FULL-DUPLEX MULTIFUNCTION TRANSCEIVER WITH JOINT CONSTANT ENVELOPE TRANSMISSION AND WIDEBAND RECEPTION

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ABSTRACT

This paper introduces and justifies a novel system concept that consists of full-duplex transceivers and uses a multifunction signal for simultaneous two-way communication, jamming and sensing tasks. The proposed device structure and waveform enable simple-yet-effective interference suppression at the cost of being limited to constant-envelope transmission—this is a weakness only for the communication functionality that becomes limited to frequency-shift keying (FSK) while frequency-modulated continuous wave (FMCW) waveforms are effective for jamming and sensing purposes. We show how the transmission and reception as well as different interference and distortion compensation procedures are implemented in such multifunction transceivers. The system could be also applied for simultaneous spectrum monitoring with the above functions. Finally, we showcase the expected performance of such a system through numerical results.

Index Terms— Full-duplex communication, jamming, radar, spectrum monitoring, RF convergence.

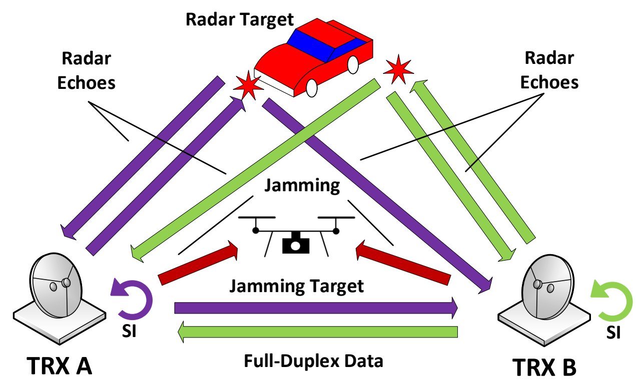

Fig. 1. A concept picture of the novel multifunction system that can be generalized to any number of transceivers (TRXs).

1. INTRODUCTION

In recent years, there has been a growing concern on improving security at the physical layer of wireless communications. Solutions such as radio shields for combating eavesdropping and jammers to impede undesired communications have become widespread. However, increased sophistication in attackers' devices demands for improved radio-frequency (RF) security technologies [1]. Cooperative jamming and randomized waveforms can be used to enhance security [2–4]. These systems' performance can be further enhanced by RF convergence, since waveforms used for jamming can be employed for communication, remote sensing (e.g., radar), and spectrum monitoring to support the security-oriented operations.

The simultaneous communication and radar functionality has been extensively studied in the literature [5–9]. One alternative to implement this combines frequency-shift keying (FSK) and frequency-modulated continuous wave (FMCW) either in different or coincident spectral resources, for isolated and also groups of radar devices [10–12]. A similar approach was presented in [13], where also external information is used to synchronize the signals at reception to enable demodulation. Full-duplex (FD) operation of a pair of FMCW radars has been proposed in [14], but the system lacks additional functionalities such as communications. Interference mitigation for multi-user joint radar and communications transmissions was presented in [15]. However, suppression of the strong self-interference (SI) component was not addressed.

As illustrated in Fig. 1, we propose a solution to perform simultaneous jamming, communication and sensing functions by relying on FD-enabled devices that employ FSK tones embedded on FMCW signals. The chosen waveforms allow simple and effective suppression of the self-interference and interference between different functions. Thanks to this, it is possible to demodulate wireless data transmissions and estimate radar target parameters from the received signals in monostatic (considered herein) and multistatic way. In principle, the receiver processing can be done using either digital filtering or through successive interference cancellation; the former approach is described in detail herein. Furthermore, the system could be also applied for simultaneous spectrum monitoring with jamming, communications and sensing.

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2. SYSTEM MODEL

We propose a full-duplex device whose transmitted signal is used for jammer/radar applications, while it also conveys useful information sent to an associated receiver. This information is encoded by using discrete frequency shifts that are superimposed on a FMCW jamming/sensing signal. The jamming operation also benefits from the frequency shifts due to their unpredictable nature from the target's perspective. At system level (cf. Fig. 1), this means that two transceivers (TRXs), A and B, communicate with each other at center frequency f_{c} while they transmit a joint jamming/sensing waveform and implement corresponding three receive functions.

The FSK waveforms could additionally be used for radar sensing, namely a continuously transmitted FMCW waveform can be used in Doppler processing while FSK coding would yield the range and velocity separation. However, the FSK modulation is herein used for data transmission only.

2.1. Multifunction Transmit Waveform

In jammers and radars, FMCW transmissions typically use triangular and sawtooth sweeps for the frequency variation over time. Our discussion herein is limited to the triangular sweep for brevity, but there are no limitations on applying the latter alternative to this system, or even any other sweep pattern. The frequency of a complex-valued baseband triangular FMCW signal sweeping over a bandwidth B_{R} is

$$f_{\mathrm{R},\star}(t) = \begin{cases} -\frac{B_{\mathrm{R}}}{2} + \frac{\rho\, t}{m}, & (m-1) < \frac{t-\delta_\star}{T_{\mathrm{R}}} \leq \frac{2m-1}{2}, \\ +\frac{B_{\mathrm{R}}}{2} - \frac{\rho\, t}{m}, & \frac{2m-1}{2} < \frac{t-\delta_\star}{T_{\mathrm{R}}} \leq m, \end{cases} \quad (1)$$

where $m \in \mathbb{N}^{+}$, and symbol '$\star$' stands either for transceiver A or B, and $\delta_\star$ is a fixed time delay. Last, $\rho = 2B_{\mathrm{R}}/T_{\mathrm{R}}$ is the sweep rate of the triangular chirp when sweep duration is T_{R}.

For simultaneous data transmission, the baseline FMCW jamming/sensing signal is further modulated with FSK. The baseband frequency of a FSK signal can be defined as

$$f_{\mathrm{D},\star}(t) = \tfrac{\Delta f}{2}\alpha(t),\ \alpha(t) \in \{\pm 1, \pm 3, \ldots, \pm(2M-1)\}, \quad (2)$$

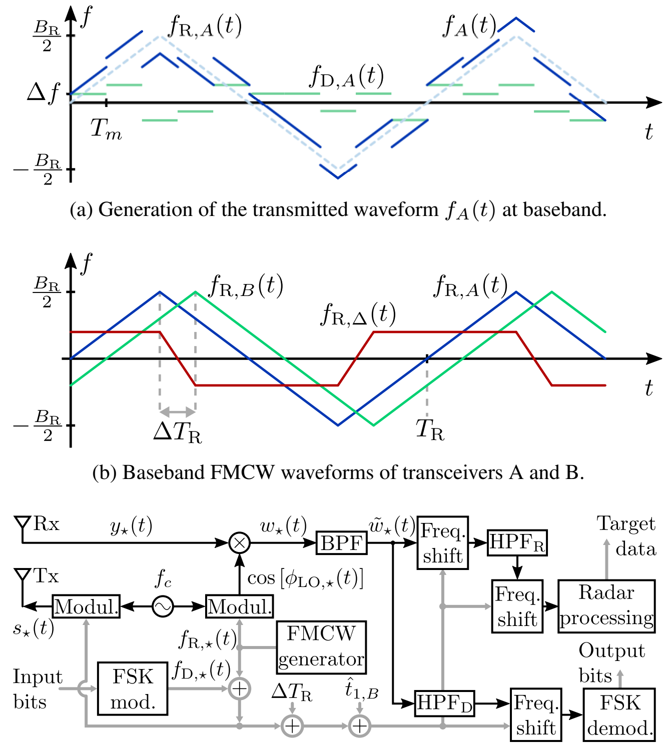
where Δf is the frequency difference of adjacent FSK tones and $\alpha(t)$ is a data stream carrying $\log_2 M$ bits per symbol.

The combined sweeping-FSK waveform with continuous phase can be modeled with $s_\star(t) = \cos\phi_\star(t)$, where

$$\phi_\star(t) = 2\pi \left[f_{\mathrm{c}} t + \int_0^t \left(f_{\mathrm{D},\star}(\tau) + f_{\mathrm{R},\star}(\tau)\right) \mathrm{d}\tau \right]. \quad (3)$$

The instantaneous transmit frequency for the transceiver is $f_\star(t) = \frac{1}{2\pi}\phi'_\star(t)$. Fig. 2(a) shows the waveform of a signal combining the triangular FMCW and FSK modulations.

The FMCW signals used in the modulation of TRXs A and B need to be properly synchronized to minimize the spectral overlap of the two signals and their multipath echoes after



(a) Generation of the transmitted waveform $f_A(t)$ at baseband.

(b) Baseband FMCW waveforms of transceivers A and B.

(c) Block diagram of a transceiver ('$\star$' refers either to A or B).

Fig. 2. Example signal waveforms and the proposed transceiver architecture. (a) The short-dashed signal is the FMCW base waveform $f_{\mathrm{R},A}(t)$, whereas $f_A(t)$ shows the information-carrying multifunction waveform after adding $f_{\mathrm{D},A}(t)$. (b) FMCW waveforms of transceiver A and B, and their difference signal $f_{\mathrm{R},\Delta}(t) = f_{\mathrm{R},A}(t) - f_{\mathrm{R},B}(t)$. (c) Transceiver structure and signal processing implemented for FSK demodulation and obtaining of radar information.

downconversion, so that $\Delta T_{\mathrm{R}} = \delta_B - \delta_A$ is sufficiently large. This can be achieved by introducing a starting frequency offset between the FMCW modulating signals used in the TRXs, as well as by assuming that the two signals have the same sweep frequency and bandwidth.

2.2. Multifunction Receive Waveform

Both transmitted signal phases from TRX A and that from TRX B are given by (3). However, they have differing data symbols and delays $\delta_\star$. We focus on receive-side processing of TRX A in what follows. The received waveform can be expressed as

$$\begin{aligned} y_A(t) &= h_{A,A}(t) * s_A(t) + h_{B,A} * s_B(t) + z(t) \quad (4) \\ &= \sum_{k=1}^{K_A} a_k s_A(t - t_{k,A}) + \sum_{k=1}^{K_B} b_k s_B(t - t_{k,B}) + z(t), \end{aligned}$$

where $h_{A,A}(t)$ is the multipath SI channel response, which also includes the wanted reflections from the targets, when

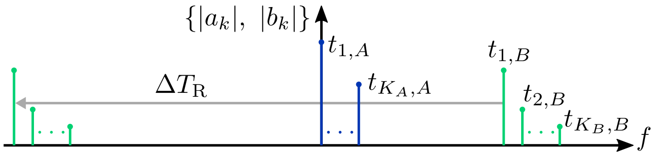


Fig. 3. (a) One-sided spectrum for L downconverted echoes of $s_B(t)$, and shift to negative frequencies during an interval ΔT_{R}. Beat frequencies for the K_A SI echoes are also shown.

$y_A(t)$ is used in radar processing; $t_{k,A}$ and $t_{k,B}$ are the delays, while a_k and b_k are the channel coefficients experienced by the echo k from TRX A and TRX B, respectively. The channel from TRX B to TRX A is likewise modeled with a multipath response, $h_{B,A}(t)$. The direct line-of-sight component of this signal can be compared to the echoes from the targets to get a second estimate of the targets' parameters. Finally, $z(t)$ represents additive white Gaussian noise.

The transmitter's FMCW frequency at RF, $f_{\mathrm{LO},A}(t) = \frac{1}{2\pi}\phi'_{\mathrm{LO},A}(t)$, is used in the downconversion, where

$$\phi_{\mathrm{LO},A}(t) = 2\pi\left[f_{\mathrm{c}}t + \int_0^t f_{\mathrm{R},A}(\tau)\,\mathrm{d}\tau\right]. \tag{5}$$

The downconverted signal is given by

$$\begin{aligned} w_A(t) &= \cos\left[\phi_{\mathrm{LO},A}(t)\right]\cdot y_A(t) \qquad (6)\\ &= \sum_{k=1}^{K_A}\frac{a_k}{2}\left\{\cos[\phi_{\mathrm{LO},A}(t) - \phi_A(t-t_{k,A})]\right.\\ &\qquad\left. + \cos[\phi_{\mathrm{LO},A}(t) + \phi_A(t-t_{k,A})]\right\}\\ &+ \sum_{k=1}^{K_B}\frac{b_k}{2}\left\{\cos[\phi_{\mathrm{LO},A}(t) - \phi_B(t-t_{k,B})]\right.\\ &\qquad\left. + \cos[\phi_{\mathrm{LO},A}(t) + \phi_B(t-t_{k,B})]\right\}\\ &+ \cos\left[\phi_{\mathrm{LO},A}(t)\right]\cdot z(t). \end{aligned}$$

The first term in the above expanded expression contains the downconverted SI and the echoes from the radar targets. Similarly, the downconverted remote signal is represented in the third term. Last, the second and fourth terms contain high-frequency components that need to be filtered out. The dynamics of the downconverted signal components require a wideband receiver capable of acquiring and processing them at any of their variable spectral locations.

3. MULTIFUNCTION RECEIVE PROCESSING

The proposed transceiver structure can be seen in Fig. 2(c). If $t_{k,A}$ for the direct SI component is small enough, it devolves into a sinusoidal signal hopping between low frequencies and can be effectively removed using a band-pass filter with a lower cutoff frequency equal to

$$f_{\mathrm{BPF_{SI}}} = \tfrac{\Delta f}{2}(2M-1) + \rho\, t_{1,A}, \tag{7}$$

where $t_{1,A}$ is the delay of the direct SI signal from TRX A.

The higher cutoff frequency for the above filter is chosen to suppress the unwanted high-frequency components in (6). After eliminating the SI, data and radar information can be retrieved from the downconverted wideband signal through adequate processing focused on the spectral portion that contains the desired information.

Since the echoes and the signal from TRX B are sweeping the frequency band with the same FMCW parameters, but with different delays $t_{k,B}$, they will be downconverted into FSK signals at a beat frequency defined by their delay. The effect can be seen in Fig. 3. The beat frequency switches rapidly from one side of the spectrum to the other when the direction of the sweep is different to the downconverting signal. At this point, the echoes and the TRX B signal would be regarded as interference to each other. Unless this interference is removed, performance is lost.

3.1. Communication Signal Processing

For data processing purposes, a second highpass filter is necessary to remove high-power echoes from the channel $h_{A,A}(t)$. This filter should have a stopband up to the frequency

$$f_{\mathrm{HPF_D}} = \tfrac{\Delta f}{2}(2M-1) + \rho\, t_{K,A}, \tag{8}$$

where $t_{K,A}$ is the longest echo delay in the channel. If the sweep phase of the FMCW signal sent by TRX B is properly synchronized so that its beat frequency after downconversion is away from the filters' stopbands, the filter will only cause short-duration attenuation to it during the rapid shift of the beat frequency.

The difference between the direct-path component $f_B(t-t_{1,B})$ in the third line of the expanded version of (6) and $f_{\mathrm{LO},A}(t)$ can be reformulated using the corresponding definitions of the instantaneous frequencies. This way we get

$$\begin{aligned} f_{B,A}(t) &= f_B(t-t_{1,B}) - f_{\mathrm{LO},A}(t) \qquad (9)\\ &= f_{\mathrm{D},B}(t-t_{1,B}) + f_{\mathrm{R},B}(t-t_{1,B}) - f_{\mathrm{R},A}(t). \end{aligned}$$

The downconverted FSK frequencies $f_{\mathrm{D},B}(t-t_{1,B})$ are affected by the FMCW sweep of transceivers B and A, and this needs to be compensated for before demodulation. If both transceivers operate with perfect knowledge about the difference in their FMCW waveforms ΔT_{R}, compensation is straightforward. This processing can be seen in Fig. 2(c) in the FSK demodulation branch. If we also assume to have a perfect estimate $\hat{t}_{1,B} = t_{1,B}$, the resulting frequency of the compensated signal is

$$\begin{aligned} \tilde{f}_B(t) &= f_{B,A}(t) + (f_{\mathrm{R,A}}(t) - f_{\mathrm{R,B}}(t-\hat{t}_{1,B}))\\ &= f_{\mathrm{D},B}(t-t_{1,B}) \qquad (10) \end{aligned}$$

Thus, after this, the FSK symbols can then be demodulated through standard digital receiver methods.

3.2. Radar Signal Processing

From the point of view of radar processing, the TRX B signal is now causing interference. In order to remove this interference, it can either be filtered after sweep compensation, or reconstructed and subtracted after data processing.

We filter the TRX B signal by first compensating for the sweeping effects of TRX A and B signals' FMCW modulation in order to have the pure FSK-modulated signal at baseband and applying a highpass filter with a stopband width

$$f_{\mathrm{HPF_R}} = \frac{\Delta f}{2}(2M-1) + \rho\, t_{K,B}, \qquad (11)$$

where $t_{K,B}$ is the longest echo delay in the channel. Then, a reverse sweeping effect compensation is done to return the signal back to the form it had after downconversion. This operation can be seen in Fig. 2(c), in the radar processing branch. After these operations, we have a clean radar signal without interference from TRX B and we can obtain the target distance and velocity information by detecting beat frequencies of echoes as with standard FMCW radar processing.

Similar operations can be performed by using the received signals from TRX B. The echoes from targets can be compared to the direct signal to gain radar information similarly as with the signals transmitted from TRX A. Furthermore, such multistatic operation can be utilized to improve sensing accuracy by fusing the target information from multiple estimates. Alternatively the locations of the targets can be estimated through triangulation in a situation where traditional radar angle of arrival estimation is not possible.

3.3. Spectrum Monitoring

If both of the TRX A and B signals are known, they can be removed either by filtering after sweep compensation or reconstruction and subtraction methods. After TRX A and B signal removal, and a compensation for the sweeping effect of the downconversion, we have a rather clean recording of the spectrum for, e.g., wideband monitoring. Additional performance gain compared to traditional wideband spectrum monitoring is gained through the sweeping operation, since a narrower reception band can be used to scan a large bandwidth.

4. SIMULATION RESULTS

To show the potential performance of an ideal system, we ran simulations with a system as depicted in Fig. 2(c). At reception, the received signal is downconverted with the transmitted signal at the carrier frequency. A highpass filter is used to remove the direct SI. In the simulation, the SI is presumed to be completely attenuated below the noise floor after the highpass filter. This signal is then treated separately for the data demodulation and radar processing.

The TRX A and B signals are FSK symbols sweeping through the ISM-band around $f_c = 2.44$ GHz. The FMCW parameters were equal for both transceivers ($B_{\mathrm{R}} = 80$ MHz and $T_{\mathrm{R}} \approx 33\ \mu$s, i.e., $\rho = 4.8$ MHz/μs), but TRX B signal's sweep frequency was set to start 20 MHz higher than that of TRX A; this corresponds to $\Delta T_{\mathrm{R}} \approx 4.2\ \mu$s. The radar target had a Doppler velocity of 100 m/s, and its radar cross section was chosen to be 200 m^2, which corresponds to a typical car. The target location was switched between 20, 60 and 100 m. The power of the TRX B was set so that certain SNR values were achieved. The symbols had 1 or 3 bits per symbol (BPS) with $\Delta f = 200$ kHz spacing and 0.1 ms symbol duration.

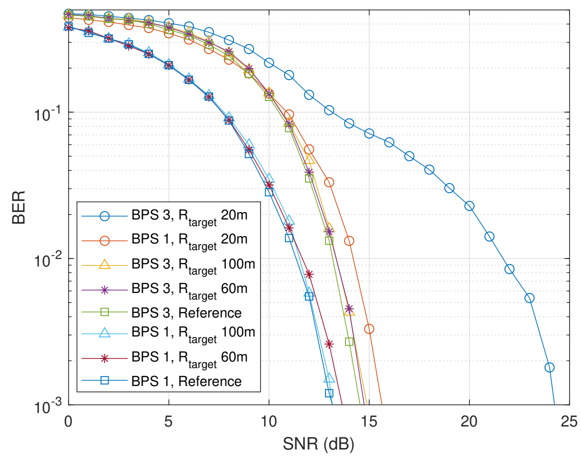


Fig. 4. Simulated FSK demodulation performance. The reference is half-duplex operation without FMCW sweeping.

Our simulation parameters were chosen to study effects of strong local transmitted signals (i.e., self-interference) due to jamming and radar operations on the BER of the communication system. Therefore, we found that our target detection system performs as good as an ideal radar system without any interference from FSK modulation or other sources, unless the signal from the remote FSK transmission reaches unrealistic SNR levels of several tens of decibels. The results of the simulation can be seen in Fig. 4. It illustrates that the system works as well as a reference system when the radar target is over a 60 m distance, but the BER performance of the proposed system worsens when the target gets closer.

5. CONCLUSIONS

This paper introduced a novel full-duplex multifunction transceiver system that performs simultaneously jamming, sensing and communications using constant-envelope transmission. The system could be also generalized to receive third-party signals for spectrum monitoring or communications. Especially, the special device structure and waveform enable simple yet effective self-interference suppression. We developed a method to estimate the desired information from the remote signal and compensation methods to obtain radar information from the echoes captured by the receive antenna and demonstrated their feasibility with simulations.

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