no hard collision as a function of the transmitter density and the bandwidth. We observe that, when the user density is large (e.g., one per 200 square meters), the probability drops to small values even if the bandwidth is 500MHz. This necessitates the interference diversity proposed in (VI).

In Fig. 9, we plotted the cumulative distribution functions (CDFs) of SINR for two individual users, using the same simulation setup as in Fig. 7. Again, we observe the performance gain when N increases. We also observe that the SINR could be very low in rare occasions. This is due to the hard collision when the time offset of interferer happens to be the same as that of the legitimate signal. Therefore, it is necessary to address the situations of hard collisions.

VIII. Conclusions

In this paper, we have proposed an approach of interference elimination in wireless communication networks, motivated by the technologies of FMCW radar and ISAC system. Essentially, it is based on the precise information of signal arrival time, given an estimation of the transmitter position endowed by ISAC, such that interference with wrong timing can be automatically eliminated, similarly to FMCW radar. We have extended the signal-carrier case to the multiple-carrier case. Numerical simulations have been carried out to demonstrate the validity of the proposed scheme.

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