TÉRAL RESEARCH

WIRELESS INDUSTRY ANALYSIS

Why Zak-Orthogonal Time Frequency and Space (OTFS) is the perfect natural fit for Integrated Sensing and Communication (ISAC)

Zak-OTFS beats all waveforms for ISAC

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Table of Contents

Key Takeaways

In the 1960s, information theory researchers found that for accurate radar sensing, the adequate waveforms were solely those offering good localization in delay and Doppler. Leveraging this major finding, R. Hadani et al [1] used mathematics, notably the Zak transform, to create a novel waveform named Orthogonal Time Frequency Space (OTFS) modulation that provides a signal representation that renders a doubly spread channel (i.e., signal degradation in both time and frequency) as an almost time-invariant and non-fading input/output relation. Because they represent the true dynamic nature of complex fast-moving environments, doubly spread channels are essential for accurate radar sensing.

As a result, OTFS enables both channel representation and information symbols multiplexing in the delay-Doppler (DD) domain, which makes the novel waveform unique and unbeatable for precise radar sensing and integration of sensing and communication (ISAC). The OTFS waveform inherently possesses the characteristics of both the pulse and the tone or "pulsones," which are introduced as information carriers perfectly suited for predictable non-fading communication. Zak-OTFS is the modulation technique that converts DD domain pulses into pulsones.

Published in May 2025, numerical simulations of effective spectral efficiency according to 3GPP standards demonstrated the superiority of Zak-OTFS over cyclic prefix orthogonal frequency-division multiplexing (CP-OFDM) currently used in 4G and 5G cellular systems.

In conclusion, no other current waveform candidate matches Zak-OTFS capabilities of supporting both precise radar sensing and wireless communications by using shared spectrum, hardware and waveforms. And as ISAC is a 6G pillar, Zak-OTFS stands as the most technically complete solution available today.

"*There comes a time when massive innovation is required to unleash new capabilities in global communications*," said **Ray Dolan**, Chairman and CEO at Cohere Technologies. "*We saw this 25 years ago at Flarion Technologies as we commercialized OFDM, while the cellular industry was struggling to evolve networks that were designed principally for voice and narrowband data. Predictably, the industry leaders at the time were focused on making incremental changes to existing CDMA solutions, thinking that the answer would lie in 'making the pipe wider' only to realize that the focus needed to also be on alignment with protocols that had already become essential for the existing wired internet.*"

Today, the wireless industry faces an analogous inflection point: just as OFDM was the answer to wideband data, Zak-OTFS is the waveform engineered from first principles to deliver the integrated sensing and communication capabilities that 6G demands.

Why Zak-OTFS Is the Strongest Candidate for Radar Sensing and ISAC

Introduced in 2016 by R. Hadani et al [1] and followed by the first IEEE paper published in 2017 [2], the novel Orthogonal Time Frequency Space modulation (OTFS) waveform provides a signal representation that renders a doubly spread channel—one exhibiting signal degradation in both time and frequency—as an almost time-invariant and non-fading input/output relation, which makes it extremely resilient to large delay and Doppler spreads. The two chief OTFS features are:

1. Channel representation in the delay-Doppler (DD) domain
2. Information symbols multiplexing in the DD domain

Consequently, OTFS differs markedly from today's wireless communications systems where both channel representation and information signaling are performed in the time-frequency domain and boasts superior radar sensing capabilities. The fundamental reasons why DD for radar sensing is superior include:

- Stable channel representation: unlike orthogonal frequency-division multiplexing (OFDM) used in 4G and 5G cellular systems, the OTFS DD channel representation remains stable even in highly mobile scenarios and prevents rapid channel aging.
- Simultaneous multi-parameter measurements: instantaneous 2D tracking in a single processing step is achieved through the combination of range (delay) and velocity (Doppler) estimation.
- High-speed and small target detection: the DD-domain representation natively supports pulse-Doppler processing, which detects low-amplitude moving targets (e.g., missiles, rain) against large-amplitude stationary clutter (e.g., mountains, ground) without the additional windowing and FFT stages required by time-domain waveforms.
- High resolution and signal-to-noise (SNR) ratio: coherent processing over multiple pulses increases the SNR and greatly improves the resolution in both range and frequency.
- Clutter elimination and multipath immunity: Doppler velocity provides the ability to distinguish targets and filter out unwanted stationary or slow-moving reflections.

PROPER RADAR WAVEFORMS ARE THOSE OFFERING GOOD LOCALIZATION IN DELAY AND DOPPLER

In 1964, Dr. Philip Woodward [3], who introduced information theory into the context of radar systems, demonstrated the importance of designing the radar signal to obtain as much information as possible instead of focusing on the transmitter. He argued that it's the waveform with its information carrier that matters the most to localize an object in the DD domain.

THEREFORE, ADEQUATE RADAR WAVEFORMS MUST BE LOCALIZED IN THE DD DOMAIN

Since both time-domain (TD) and frequency-domain (FD) pulses are not localized simultaneously along both delay and Doppler domains, they are not good enough waveforms for radar applications.

- TD pulses are just localized along delay and not along Doppler and therefore can't be used for estimating Doppler shifts due to targets. The information carrier is just a TD pulse.
- Conversely, FD pulses are just localized along Doppler and not along delay, which makes them unable to estimate target delays. The information carrier is just an FD pulse.

By contrast, in DD domain modulation, the information carrier is a pulse in the DD domain, and this DD pulse provides a sparse, stable, and highly accurate representation of the environment, making it ideal for tracking and sensing. As a result, a DD pulse becomes the premier information carrier in radar sensing because it simultaneously measures target range (via time delay) and velocity (via Doppler shift) while providing superior noise immunity, high resolution, and effective clutter rejection. By operating in the DD domain, it detects small, fast-moving targets close to large, slow-moving reflectors.

Table 1 summarizes the channel action, transform, and information carrier in time domain modulation (TDM), frequency domain modulation (FDM), and DD domain modulation.

Table 1: TDM, FDM, and DD domain modulation characteristics

Modulation	Channel	Domain	Transform	Channel action	Information carrier
TDM	Delay-only	TD	Identity	Linear convolution	TD pulse
FDM	Doppler-only	FD	Fourier	Linear convolution	FD pulse
DD	Doubly spread	DD	Zak	Twisted convolution	DD pulse

Source: [4]

BECAUSE THEY REPRESENT THE TRUE, DYNAMIC NATURE OF COMPLEX, FAST-MOVING ENVIRONMENTS, DOUBLY SPREAD CHANNELS ARE ESSENTIAL FOR ACCURATE RADAR SENSING

Relying on simplified channel models in these scenarios causes significant, unpredictable fading and Doppler-induced errors in range and velocity estimation. Accurate radar sensing requires the implementation of DD-domain based doubly spread channel models for the following reasons:

- **Accurate Representation of High-Mobility Environments:** In scenarios like V2X (vehicle-to-everything) or vehicular radar, high mobility causes severe Doppler shifts that change over the duration of a frame, making the channel both time- and frequency-selective. A doubly spread channel model stands out because it captures the time-varying Doppler.
- **Predictability in Dynamic Environments:** While TD signals fade unpredictably in high-mobility scenarios, they are relatively stable and predictable in the DD domain. Channel modeling the DD domain produces precise tracking of moving targets regardless of how fast the environment is changing.
- **Improved Resolution of Targets:** Waveforms designed for doubly spread channels, such as OTFS, provide superior DD localization, which allows for better separation of closely spaced, small-radar-cross-section objects such as pedestrians or cyclists from larger, stationary clutters.
- **Mitigation of Inter-Carrier Interference (ICI):** Traditional OFDM radar suffers from high Doppler, which leads to severe ICI in high-speed scenarios. As doubly spread channel models enable advanced modulation like OTFS to operate natively in the DD domain, they turn ICI into a source of diversity rather than a source of error.
- **Foundation for ISAC:** ISAC is widely recognized as a 6G pillar, and a strong research trajectory favors using a unified waveform for both communication and sensing. In this scenario, a DD-domain model acts as a unified framework that allows for precise, simultaneous estimation of delay (range) and Doppler (velocity) for both communication channel state information (CSI) and radar imaging.

THAT UNDENIABLY MAKES THE “PULSONE” NATURE OF OTFS A PERFECT FIT FOR SENSING APPLICATIONS

Based on Woodward’s findings, OTFS is a de facto natural fit for the two following fundamental reasons:

1. Being a pulse train modulated by a tone—what Cohere Technologies coined as pulsone, the OTFS waveform inherently possesses the characteristics of both the pulse and the tone.

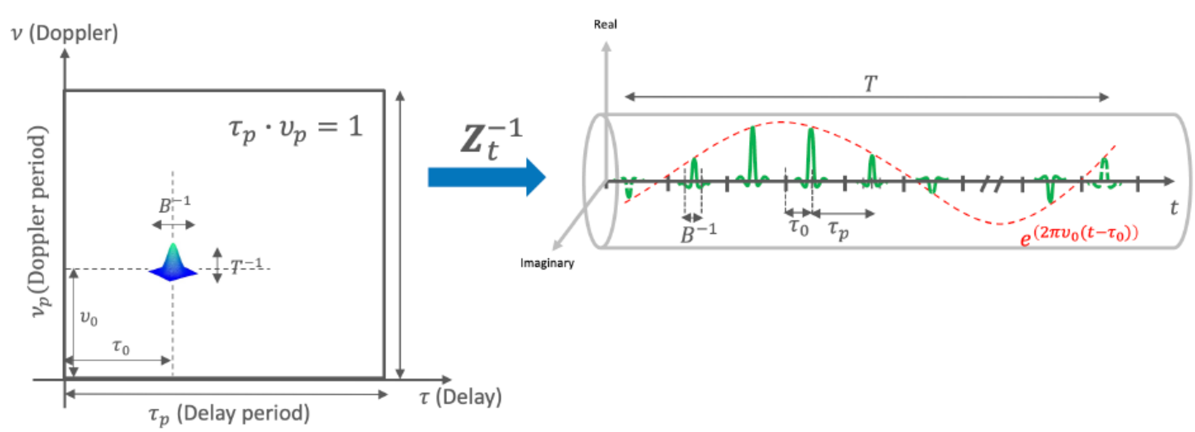
2. Pulsones, which combine the pulse of a radar with the tone-based technology of 4G/5G (i.e. OFDM), have solid DD localization.

Put another way, pulsones are introduced as information carriers naturally suited for predictable and non-fading communication.

ZAK-OTFS IS THE MODULATION TECHNIQUE THAT CONVERTS DD DOMAIN PULSES INTO TD PULSONES

The Zak transform is a mathematical tool that maps a 1D time-domain signal into a 2D time-frequency representation and is often used for analyzing sampled continuous signals. As illustrated in Figure 1, a Zak-OTFS carrier waveform is a pulse in the DD domain, and a quasi-periodic localized function defined by a delay domain period (τ_{p}) and a Doppler domain period υ_{p} = 1/ τ_{p}. The inverse Zak transform converts the DD signal to the time domain [5] [6]. The generalized nature of Zak-OTFS means that this waveform can range from an OFDM-type with minimum delay period, to TDM-type with low peak-to-average power ratio (PAPR) with minimum Doppler period. Contrastingly, OFDM boasts a high PAPR and is sensitive to frequency synchronization errors and Doppler shift.

Figure 1: Illustration of the inverse Zak transform



Source: [5] [6]

When both the delay period and the Doppler period are sufficiently larger than the delay spread and the Doppler spread, which refers as to the crystalline regime or the crystallization condition, Zak-OTFS exhibits a predictable and non-fading input-output (I/O) relation—refers to the relation between the information-bearing carrier (sub-carrier in the case of OFDM and pulsone in the case of Zak-OTFS) input to the channel and its channel response (output). "Crystalline," means the I/O relation does not exhibit deep fades. Put another way, it’s under this condition that the communication system leverages the Zak transform to convert the time-varying wireless channel into a time-invariant channel in the DD domain where the channel gains are stable and easily characterized.

Conversely, because TDM and FDM are suited to delay-only and Doppler-only channels (see Table 1), respectively, they exhibit non-predictable and fading I/O relation in doubly spread channels.

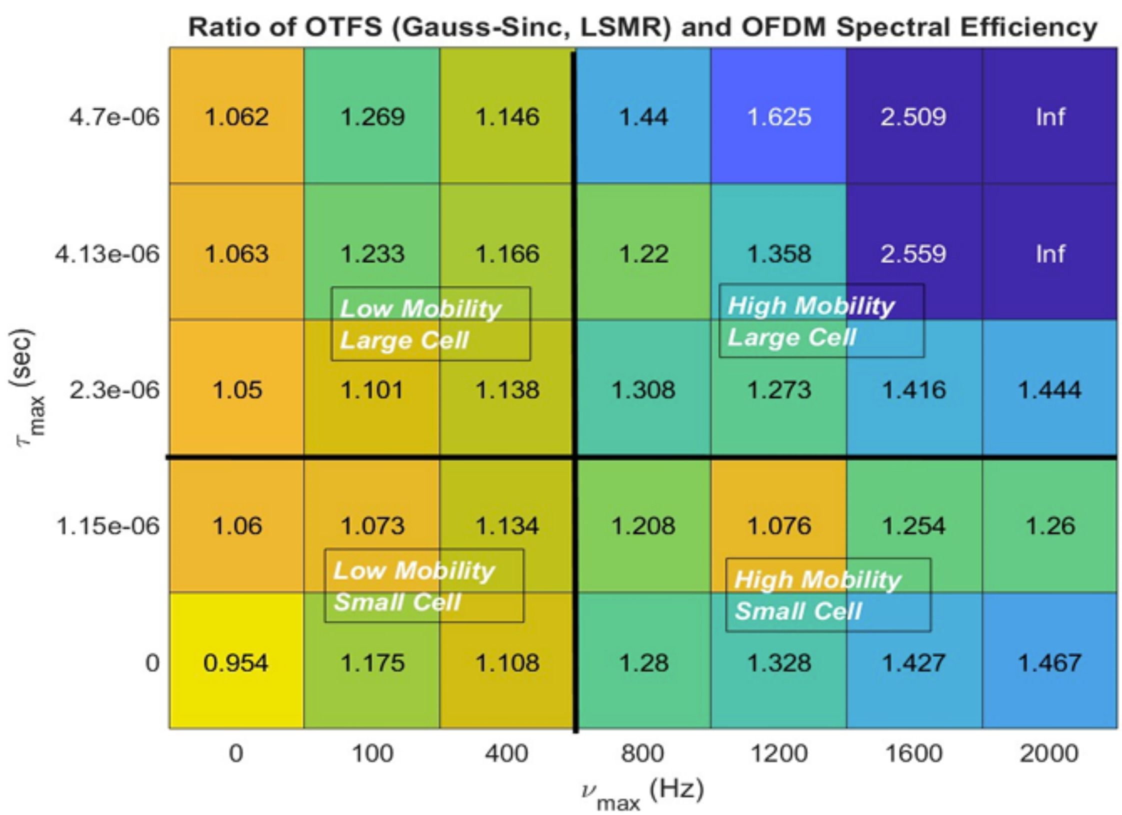
RECENT NUMERICAL SIMULATIONS PROVED THE SUPERIORITY OF ZAK-OTFS OVER CP-OFDM

The recent research paper published in May 2025 comparing Zak-OTFS to OFDM [6] provides an excellent overview and performance summary. Figure 2 shows the ratio of effective spectral efficiency (SE) for Zak-OTFS to effective SE for cyclic prefix OFDM (CP-OFDM). SE is defined as the ratio of the total number of information bits transmitted reliably divided by the time-bandwidth product. A single radio resource with finite time duration (1ms for both CP-OFDM and Zak-OTFS) and bandwidth (720KHz for CP-OFDM and 672KHz for Zak-OTFS) were used; the bandwidth difference reflects the Zak-OTFS crystallization guard band overhead, ensuring a fair comparison on a per-resource-block basis. 3GPP standards were met, CP-OFDM parameters were optimized for all scenarios, including MCS, subcarrier spacing, DMRS allocation and power, etc. Similarly, Zak-OTFS delay and Doppler periods and DMRS allocations and power were optimized.

The results of this simulation presented in Figure 2 point to the following:

- For high mobility/large cell systems such as non-terrestrial networks (NTN) and aircraft-to-ground communications, the effective SE of Zak-OTFS is more than double that of CP-OFDM.
- In high mobility/small cell systems such as high-speed trains and cars at highway speeds, Zak-OTFS improves effective SE by more than 20% in most cases.
- In low mobility/large cell systems typical of rural connectivity in large parts of India, Australia, Africa and South America, Zak-OTFS also improves effective SE
- And for low mobility and small cell scenarios (i.e., low delay and Doppler spread), the SE achieved by both CP-OFDM and OTFS is similar. It’s worth noting that in this scenario, there is insignificant ICI in CP-OFDM and therefore low-complexity per sub-carrier equalization is nearly optimal.

Figure 2: Ratio of effective SE for Zak OTFS to effective SE for CP-OFDM



Source: [7]

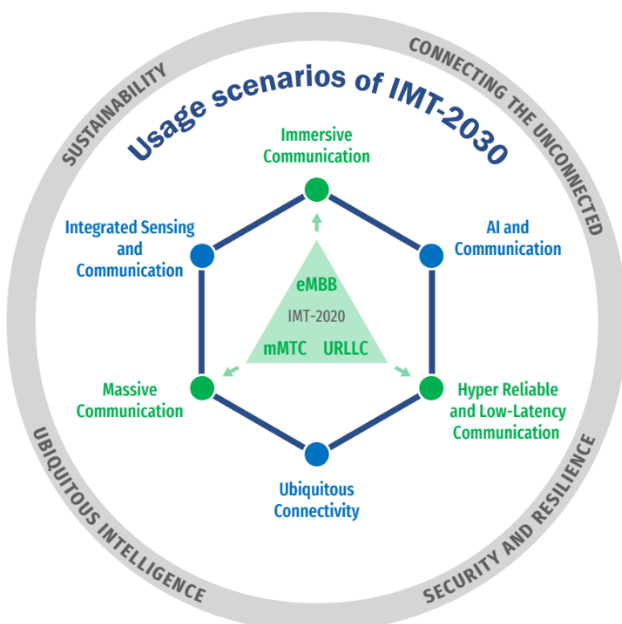
ADDRESSING RECEIVER COMPLEXITY: NEURAL RECEIVERS CLOSE THE GAP

A common objection to DD-domain waveforms is receiver complexity. Traditional MMSE equalization of the full delay-Doppler grid requires matrix inversion with $O((MN)^3)$ complexity—substantially higher than the per-subcarrier $O(1)$ equalization used in CP-OFDM. This gap has historically been cited as a barrier to practical deployment. However, recent advances in neural receiver architectures have fundamentally changed this equation. In November 2025, Cohere Technologies, Duke University, and Virginia Tech demonstrated the industry's first real-time Zak-OTFS neural receiver at the NVIDIA GTC-DC conference, running on NVIDIA's Jetson edge platform. The neural receiver achieves $O(MN)$ linear complexity through a learned forward pass that replaces explicit matrix inversion, delivering 100–1,000× speedup over traditional MMSE for large delay-Doppler grids. Critically, the Zak-OTFS neural receiver converges within a single symbol period and requires no offline training—it learns the channel inverse in real time, adapting to dynamic delay-Doppler environments without pre-trained models. As Dr. Lingjia Liu of Virginia Tech noted, this milestone "opens the door to flexible, resilient, and real-time ISAC networks that can operate seamlessly across waveforms, protocols, and missions." The practical implication is clear: neural receivers eliminate the complexity objection that has historically favored CP-OFDM, while simultaneously enabling the real-time adaptability that ISAC deployments demand.

CONSEQUENTLY, ZAK-OTFS IS THE UNMATCHED CANDIDATE FOR ISAC, A 6G PILLAR

Integrated Sensing and Communication (ISAC) is an emerging paradigm that has rapidly evolved since approximately 2018 from separate systems into an integrated, dual-functional technology. Consequently, it has now become a key pillar of 6G development (Figure 3), with the first official standardization expected to arrive in 3GPP Release 21 (study items targeted for the 2028–2029 timeframe) and has attracted great attention from both academia and industry to tackle the full integration of sensing and communication functions.

Figure 3: ITU's usage scenarios of International Mobile Telecommunications (IMT) 2030



Source: ITU

Integrated or joint sensing and communications holds great promise as a new vertical for 6G. ISAC is expected to require acquisition of many targets (e.g., drones, traffic, pedestrians). Zak-OTFS is inherently a radar waveform with information and pilots carried in the Delay-Doppler/sensing domain. As such, Zak-OTFS directly senses the environment. Compared with chirp-based radar, Zak-OTFS achieves greatly improved resolution, larger number of simultaneously acquired targets, and lower computational complexity, as demonstrated by the

LTV system identification framework in [8] where Zak-OTFS resolves O(N) targets versus O(√N) for chirp-based approaches. Zak-OTFS also uniquely enables joint optimization of the radar ambiguity function and the communications waveform because both the ambiguity function and the communication I/O relation are expressed in a common delay-Doppler representation, eliminating the design trade-offs inherent in time-frequency waveforms.

ZAK-OTFS AND NTN: ISAC FROM ORBIT

The spectral efficiency results presented above carry particular significance for non-terrestrial networks (NTN), where Zak-OTFS delivers more than double the effective SE of CP-OFDM. LEO satellites traveling at over 27,000 km/h create Doppler shifts up to ±50 kHz at typical cellular frequencies, propagation delays exceeding 25 ms, and differential delays across massive cell footprints—conditions that expose OFDM's fundamental limitations. The 3GPP Release 17 NTN approach requires extensive workarounds to force OFDM into satellite service: mandatory GNSS chipsets, device-side timing advance and frequency pre-compensation from satellite ephemeris data, extended HARQ processes, and single-satellite operation that prevents macro-diversity gains. By contrast, Zak-OTFS transforms these satellite channel impairments from obstacles into exploitable features. In the delay-Doppler domain, rapid Doppler changes appear as static channel conditions over transmission frames, multi-satellite diversity provides genuine performance gains rather than destructive interference, and channel estimation overhead drops dramatically because the stable DD representation requires far fewer pilot signals. Beyond connectivity, an OTFS-enabled LEO constellation becomes a global, persistent, multistatic radar network—simultaneously providing communications while sensing aircraft, ships, weather systems, and surface targets through ISAC with zero spectral efficiency overhead. This dual-use capability positions Zak-OTFS as the natural waveform for satellite-terrestrial convergence as 6G standards incorporate NTN as a core design requirement rather than an afterthought.

ZAK-OTFS VERSUS ALTERNATIVE ISAC WAVEFORM CANDIDATES

Table 2 provides a qualitative comparison of Zak-OTFS against the incumbent CP-OFDM baseline and the principal alternative waveform candidates proposed for ISAC, across the key dimensions that determine suitability for integrated sensing and communication.

Table 2: Qualitative comparison of ISAC waveform candidates

Criterion	Zak-OTFS	CP-OFDM	AFDM	ODDM	FMCW
DD-Domain Localization	Full 2D (delay + Doppler)	None; time-frequency domain processing only	Partial (DAFT-based, 1D affine)	Delay-only (1D)	Range-Doppler via chirp sweep

Criterion	Zak-OTFS	CP-OFDM	AFDM	ODDM	FMCW
Comms Spectral Efficiency	Superior (crystalline regime, non-fading I/O)	Baseline; degrades >20% in high-mobility due to ICI and pilot overhead	Comparable to OTFS in high-mobility; no crystalline guarantee	Limited; delay-only processing misses Doppler diversity	N/A (sensing-only waveform)
ISAC Integration	Native; zero SE overhead, joint ambiguity/comms optimization	Requires dedicated sensing resources (5–20% SE overhead); 3GPP Rel-18/19 study items active	Possible but not demonstrated; no ISAC-specific framework	Not addressed; delay-only processing insufficient for sensing	Sensing-only; requires separate comms waveform, defeating ISAC purpose
Target Resolution	O(N) resolvable targets	Limited by CP length and subcarrier spacing; Doppler ambiguity from OFDM symbol duration	Not characterized for multi-target sensing	Limited to delay dimension	O(√N); range-Doppler coupling limits target count
High-Mobility Performance	Excellent; channel appears time-invariant in DD domain	Poor; ICI destroys subcarrier orthogonality, rapid channel aging	Good; DAFT exploits Doppler diversity	Moderate; Doppler effects not exploited	Good for sensing; range-Doppler coupling at extreme speeds
Research Maturity	1,500+ publications; real-world trials (Vodafone, Bell Canada); real-time neural receiver demo	Mature for comms; ISAC sensing via pulse-Doppler actively studied (Rel-18/19)	Emerging (post-2023); limited experimental validation; no field trials	Early academic stage; limited community	Mature for radar-only; no comms integration path
Standards Position	3GPP 6G study item candidate; active standards participation	Incumbent; 3GPP ISAC study items built on CP-OFDM baseline	No 3GPP engagement; IEEE-only publications	No standards trajectory	Separate radar standard (IEEE 802.11ad); no cellular integration

AFDM (Affine Frequency Division Multiplexing) uses the Discrete Affine Fourier Transform to achieve Doppler resilience, but operates in a one-dimensional affine domain rather than the full two-dimensional delay-Doppler plane, lacks the crystalline regime guarantees that provide Zak-OTFS with predictable non-fading I/O, and has no demonstrated ISAC framework. ODDM (Orthogonal Delay Division Multiplexing) processes only the delay dimension and therefore cannot exploit Doppler diversity for either communication or sensing. FMCW (Frequency Modulated Continuous Wave) is a mature and widely deployed radar waveform—particularly in automotive applications—but is fundamentally a sensing-only technology. It cannot carry communication data, requires dedicated spectrum separate from the communication band, and its chirp-based range-Doppler coupling limits the number of simultaneously resolvable targets to $O(\sqrt{N})$ versus $O(N)$ for Zak-OTFS. CP-OFDM is the incumbent baseline and benefits from active 3GPP standardization of ISAC sensing modes (Rel-18/19 study items), but its time-frequency domain processing requires dedicated sensing resource allocation that consumes 5–20% of spectral efficiency, and performance degrades sharply in the high-mobility scenarios most critical for ISAC. Only Zak-OTFS provides native, simultaneous sensing and communication in a unified delay-Doppler framework with zero SE overhead, a demonstrated real-time neural receiver, and an active 6G standards trajectory.

BOTTOM LINE: ZAK-OTFS: THE LEADING WAVEFORM FOR ISAC AND BEYOND

As the chief goal of ISAC systems is to merge radar sensing and wireless communication into a single system that uses shared spectrum, hardware, and waveforms not only to boost 6G network efficiency but also to enable the novel infrastructure to simultaneously transmit data, detect, and track physical objects, the need for future wireless systems to operate in high-Doppler channels such as Zak-OTFS has never been greater.

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