Vehicular RF Convergence: Simultaneous Radar, Communications, and PNT for Urban Air Mobility and Automotive Applications

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***Abstract*—Modern RF environments are becoming increasingly congested. This limits the opportunities and capabilities of modern RF systems, obstructing the development and proliferation of new technologies. Novel vehicular RF technologies promise a new era of transportation capabilities, but legacy design techniques cannot adapt to the current spectral congestion. We summarize recent RF Convergence results and discuss how they mitigate spectral congestion in modern vehicular applications. We propose a joint radar, communications, positioning, navigation, and timing (JRCPNT) system architecture as a suitable candidate for future automotive applications. We present relevant performance bounds and initial experimental results to demonstrate the potential performance enhancements of such multiple-function RF systems. We define multiple-channel, multiple-user receiver (MCMUR) techniques that enable this architecture and discuss how these components cooperate to enable these performance enhancements. We summarize initial experimental results to demonstrate the viability of such multiple-function architectures in the context of urban air mobility (UAM) and other automotive applications.**

***Index Terms*—RF Convergence, multiple-function RF systems, urban air mobility, automated vehicles, space-time adaptive processing, radar, communications, PNT**

I. Introduction

Modern vehicular applications such as collision avoidance, traffic management, and automatic navigation rely on a broad range of RF sensors and devices. Intelligent transport systems (ITS) enable these sensing and signaling capabilities by simultaneously operating multiple RF platforms. These systems promise incredible performance but also significantly congest the RF spectrum. Spectral congestion limits the opportunities and capabilities of all RF systems, and is the primary obstacle preventing the realization of modern vehicular RF applications.

RF convergence [1] demonstrates that cooperation between different RF systems reduces spectral congestion and increases individual performance [2], [3]. We applied these design principles to develop a multiple-function RF platform that simultaneously enables positioning, navigation, and timing (PNT) and communications for both ground and air vehicles [4]. We propose a joint radar, communications, positioning, navigation, and timing (JRCPNT) extension to this system architecture as a suitable platform for future urban air mobility (UAM) and automotive applications.

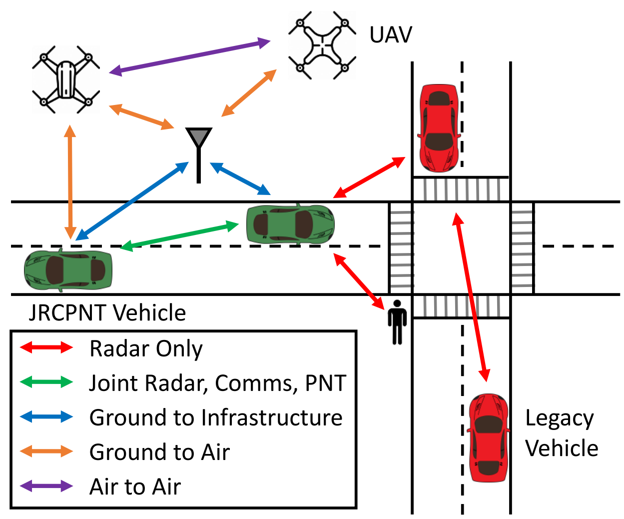

Fig. 1. Numerous vehicular applications benefit from simultaneous sensing and communications capabilities. PNT services offer extremely precise positioning and navigation capabilities, but radar systems are still critical for detecting and tracking uncooperative targets such as pedestrians or legacy vehicles. Integrated communications provides a feedback channel for the radar and PNT services, increasing performance and also improving security against cyberattack.

Modern automotive applications leverage multiple sensing modalities to execute sophisticated tasks. Our proposed JRCPNT architecture provides the multiple functionalities needed to enable safety-critical automotive applications such as collision avoidance, traffic management, and automatic navigation. By consolidating these functions into a single platform, we reduce the overall spectral demand. The multiple-channel, multiple-user receiver (MCMUR) leverages the intrinsic cooperation of these services to improve performance and reliability. We explore several multiple-function waveform techniques that are suitable for this design. This problem is

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generally discussed in the context of cars and other ground vehicles, but with the advent of low-cost UAVs and flying cars, these results may be readily extensible to UAM applications.

II. Theoretical Limits

Comprehensive performance limits are difficult to formulate for RF convergence systems because the performance metrics for each sub-system may be generally unrelated. We define a set of performance metrics for radar, communications, and PNT systems and discuss how to jointly compare these sub-systems in the context of RF convergence.

A. Performance Metrics

Radar, communications, and PNT systems may be characterized by numerous performance metrics, each of which capture different aspects of the system. We briefly discuss some of the most relevant metrics in the context of vehicular RF convergence.

1) Radar Performance Metrics: Traditional radar systems detect and measure the relative position and velocity of moving targets. Detection performance is usually characterized by the probability of detection P_d and the probability of false alarm P_f. Tracking performance may be coarsely characterized by range resolution S_R, angular resolution S_A, and velocity resolution S_V. An information theoretic metric called **estimation rate** was formulated in [5], which captures how much information is learned about a target by conducting a radar measurement. This non-traditional metric is useful when comparing radar systems to communications systems, which are usually characterized by the rate of information transfer rather than estimation of physical parameters.

2) Communications Performance Metrics: Standard communications systems transfer information. The rate of this transfer is characterized by the data rate R, and the rate of any errors in the received data is characterized by the bit error rate (BER). The capacity C of a communications link is the maximum rate at which the system can operate with negligible errors in the decoded message. This metric is commonly used to compare the theoretical performance of different types of communications systems.

3) PNT Performance Metrics: PNT refers to a broad class of RF systems that enable some or all of these three services. We focus on two-way ranging (TWR) systems, which execute range estimation and time synchronization between users. We characterize TWR performance using mean squared error (MSE) on time-of-flight (ToF) σ_τ and time offset σ_T. MIMO TWR platforms can extend these ranging capabilities to estimate relative position and orientation [4], which have corresponding MSE performance metrics depending on the geometric representation (Cartesian, polar, spherical, etc.). This transformation is referred to as geometric dilution of precision (GDoP).

B. Limits on Communications and Sensing

Joint radar-communications was one of the first research topics in the field of RF convergence. Theoretical and simulated performance bounds on joint radar-communications performance have been explored for different types of radar systems, including mono-static [2], [3], multi-static [6], and synthetic aperture radar (SAR) [7].

Several bounds were derived and compared in [2] for cooperative radar and communications systems. These bounds compare the radar estimation rate and communications data rate under different cooperation strategies, demonstrating that cooperative RF convergence techniques may improve performance for both users simultaneously. These bounds are recreated (with permission) in Figure 2.

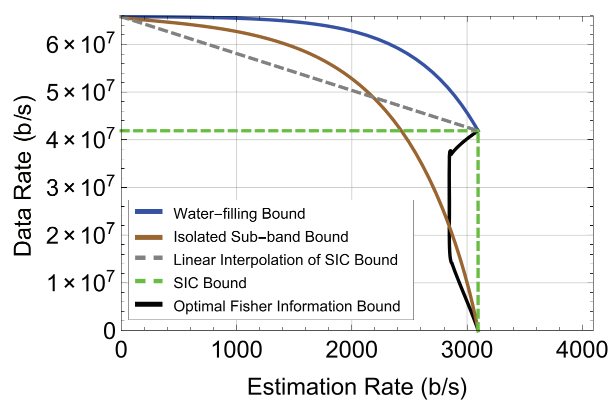

Fig. 2. Theoretical performance bounds for different radar-communications cooperation strategies, as derived in [2]. RF convergence techniques (successive interference cancellation, water-filling) simultaneously improve performance of both sub-systems.

C. Limits on Communications, Sensing, and PNT

Two-dimensional performance manifolds like the ones depicted in Figure 2 can inform system design decisions, but when the metric space grows to include more systems and more performance metrics, it becomes increasingly difficult to visualize. For JRCPNT systems, we are primarily concerned with data rate, estimation rate, and MSE on ToF and time offset (σ_τ, σ_T). The latter two are closely related [8], so we can sufficiently capture a JRCPNT system performance manifold using three dimensions. Defining this manifold is an open problem that we are currently pursuing in several parallel studies [9]. Figure 3 depicts a notional performance manifold and how it facilitates optimizing JRCPNT system parameters.

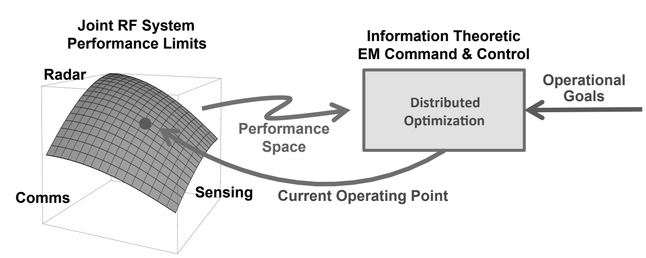

Fig. 3. Notional performance manifold for a joint radar, communications, and sensing system, and how this manifold influences system design and optimization decisions.

III. Multiple-Function Waveforms

Multi-function RF systems may be implemented by deploying multi-function waveforms that simultaneously enable multiple functionalities. Historically, waveform design has been severely limited by hardware capabilities, especially for high-power systems like radars. With the advent of programmable software-defined radios (SDRs) and efficient RF front ends, however, we can now afford significantly more flexibility in the design and implementation of RF waveforms. Unfortunately, many of the design decisions that improve performance for one sub-system limit performance for the others, so multi-function waveform design requires careful balance and optimization between the different tasks depending on the application.

A. Waveform Design

Numerous studies have considered integration of communications data in radar waveforms using a variety of techniques [10], [11]. Radar waveforms typically have desirable cross-correlation properties, making them suitable for TWR systems as well [4]. We have previously developed a family of polyphase-coded frequency modulated (PCFM) waveforms that have been validated on hardware and are suitable candidates for a JRCPNT system. This family includes tandem-hopped radar communications (THoRaCs) [12], phase-attached radar communications (PARC) [13], and far-field radiated emission design (FFRED) [14], which we briefly describe below.

1) THoRaCs: tandem-hopped radar communications (THoRaCs) uses spectral hopping to create spectral gaps in an FM noise radar emission, into which orthogonal frequency-division multiplexing (OFDM) communications may be embedded. With proper spectral shaping, this creates a composite radar-communications waveform with good spectral containment and low range sidelobes [12].

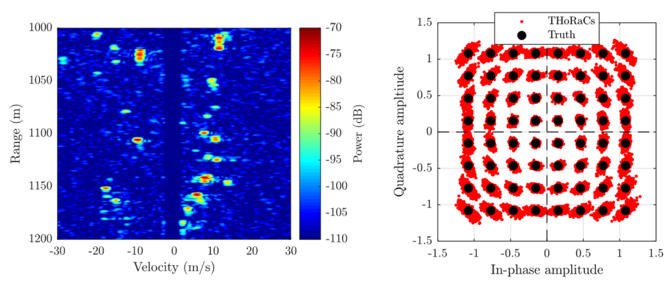

Fig. 4. Free-space experimental demonstration of THoRaCs dual-function radar/communication waveforms. (L) Range-Doppler response from moving vehicles traversing an intersection 1 km from the test setup. (R) Demodulated 64-QAM constellation at the intended receiver after synchronization and equalization [12].

2) PARC: The phase-attached radar communications (PARC) framework combines continuous phase modulation (CPM) and PCFM to embed communications data in the phase of a radar waveform, which enables wide-band imaging and communications (up to 8 MB/s has been demonstrated) [13].

3) FFRED: FFRED is a two-stage iterative optimization approach for designing multi-function waveforms in far-field conditions. This approach generates a set of FM waveforms that combine in the far-field to realize a radar waveform in one direction and a communications signal in another, without sub-arraying (experimentally demonstrated in [15]).

B. Active Hypothesis Testing

For dynamic applications, an "optimal" operating point on the manifold in Figure 3 may become suboptimal as the scenario evolves. An optimal waveform design strategy may then become suboptimal over an ensemble of different scenarios. We may instead consider a family of waveforms that achieve different operating points on the performance manifold, and use active hypothesis testing (AHT) to dynamically choose the most appropriate option at any given time. For each observation, AHT chooses an operating mode that yields maximally informative statistics. In this context, an observation is an RF emission event and an operating mode is a choice of waveform.

We developed tight, non-asymptotic bounds on the probability of error in a fixed horizon setting [16], [17], which suggest novel adaptive strategies that significantly reduce the amount of data required to make a reliable inference. In the context of vehicular applications, consider the detection of an anomaly in one of multiple vehicles. We compare our Deterministic Adaptive Strategy (DAS) to the classical Open-Loop Randomized Strategy (ORS) [18] in Figure 5. To achieve a mis-classification probability of the order 10^{-7}, the classical approach takes about 30% more samples. Furthermore, our new bounds provide tight approximation to the observed performance. These results may be readily extended to the problem of dynamic waveform selection using the mixed metrics described above [19].

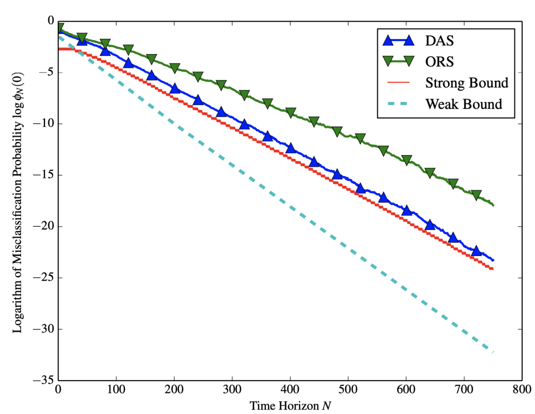

Fig. 5. Performance comparison of DAS and ORS against strong and weak performance bounds for anomaly detection.

C. Integrated Security and Privacy

Cybersecurity is a growing threat for many safety-critical applications, including automated vehicles and flying cars. Many consumer-grade RF systems rely on GPS to provide timing and positioning services, but this system is increasingly vulnerable to spoofing and hijacking [20]–[22]. Furthermore, traditional medium-access control techniques cannot scale to meet the increasing size of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) networks. We consider several decentralized methods for scheduling exchanges in V2V networks, and discuss how integrated communications can secure these networks from spoofing cyberattacks.

We have designed and analyzed decentralized remote estimation strategies with and without local communication [23]. Figure 6 compares various decentralized strategies against theoretical performance bounds. The consensus-based scheme that computes order statistics in a distributed fashion offers fast convergence, but a higher convergent MSE. The consensus-based quantile scheme (adapting the method in [24]) offers a much lower convergent MSE, but at the expense of a slower convergence rate. Our novel hybrid scheme achieves the best of both strategies.

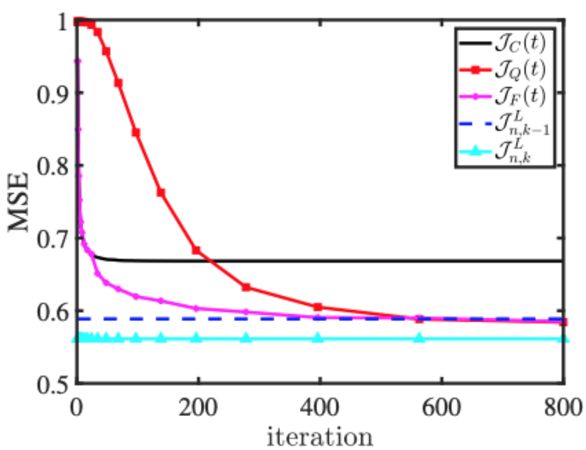

Fig. 6. Performance comparison of the consensus method, distributed quantile estimation, and new hybrid consensus strategy for remote estimation/sensor scheduling versus theoretical bounds.

IV. Multiple-Function Processing Techniques

Many limitations constrain the design and development of RF technologies, including computational complexity, hardware capabilities, and size, weight, power, and cost (SWaP-C). As high-performance hardware becomes more readily available, many processing techniques that were previously considered too cumbersome for practical implementation have now become viable solutions to advanced processing challenges. These techniques are critical for enabling multi-function transceivers.

A. Channel Models and Estimation

Channel modeling and estimation are persistent challenges for numerous types of RF systems, especially for multi-function systems in vehicular applications. In [25], we developed channel models and estimation strategies for V2V communications. We observed that a sparse-clustered channel model arises from highway driving constraints. We express this channel model in terms of impact on the sampled multiple-antenna, received-signal data matrix $\mathbf{Z} \in \mathbb{C}^{n_{ant} \times n_{samp}}$, given by

$$\mathbf{Z} = \sum_k \mathcal{D}_{RX,k}\left\{\sum_m \sum_n \mathbf{H}_{m,n}\, \mathcal{D}_{m,n}(\mathbf{S}^r_n)\right\} + \sum_j \mathcal{D}_{RX,j}\left\{\sum_m \sum_n \mathbf{H}_{m,n}\, \mathcal{D}_{m,n}(\mathbf{S}^c_n)\right\} + \mathbf{N} \qquad (1)$$

for the n^{th} multiple-antenna source $\mathbf{S}_n \in \mathbb{C}^{n_{rxant} \times n_{samp}}$. The n^{th} source has a set of distortions, where the m^{th} distortion is indicated by $\mathcal{D}_{m,n}(\cdot)$. Each transmitter and distortion has a corresponding channel matrix $\mathbf{H}_{m,n}$, though they may also indicate non-linearities, frequency shifts, or some combination thereof. Finally, the receiver has a set of potential distortions, with the k^{th} receiver distortion indicated by $\mathcal{D}_{RX,k}(\cdot)$. For clarity, we distinguish communication signals from radar/sensing signals, but we can extend these results to multiple-function waveforms. We observe that hardware distortion is often ignored except in the context of peak-to-average-power-ratios for OFDM signals.

Numerous estimation strategies have been proposed for multiple-function receivers [26]–[29], but optimal channel estimation for integrated radar, communications, and PNT remains an open problem. We consider joint channel estimation (with some abuse of notation) in the context of mixed-metrics:

$$\mathbf{H}_{m,n} = \arg\min_{\hat{\mathbf{H}}_{m,n}} \left\{\left\|\mathbf{Z} - \sum_k \mathcal{D}_{RX,k}\left\{\sum_m \sum_n \mathbf{H}_{m,n}\, \mathcal{D}_{m,n}(\mathbf{S}^r_n)\right\}\right\|^2 + \sum_n \lambda_n \mathbb{P}\left[\hat{\mathbf{S}}^c_n(\hat{\mathbf{H}}_{m,n}, \mathbf{Z}) \neq \mathbf{S}^c_n\right]\right\}. \qquad (2)$$

We further contend that as the vehicular spectrum becomes more densely occupied, interference mitigation will require precise understanding of channel estimation errors and hardware model mismatch. Parameter estimation bounds that account for model mismatch can substantially assist in identifying which errors are most essential to address.

B. Multi-Function Receiver Techniques

Temporal and spatial mitigation techniques allow joint receivers to disentangle individual components from composite waveforms. We generalize our previously formulated multiple-antenna, multiple-user receiver [30] to include temporal mitigation and space-time adaptive processing (STAP) techniques.

1) Temporal Mitigation: One of our basic algorithmic building blocks is temporal mitigation. If we have n_{samp} samples of n_{sig} impinging signals (which can be extended to include distortion such as delays), then we can build a matrix that contains all these signals, $\tilde{\mathbf{X}} \in \mathbb{C}^{n_{sig} \times n_{samp}}$. This matrix $\tilde{\mathbf{X}}$ contains a stacked set of known or estimated distorted transmitted signals $\mathbf{S}_n$. Using an n_{ant} receive data matrix

$\mathbf{Z} \in \mathbb{C}^{n_{ant} \times n_{samp}}$, we construct an interference-mitigated data matrix $\tilde{\mathbf{Z}}$ by projecting onto an orthogonal basis to some known or estimated waveform:

$$\tilde{\mathbf{Z}} = \mathbf{Z}\,\mathbf{P}^{\perp}_{\mathbf{X}_{\not m}} = \mathbf{Z} - \mathbf{Z}\,\mathbf{X}^{H}_{\not m}\,(\mathbf{X}_{\not m}\,\mathbf{X}^{H}_{\not m})^{-1}\,\mathbf{X}_{\not m}\,, \tag{3}$$

$$\tilde{\mathbf{X}} = \begin{pmatrix} \underline{\mathbf{x}}_m \\ \mathbf{X}_{\not m} \end{pmatrix}, \tag{4}$$

where we can decompose the matrix $\tilde{\mathbf{X}}$ of currently estimated signals into $\underline{\mathbf{x}}_m$, the signal of interest, and $\mathbf{X}_{\not m}$, the "other" estimated signals. The signal $\tilde{\mathbf{Z}}$ can be used directly by radar signal processing. This approach is applied iteratively, and the dimension of the interference subspace typically grows upon successive passes of this nonlinear receiver. Consequently, the estimated sequence might start without any estimated sequences and the number of rows might grow on each iteration (indicated by $\cdot^{(k)}$), so that rows $\left\{\mathbf{X}^{(k+1)}_{\not m}\right\} \geq$ rows $\left\{\mathbf{X}^{(k)}_{\not m}\right\}$.

2) Space-Time Adaptive Processing: By combining spatial and temporal approaches, we construct a receiver [30] that is a multiple-function extension to the multiple-antenna multiple-user detector [31]–[33]. Starting with the most easily decodeable signal, we iteratively apply space-time adaptive processing (STAP) by building the matrix $\breve{\mathbf{Z}}$ that contains a stacked set of delayed versions of $\tilde{\mathbf{Z}}$. Given some training data and reference $\underline{\mathbf{x}}'_m$ and temporally mitigated training data $\breve{\mathbf{Z}}'$, the STAP beamformer $\mathbf{w}$ is given by

$$\hat{\underline{\mathbf{x}}}_m = \mathbf{w}^H\,\breve{\mathbf{Z}}\ ,\ \ \mathbf{w} = (\breve{\mathbf{Z}}'\,\breve{\mathbf{Z}}'^H)^{-1}\,\breve{\mathbf{Z}}'\,(\underline{\mathbf{x}}'_m)^H \tag{5}$$

where $\hat{\underline{\mathbf{x}}}_m$ is the multiple-channel mutliple-user receiver (MCMUR) STAP beamformer output. This signal is then used by the communications and PNT portions of the processing chain. After decoding, remodulated signals are used to construct $\mathbf{P}^{\perp}_{\mathbf{X}_{\not m}}$.

V. Multiple-Function Receiver Architecture

Multiple-function receivers significantly increase the computational complexity of the receive processing chain, but also offer an opportunity for the sub-systems to share information to reduce complexity, improve performance, and enable new hybrid applications. The receiver techniques defined above are generally considered impractical because of the computational cost, but we assert that the newest class of domain-specific hardware will make these techniques viable. In a previous study [4], we developed, implemented, and validated a joint communications-PNT system. In Figure 7, we extend that receiver architecture to include STAP processing techniques and basic radar functionalities. We briefly discuss how these sub-systems might interact to improve performance and enable multiple functions for vehicular applications.

A. Communications Processing

Integrated communications enable back-channel information for the radar and PNT systems, which improves performance and also enables phase-accurate distributed coherence algorithms [4]. Cooperative targets can use this communications link to share telemetry data that improves time

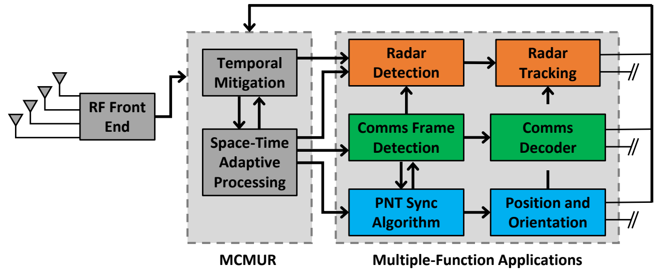

Fig. 7. Joint radar, communications, and PNT receiver processing chain. We extend the receiver architecture developed and validated in [4] to include radar processing and space-time adaptive processing techniques. This architecture would generally be considered impractical for real implementations, but we assert that the newest generation of domain-specific RF hardware platforms will begin to support this level of receiver processing.

synchronization and estimation techniques. The communications component may also be leveraged to execute successive interference cancellation (SIC) to reduce interference for other users in the same band, as depicted in Figure 8.

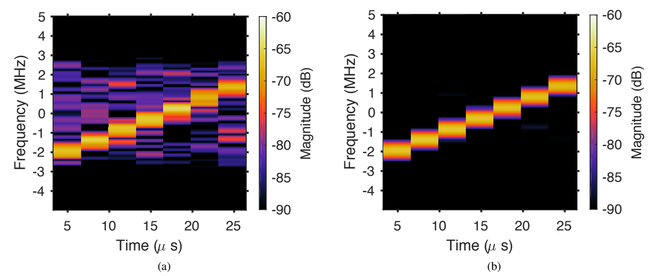

Fig. 8. Time frequency representation of in-band radar and communications users before and after successive interference cancellation. The communications signal is almost completely removed, allowing the radar system to process the return with essentially no interference.

B. PNT Processing

In a previous study [4], we demonstrated that a distributed PNT synchronization algorithm enabled extremely precise ranging (< 5 cm) with moderately low bandwidth (10 MHz). This system also synchronizes users to within fractions of a nanosecond. These results may be extended here to provide feedback mechanisms for the other two tasks. If cooperative users execute this PNT algorithm, many of the synchronization aspects of the communications processing chain are redundant; the PNT algorithm generates much better carrier frequency offset (CFO) and time-of-arrival (ToA) estimates than traditional communications processing is capable of, so these can be used directly to skip some processing steps and improve performance. The ranging capabilities of this algorithm can also inform radar tracking techniques to reduce the necessary search space for tracking cooperative targets.

C. Radar Processing

Despite the high-precision ranging capabilities of the PNT task, the radar task is critical for detecting and tracking noncooperative targets. While PNT ranging is suitable for traffic management in cooperative networks, radar is critical for detecting non-cooperative obstacles such as legacy vehicles, vehicles in failure states, pedestrians, debris, and other potentially life-threatening obstructions. Traditional radar systems operate at significantly higher power and bandwidth than the other two tasks, so being forced in to the low-power, narrow-band paradigm is generally viewed as a harsh restriction. Modern RF Convergence results [1]–[3], however, demonstrate that radar systems can leverage these other tasks to significantly improve performance even in this low-power regime.

VI. Conclusion

We proposed a novel joint radar, communications, positioning, navigation, and timing (JRCPNT) radio architecture and discussed its relevance to urban air mobility (UAM) and automotive applications. We identified relevant performance metrics for comparing these sub-systems and discussed relevant lower bounds on performance. We presented several appropriate multiple-function waveform design methods and multiple-function receiver processing techniques. We assert that this RF system is a viable solution for future spectrum challenges and transportation applications.

References

[1] B. Paul, A. R. Chiriyath, and D. W. Bliss, "Survey of rf communications and sensing convergence research," *IEEE Access*, vol. 5, pp. 252–270, 2016.

[2] A. R. Chiriyath, B. Paul, G. M. Jacyna, and D. W. Bliss, "Inner bounds on performance of radar and communications co-existence," *IEEE Transactions on Signal Processing*, vol. 64, no. 2, pp. 464–474, 2015.

[3] B. Paul, A. R. Chiriyath, and D. W. Bliss, "Joint communications and radar performance bounds under continuous waveform optimization: The waveform awakens," in *2016 IEEE Radar Conference (RadarConf)*. IEEE, 2016, pp. 1–6.

[4] A. Herschfelt, H. Yu, S. Wu, S. Srinivas, Y. Li, N. Sciammetta, L. Smith, K. Rueger, H. Lee, C. Chakrabarti, and D. W. Bliss, "Joint positioning-communications system design and experimental demonstration," in *2019 IEEE/AIAA 38th Digital Avionics Systems Conference (DASC)*. San Diego, CA: IEEE, 2019.

[5] D. W. Bliss, "Cooperative radar and communications signaling: The estimation and information theory odd couple," in *2014 IEEE Radar Conference*. IEEE, 2014, pp. 0050–0055.

[6] A. Herschfelt and D. W. Bliss, "Spectrum management and advanced receiver techniques (smart): Joint radar-communications network performance," in *2018 IEEE Radar Conference (RadarConf18)*. IEEE, 2018, pp. 1078–1083.

[7] ——, "Multi-static space-time-frequency multiple access channel simulation and results," in *2017 IEEE Radar Conference (RadarConf)*. IEEE, 2017, pp. 0975–0980.

[8] S. Srinivas, A. Herschfelt, and D. W. Bliss, "Joint positioning-communications system: Optimal distributed coherence and positioning estimators," in *2019 53rd Asilomar Conference on Signals, Systems, and Computers*. IEEE, 2019, pp. 317–321.

[9] O. Ma, A. R. Chiriyath, A. Herschfelt, and D. W. Bliss, "Cooperative radar and communications coexistence using reinforcement learning," in *2018 52nd Asilomar Conference on Signals, Systems, and Computers*. IEEE, 2018, pp. 947–951.

[10] C. Sturm and W. Wiesbeck, "Waveform design and signal processing aspects for fusion of wireless communications and radar sensing," *Proceedings of the IEEE*, vol. 99, no. 7, pp. 1236–1259, 2011.

[11] A. Hassanien, M. G. Amin, Y. D. Zhang, and F. Ahmad, "Signaling strategies for dual-function radar communications: An overview," *IEEE Aerospace and Electronic Systems Magazine*, vol. 31, no. 10, pp. 36–45, 2016.

[12] B. Ravenscroft, P. M. McCormick, S. Blunt, E. S. Perrins, C. Sahin, and J. G. Metcalf, "Experimental assessment of tandem-hopped radar and communications (thoracs)," *2019 SEE International Radar Conference*, Sept. 2019.

[13] P. M. McCormick, C. Sahin, J. G. Metcalf, and S. Blunt, "Fmcw implementation of phase-attached radar/communications," *2019 IEEE Radar Conference*, Apr. 2019.

[14] P. M. McCormick, S. D. Blunt, and J. G. Metcalf, "Simultaneous radar and communications emissions from a common aperture, part i: Theory," in *2017 IEEE Radar Conference (RadarConf)*. IEEE, 2017, pp. 1685–1690.

[15] P. M. McCormick, B. Ravenscroft, S. D. Blunt, A. J. Duly, and J. G. Metcalf, "Simultaneous radar and communication emissions from a common aperture, part ii: experimentation," in *2017 IEEE Radar Conference (RadarConf)*. IEEE, 2017, pp. 1697–1702.

[16] D. Kartik, A. Nayyar, and U. Mitra, "Fixed-horizon active hypothesis testing," *arXiv preprint arXiv:1911.06912*, 2019.

[17] ——, "Active hypothesis testing: beyond chernoff-stein," in *2019 IEEE International Symposium on Information Theory (ISIT)*. IEEE, 2019, pp. 897–901.

[18] S. Nitinawarat, G. K. Atia, and V. V. Veeravalli, "Controlled sensing for multihypothesis testing," *IEEE Transactions on Automatic Control*, vol. 58, no. 10, pp. 2451–2464, 2013.

[19] O. E. A. Alkhateeb, G. Leus, and R. W. Heath, "Channel estimation and hybrid precoding for millimeter wave cellular systems," *IEEE Journal of Selected Topics in Signal Processing*, vol. 8, no. 5, pp. 831–846, 2014.

[20] D. P. Shepard, J. A. Bhatti, T. E. Humphreys, and A. A. Fansler, "Evaluation of smart grid and civilian uav vulnerability to gps spoofing attacks," in *Radionavigation Laboratory Conference Proceedings*, 2012.

[21] T. Humphreys, "Statement on the vulnerability of civil unmanned aerial vehicles and other systems to civil gps spoofing," *University of Texas at Austin (July 18, 2012)*, pp. 1–16, 2012.

[22] A. J. Kerns, D. P. Shepard, J. A. Bhatti, and T. E. Humphreys, "Unmanned aircraft capture and control via gps spoofing," *Journal of Field Robotics*, vol. 31, no. 4, pp. 617–636, 2014.

[23] M. M. Vasconcelos and U. Mitra, "Observation-driven scheduling for remote estimation of two gaussian random variables," *IEEE Transactions on Control of Network Systems*, 2020.

[24] J. Lee, C. Tepedelenlioglu, and A. Spanias, "Consensus-based distributed quantile estimation in sensor networks," *arXiv preprint arXiv:1805.00154*, 2018.

[25] S. Beygi, U. Mitra, and E. G. Ström, "Nested sparse approximation: Structured estimation of v2v channels using geometry-based stochastic channel model," *IEEE Transactions on Signal Processing*, vol. 63, no. 18, pp. 4940–4955, 2015.

[26] J. Chen and U. Mitra, "Unimodality-constrained matrix factorization for non-parametric source localization," *IEEE Transactions on Signal Processing*, vol. 67, no. 9, pp. 2371–2386, 2019.

[27] ——, "A modified frank-wolfe algorithm for tensor factorization with unimodal signals," in *ICASSP 2019-2019 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*. IEEE, 2019, pp. 7938–7942.

[28] A. Elnakeeb and U. Mitra, "Line constrained estimation with applications to target tracking: Exploiting sparsity and low-rank," *IEEE Transactions on Signal Processing*, vol. 66, no. 24, pp. 6488–6502, 2018.

[29] A. ElNakeeb and U. Mitra, "Variety-based background subtraction for nonlinear trajectory tracking," in *Asilomar Conference on Signals, Systems and Computers*. IEEE, November 2019.

[30] D. W. Bliss, "Multiple-channel multiple-user receiver for joint radar and communications systems," in *2018 52nd Asilomar Conference on Signals, Systems, and Computers*, Oct 2018, pp. 1031–1035.

[31] K. W. Forsythe, D. W. Bliss, and C. M. Keller, "Multichannel adaptive beamforming and interference mitigation in multiuser CDMA systems," *IEEE Asilomar Conference on Signals, Systems and Computers*, vol. 1, pp. 506–510, Oct. 1999.

[32] D. W. Bliss, P. H. Wu, and A. M. Chan, "Multichannel multiuser detection of space-time turbo codes: Experimental performance results," *IEEE Asilomar Conference on Signals, Systems and Computers*, vol. 2, pp. 1343–1348, Nov. 2002.

[33] D. W. Bliss and S. Govindasamy, *Adaptive Wireless Communications: MIMO Channels and Networks*. New York, New York: Cambridge University Press, 2013.