

# Appendix

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Table 1: Summary of OF-ISAC Techniques Based on Signal Transmission Directions.

Signal transmission direction	Re-source	Year	Communication		Sensing		Advantages & Limitations
			Signal	Distance	Resolution	Performance	
<b>Counter-propagation</b>	Ref.[24,25]	2019	8.28 b/s/Hz DP-144-QAM	110 km for communication; 55 km for sensing	m-level	Accuracy: 98.5% (vehicle speed); 94.5% (vehicle density); > 85% (road conditions)	Nonlinear interference suppression adds hardware complexity, cost, and bulk, and exhibits low compatibility with communication systems.
	Ref.[26]	2020	–	–	–	–	–
<b>Co-propagation</b>	Ref.[27]	2009	PON	17 km	100 m	–	Offer full-link sensing capability.
	Ref.[28,29]	2021	10 Gbps PAM-4	6 km	–	$0.35 \text{ n}\epsilon/\sqrt{Hz}$	Distinguish inter-branch vibrations but requires an RSOA controller, adding complexity.
	Ref.[30]	2025	25 G PON	~7 km	–	A gauge length of 6–10 m	Pave the way to geolocation of events in point to multipoint fiber topologies using DAS.
	Ref.[31]	2022	32 GBaud DP-16QAM	4.8 km	13.3 m	$20 \text{ p}\epsilon/\sqrt{Hz}$	Extra pilots are needed for phase and frequency compensation, lowering spectral efficiency and raising cost.
	Ref.[32]	2022	DP-16QAM	82 km	–	600 Hz vibration	The system avoids data impact at 2 GHz spacing; but its sensing range is limited by coherent detection and low probe power.
Ref.[33]	2022	100 Gbps DP-QPSK	50 km	10 m	PZT vibration	Chirped-pulse modulation maintained stable data transmission performance.	

Table 1 (continued): Summary of OF-ISAC Techniques Based on Signal Transmission Directions.

Signal transmission direction	Re-source	Year	Communication		Sensing		Advantages & Limitations
			Signal	Distance	Re-solution	Per-formance	
	Ref.[34]	2023	10 Tbps DP-16QAM	Over 1000 km	20 m	$100 \text{ p}\varepsilon/\sqrt{Hz}$	Raised-cosine shaping reduces XPM, enhancing SNR for ultra-long transmission.
	Ref.[37]	2024	24*400 Gb/s 16QAM	1.3 km	-	Detected real-world vibration events with a 19.2 m gauge length	Confirm the feasibility of combining high-capacity DWDM transmission with distributed sensing in HCF.
	Ref.[38]	2018	-	15 km	m	From 0.05 Hz to >100 Hz	Demonstrates dynamic strain sensing using standard telecom fibers.
	Ref.[39]	2022	-	200 km	-	Earthquake and microseism detection, and ferry monitoring	Offers low-cost, high versatility, no need for underwater installation, and minimal environmental impact.
	Ref.[40]	2025	7.59 Gbps OOK	1 km	-	Classified 4 acoustic signatures with an accuracy of $\approx 85\%$	Demonstrates the potential for advanced ocean monitoring without deploying new subsea fibers.
	Ref.[41]	2019	-	27 km	2 m	Observed watershed-scale hydrological changes and recorded the M8.1 Chiapas earthquake (2017).	Use dark fibers as dedicated sensing links, ensuring stable, independent operation without affecting active communications.
	Ref.[42]	2019	-	20 km	-	Detected the March 11, 2018 Gilroy, CA strike-slip earthquake.	

Table 1 (continued): Summary of OF-ISAC Techniques Based on Signal Transmission Directions.

Signal transmission direction	Re-source	Year	Communication		Sensing		Advantages & Limitations
			Signal	Distance	Re-resolution	Per-formance	
	Ref.[43]	2019	–	–	–	Monitored the August 19, 2018 Fiji deep earthquake.	
	Ref.[44]	2025	100 Gbaud 64QAM	1000 km	–	MSE is about -14 dB.	Breaks through ISAC trade-offs in performance, spectral efficiency, and noise robustness, but lacks experimental validation.

Table 2: Summary of OF-ISAC Based on Different Hardware Resource and Spectrum Utilization Strategies.

Tech -nology	Resource	Year	Distance	Signal	Communication		Sensing	Advantages & Limitations
					Feature	Re -solution	Performance	
WDM	Ref.[27]	2009	–	1310,1490 nm for communication, 1550 nm for sensing	PON	100 m	–	Sensing signals occupy part of the communication spectrum, reducing overall spectral efficiency.
	Ref.[40]	2025	1 km	1310 nm for communication, 1550 nm for sensing	7.59 Gbps	–	Accuracy $\approx 85\%$	
	Ref.[30]	2025	$\sim 7$ km	1358,1286 nm for communication, 1550 nm for sensing	25G PON	–	a gauge length of 6–10 m	
	Ref.[37]	2024	1.3 km	1538.0 to 1557.6 nm for communication, 1550.12 nm for sensing	HCF	–	a gauge length of 19.2 m	
PDM	Ref.[44]	2025	1000 km	Polarization for sensing, phase for communication	100GBaud 64QAM	–	MSE is about -14 dB	Breaks through ISAC trade-offs in performance, spectral efficiency, and noise robustness, but lacks experimental validation.

Table 2 (continued): Summary of OF-ISAC Based on Different Hardware Resource and Spectrum Utilization Strategies.

Tech -nology	Resource	Year	Distance	Signal	Communication		Sensing	Advantages & Limitations
					Feature	Re -solution	Performance	
LFM	Ref.[45]	2023	24.5 km	PAM4	57 Gbit/s, SNR+1.3 dB	4 m	$4.32 \frac{n\varepsilon/\sqrt{Hz}}$ over 21 kHz vibration	Improves SNR and spectral efficiency but limited to IM/DD systems.
	Ref.[46]	2024	10 km	16QAM	60 GBaud	0.5 m	–	Shares spectral resources and the transmitter while enhancing DAS spatial resolution.
DSCM	Ref.[47]	2023	10 km	DP-QPSK, 16QAM	100 Gb/s, 200 Gb/s	–	$69 \text{ p}\varepsilon/\sqrt{Hz}$ $89 \text{ p}\varepsilon/\sqrt{Hz}$	Enables a shared transmitter, with FrFT reducing probe power and nonlinear effects, but dedicated sensing sub-band limits spectral efficiency.
	Ref.[48]	2024	10 km	16QAM	100 Gb/s	5 m	$70 \text{ p}\varepsilon/\sqrt{Hz}$	Optimizes the FDM structure of synchronous FrFT-based TS, enabling joint sensing without extra sub-bands.
SDM	Ref.[49]	2022	1 km	TMF: LP <sub>11a</sub> (DAS), LP <sub>01</sub> (OOK)	4.2 Gbps, BER= $3.2 \times 10^{-3}$	–	Detected vibrations at 500 Hz and 800 Hz	TMF provides higher nonlinear tolerance and lower intermodal crosstalk.
	Ref.[50]	2023	1 km	Combine KK reception with TMF.	2.04 Gbps	–	SNR>2 dB	

Table 2 (continued): Summary of OF-ISAC Based on Different Hardware Resource and Spectrum Utilization Strategies.

Tech -nology	Resource	Year	Distance	Signal	Communication		Sensing	Advantages & Limitations
					Feature	Re -solution	Performance	
	Ref.[51]	2023	–	Seven-core fiber: one for sensing, six for communication.	BER= $8.55 \times 10^{-3}$ (sensing enabled), BER= $8.50 \times 10^{-3}$ (sensing disabled)	–	15.9 dB rel. $p\epsilon$ Hz <sup>1/2</sup>	Low inter-core crosstalk allows highly sensitive vibration detection.
Back-scattering of communication signals for sensing	Ref.[52]	2007	10 km	Existing data bursts in TDM	GPON	–	Resolve reflectors 15 m apart at 10 km, sensitivity -74.7 dBm	Achieve ISAC without introducing additional probe signals, enhancing spectral efficiency.
	Ref.[53]	2007	–	NRZ	1.25 Gbit/s	–	–	
	Ref.[54]	2016	500 m	Real-time PSK data for DAS	–	2.5 cm	500 Hz vibration	
	Ref.[55]	2025	10.2 km & 40 km	125 MBaud QPSK	No BER	10 m	$0.50 \frac{n\epsilon}{\sqrt{Hz}}$ (10.2 km), $0.65 \frac{n\epsilon}{\sqrt{Hz}}$ (40 km)	Use OSC channel for ISAC to improve spectral efficiency with no additional hardware.
Ref.[56]	2025	20 km	25 Mbps & 25 Gbps PAM4	a 0.6dB & 0.98dB power penalty compared with conventional IMDD	12.28 cm & 0.7 m	A sensing range of 38 m & 20 km	Enable communication and sensing on a single wavelength, greatly improving spectrum and hardware efficiency.	

Table 3: Summary of OF-ISAC Techniques Based on Brillouin Backscattering Technologies.

Tech -nology	Resource	Year	Distance	Signal	Communication		Sensing	Advantages & Limitations
					Feature	Resolution	Performance	
BOTDR	Ref.[57]	2009	15 km	1650 nm for sensing	PON	–	Detected 4.1 dB bending loss with 17 dB dynamic range	Realize fault localization in PON without disrupting normal communication services.
	Ref.[58]	2020	25 km	1550 nm for communication; 1546.12 nm for sensing	16 Mbps QPSK, 33Mbps 16 QAM, 50 Mbps 64QAM	5 m	A temperature error of $\pm 0.49^\circ\text{C}$ at $50^\circ\text{C}$	-
BOTDA	Ref.[59]	2023	16 km	–	50 Gbaud DP-16QAM	3 m	The temperature accuracy is $1^\circ\text{C}$	Lower system cost and improve compatibility with existing DC links.

Table 4: Summary of Polarization-Based Forward Sensing and Communication Integration.

Sensing Type	Sensing			Communication		Architecture	Advantages
	Transmission Direction	Distance	Precision/Sensitivity	Signal Type	Distance		
Stokes vector of polarization-based Forward Sensing [62]	Forward	Up to 10,000 km	High localization accuracy	100 Gb/s	Up to 10,429 km	Curie transcontinental submarine cables	Two of the three Stokes parameters are independent, high sensitivity.
Angle of the polarization-based Forward Sensing [63]	Forward (Bidirectional)	121.5 km	$\pm 34$ m	-	-	Dual-wavelength, bidirectional fiber-optic system	Long-range vibration sensing, high sensitivity.
Polarization-based OF-ISAC [65]	Forward	50 km	High sensitivity to low-frequency micro-strain is $2.4 \text{ n}\epsilon$	400 Gb/s DP-16QAM	Over 2 km	ARepurposes LO & APC	Low-frequency response, APC can be used for sensing in JACS networks.
Polarization-based Forward Sensing (Ip et al.) [66]	Forward (Bidirectional)	20 km	$70 \text{ p}\epsilon/\sqrt{Hz}$	60 Gb/s 16QAM	20 km	Integrated with DAS in a bidirectional coherent communication system.	Highly practical for long-haul, high-resolution DAS sensing networks, cost-effective integration.
Integrated coherent transmission and distributed fiber sensing [67]	Forward	50.5 km	STD of localization $< 25$ m	Dual-polarization QPSK (C-band, L-band)	50 km	C+L unidirectional WDM transmission	Cost-effective, no need for precise timing synchrony, high localization accuracy.

Table 5: Summary of Phase-Based Forward Sensing and Communication Integration.

Sensing Type	Sensing			Communication		Architecture	Advantages
	Transmission Direction	Distance	Precision/Sensitivity	Signal Type	Distance		
Bidirectional Phase-based ISAC (Ip et al., NEC Labs America) [68]	Forward (Bidirectional)	489 km	$\pm 5$ km	32 GBaud DP-16QAM	380 km	Bidirectional fiber-pair with digital coherent transponders, FWHM of the correlation function	Forward transmission-based bidirectional phase correlation, identify two closely simultaneous vibration events.
SF-DVS (Guo Zhu et al., 2024) [69]	Forward	122 km	Tens of meters	-	-	Single fiber with FS-TDM and delay arm	Enables localization and vibration analysis in a single fiber.
PDEA-based Forward Sensing (W. Kong et al., 2024) [71]	Forward	122 km	$\pm 51$ m	-	-	Phase differentiation endpoint amplification	Improved low-frequency response and localization accuracy.
AFS-FTDVS (Chen et al., 2025) [72]	Forward	272 km	35.6 m accuracy; $3.14 \text{ p}\epsilon/\sqrt{Hz}$	-	-	AOM frequency-shift & coherent detection	Ultra-long range; standard fiber; low cost.

Table 5 (continued): Summary of Phase-Based Forward Sensing and Communication Integration.

Sensing Type	Sensing			Communication		Architecture	Advantages
	Transmission Direction	Distance	Precision/Sensitivity	Signal Type	Distance		
Phase-based vibration sensing utilizing frequency combs (Lu et al., 2025) [73]	Forward	55.9 km	Detects vibration-induced strain as small as $11.8 \text{ n}\epsilon$	20 GBaud 16QAM	50 km	External cavity laser (ECL) combined with laser frequency combs, WDM	Cost-effective, differential phase mitigates laser phase noise.
7-core fiber Distributed Vibration Sensor [74]	Forward	55.9 km	Detects low-frequency vibrations (149 Hz sensitivity)	-	-	3 MHz linewidth DFB laser, 7-core fiber, balanced delay line interferometry	Cost-effective, reduces phase noise, scalable, high sensitivity to low frequencies.
Urban Fiber Forward Sensing [75]	Forward	80 km (deployed fiber)	High sensitivity to weak events	-	-	Forward transmission with adaptive time-frequency masking	Detects real-world vibrations (footsteps, impacts) under strong noise.
Seismic Monitoring via Telecom Fibers [76]	Forward (Fiber Pair)	75–535 km	High seismic sensitivity	-	-	Dual-fiber interferometric loop in submarine cables	Detects oceanic seismic events; scalable global sensing potential.

Table 6: Summary of Other Approaches to Integrating Forward Sensing and Communication.

Sensing Type	Sensing			Communication		Architecture	Advantages
	Transmission Direction	Distance	Precision/Sensitivity	Signal Type	Distance		
FPT-Enhanced Forward Phase Sensing [78],[79]	Forward	tens of km (coherent DSCM link)	10 kHz sensing; 10 dB SNR	4x8 GBaud/s DP-16QAM	40 km	DSCM with pilot tones	Low-cost lasers; improved low-frequency sensing.
Integrated OPM & DFOS Coherent System [80]	Forward	40 km	10 m DFOS; accurate OSNR/CD/FO	45 GBaud 16QAM	40 km	LFM-pilot frame-based coherent system.	Joint sensing & monitoring; no comm penalty

Table 7: Summary of Forward Sensing Schemes Based on PPE.

Sensing Type	Sensing			Communication		Architecture	Advantages
	Transmission Direction	Distance	Precision/Sensitivity	Signal Type	Distance		
CM-PPE Forward Link Monitoring [81],[82].	Forward	260 km multi-span link	Sub-km localization	506 Gbit/s DP-16QAM	260 km multi-span link	Correlation-based PPE at coherent receive	In-band sensing; no probe signals; simple DSP
MMSE-PPE / LLS-Based Longitudinal Power Monitoring [83].	Forward (Bidirectional)	50 km $\times$ 3-span link	0.2 dB power accuracy	64QAM 130 GBd	50 km $\times$ 3-span link	MMSE-based PPE with linear least-squares solution	High accuracy; no reference state; robust estimation.
DBP-Based PPE / Digital Longitudinal Monitoring [84].	Forward	260 km multi-span link	Component-resolved estimation	64QAM 64 GBd	260 km multi-span link	DBP-assisted channel reconstruction	Multi-parameter sensing; digital twin of optical link.