

Toward Multiband Sensing in FR3: Frequency Anisotropy Characterization and Non-Contiguous Bands Aggregation Algorithms

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Abstract

Frequency Range 3 (FR3) in the 7-24 GHz band will be the new spectrum for 6G wireless networks. The bandwidth availability and diversity of FR3 offer unprecedented opportunities for coherent multiband Integrated Sensing And Communication (ISAC), which aggregates the carrier phase information from multiple frequency bands to increase the sensing resolution to the cm-level. However, the frequency anisotropy of sensing targets over GHz-wide bands and the non-contiguity of the 6G spectrum, pose critical challenges to the application of existing multiband ISAC techniques. We present the first study on coherent multiband sensing in FR3. We experimentally characterize the frequency anisotropy of targets and propose new phase coherence metrics for multiband processing. Then, we analyze the impact of non-contiguous FR3 bands considered by 3GPP, and design a new algorithm to mitigate the resulting sensing artifacts, outperforming existing techniques. Our results represent a first step toward fully developing multiband ISAC for FR3.

Keywords: FR3, multiband, carrier aggregation, ISAC, ranging, frequency anisotropy

Introduction

There is a general consensus that Integrated Sensing And Communication (ISAC) will be one of the key pillars of Sixth Generation (6G) cellular networks [1], endowing them with radar-like capabilities to sense the location and movements of objects and people in the environment. However, the limited spectrum availability and the non-contiguity of the frequency bands allocation represent a bottleneck that prevents the sensing accuracy and resolution of ISAC systems from achieving their cm-level theoretical value. These limitations have recently sparked the research on *coherent multiband* ISAC [2, 3], which leverages the *carrier phase* information contained in the channel state information acquired in multiple, possibly non-contiguous, frequency bands to increase the delay and range resolution. This line of work naturally aligns with the opportunities offered by the Frequency Range 3 (FR3) spectrum, spanning approximately 7-24 GHz.

The FR3 spectrum has emerged as a ‘goldilocks’ range for 6G, striking a balance between the favorable propagation characteristics of FR1 and the abundant bandwidth of FR2 mmWave bands [4]. Unlike sub-6 GHz, FR3 offers much larger contiguous and non-contiguous allocations, which are critical to support the surge in mobile data traffic and artificial intelligence-driven applications anticipated by 2030. At the same time, its propagation loss and penetration characteristics remain far more manageable than those in mmWave, enabling coverage in urban and suburban areas with existing tower infrastructure. This unique combination makes FR3 a key enabler for high-capacity, mid-range coverage with resilience to blockage [5].

A further opportunity lies in the inherent disaggregation of FR3 spectrum. Allocations are fragmented across multiple non-contiguous bands due to incumbent services such as satellites, radio astronomy, and radar, as depicted in Fig. 1. While this fragmentation poses challenges for traditional single-band systems, it naturally motivates multiband and frequency-agile designs. By dynamically hopping or aggregating carriers across the FR3 range, networks can trade-off coverage and rate depending on propagation and blockage conditions.

Importantly, FR3’s multiband nature also creates opportunities for ISAC, for example, to perform high-resolution imaging of the environment [6]. Rather than a drawback, the FR3 disaggregation can be turned into a feature. Coherent multiband ISAC techniques can exploit non-contiguous FR3 bands to jointly enhance communication and sensing resolution by *aggregating* the available bands, thus increasing the total bandwidth with minimal spectrum occupation. However, several challenges arise in using such disaggregated wideband spectrum for coherent multiband ISAC.

First, real targets exhibit frequency-dependent (*incoherent*) electromagnetic scattering properties when signals having very different carrier frequencies are used. Given the extremely wide span of FR3, sensing targets can not be modeled as *frequency isotropic*, i.e., idealized point-like scatterers that scatter the signal in the same way

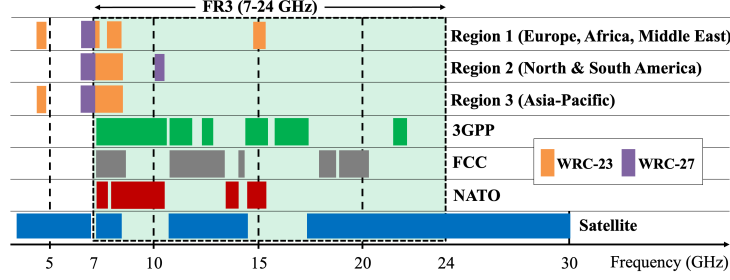


Fig. 1: Considered frequency allocations in FR3 for 6G and existing allocations for satellite and military usage. The use of non-contiguous bands in FR3 over a very wide bandwidth represents an opportunity but also a challenge for coherent multiband ISAC.

regardless of the carrier frequency, as commonly done in multiband ISAC works [7, 8]. This means that the complex-valued coefficients of such targets in the Channel Impulse Response (CIR) are not constant in frequency, which invalidates existing coherent multiband algorithms and phase offset compensation techniques across bands. The incoherence becomes more significant in *high fractional bandwidth* scenarios, i.e., when the total bandwidth exceeds 20 % of the carrier frequency. Unlike FR1 (low carrier frequency, narrow bandwidth) and FR2 (high carrier frequency, wide bandwidth), FR3 can reach over 100% fractional bandwidth if multiple disaggregated bands are combined.

Second, the use of disaggregated spectrum introduces *grating lobes* in the range profile obtained by aggregating multiple bands. This is because uniform sampling in the frequency domain, i.e., without gaps, is a necessary condition to obtain an impulse-like range profile for sensing targets. This significantly degrades the sensing results, introducing ambiguity in the targets' detection and nullifying the multiband resolution gain.

To date, existing research has focused on modeling and experimentally characterizing FR3 for communications and ISAC [9] without considering the challenges of coherent multiband sensing. Specifically: (i) *experimental characterization* of frequency anisotropy over FR3 band is lacking, so it is unclear when existing multiband algorithms are applicable and when instead they are not, (ii) *metrics* to evaluate the *phase coherence* of common targets and the impact of high fractional bandwidth on multiband ISAC algorithms are missing, and (iii) analysis and *countermeasures for the grating lobes* due to non-contiguous bands are still in their early stages and no results are available for FR3 considered allocations yet.

In this work, we tackle the above challenges by presenting the first experimental characterization for coherent multiband ISAC over FR3, including novel coherence evaluation metrics and bandwidth aggregation algorithms. We focus on *ranging*, i.e., the measurement of a target's distance from the ISAC device, combining multiple frequency bands coherently. This is commonly the first step in ISAC systems, to localize the targets of interest, hence our results also apply to other, more advanced, sensing applications such as motion analysis and respiration monitoring, among others. Our contributions are summarized below.

1. We present the first experimental characterization of coherent multiband ISAC over the FR3 band. Our analysis encompasses both the frequency anisotropy phenomenon and the impact of non-contiguous bands. The collected data is made available to the research community at [10].
2. We propose three novel metrics to evaluate the phase coherence of common targets, including humans, to check the applicability of existing multiband ISAC algorithms and assess their performance.
3. We propose a heuristic algorithm, named Subsets Product Backprojection (SPBP), for coherent multiband combination that mitigates the grating lobes due to the use of non-contiguous subbands and outperforms existing approaches like Backprojection (BP) and Orthogonal Matching Pursuit (OMP) on our data.

Our findings point out that the high fractional bandwidth of FR3 and the frequency anisotropy of common targets is a neglected but key aspect to take into account in the design of multiband ISAC algorithms and their integration in 6G. In addition, our results suggest that existing multiband aggregation algorithms are unlikely to be effective when considering very wide portions of FR3 and real extended targets such as humans.

The paper is organized as follows. In the [Results](#) section, we present the main results from our experimental characterization of phase coherence and fragmented spectrum, along with the proposed metrics. In the [Discussion](#) section, we discuss the main takeaways from the experimental results and we compare them to the existing literature. In the [Methods](#) section, we detail the methodology used in the paper, including the system and signal models, the description of the algorithms, and the experimental protocol. Supplementary material with additional information on the methodology is provided as a separate file.

Results

In this section, we present our results on FR3 multiband measurements. For a detailed explanation of the system model and algorithms, the reader is referred to the [Methods](#) section.

Our objectives are:

1. To provide a practical way of evaluating the phase coherence of sensing targets and the applicability of existing multiband aggregation algorithms that assume frequency isotropic targets.
2. To experimentally demonstrate and quantify the non-coherence of complex targets when a large bandwidth is aggregated (several GHz), providing insights into the difference between extended and point-like targets.
3. To evaluate the impact of non-contiguous subbands allocation in FR3, and propose countermeasures to mitigate the appearance of grating lobes. For this, we focus on *the actual frequency bands* considered by 3rd Generation Partnership Project (3GPP) for 6G.

To this end, we collect a dataset of monostatic Channel Frequency Response (CFR) measurements in FR3 with different target types (corner reflector, metal plate, and

humans), as detailed in the [Dataset](#) section. We then propose three novel metrics to evaluate phase coherence and use them to address objective 1 (the [Performance metrics](#) section). Experimental results in terms of the three metrics are provided, achieving objective 2 in the [Multiband target coherence](#) section. Finally, in the [Multitarget resolution](#) section, we tackle objective 3 by analyzing the grating lobes for actual FR3 subbands and comparing a newly proposed multiband aggregation algorithm to two state-of-the-art methods from the ISAC literature.

Since the focus of this paper is to evaluate the frequency anisotropy of real targets and assess the multiband coherent resolution gain in FR3, we do not perform Doppler estimation in our experiments. This is outside the scope of this work, but represents an interesting future research direction.

Dataset

In our experimental campaign, we collect a dataset of 475 Over-the-Air (OTA) CFR measurements [10] obtained with a multiband monostatic transceiver spanning the frequency range 6-22 GHz. The transceiver sweeps the full frequency range, transmitting Orthogonal Frequency Division Multiplexing (OFDM) pilot signals with a bandwidth of 500 MHz or 1 GHz with different carrier frequencies. We perform multiband ranging with pilot signals intended for channel estimation for communication purposes. We do not use the data part of the communication packet, although our processing could be applied to data as well, provided that the data symbols are properly estimated at the receiver and removed from the signal. More details on the frequency sweep and the measurement device can be found in the [Measurement system and experimental protocol](#) section. From each CFR measurement, the corresponding CIR is obtained by applying an Inverse Discrete Fourier Transform (IDFT) along the OFDM subcarriers dimension. The dataset consists of 200 calibration measurements, 150 single-target measurements, and 125 multitarget measurements. We consider three target types: a calibrated corner reflector, a metal plate, and humans, as detailed in the [Measurement system and experimental protocol](#) section. To evaluate the impact of using non-contiguous subbands, in some of our experiments, we extract *subsets* of the subbands collected in the frequency sweep that do not cover the full frequency range. This allows us to generate a large number of non-contiguous subband patterns that we use to evaluate the considered algorithms in different scenarios. As complementary data, we also collect phase response measurements for the corner reflector using a Vector Network Analyzer (VNA) over the bandwidth 6-24 GHz. These measurements constitute a reference for the expected target phase response, since the VNA is calibrated and does not introduce phase distortions across the measured band.

Some of the experiments conducted in this work involve Radio Frequency (RF) measurements with human subjects. Such experiments do not collect any personal data or sensitive information about the subjects, are not linked to the identity of the individuals involved, pose no harm to their health, and do not constitute a clinical trial. All the experiments were conducted in accordance with the ethical regulations of the Polytechnic University of Milan, Italy, which does not require the approval of an Ethical Committee for this kind of data. The involved subjects provided their informed written consent.

Multiband combination algorithms

We consider two multiband ISAC algorithms from the literature, BP and OMP, and propose a third one, called SPBP, to mitigate the impact of grating lobes due to non-contiguous subbands. Moreover, we also consider non-coherent combination of the subbands as a baseline. BP is used as the default algorithm in single-target measurements with contiguous subbands (the [Multiband target coherence](#) section), since it is not affected by grating lobes in this case. The results obtained with OMP, non-coherent processing, and SPBP are instead presented in the [Multitarget resolution](#) section to evaluate the impact of grating lobes on multitarget resolution. The algorithms are listed in the following, and explained more in depth in the [Methods](#) section.

- **BP:** This method is commonly used in the Synthetic Aperture Radar (SAR) literature and has been used in ISAC in [11, 12]. It combines the subbands by oversampling the CIR of each subband, compensating for the propagation phase term of each CIR, and summing the CIRs coherently. Grating lobes due to non-contiguous subbands affect the result since no mitigation is performed.
- **OMP:** This algorithm is based on Compressed Sensing (CS) [13] and it was previously used in multiband sensing in [7]. It tackles the combination of the subbands as a sparse reconstruction problem. It is well-suited to mitigate the grating lobes due to non-contiguous subbands. However, the nominal multitarget resolution of OMP is hard to estimate and certainly lower than that of BP. Moreover, OMP is an *on-grid* method, meaning its performance heavily depends on the granularity of a pre-defined grid of possible range values. For a detailed description of the OMP algorithm applied to our measurements, we refer to the supplementary material (Supplementary note - 2).
- **Non-coherent processing:** This approach combines the different subbands non-coherently, by taking the average of the CIR magnitudes of the subbands. Although it does not exploit the CIR phase, thus not improving the ranging resolution, non-coherent processing can improve the ranging Signal-to-Noise Ratio (SNR).
- **SPBP:** This method is based on BP but attempts to mitigate the grating lobes by using non-linear processing on the multiband range profile (see the [Subsets Product BP algorithm](#) section). Specifically, SPBP splits the available subbands into two sets, optimized to have grating lobes at different locations, then applies BP to each of them and takes the product of the resulting combined CIRs. As a result, grating lobes are strongly attenuated by the product while the targets persist.

Performance metrics

In this section, we introduce the metrics used in the experimental results to evaluate the coherence of targets in multiband ISAC and the multitarget ranging resolution and accuracy in empirical settings.

Assessing the multiband coherence, i.e., coherence over a wide range of frequencies, of an extended target is challenging and requires considering the CIRs obtained in different bands and the combined *range profile* as a result of multiband processing. The range profile contains the complex-valued coefficients of scattering points in the

environment as a function of the distance (range) from the ISAC device. Coefficients with high magnitude indicate the presence of scatterers or reflectors at certain ranges.

Our contribution is to propose novel metrics to evaluate: (i) the phase coherence of the target in the different measured subbands and (ii) the quality of the resulting multiband range profile. We design three metrics, which are a function of the target index ℓ , detailed in the following. In the definitions below, we denote by R_ℓ the range value corresponding to target ℓ and by $\eta_k(R)$ the range profile in subband k evaluated at distance R . We consider a total of K combined subbands. The range profile is obtained from the CIR of subband k by compensating for the contribution of the carrier phase, as explained in detail in the [Backprojection algorithm](#) section, Eq. (16).

1. The Multiband Phase Coherence (MPC) measures the spread of the scattering phases across the subbands as

$$\text{MPC}(\ell) = \left| \frac{1}{K} \sum_{k=0}^{K-1} e^{j\angle \eta_k(R_\ell)} \right|, \quad (1)$$

where $\angle \cdot$ is the phase operator. The MPC lies in $[0, 1]$ and equals 1 if the phases are all identical across the subbands, indicating maximal coherence. In this case, the terms $e^{j\angle \eta_k(R_\ell)}$ all add up coherently. Conversely, its value is 0 if the phases combine destructively, leading to a perfect cancellation of the $e^{j\angle \eta_k(R_\ell)}$ in the sum, indicating maximum incoherence. The target locations R_ℓ to be used in Eq. (1) are obtained by performing peak detection on the range profiles obtained in multiple subbands. The MPC is very informative since it directly evaluates the phase coherence of the K multiband range profiles when considering a specific target. However, it only *indirectly* evaluates the quality of the combined multiband range profile. Indeed, it does not capture slight misalignments of the range profile peaks in the different subbands, which may reduce the quality of the final combination.

2. The Normalized Multiband Peak Magnitude (NMPM) evaluates the relative magnitude of the peak corresponding to a target in the combined range profile compared to the average magnitude of the same target across the single subbands. Denoting the multiband combined range profile as $\eta(R)$, the NMPM in dB is

$$\text{NMPM}(\ell) = 20 \log_{10} \left(\frac{|\eta(R_\ell)|}{\frac{1}{K} \sum_{k=0}^{K-1} |\eta_k(R_\ell)|} \right). \quad (2)$$

If, after multiband combination, the magnitude of the target peak lowers with respect to the mean peak magnitude across subbands, this is a sign that the combined subbands are not coherent. This could be either due to phase incoherence, as evaluated by the MPC, or due to slight peak misalignment or other inconsistencies in the range profiles between the subbands. Hence, NMPM evaluates the quality of the range profiles combination rather than the multiband coherence directly.

3. The Empirical Multiband Peak Width (EMPW) evaluates the empirical 3 dB peak width in the multiband combined range profile. This is a direct measure (in meters)

of the resolution of the range profile after multiband processing, and can be compared to the theoretical resolution given by $c/(2B)$ where c is the speed of light and B is the bandwidth of the signal (either the single subband, B_k , or the total multiband occupation). The EMPW is obtained as

$$\text{EMPW}(\ell) = \text{supp}_{-3\text{dB}}|\eta(R)| = \{R \mid \eta(R) \geq \eta(R_\ell)/2\}, \quad (3)$$

where $\text{supp}_{-3\text{dB}}$ denotes the -3 dB support of the range profile around target ℓ . Similar to NMPM, EMPW evaluates the quality of the multiband range profile and is an indirect measure of the multiband coherence.

To evaluate the empirical multitarget resolution when we aggregate different subbands, we use the Optimal Subpattern Assignment (OSPA) metric from the literature [14]. The OSPA measures the distance between sets of points, effectively capturing the contribution of cardinality differences and distance between the points in the sets. It is widely used in the evaluation of multitarget tracking algorithms. Intuitively, the OSPA finds the minimum average Euclidean distance between the points in the two sets over all possible permutations of the points, then it adds a penalty of μ for each unit difference in the cardinality of the two sets. In this computation of the Euclidean distance, the distance values are cropped at a maximum value of μ , so that the OSPA values are in $[0, \mu]$. Further details on the formulation of the OSPA metric are given in the supplementary material (Supplementary note - 1).

Multiband target coherence

In this section, we present our experimental results on the coherence of single targets in wide multiband settings in FR3. We start by providing qualitative results of the range profile obtained by combining multiple bands across different bandwidths and carrier frequencies. Then, we give a quantitative evaluation of the targets' coherence in terms of the metrics proposed in the [Performance metrics](#) section.

In Fig. 2, we show the CIR obtained from a corner reflector target at 1.5 m from the measurement device (vertical dashed line) with a 500 MHz bandwidth and 6.5 GHz carrier frequency (red curve), compared to the multiband range profile with *contiguous subbands* using BP (blue curve). To obtain the latter, we use the BP algorithm detailed in the [Backprojection algorithm](#) section. In the subfigures (a-d), we show the impact of changing the total combined bandwidth for multiband processing, which we call B_{tot} , ranging from 1 to 7 GHz. B_{tot} is incremented by combining adjacent frequency bands of 500 MHz starting from 6.5 GHz. We notice the resolution improvement demonstrated by the significant reduction in the width of the main range profile peak corresponding to the target. When a bandwidth of 3 GHz or more is coherently combined, this reveals a *secondary peak*, 6 dB below the main one, that is not observed using 500 MHz bandwidth. This is likely due to a multipath reflection. Increasing the total combined bandwidth, we also observe a reduction in the peak height of the main target, with an overall loss of around 3 dB at $B_{\text{tot}} = 7$ GHz. The reduction is due to the imperfect target coherence across frequencies and hardware non-ideality, as further investigated in the next section. In the case of a perfectly coherent combination of different subbands and ideal hardware, the peak should not decrease in magnitude, since

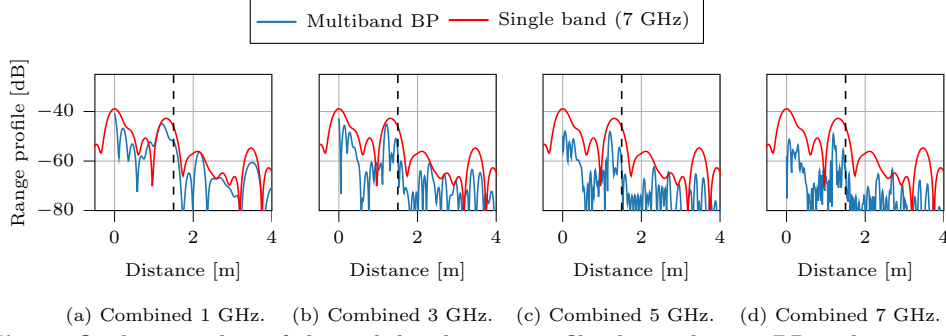


Fig. 2: Qualitative plots of the multiband range profile obtained using BP with a **corner reflector**, at 6.5 GHz starting frequency. Different plots (a)-(d) represent different combined total bandwidths from 1 to 7 GHz. The black dashed line represents the location of the target measured with a laser telemeter.

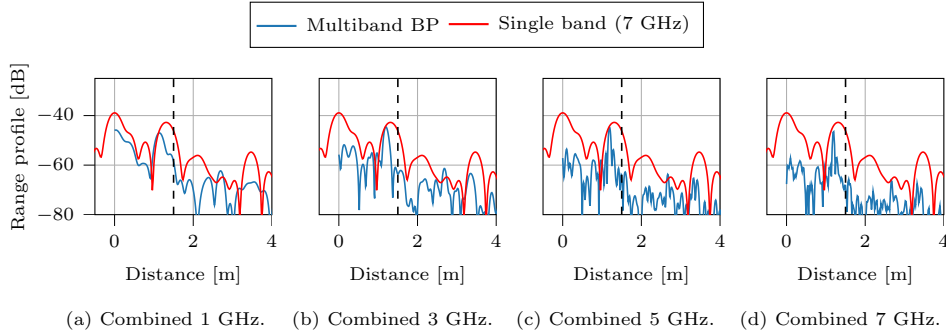
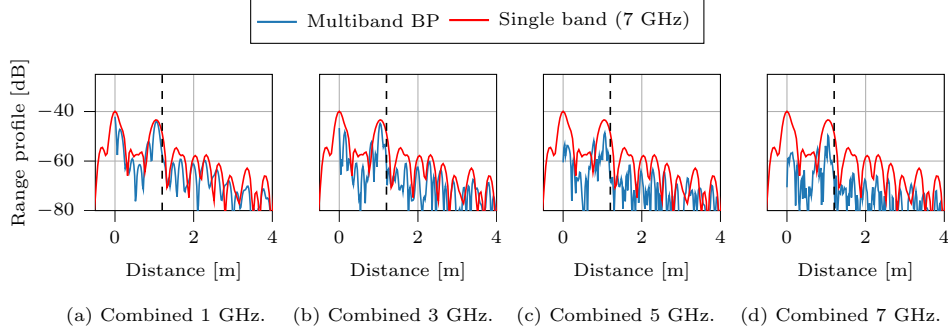


Fig. 3: Qualitative plots of the multiband range profile obtained using BP with a **corner reflector**, at 14 GHz starting frequency. Different plots (a)-(d) represent different combined total bandwidths from 1 to 7 GHz. The black dashed line represents the location of the target measured with a laser telemeter.

all the target's contributions would sum in phase. Note that the strong peak around 0 m is due to the direct signal path from the transmitter to the receiver antenna.

In Fig. 3, the same experiment is repeated, starting from 14 GHz. We notice that the multiband range profile exhibits a main target peak located at the same distance as in the 6.5 GHz experiment of Fig. 2, which confirms the target presence. A similar reduction of 3 dB in main peak magnitude is evident, going from 1 to 7 GHz total bandwidth. However, the secondary peak observed in Fig. 2 is not present, demonstrating that besides the total combined bandwidth, another critical parameter to consider in multiband ISAC is the carrier frequency. The different scattering response at different frequencies could be due to the size of the corner reflector compared to the wavelength: reducing the wavelength makes the size of the corner relatively larger from an electromagnetic perspective, reducing border effects.

This experiment suggests that exploring the variations of the target coherence metrics across different values of B_{tot} and carrier frequency is necessary to gain a deeper insight into how to design multiband sensing algorithms.



(a) Combined 1 GHz. (b) Combined 3 GHz. (c) Combined 5 GHz. (d) Combined 7 GHz.
Fig. 4: Qualitative plots of the multiband range profile obtained using BP with a **human**, at 6.5 GHz starting frequency. Different plots (a)-(d) represent different combined total bandwidths from 1 to 7 GHz. The black dashed line represents the location of the target measured with a laser telemeter.

In Fig. 4 and Fig. 5, we repeat the experiments of the previous section with a human target instead of a corner reflector. To reduce the total frequency sweep duration and to avoid artifacts due to the person’s involuntary movements, we increase the single band bandwidth to 1 GHz. We notice that the results obtained starting from 6.5 GHz (Fig. 4) or 14.5 GHz (Fig. 5) are now completely different. Starting from 6.5 GHz, the range profile presents a clear target peak, which narrows as B_{tot} increases. However, a secondary peak with slightly lower magnitude appears when increasing the combined bandwidth above 1 GHz. This represents a secondary scattering center of the target, due to the more complex structure of the human body with respect to the corner reflector. Conversely, at 14.5 GHz the peak corresponding to the target is barely visible and does not seem to gain significant resolution when B_{tot} increases.

This experiment demonstrates that for complex extended targets: (i) the target response in the range profile deviates from a single clear peak when multiple target parts combine coherently, especially when combining multiple GHz of bandwidth over a large *fractional bandwidth*, (ii) the number of visible scattering centers highly depends on the carrier frequency of the total combined bandwidth (frequency anisotropy).

In Fig. 6, Fig. 8, and Fig. 9, we show our results for multiband target coherence using the three targets of the [Measurement system and experimental protocol](#) section, respectively. For each target, we show the three metrics proposed in the [Performance metrics](#) section for different values of B_{tot} , which is the contiguous aggregated bandwidth, and carrier frequency. Specifically, each curve (with a different color) represents the result obtained by combining a different B_{tot} . Darker colors represent narrower B_{tot} while lighter colors represent wider B_{tot} . Each point in the curves is obtained with a different value of the carrier frequency, as specified by the x -axis. Note that curves corresponding to wider B_{tot} also contain fewer points, since there are fewer possibilities to fit a wide bandwidth in the considered frequency range of 6 – 22 GHz. All the results shown in the following are obtained by averaging 50 measurements taken in a row, with a few seconds’ pause between subsequent captures. A moving average smoothing filter along the frequency dimension, with a window of 3 points, is applied to the averaged curves with more than 5 points to improve readability.

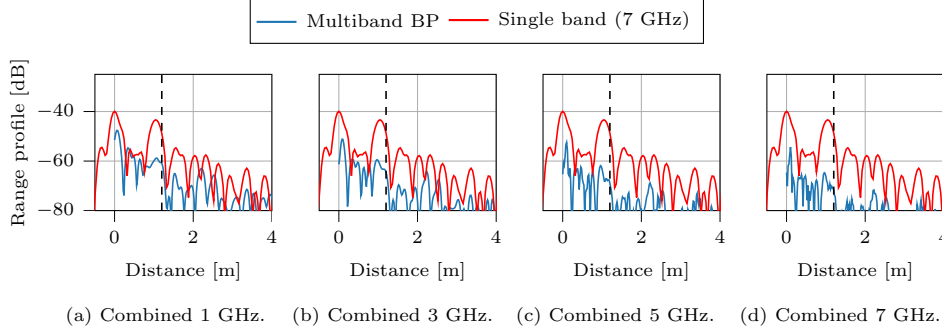


Fig. 5: Qualitative plots of the multiband range profile obtained using BP with a **human**, at 14.5 GHz starting frequency. Different plots (a)-(d) represent different combined total bandwidths from 1 to 7 GHz. The black dashed line represents the location of the target measured with a laser telemeter.

Fig. 6 shows that the corner reflector can be considered coherent over a very wide bandwidth, with slight differences depending on the carrier frequency. The phase coherence (MPC metric) is above 0.8 for almost all the considered carrier frequencies and bandwidth values. It shows its minimum for a carrier frequency of 9 GHz, consistently across all values of B_{tot} . Additionally, it gradually decreases as B_{tot} increases. It stabilizes to 0.85, which is a relatively high coherence, when combining the full frequency range 6 – 22 GHz. The main range profile peak magnitude loss with respect to the mean magnitude of the combined subbands (NMPM metric) does not fall below –2 dB regardless of the carrier frequency, and shows the most significant degradation (1.9 dB) when combining 1 to 4 GHz of bandwidth around a carrier frequency of 17 GHz. The EMPW results are coherent with the other metrics, showing that the main peak width of the target consistently shrinks when the combined bandwidth increases. The final resolution approaches the ideal one (red dashed line), but does not achieve it, likely due to the combined effect of imperfect target coherence (lower than 1), antenna response non-ideality, and the residual impact of noise on the channel estimation process.

In Fig. 7, we provide the phase response obtained from a VNA measurement on the corner reflector to verify that it can be considered coherent over a wide bandwidth. We report the phase response over the full bandwidth obtained in 5 trials (blue to yellow curves) compared to the phase response obtained from a point-to-point link (red curve) without any target to measure the phase response of the antenna. Our results show that the phase presents oscillations of $\pm 25^\circ$ and a general increasing trend. However, both these variations have to be mainly attributed to the non-ideal antenna response, which shows very similar variations. This shows that, in terms of our metrics, the $\pm 25^\circ$ phase oscillations due to the antenna response do not have a significant impact on the coherence of the target and still allow coherent multiband processing over several GHz of bandwidth. Additional information on how we collected the measurements to obtain Fig. 6 and the VNA CIR is provided in the supplementary material (Supplementary note - 4), in Fig. S2.

Fig. 8 shows that the metal plate target has a similar behavior to the corner reflector, showing high coherence over a very wide bandwidth. The MPC is above 0.8 for

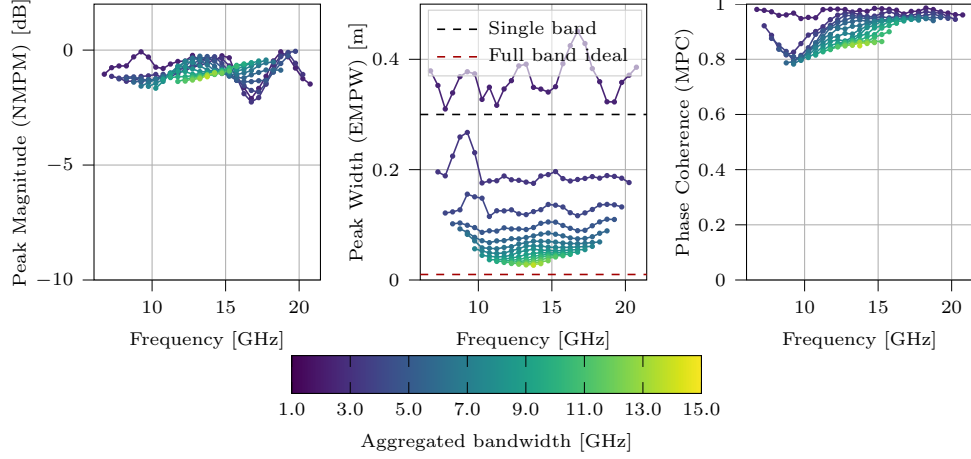


Fig. 6: Coherence metrics of a corner reflector target in the range 6-22 GHz. The bandwidth of a single subband is 0.5 GHz. We report the NMPM, EMPW, and the MPC obtained for different carrier frequencies (on the x -axis) and different total combined bandwidth (corresponding to the different colored curves as specified in the colorbar). For the EMPW, we report the single band and full band ideal resolutions with dashed black and red lines, respectively.

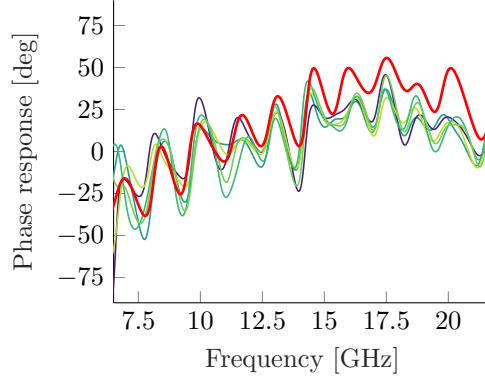


Fig. 7: VNA phase response for a corner reflector (colors blue-yellow indicate 5 different trials) compared to the response of the antenna measured on a point-to-point link (red line).

all the considered carrier frequencies and bandwidth values. Similarly to the corner reflector, the target appears to be slightly less coherent when lower carrier frequencies are considered, i.e., less than 14 GHz. This may be because at higher carrier frequencies, the dimensions of the corner reflector and metal plate become large compared to the wavelength, reducing border effects and non-idealities. Another possibility is that the slight incoherence for frequencies lower than 14 GHz is due to the flatter phase response of the antenna in the range 14-22 GHz (see Fig. 7). The coherence obtained by combining 15 GHz of bandwidth is slightly lower than in the corner reflector case. The NMPM is also quite constant and shows the most significant degradation (2.1 dB)

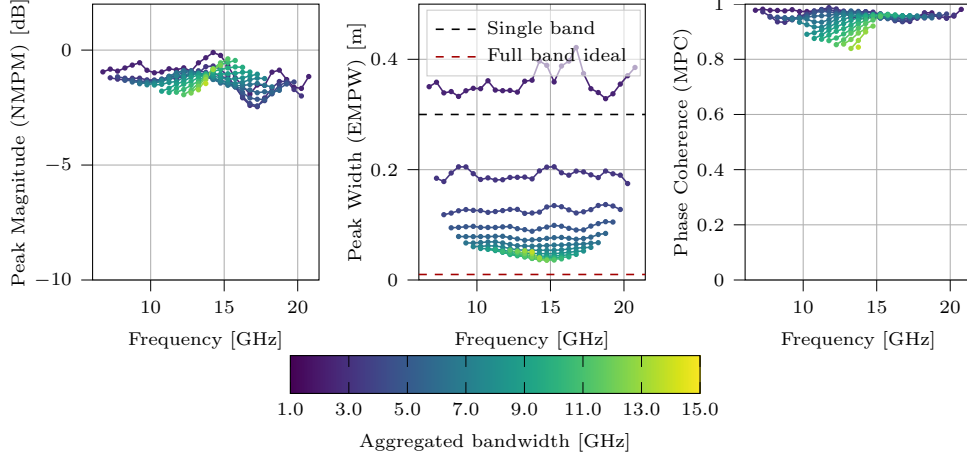


Fig. 8: Coherence metrics of a metal plate target in the range 6-22 GHz. The bandwidth of a single subband is 0.5 GHz. We report the NMPM, EMPW, and the MPC obtained for different carrier frequencies (on the x -axis) and different total combined bandwidth (corresponding to the different colored curves as specified in the colorbar). For the EMPW, we report the single band and full band ideal resolutions with dashed black and red lines, respectively.

when combining 1 to 4 GHz of bandwidth around a carrier frequency of 17 GHz. As in the corner reflector case, since this degradation at 17 GHz is not evident in the MPC, it is likely due to the antenna response or to a residual effect of the measurement device rather than to a property of the target. The EMPW shows that the main peak width of the target consistently shrinks when the combined bandwidth increases, except for very wide bandwidth values above 13 GHz. In this case, the resolution stops improving and slightly degrades, increasing the peak width. This can be appreciated in Fig. 8 by observing that the EMPW corresponding to $B_{\text{tot}} = 15$ GHz is higher than its $B_{\text{tot}} = 12$ GHz counterpart, meaning that the effective range resolution of the system degrades. This is in line with the phase coherence degradation observed for very wide combined bandwidths.

In Fig. 9, we report our results for the human target, which include measurements with a person at 1 m and 1.2 m from the measurement device, performing frequency sweeps with 1 GHz bandwidth for a single subband. In this case, MPC shows a decreasing trend with an increasing carrier frequency. This trend is consistent across multiple values of the combined bandwidth. A bandwidth of 2 GHz can be combined with a moderate decrease in the coherence, which is over 0.8 for all carrier frequencies. Conversely, combining bandwidths over 3 GHz significantly degrades the phase coherence down to lower than 0.5. This indicates that a human does not provide a coherent point reflector-like response when increasing the resolution to the cm-level, differently from the corner reflector or metal plate targets. Although the time taken for a frequency sweep is at most 150 ms in this case (see the [Measurement system and experimental protocol](#) section), for high carrier frequencies and wide bandwidth, minimal movements of the subjects could also contribute to slightly degrade coherence. The NMPM and EMPW metrics are in agreement with the MPC. The EMPW

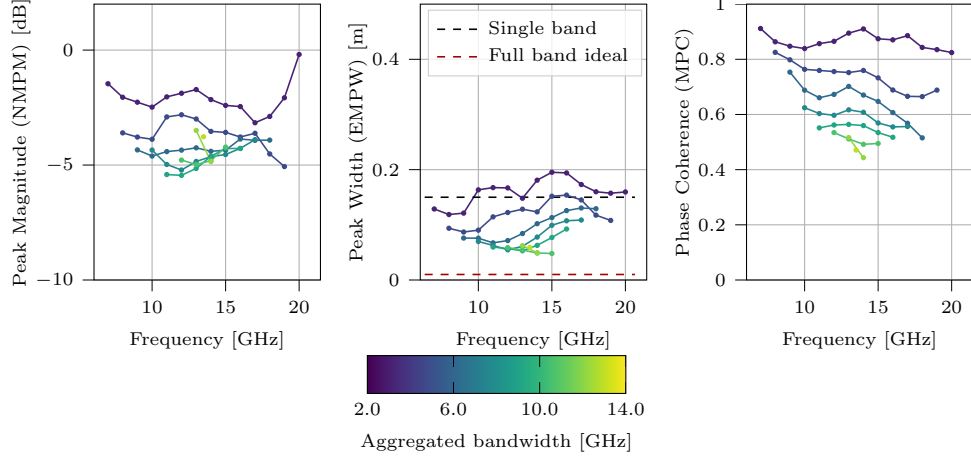


Fig. 9: Coherence metrics of a human target in the range 6-22 GHz. The bandwidth of a single subband is 1 GHz. We report the NMPM, EMPW, and the MPC obtained for different carrier frequencies (indicated on the x -axis) and different total combined bandwidth (corresponding to the different colored curves as specified in the colorbar). For the EMPW we also report the single band and full band ideal resolutions with dashed black and red lines, respectively.

falls to -5 dB around $17 - 18$ GHz carrier frequency and shows an irregular behavior compared to the corner reflector and metal plate cases. The EMPW shows that the resolution gain for the human target is higher at lower carrier frequencies, which is consistent with the lower coherence of the subbands for higher carrier frequencies observed in the MPC and NMPM. This could be because at higher frequencies the wavelength of the signal interacts differently with (i) body tissues due to the higher penetration depth compared to conducting materials, and (ii) the roughness of the targets, including clothes and different body parts. In complex targets such as humans, this produces an unpredictable effect on the scattering phase.

Remark: We verified that changes with respect to the corner reflector and metal plate results are due to the different target and not to hardware artifacts due to the wider employed bandwidth (1 GHz compared to 0.5 GHz). Specifically, the average MPC obtained with 1 GHz subbands with the corner reflector and 15 GHz combined bandwidth (worst case) is 0.77, while the NMPM and EMPW are -2 dB and 2.5 cm, respectively. These values are comparable to those obtained with 0.5 GHz subbands and indicate significantly higher coherence than those obtained with a human target.

Multitarget resolution

In this section, we evaluate the multitarget resolution capabilities of multiband processing with non-contiguous subbands. We present experimental results using spectrum portions being considered for FR3 frequency allocations by 3GPP [4, 15], discussed at the World Radio Congress (WRC) in 2023. Specifically, we consider the spectrum portions $7.125 - 10.5$ GHz, $12.7 - 13.25$ GHz, and $14.8 - 17.35$ GHz, divided into 5 subbands determined by the frequency intervals $S_1 = [7.125, 8.5]$ GHz, $S_2 = [8.5, 10.5]$ GHz, $S_3 = [12.7, 13.25]$ GHz, $S_4 = [14.8, 15.35]$ GHz, and $S_5 =$

[15.35, 17.3] GHz. Our measurement system collects CFR measurements with 0.5 or 1 GHz bandwidth granularity, depending on whether we consider object targets (corner reflector or metal plate) or human targets, respectively. Therefore, in the following experiments, we approximate the 3GPP intervals with sets of subbands collected by our system that include them, but do not match exactly the 3GPP bands. We define $\mathcal{F}_i$ as the subset of subbands taken from the full set of measured subbands, $\{6.5, 7, \dots, 22\}$ GHz, that approximates the frequency interval S_i , with $i \in \{1, \dots, 5\}$.

We verified that this approximation does not significantly change the resulting Range Ambiguity Function (RAF), which we analyze in the next section.

The RAF represents the response of the multiband ISAC systems to a point-like ideal reflector and highly depends on the location of the available subbands in the frequency domain and on their bandwidth. We thoroughly discuss how to compute it in the [Backprojection algorithm](#) section, for different cases. In this case, we use the RAF expression of Eq. (18), assuming frequency isotropic targets.

In Fig. 10, we represent the ideal RAF obtained by combining different combinations of the 5 subbands. The aggregation of such a wide bandwidth with algorithms that assume a frequency isotropic target only makes sense for coherent targets like corner reflectors or metal plates, as discussed in the [Multiband target coherence](#) section.

Using $\mathcal{F}_1$ and $\mathcal{F}_2$ gives over 3 GHz of *contiguous* bandwidth, which leads to a resolution of 4.4 cm. Similarly, the combination of $\mathcal{F}_4$ and $\mathcal{F}_5$ also provides a wide contiguous frequency band with a resolution of 4.9 cm. Aggregating different combinations of the 5 subbands improves the resolution at the cost of introducing grating lobes due to the non-contiguity of the subbands. Notably, aggregating $\mathcal{F}_2$ and $\mathcal{F}_3$ causes high grating lobes spaced by around 7 cm that make this combination unsuitable for accurate ranging with multiple targets. Aggregating all the 5 subbands gives the highest nominal resolution of 1.46 cm, but the RAF exhibits a pair of grating lobes close to the main peak around 6 dB below the main peak. This reduces the nominal resolution in practice, especially in the case of close targets with very different Radar Cross-Sections (RCSs). Combining $\mathcal{F}_1, \mathcal{F}_2, \mathcal{F}_3$ or $\mathcal{F}_3, \mathcal{F}_4, \mathcal{F}_5$ lowers the grating lobes at the cost of a worse resolution (around 2.5 cm). Notably, in this case, using $\mathcal{F}_3, \mathcal{F}_4, \mathcal{F}_5$ is preferable since it leads to a narrower frequency gap and, in turn, 2.5 dB lower grating lobes. However, it may still be insufficient to properly resolve targets in practice if no compensation for the grating lobes is applied.

In Fig. 11, we report the multiband range profile squared magnitude obtained by BP, OMP, and SPBP with two targets: a corner reflector and a metal plate. For OMP, we use a grid spacing of 1 mm, since it is an on-grid method. In Fig. 11a, we use a contiguous bandwidth given by the union of subbands with carrier frequencies in $\mathcal{F}_1 \cup \mathcal{F}_2$, so SPBP is not used since grating lobes are absent. While OMP only detects one target, BP correctly resolves both and matches their real location with an error of a few centimeters. However, as shown in Fig. 11b, when using a non-contiguous bandwidth including all the subbands $\mathcal{F}_1, \dots, \mathcal{F}_5$, the grating lobes significantly degrade the multiband range profile. BP and SPBP exhibit significant grating lobes, and identifying the two targets is infeasible from the resulting multiband range profile. In Fig. 11c we show the range profile obtained using non-contiguous subbands $\mathcal{F}_1, \mathcal{F}_2$ and

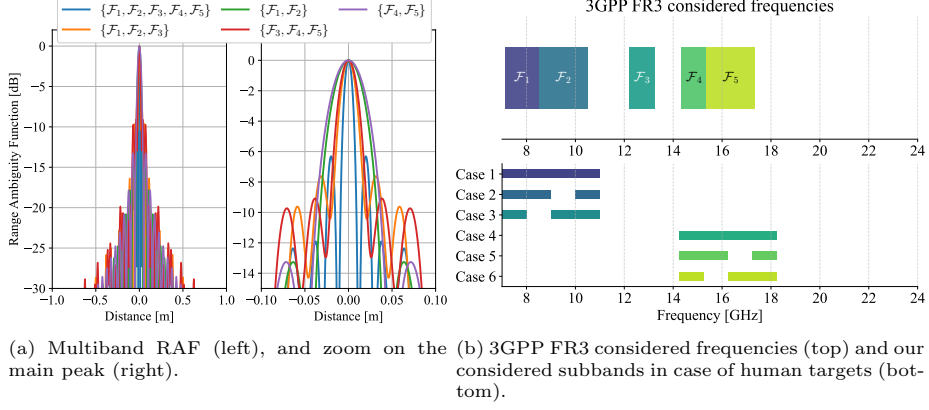


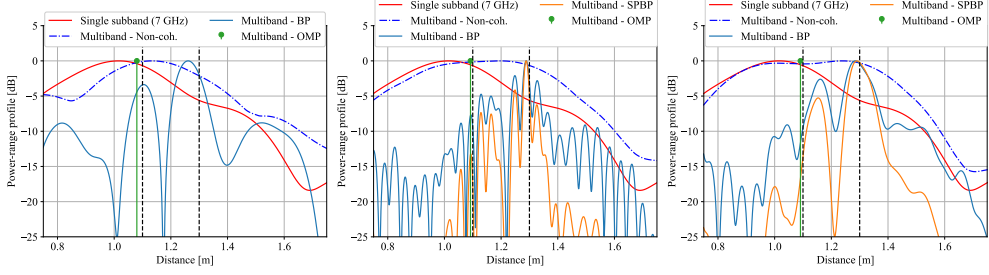
Fig. 10: RAF of different combinations of the multiband sets considered by 3GPP (a), 3GPP subbands and different sub-allocations considered in our experiments (b).

$\mathcal{F}_3$, which occupy a less fragmented spectrum portion than the previous case. BP can identify the two targets but is affected by significant grating lobes that reach up to -6 dB from the weaker target. SPBP instead lowers the grating lobes down to -13 dB lower than the weaker target, improving the overall quality of the range profile. The cost for this improvement is a relative reduction of the magnitude of the weaker target with respect to the stronger one.

In Fig. 12, we show the range profile squared magnitude for two human targets with a contiguous bandwidth of 4 GHz (Fig. 12a) and with a non-contiguous bandwidth of the same aperture (Fig. 12b). Even in this case, we observe the impact of grating lobes on the results of BP, which is significantly mitigated by using SPBP instead. Specifically, in Fig. 12b, the two subjects represented by BP as 4 different peaks of different magnitude, while SPBP can correctly reconstruct two distinct peaks. Notably, non-coherent processing produces wide peaks with low resolution. This is because with human targets, the location of the peaks in each subband changes slightly. We observe this phenomenon to be more significant with humans than with the corner reflector and the metal plate. During the CIR averaging operation, this causes a loss of accuracy in the localization of each peak.

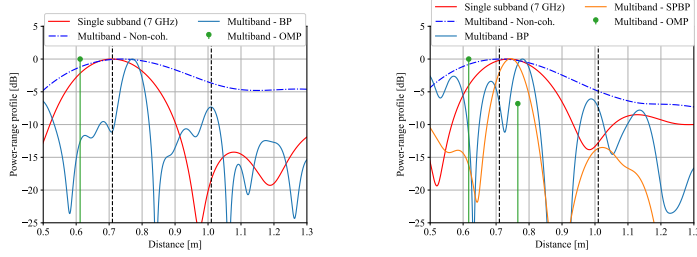
In Fig. 13, we show the average number of targets (Fig. 13a) and OSPA (Fig. 13b) over 100 tests obtained using two targets: a corner reflector and a metal plate. Targets are located approximately 1.2 m from the measurement device and spaced by $d_{\text{trg}} = 0.2$ m. The ground truth target locations are obtained with a laser telemeter. For a given target and set of measurements, the laser readings contain a systematic bias with respect to the exact reflection points of the radio signal on the target. For this reason, a discrepancy exists between the ground truth and the actual locations reconstructed by the multiband processing algorithms. To mitigate this source of error, we align the final obtained range profiles to the ground truth with a rigid translation along the range dimension.

We use different combinations of the 5 subbands $\mathcal{F}_i$, with $i = 1, \dots, 5$, and a cardinality penalty $\mu = d_{\text{trg}}$, so that in the OSPA errors larger than the distance between the two targets are penalized as a missed detection.



(a) Contiguous bandwidth using $\mathcal{F}_1$ and $\mathcal{F}_2$. (b) Non-contiguous bandwidth using $\mathcal{F}_1, \dots, \mathcal{F}_5$. (c) Contiguous bandwidth using $\mathcal{F}_1, \mathcal{F}_2$, and $\mathcal{F}_3$.

Fig. 11: Qualitative example of the combination of multiple subbands using BP, OMP, and SPBP on corner reflector and metal plate targets with contiguous subbands (a), strongly non-contiguous subbands (b), and moderately non-contiguous subbands (c). Black dashed lines represent the approximate real location of the targets, measured with a laser telemeter.



(a) Contiguous bandwidth 7-11 GHz (b) Gapped bandwidth 7-11 GHz (case 1). BP resolves the two subjects. 3). SPBP mitigates the grating lobes due to non-contiguous subbands.

Fig. 12: Qualitative example of the range profile squared magnitude obtained with the combination of multiple subbands using non-coherent processing, BP, OMP, and SPBP on two human targets with contiguous (a) and non-contiguous (b) subbands. Black dashed lines represent the approximate real location of the targets, measured with a laser telemeter.

Non-coherent processing has insufficient resolution to distinguish the two targets, since it has the same resolution as the single-band CIRs. Consequently, it only detects a single peak in most cases, and its OSPA is always over 12 cm. The performance does not change significantly when using different sets of bands, since only the SNR is affected by the number of aggregated subbands. This shows the limitations of non-coherent processing when targets are closely located in space.

Similarly, OMP only detects one target in most of the tests. It achieves the worst OSPA performance, as it is almost always penalized due to outputting the wrong cardinality for the set of targets. The unsatisfactory performance of OMP is not due to insufficient resolution but to its sensitivity to model errors. Even a slight incoherence among the subbands introduces a model error in the OMP formulation, which assumes perfect coherence. This results in unpredictable effects in the OMP reconstruction and in a loss of resolution.

When using contiguous sets of subbands, i.e., $\mathcal{F}_1$ and $\mathcal{F}_2$ or $\mathcal{F}_4$ and $\mathcal{F}_5$, only $\mathcal{F}_1$, SPBP is not used since the grating lobes due to non-contiguous subbands are not present. Hence, in these cases, SPBP is represented with the same performance as BP.

BP works well with contiguous subbands, obtaining an accurate estimate of the number of targets and 5 cm OSPA with $\mathcal{F}_1 \cup \mathcal{F}_2$, and 7.5 cm OSPA with $\mathcal{F}_4 \cup \mathcal{F}_5$. This shows that the multiband range profile correctly reconstructs the number and locations of the two targets.

Conversely, BP has degraded performance when non-contiguous subbands are used. Using $\mathcal{F}_1 \cup \mathcal{F}_2 \cup \mathcal{F}_3$ and $\mathcal{F}_3 \cup \mathcal{F}_4 \cup \mathcal{F}_5$ BP detects on average 3.15 ± 0.57 and 3.18 ± 0.90 targets, respectively, showing that even a smaller frequency gap can lead to the wrong estimation of the number of targets. The resulting OSPA reflects this, increasing with respect to the contiguous case to 7.15 ± 2.1 cm and 9.33 ± 2.3 cm, respectively. SPBP instead estimates on average 2.20 ± 0.40 and 2.34 ± 0.53 targets with $\mathcal{F}_1 \cup \mathcal{F}_2 \cup \mathcal{F}_3$ and $\mathcal{F}_3 \cup \mathcal{F}_4 \cup \mathcal{F}_5$, respectively, which well approximate the real number. The resulting OSPA outperforms that of BP

Using all subbands $\mathcal{F}_1, \dots, \mathcal{F}_5$ introduces strong grating lobes, caused by the non-contiguity of the subbands, degrading the performance of all methods. In this case, BP detects on average 9.19 ± 0.87 targets, with an OSPA of over 15 cm. SPBP only provides a slight gain but is also not able to estimate the correct number of targets, detecting 8.62 ± 1.17 targets on average.

In Fig. 14, we show the number of detected targets and OSPA obtained by SPBP for different values of the SNR from -5 dB to 15 dB. To lower the SNR in our measurements, we artificially added noise to the CFR in each subband. Using sets $\mathcal{F}_1, \dots, \mathcal{F}_5$, the SNR does not impact the OSPA significantly, since the main source of error is due to the grating lobes. In the other cases, SPBP is robust to the SNR variation as long as it is larger than or equal to 0 dB, while it increases significantly for an SNR of -5 dB. This demonstrates that although SPBP reduces the SNR on the CIR, as discussed in the [Subsets Product BP algorithm](#) section and in Supplementary note 4, the grating lobes reduction more than compensates this drawback.

In Fig. 15, we show the mean number of targets (Fig. 15a) and OSPA (Fig. 15b) over 25 tests obtained using two human targets. The two subjects are located approximately 1 m from the measurement device and spaced by 30 cm. Since human targets exhibit degraded coherence over very wide combined bandwidth, as shown in the [Multi-band target coherence](#) section, we consider narrower frequency ranges as shown in the bottom plot in Fig. 10b.

Cases 1 and 4 represent contiguous 4 GHz bandwidth allocations, which, according to Fig. 9, give a target coherence of above 0.75 . From this, we expect humans to cause a single dominant peak in the multiband range profile, which would not be the case for a wider bandwidth combination. The remaining cases are non-contiguous bandwidth allocations obtained by removing 1 GHz bandwidth chunks, at different locations, from cases 1 and 4.

Fig. 15a shows that BP overestimates the number of targets in all cases, with an average of 3.75 ± 0.31 across all cases. Conversely, non-coherent processing and OMP have the same problem observed with the corner reflector and metal plate, i.e., they

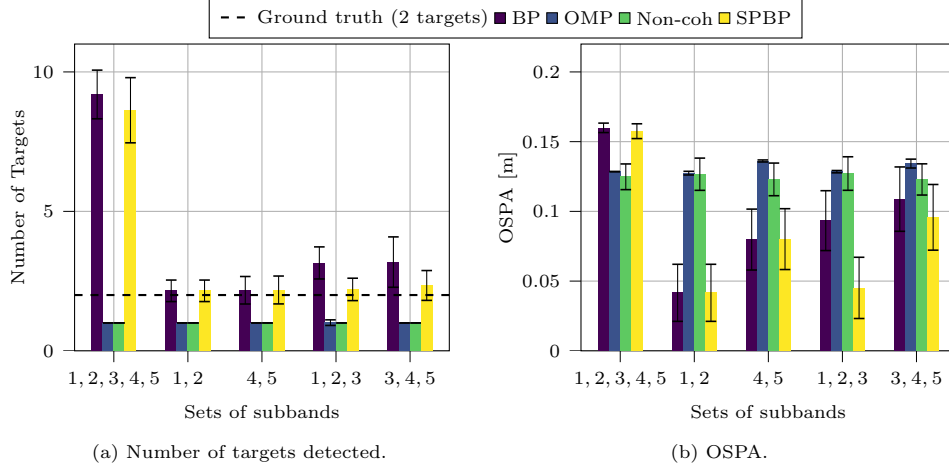


Fig. 13: Average number of targets (a) and OSPA (b) obtained by BP, OMP, non-coherent processing, and the proposed SPBP on corner reflector and metal plate targets. The black whiskers represent one standard deviation. SPBP outperforms the other two algorithms by better reconstructing the correct number of targets and obtaining the lowest OSPA. When using the full set of subbands $\mathcal{F}_1, \dots, \mathcal{F}_5$, none of the algorithms can correctly detect the two objects.

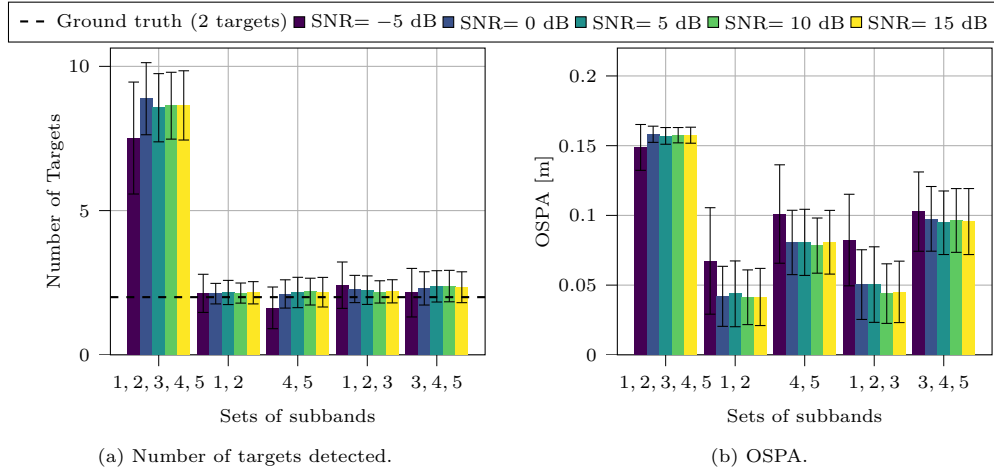


Fig. 14: Average number of targets (a) and OSPA (b) obtained by the proposed SPBP on corner reflector and metal plate targets, varying the SNR on the CFRs of the single subbands. The black whiskers represent one standard deviation. SPBP is robust to SNR degradation down to -5 dB, where the OSPA increases significantly. The OSPA using sets $\mathcal{F}_1, \dots, \mathcal{F}_5$ is dominated by the grating lobes and not affected by the SNR variation.

can not resolve the two targets. SPBP obtains a more accurate estimation of the real number of targets, with an average of 2.46 ± 0.68 detected targets over all cases.

Fig. 15b confirms that SPBP outperforms both BP and OMP on our measurements. Averaging over all tests, SPBP has an OSPA of 12.25 ± 1.54 cm, compared to the

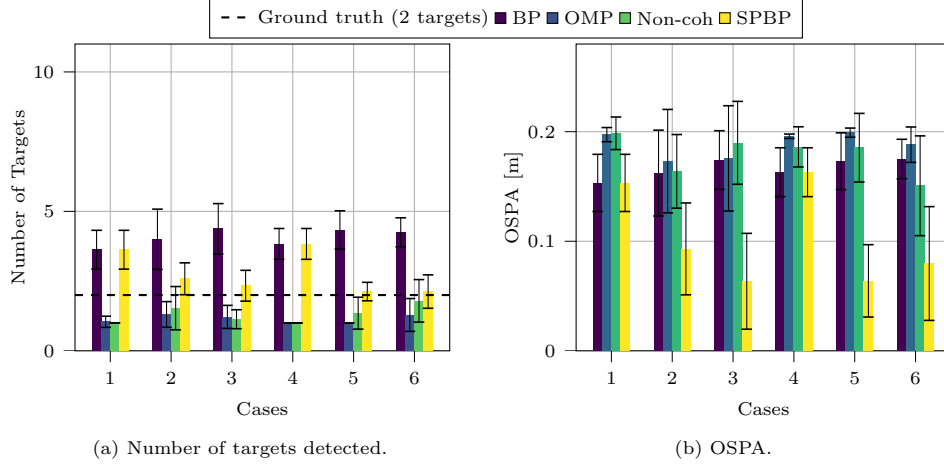


Fig. 15: Number of targets (a) and OSPA (b) obtained by BP, OMP, non-coherent processing, and the proposed SPBP on two human targets. The black whiskers represent one standard deviation. SPBP outperforms the other two algorithms by better reconstructing the correct number of targets and obtaining the lowest OSPA.

15.45 ± 1.19 and 16.01 ± 1.34 cm of BP and OMP, respectively. Fig. 15b also agrees with the results in Fig. 9, showing that humans are less coherent at higher frequencies. This can be seen from the fact that the OSPA in cases 4 – 6 (frequencies from 14 to 18 GHz) of BP is slightly higher than that of cases 1 – 3 (frequencies from 7 to 11 GHz).

We now evaluate the performance of SPBP in more realistic scenarios where: (i) we remove the radio frequency absorbing panels, as shown in Fig. 18, so that multipath signal components reflected and scattered from the environment are present (including tables, chairs, screens, etc.), and (ii) we consider two targets with significantly different RCS, namely a human subject (lower RCS) and a corner reflector (higher RCS). In these experiments, we use a baseband bandwidth of 500 MHz for the single subbands.

In Fig. 16, we show the number of detected targets and OSPA obtained with two corner reflectors in a multipath-affected scenario. We consider the 3GPP sets of subbands defined in the top part of Fig. 10. The performance of SPBP is comparable to that without multipath, shown in Fig. 13, demonstrating that our approach is robust to multipath interference. This is because multipath components are easily separated from the target-related contribution in the CIR, unless they appear at a very similar range. In this case, the contributions should be separated using information from other domains such as Doppler or Angle of Arrival (AoA).

In Fig. 17, we show the number of detected targets and OSPA obtained with a human subject and a corner reflector in a multipath-affected scenario. The two targets have different RCS, with the corner reflector causing a much stronger reflection. We consider the sets of subbands defined in cases 1-6 in the bottom part of Fig. 10. SPBP increases the relative differences in the targets' RCSs, as discussed in the [Subsets Product BP algorithm](#) section and in Supplementary note 4. Nevertheless, its performance is still superior to other methods used for comparison, although the gap in performance with respect to BP is slightly reduced with respect to Fig. 15, where we consider two human targets with comparable RCS.

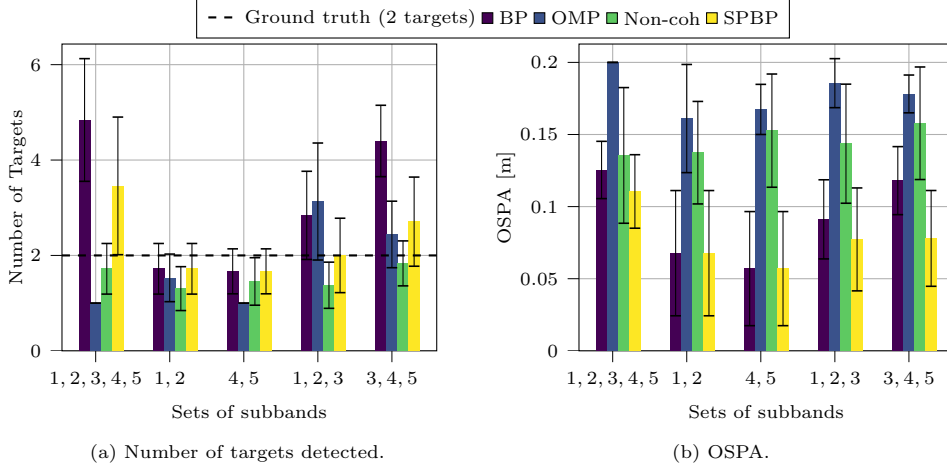


Fig. 16: Number of targets (a) and OSPA (b) obtained by BP, OMP, non-coherent processing, and the proposed SPBP on two corner reflectors in the presence of *multipath reflections* from the surroundings. The black whiskers represent one standard deviation.

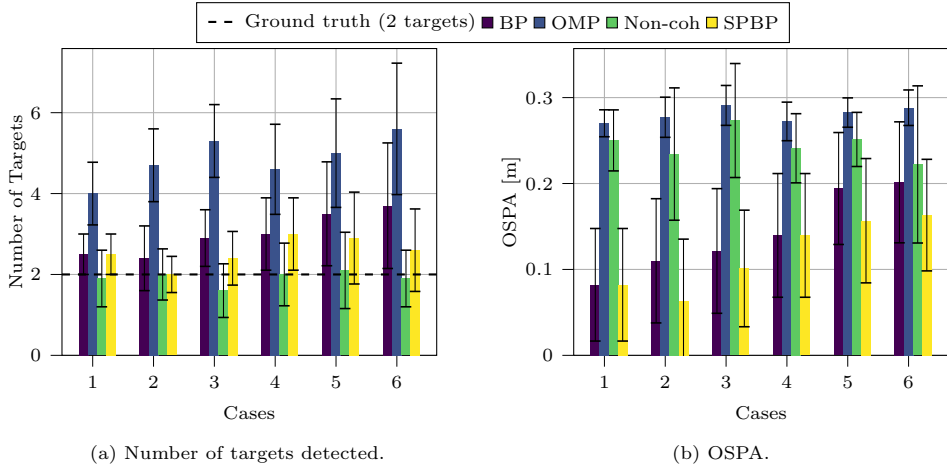


Fig. 17: Number of targets (a) and OSPA (b) obtained by BP, OMP, non-coherent processing, and the proposed SPBP on a human subject and a corner reflector in the presence of *multipath reflections* from the surroundings. The black whiskers represent one standard deviation.

In the experiments, human targets were standing still and were asked to avoid any possible movement, while the total frequency sweeping lasted no more than 150 ms. In the following, we provide a numerical example to clarify the impact of small involuntary body movements on the result.

Consider, for example, a displacement of the torso of 2 mm within the 150 ms sweep time. This corresponds to an average moving speed of 1.3 cm/s (involuntary movements are likely even slower). The 2 mm displacement corresponds to, approximately,

- 1/21 of the wavelength at 7 GHz. This causes a phase displacement of 16.8° . In terms of the proposed MPC metric, this is negligible in terms of phase coherence since it corresponds to a reduction of the MPC from 1 to 0.989.
- 1/10 of the wavelength at 15 GHz. This causes a phase displacement of 36° , which lowers the MPC from 1 to 0.951. We consider this to be still almost negligible compared to the more significant effects due to the target’s reflectivity.
- 1/7 of the wavelength at 22 GHz. This causes a phase displacement of 52° , which lowers the MPC from 1 to 0.899. This variation is small but may bias the evaluation of the MPC when considering higher frequencies.

From the above discussion, we conclude that small movements of the human body may slightly affect the MPC evaluation at higher frequencies, around 20 GHz.

Nevertheless, the small body movements are *inevitable* in practice, and would be larger in real ISAC settings when subjects are not instructed to stay still. In this sense, our paper analyzes the *best case*, which minimizes the possible incoherence due to movement thanks to the short sweep time and absence of voluntary movement. Incoherence due to small motions may be regarded as an *intrinsic feature* of human targets, which is always present in practice and can not be separated from the incoherence due to the target shape and reflectivity.

Discussion

In this work, we experimentally characterize the frequency-dependent scattering response of ISAC targets for coherent multiband sensing algorithms in FR3 (6–22 GHz). We propose three new metrics to evaluate the coherence of the target response over the considered bandwidth: the Multiband Phase Coherence (MPC), the Normalized Multiband Peak Magnitude (NMPM), and the Empirical Multiband Peak Width (EMPW). We test and validate these metrics on multiband scattering response data of a corner reflector, a metal plate, and human targets, demonstrating their effectiveness in capturing key aspects of coherent multiband ranging quality. We assess the impact of using non-contiguous subbands and the consequent grating lobes on the resolution of multiple targets. To mitigate the impact of grating lobes, we propose a heuristic algorithm (SPBP) and experimentally demonstrate its superiority to BP and OMP, using FR3 bands considered by 3GPP, in terms of target detection and OSPA.

Our results demonstrate that the high fractional bandwidth of FR3 frequencies is a critical aspect to take into account when applying coherent multiband ISAC. The **main takeaways** of our work are summarized as follows.

1. Different targets exhibit different **frequency-dependent behavior** and have coherent responses over different carrier frequencies and bandwidths.
2. Frequency anisotropy poses a **hard limit** on coherent multi-band data fusion. *Compensating* for anisotropy across frequency bands would lead to reconstructions that misrepresent the true scattering behavior of the object and would introduce artifacts lacking physical meaning. A more meaningful approach that preserves the physical properties of the target is to **limit the coherent processing** only over a set of subbands for which the target is phase-coherent.

3. While corner reflectors and flat metal surfaces are coherent over wide frequency ranges (almost the whole FR3), **more complex targets** such as humans have an **incoherent response** if more than 3-4 GHz bandwidth is used.

4. Our experiments suggest that **higher carrier frequencies** (above 14 GHz) lead to a **less coherent response** for human targets. The carrier frequency dependency of the target response aspect is not considered in the current ISAC literature but is here shown to be significantly impacting the multiband combination result. Further research is needed on this aspect to determine whether this is a characteristic of the target or a consequence of slight movement of the person during the frequency sweep time, which leads to a larger phase variation at higher frequencies. This aspect is discussed at the end of the [Multitarget resolution](#) section.

5. Using the currently considered allocations for wireless networks in FR3 by 3GPP, one must carefully consider the impact of grating lobes on coherent multiband ranging. Our results indicate that, **even for coherent targets** (e.g., corner reflectors or metal plates), combining all the considered non-contiguous subbands over a wide bandwidth leads to a **degraded range profile** due to the grating lobes. Therefore, it is key to design algorithms that mitigate the grating lobes to fully reap the benefit of the wide total frequency aperture in FR3.

6. Our results with the proposed SPBP algorithm suggest that (i) using non-contiguous bands with **intermediate aperture sizes**, and (ii) combining **different subsets** of the available subbands in a **non-linear** fashion to cancel out the grating lobes represent interesting research directions to enable coherent multiband ranging in FR3.

Most of the existing radar literature on target anisotropy has focused on *spatial anisotropy*, see, e.g., [16–18], using a single frequency band. The frequency anisotropy of targets has been studied in [18–22]. These works have applied the Prony model [19] or Geometrical Theory of Diffraction (GTD) [23, 24] to explicitly model the frequency dependency of the complex-valued RCS of the targets. However, these models are only accurate for targets with predefined shapes, such as curved surfaces, edges, corners, flat plates, etc. This limits their usability in practice for complex targets, such as humans, and does not provide direct insight into the coherence of targets over wide frequency bands. In Ultra-Wide Band (UWB) radar [25] instead, frequency anisotropy is typically not modeled, and the observed complex-valued RCS of the targets over very wide contiguous bands is considered an average response over the total bandwidth.

In the ISAC literature, fewer works have tackled this aspect by either experimentally measuring the real-valued RCS of targets in multiple bands [9], or using neural networks to learn the target response across a wide frequency aperture [8] without modeling phase coherence explicitly.

The frequency anisotropy characterization done in this work takes a new and different approach compared to the above papers. Rather than directly modeling the behavior of the scattering phase, we design new practical metrics that can be used to *assess* the coherence of a target’s response in multiple bands either before (MPC) or after applying multiband combination (NMPM, EMPW). The proposed metrics provide insights into when it is feasible or convenient to use multiband processing with data collected from practical ISAC devices, especially in high fractional bandwidth scenarios like FR3.

Our result regarding the decreasing coherence of human targets with increasing carrier frequencies within the range 6-22 GHz, given the same combined bandwidth, has not been observed before in the ISAC literature, which has previously considered coherence to be independent of the carrier frequency [7, 8]. This encourages further research to characterize the coherence in the sub-6 GHz and Millimeter-Wave (mmWave) frequency ranges.

Several works in the literature address multiband coherent processing for radar [26–32] or ISAC [7, 8, 33–37] using non-contiguous bands. These works assume frequency isotropic target response [7, 29, 36, 37] or use GTD [26, 31] to simplify the frequency dependence of the complex-valued RCS. The employed algorithms to compensate for the non-contiguous bandwidth rely on all-pole modeling of the signal in the two bands [26, 27, 32] or CS [7, 8, 34, 37]. Both approaches suffer from high computational complexity and *model mismatch* in case the target is not isotropic or does not satisfy the GTD model, which significantly degrade the performance. Our results specifically show that the OMP CS algorithm is unable to resolve two targets in most cases, due to slight incoherence among different subbands and the consequent model mismatch.

The work in [33] compensates for the incoherence of targets, eliminating phase differences in the scattering response due to frequency anisotropy. Although this allows multiband processing of the multiband data even under incoherence of the target, the resulting output may be misleading since it fails to capture intrinsic frequency-dependent features of the targets and reconstructs a single synthetic scattering point that may not represent a physical scattering point.

The approach used in this paper is instead to limit the aperture of the considered multiple subbands to a frequency range where the target is coherent according to the proposed metrics. Then, we propose the SPBP algorithm with limited computational complexity that does not require explicit modeling of the target phase response as a function of frequency and mitigates the grating lobes.

This work also fills a gap in terms of experimental measurements for coherent multiband ISAC in FR3. Previous work has extensively provided incoherent radar RCS measurements in the S, X, Ku, and K bands [21, 38–40]. Notably, these works do not address the *combination* of multiple bands in a coherent fashion, which is the key problem considered in this paper. In the ISAC literature, some works have characterized the communication channel in FR3 [9, 41, 42], the real-valued RCS of targets [9, 42–45], or the ISAC channel [46]. However, these works do not analyze the *phase coherence* of targets in FR3, which is critical for coherent multiband ISAC. Moreover, most of the above studies consider a limited set of carrier frequencies and bandwidths in FR3, e.g., only 6.5 GHz and 8.5 GHz in [46]. Other works [47–49] have tackled multiband active localization where the objective is to compute the range of a communication device. Since no passive targets are involved, frequency anisotropy does not pertain to these works, and the proposed approaches do not model it.

To the best of our knowledge, this is the first study providing an evaluation of coherent multiband processing over almost the *whole* FR3 (6-22 GHz), with a focus on coherent multiband ISAC algorithms. The obtained results shed light on key aspects of multiband FR3 ISAC and represent a first step towards designing multiband

algorithms for 6G wireless networks and planning spectrum allocation for maximum coherent multiband aggregation performance.

Further research should incorporate the concept of frequency anisotropy into the design of algorithms for coherent multiband aggregation. For example, the experimental characterization of the scattering phase from complex targets could be leveraged to build statistical models, used as inputs for new aggregation algorithms. Data-driven approaches stand out as promising candidates to extract non-linear frequency-dependent target scattering properties in this sense.

Moreover, further investigation of the SPBP approach for grating lobes mitigation should be conducted, addressing the attenuation of weaker targets with respect to dominating ones. This aspect represents a challenging problem in complex ISAC scenarios with multiple targets having RCSs with orders of magnitude differences.

Finally, the target anisotropy characterization should be extended to the *spatial dimension*, evaluating the phase coherence for different incidence angles of the ISAC signals. Indeed, complex extended targets may exhibit different scattering properties at different angles, which is not addressed in the ISAC literature [12]. This aspect is critical to enable coherent ISAC processing over multiple distributed nodes, such as different base stations or access points.

Methods

In this section, we describe the methodology used in this work, including the mathematical system model, the description of the algorithms used, and details on the experimental data collection. Some of the experiments conducted in this work involve RF measurements with human subjects. Such experiments do not collect any personal data or sensitive information about the subjects, are not linked to the identity of the individuals involved, pose no harm to their health, and do not constitute a clinical trial. All the experiments were conducted in accordance with the ethical regulations of the Polytechnic University of Milan, Italy, which does not require the approval of an Ethical Committee for this kind of data. The involved subjects provided their informed written consent.

System and signal models

In this work, we consider a multiband Single Input Single Output (SISO) system with a transmitter (Tx) antenna and a receiver (Rx) antenna, which share the same Local Oscillator (LO). The SISO system operates on K subbands, each centered on a carrier frequency f_k and of bandwidth B_k . We collect the carrier frequencies and bandwidths in sets $\mathcal{F} = \{f_k\}_{k=0}^{K-1}$, and $\mathcal{B} = \{B_k\}_{k=0}^{K-1}$, respectively. We assume that L static scattering centers are present in the environment, indexed by $\ell = 1, \dots, L$, located at distances R_ℓ from the SISO ISAC terminal. Each sensing target may be composed of a single scattering center or *multiple* scattering centers (extended target, for example, a human body), which are only resolved by the ISAC system if sufficient bandwidth is available. Therefore, the number of sensing targets is, in general, lower than or equal to L .

Each scattering center is characterized by a complex *frequency-dependent* RCS, $\rho_{\ell,k}e^{j\theta_{\ell,k}}$, whose magnitude $\rho_{\ell,k}$ and phase $\theta_{\ell,k}$ contain the effect of the combined path loss and scattering attenuation, and of the scattering phase response, respectively. Obtaining an explicit model for $\rho_{\ell,k}e^{j\theta_{\ell,k}}$ as a function of frequency is hard. The phase of the ℓ -th scattering center, in general, is a function of its physical composition, namely material, wave polarization, angles of incidence and observation, and frequency of operation. We characterize scattering centers from a single monostatic angle of observation and a single polarization, observing the implicit relation between the target's material, shape, and carrier frequency. Existing works have found models that hold for specific classes of ideal scatterers using GTD [23]. In this paper, instead, we do not explicitly model $\rho_{\ell,k}e^{j\theta_{\ell,k}}$ and rather evaluate its variation across frequency indirectly, using the metrics in the [Performance metrics](#) section. We stress that while existing multiband ISAC works model the RCS as constant across frequency in both magnitude and phase [7, 8], this is the first ISAC work to consider the frequency anisotropy of the targets and its impact on multiband processing.

The SISO ISAC system emits an OFDM signal over the K subbands, each subband having N_k subcarriers and fixed subcarrier spacing Δ_f . The propagation delay from the ℓ -th scattering center is $\tau_\ell = 2R_\ell/c$, with c being the speed of light and R_ℓ the distance between the scattering center and the ISAC device, respectively. To perform a frequency sweep of multiple subbands, one OFDM symbol per subband is emitted sequentially in time, as detailed in the [Measurement system and experimental protocol](#) section.

The baseband signal for the k -th OFDM symbol (hence for the k -th subband), assumed to have unit-power, is

$$x_k(t) = \sum_{n=-\frac{N_k}{2}}^{\frac{N_k}{2}-1} a_n e^{j2\pi n \Delta_f t}, \quad \text{for } t \in [kT, kT + T] \quad (4)$$

where $a_n \in \mathbb{C}$ is the frequency domain sequence of known preamble pilots, equal for all subbands, N_k is the number of subcarriers for subband k , and $T = 1/\Delta_f$ is the duration of the OFDM symbol. The pass-band Tx signal is

$$x_k^{\text{RF}}(t) = x_k(t) e^{j2\pi f_k t}. \quad (5)$$

The Tx signal propagates through the environment and undergoes scattering from the L scattering centers. The SISO CIR is defined as follows

$$h_k(t) = \sum_{\ell=1}^L \rho_{\ell,k} e^{j\theta_{\ell,k}} \delta(t - \tau_\ell), \quad (6)$$

where $\delta(\cdot)$ is the Dirac delta. The scattering amplitude is a function of the distance and of the RCS, $\sigma_{\ell,k}$, given by the *radar equation* [50]

$$\rho_{\ell,k} = \sqrt{\frac{c^2 G_{k,\text{tx}} G_{k,\text{rx}} \sigma_{\ell,k}}{f_k^2 (4\pi)^3 R_\ell^4}} \quad (7)$$

where $G_{k,\text{tx}}, G_{k,\text{rx}}$ are the frequency-dependent antenna gains at the Tx and Rx, respectively.

The Rx signal in the time domain on the k -th subband (thus the k -th OFDM symbol) is the convolution of the Tx signal and the CIR. The Rx then introduces timing errors due to the non-ideality of the LO. We define the timing error on subband k at time t as [51]

$$\epsilon_k(t) = \epsilon_{k,0} + \epsilon_{k,1}t + \epsilon_{k,\text{rnd}}(t) \quad (8)$$

where $\epsilon_{k,0}$ is the Timing Offset (TO), $\epsilon_{k,1}$ is the normalized Carrier Frequency Offset (CFO), and $\epsilon_{k,\text{rnd}}(t)$ is the random timing error due to the phase noise of the LO.

Defining $\Delta\epsilon_{k,\text{rnd}}(t, \tau_\ell) = \epsilon_{k,\text{rnd}}(t - \tau_\ell) - \epsilon_{k,\text{rnd}}(t)$, the passband Rx signal affected by timing errors can be written as

$$\begin{aligned} y_k^{\text{RF}}(t) &= \sum_{\ell=1}^L \rho_{\ell,k} e^{j\theta_{\ell,k}} x_k^{\text{RF}}(t - \tau_\ell + \epsilon_k(t - \tau_\ell) - \epsilon_k(t)) + z_k(t) \\ &= \sum_{\ell=1}^L \rho_{\ell,k} e^{j\theta_{\ell,k}} x_k^{\text{RF}}(t - \tau_\ell + \epsilon_{k,1}\tau_\ell + \Delta\epsilon_{k,\text{rnd}}(t, \tau_\ell)) + z_k(t) \\ &= \sum_{\ell=1}^L \rho_{\ell,k} e^{j\theta_{\ell,k}} \sum_{n=-\frac{N_k}{2}}^{\frac{N_k}{2}-1} a_n e^{j2\pi(f_k+n\Delta_f)t} e^{-j2\pi(f_k+n\Delta_f)\tau_\ell} \\ &\quad \cdot e^{-j2\pi(f_k+n\Delta_f)\epsilon_{k,1}\tau_\ell} e^{j2\pi(f_k+n\Delta_f)\Delta\epsilon_{k,\text{rnd}}(t, \tau_\ell)} + z_k(t). \end{aligned} \quad (9)$$

The signal is corrupted by non-linear clock errors and by an additive white Gaussian noise term, $z_k(t) \sim \mathcal{CN}(0, \sigma_z^2)$. Notably, since we consider a monostatic system, the TOs cancel out in Eq. (9). To simplify the above expression, we make the following assumptions: (i) the CFO does not significantly affect the Rx signal, as it is typically $\epsilon_{k,1} \ll 1$ (for RF clocks, $\epsilon_{k,1} \sim \mathcal{N}(0, 10^{-6})$ and, for distances in the order of meters to tens of meters and FR3 frequencies, the resulting carrier phase rotation $e^{-j2\pi f_k \epsilon_{k,1} \tau_\ell}$ is negligible [12]; (ii) the random time error is much less than the typical pulse duration, i.e., $|\epsilon_{k,\text{rnd}}(t - \tau_\ell) - \epsilon_{k,\text{rnd}}(t)| \ll 1/B_k$, always verified in practice; (iii) the phase rotation due to differential phase noise $\varphi_k(\tau_\ell) = 2\pi f_k \Delta\epsilon_{k,\text{rnd}}(t, \tau_\ell)$ is negligible in the considered monostatic setup. This latter assumption is motivated by applying standard modeling of the LO as a random process with a power law spectrum to our scenario. For typical observation times of tens/hundreds of microseconds and typical ranges of tens of meters (propagation delays τ_ℓ in the order of tens of nanoseconds), the differential phase noise $\varphi_k(\tau_\ell)$ is only due to the white component of the phase spectrum of the LO $S_\phi(\nu)$, namely its variance is $\sigma_{\varphi_k}^2(\tau_\ell) \simeq (f_k/\bar{\nu})^2 2\alpha_0 B_k$ [52] where

α_0 is the power spectral density of the white component of the phase noise and $\bar{\nu}$ is the nominal frequency of the LO. For good clocks, α_0 is low enough to neglect the impact of phase noise. For the considered HW setup, $\alpha_0 = -210$ dBc/Hz, $B_k = 1$ GHz, $f_k = 22$ GHz (max) and $\bar{\nu} = 10$ MHz, thus $\sigma_{\varphi_k}(\tau_\ell) \approx 0.2$ deg. This latter derivation justifies neglecting the phase noise in the work hereafter. In any case, the power of the phase noise after matched filtering (CIR estimation) is further reduced by the time-bandwidth product $TB_k = N_k$ (number of subcarriers). For low-end clocks, characterized by a higher intrinsic phase noise, the only opportunity is to employ multiple OFDM symbols per subband and average the estimated CIRs.

Using the above simplifications, the baseband Rx signal after downconversion is

$$y_k(t) = y_k^{\text{RF}}(t)e^{-j2\pi f_k t} = \sum_{\ell=1}^L \rho_{\ell,k} e^{j\theta_{\ell,k}} x_k(t - \tau_\ell) e^{-j2\pi f_k \tau_\ell} + z_k(t) \quad (10)$$

In the next section, we detail the preprocessing steps applied to the baseband Rx signal to prepare it for coherent multiband combination.

Pre-processing of the Rx signal

The RF signal in Eq. (10) is pre-processed before the extraction of the target's coherence metrics. The goal is to obtain the CIR for each subband, which requires the following steps:

1. Sampling with sampling interval $1/B_k$ and conversion to the frequency domain using a Discrete Fourier Transform (DFT), obtaining

$$Y_k(n\Delta_f) = X_k(n\Delta_f) \sum_{\ell=0}^L \rho_{\ell,k} e^{j\theta_{\ell,k}} e^{-j2\pi(f_k + n\Delta_f)\tau_\ell} + Z_k(n\Delta_f) \quad (11)$$

where $X_k(n\Delta_f)$ is the frequency domain Tx signal and $Z_k(n\Delta_f)$ is the noise in the frequency domain. Note that subsequent multiband processing will require higher time granularity than $1/B_k$, thus requiring interpolation.

2. Estimation of the SISO channel. The ideal CFR in subband k is

$$H_k(n\Delta_f) = \sum_{\ell=0}^L \rho_{\ell,k} e^{j\theta_{\ell,k}} e^{-j2\pi(f_k + n\Delta_f)\tau_\ell}. \quad (12)$$

In practice, we estimate the CFR in the frequency domain through elementwise division of the Rx symbols and the known Tx ones as

$$\tilde{H}_k(n\Delta_f) = \frac{Y_k(n\Delta_f)}{X_k(n\Delta_f)} = H_k(n\Delta_f) H_k^{\text{hw}}(n\Delta_f) + W_k(f), \quad (13)$$

where $H_k^{\text{hw}}(n\Delta_f)$ is the frequency response of the measurement device and $W_k(f) = Z_k(f)/X_k(n\Delta_f)$.

3. Hardware calibration. This step is needed to compensate for the frequency response of the measurement device in subband k , $H_k^{\text{hw}}(n\Delta_f)$, which may introduce distortion in the phase of the estimated channel. We estimate $H_k^{\text{hw}}(n\Delta_f)$ using the procedure detailed in the supplementary material (Supplementary note - 3), and show the resulting phase response in Fig. S1. The calibration step obtains a calibrated version of the CFR in Eq. (13) as

$$\hat{H}_k(n\Delta_f) = \tilde{H}_k(n\Delta_f)/H_k^{\text{hw}}(n\Delta_f), \quad (14)$$

which removes undesired phase variations due to the non-ideal hardware response across frequency.

4. Estimation of the SISO CIR by computing the IDFT of $\hat{H}_k(n\Delta_f)$

$$\hat{h}_k(t) = \sum_{\ell=0}^L \rho_{\ell,k} e^{j\theta_{\ell,k}} \text{sinc}[B_k(t - \tau_{\ell})] e^{-j2\pi f_k \tau_{\ell}} + w_k(t), \quad (15)$$

where $w_k(t)$ is the IDFT of the noise, and $\text{sinc}(x) = \sin(\pi x)/(\pi x)$ is the cardinal sine function. In Eq. (15) we use the continuous time variable t for the CIR although in practice this is discretized in the output of the IDFT. Our choice of using t stems from the fact that we compute the IDFT on a much denser time grid than the original sampling interval $1/B_k$, approximating the continuous-time CIR. This is done because the BP algorithm, detailed in the next section, requires evaluating the CIR at arbitrary delay values that may not lie on the coarse grid determined by the original sampling interval.

Eq. (15) is a collection of scaled and shifted cardinal sine functions affected by the scattering phase $\theta_{\ell,k}$ of the ℓ -th scattering center in subband k . Moreover, an additional phase term due to the propagation of the carrier is present, $-2\pi f_k \tau_{\ell}$, which prevents a direct combination of the CIRs since it introduces a subband-dependent phase shift for that same delay τ_{ℓ} . The resolution of Eq. (15) in distinguishing multiple scattering centers is limited by the bandwidth of a single subband. Specifically, the resolution is given by the width of the main lobe of the sinc functions, which is $1/B_k$ in delay units and $c/(2B_k)$ in range units.

In the following sections, we detail the multiband combination algorithms used in this work, namely BP and the proposed SPBP. OMP is described in detail in the supplementary material (Supplementary note - 2).

Backprojection algorithm

To increase the resolution of the estimated CIR using K subbands, we adopt the time-domain BP algorithm used in [12], adapting it to one-dimensional multiband ranging. The pre-processing provides the CIRs of the subbands, which are still affected by the propagation carrier phase. The first step in BP is to isolate the target's scattering phase by compensating for the propagation-dependent carrier phase term $2\pi f_k \tau_{\ell}$. This is done by expressing the propagation delay τ_{ℓ} as a function of the scattering center's

distance, i.e., $\tau_\ell = 2R_\ell/c$, and computing

$$\begin{aligned}\eta_k(R) &= \hat{h}_k \left(\frac{2R}{c} \right) e^{j\frac{4\pi f_k}{c} R} \\ &= \sum_{\ell=0}^L \rho_{\ell,k} e^{j\theta_{\ell,k}} \underbrace{\text{sinc} \left[\frac{2B_k}{c} (R - R_\ell) \right]}_{\chi_k(R - R_\ell)} e^{j\frac{4\pi f_k}{c} (R - R_\ell)} + w_k(R)\end{aligned}\quad (16)$$

where $w_k(R)$ is a noise term, and $\chi_k(R)$ is called RAF of the single subband and coincides with a sinc function that depends uniquely on bandwidth B_k . At $R = R_\ell$, the term $e^{j\frac{4\pi f_k}{c} R}$ cancels out the carrier phase term, so that the phase of the ℓ -th element in the sum equals the phase of the scattering center's phase response $\theta_{k,\ell}$.

As a second step, BP sums the K range profiles obtained by Eq. (16) coherently as

$$\eta(R) = \sum_{k=0}^{K-1} \eta_k(R) = \sum_{\ell=0}^L \sum_{k=0}^{K-1} \rho_{\ell,k} e^{j\theta_{\ell,k}} \chi_k(R - R_\ell) e^{j\frac{4\pi f_k}{c} (R - R_\ell)} + w(R), \quad (17)$$

where $w(R)$ is a noise term. Eq. (17) represents the most general output of the BP algorithm, when the complex RCS of the target changes with frequency, and the carrier frequencies and bandwidths of the subbands are unequal. In this case, the scattering responses of the single scattering centers can not be taken out of the sum over k , so the resulting multiband response is *different for each target*. From Eq. (17), it is not immediately evident why BP achieves a resolution improvement with respect to single subband processing. Therefore, in the following, we simplify Eq. (17) by making some assumptions to highlight the factors that contribute to the resolution improvement.

If the response of the scattering centers is constant across the considered frequency range (*frequency isotropic*), i.e., $\rho_{\ell,k} e^{j\theta_{\ell,k}} = \rho_\ell e^{j\theta_\ell}$, $\forall k$, Eq. (17) can be simplified. In this case, Eq. (17) becomes

$$\begin{aligned}\eta_{\text{iso}}(R) &= \sum_{\ell=0}^L \rho_\ell e^{j\theta_\ell} \sum_{k=0}^{K-1} \chi_k(R - R_\ell) e^{j\frac{4\pi f_k}{c} (R - R_\ell)} + w(R) \\ &= \sum_{\ell=0}^L \rho_\ell e^{j\theta_\ell} \Psi_{\mathcal{F},\mathcal{B}}(R - R_\ell) + w(R),\end{aligned}\quad (18)$$

where $\Psi_{\mathcal{F},\mathcal{B}}(R)$ is the ideal RAF for frequency isotropic targets and depends on the location and width of the subbands in the frequency domain. Importantly, assuming isotropy in the frequency domain is necessary to write a single RAF that is *independent* of the specific target. Eq. (18) can be further simplified if the subbands are chosen with (i) equal bandwidth, $B_k = B, \forall k$, or (ii) equal bandwidth and equally spaced carrier frequencies, $B_k = B, \forall k$, $f_k = f_0 + k\Delta f_b$ where Δf_b is the inter-carrier spacing.

In the first case (equal bandwidth) the single-band sinc function has equal width for all subbands and is denoted by $\chi(R)$. The range profile becomes

$$\begin{aligned}\eta_{\text{EB}}(R) &= \sum_{\ell=0}^L \rho_{\ell} e^{j\theta_{\ell}} \chi(R - R_{\ell}) \sum_{k=0}^{K-1} e^{j \frac{4\pi f_k}{c} (R - R_{\ell})} + w(R) \\ &= \sum_{\ell=0}^L \rho_{\ell} e^{j\theta_{\ell}} \Psi_{\mathcal{F}}(R - R_{\ell}) + w(R),\end{aligned}\tag{19}$$

where the RAF now only depends on the single bandwidth B and on the carrier frequencies $\mathcal{F}$.

In the second case (equal bandwidth and equally spaced carrier frequencies) the range profile is

$$\begin{aligned}\eta_{\text{ES}}(R) &= \sum_{\ell=0}^L \rho_{\ell} e^{j\theta_{\ell}} \chi(R - R_{\ell}) \sum_{k=0}^{K-1} e^{j \frac{4\pi f_k}{c} (R - R_{\ell})} + w(R) \\ &= \sum_{\ell=0}^L \rho_{\ell} e^{j\theta_{\ell}} \chi(R - R_{\ell}) \Lambda(R - R_{\ell}) + w(R) \\ &= \sum_{\ell=0}^L \rho_{\ell} e^{j\theta_{\ell}} \Psi(R - R_{\ell}) + w(R),\end{aligned}\tag{20}$$

where

$$\Lambda(R) = \sum_{k=0}^{K-1} e^{j \frac{4\pi f_k}{c} R} = e^{j \frac{2\pi}{c} [2f_0 + (K-1)\Delta f_b] R} \frac{\sin\left(\frac{2\pi}{c} K \Delta f_b R\right)}{\sin\left(\frac{2\pi}{c} \Delta f_b R\right)}\tag{21}$$

is a Dirichlet kernel whose main lobe width defines the theoretical multiband range resolution

$$\rho_{R,\text{MB}} = \frac{c}{2K\Delta f_b},\tag{22}$$

related to the total bandwidth aperture of the multiband system, $B_{\text{tot}} = K\Delta f_b$. This explains why BP achieves a resolution improvement with respect to single subband processing by summing the CIRs of the single subbands after removing the carrier phase contribution. $\Lambda(R)$ has a peak in $R = 0$ and is periodic of period $c/(2\Delta f_b)$. Therefore, by increasing the spacing among carrier frequencies above $B/2$ (non-contiguous subbands), more than one repetition of the peak $\Lambda(0)$ falls inside the mainlobe of the single-band sinc, $\chi(R)$. This mathematically explains the appearance of grating lobes for non-contiguous subbands.

The consequence of the above properties is that the multiband system potentially has a resolution equal to a *fullband* system with a contiguous bandwidth spanning from the smallest to the largest frequency in the spectrum of the Tx signals in all subbands. However, the grating lobes degrade such resolution by introducing artifacts. The two primary outcomes of multiband processing, namely resolution improvement

and ambiguity due to grating lobes, are reflected in the metrics used in our experiments. The EMPW directly measures the width of the main lobe of the range profile at the target's range, thus evaluating the resolution of the multiband system. Note that the EMPW works even in cases where the subbands are not of equal width or equally spaced, thus generalizing the above discussion. The OSPA instead takes into account additional target detections that do not correspond to real ground truth targets, penalizing them with a tunable error. This effectively accounts for additional target detections due to grating lobes.

Subsets Product BP algorithm

We design a heuristic modification of the BP algorithm to mitigate the impact of grating lobes in the RAF, called SPBP. The key idea is that different sets of subbands will produce grating lobes at different locations, since the portions of the spectrum occupied by the subbands are different. Conversely, targets will appear at the same ranges regardless of the subbands' location in the frequency domain. We exploit this property to cancel out grating lobes by taking the *product* of range profiles obtained using different sets of subbands.

Consider two different subsets of the set of indices of the available subbands $\mathcal{K} = \{1, \dots, K-1\}$, termed $\mathcal{K}_0$ and $\mathcal{K}_1$, respectively, and denote by $\Psi_{\mathcal{K}}(R)$ the multiband RAF obtained by combining the subbands whose indices are in set $\mathcal{K}$. We select $\mathcal{K}_0$ in such a way that the corresponding subbands have the same total bandwidth as the original set of subbands, to ensure the nominal resolution is the same. This is done by including in $\mathcal{K}_0$ the first and last indices of the subbands, namely 0 and $K-1$. The remaining elements of $\mathcal{K}_0$ are selected randomly from $\mathcal{K}$, so that $|\mathcal{K}_0| = K-1$, where $|\cdot|$ denotes the set cardinality, i.e., its number of elements. This is done to include the maximum number of possible subbands, thus reducing the gaps in the frequency domain, without taking $\mathcal{K}_0 = \mathcal{K}$.

Once $\mathcal{K}_0$ is selected, we numerically compute the corresponding RAF $\Psi_{\mathcal{K}_0}(R)$ as

$$\Psi_{\mathcal{K}_0}(R) = \sum_{k \in \mathcal{K}_0} \chi_k(R) e^{j \frac{4\pi f_k}{c} R}. \quad (23)$$

Then we construct all the possible subsets of $\mathcal{K}$, which are collected in the product set $\Pi(\mathcal{K})$. SPBP searches for the set $\mathcal{K}_1 \in \Pi(\mathcal{K}) \setminus \mathcal{K} \setminus \mathcal{K}_0$ that has a RAF whose product with $|\Psi_{\mathcal{K}_0}(R)|$ (in magnitude) leads to the minimum Peak-to-Sidelobe Ratio (PSLR) [11]. The PSLR evaluates the ratio between the peak of the RAF and the maximum magnitude of its sidelobes, intended as the set of peaks outside of the main lobe. The RAF product of the two subsets is

$$\Gamma_{\mathcal{K}_0, \mathcal{K}_1}(R) = \Psi_{\mathcal{K}_0}(R) \Psi_{\mathcal{K}_1}(R), \quad (24)$$

and the minimization of the PSLR can then be written as

$$\mathcal{K}_1 = \min_{\mathcal{K}' \in \Pi(\mathcal{K}) \setminus \mathcal{K} \setminus \mathcal{K}_0} \left(\frac{|\Gamma_{\mathcal{K}_0, \mathcal{K}'}(0)|}{\max_{R \in [-R_{\max}, R_{\max}] \setminus \Omega} |\Gamma_{\mathcal{K}_0, \mathcal{K}'}(R)|} \right), \quad (25)$$

where $R_{\max}$ is the maximum range of interest and Ω is the main lobe region of the RAF. Eq. (25) is solved by exhaustive search since $|\mathcal{K}|$ is small in practice due to the non-ideal coherence of the target, which limits the number of subbands that can be combined. If the ISAC system does not dynamically change its operation bandwidth across time, the optimal combinations that minimize the PSLR can be computed *offline* and tabulated, so that no computational burden is introduced in the real-time implementation.

Further conditions can be imposed on the candidate sets considered in the search to speed it up, e.g., restricting to subsets with at least a certain number of elements or that have at least a certain spectral coverage.

The final magnitude of the range profile obtained with SPBP is

$$|\eta_{\text{SPBP}}(R)| = \left| \left(\sum_{k \in \mathcal{K}_0} \eta_k(R) \right) \cdot \left(\sum_{k \in \mathcal{K}_1} \eta_k(R) \right) \right|. \quad (26)$$

The product in Eq. (26) strongly attenuates the grating lobes, since these will appear at different locations in each of the two range profiles. However, it relatively attenuates weak scatterers with respect to stronger ones and reduces the SNR of the final range profile. If some targets are significantly weaker than others, they may be canceled out and become undetectable. In our results, this phenomenon was not significant, as shown in the [Multitarget resolution](#) section, but further research is needed to mitigate this problem.

To provide insights into the trade-off between grating lobes cancellation and SNR reduction, we derive the analytical expression of the SPBP SNR in Supplementary note 4 of the supplementary material.

Moreover, in Supplementary note 6, we compare SPBP and BP in terms of PSLR and Integrated Sidelobe Ratio (ISLR) in Tab S1, showing the gain given by applying Eq. (24) to the RAFs.

Measurement system and experimental protocol

In this section, we detail our experimental setup for multiband ranging, including details on the measurement system, targets, hardware calibration procedures, and measurement protocol.

To implement our experiment in FR3, we utilize a Software Defined Radio (SDR) platform in monostatic configuration, using 1 transmit and 1 receive chains. The SDR includes the following components

- **Digital baseband RFSoc:** A Xilinx Radio Frequency System on a Chip (RFSoc) 4x2 Kit equipped with a ZU48DR processor is used for baseband signal processing, including digital-to-analog (and vice-versa) conversion. The board is capable of generating RF signals up to 6 GHz, and therefore cannot directly generate FR3 signals. It is instead utilized to generate an Intermediate Frequency (IF) signal centered at 1 GHz that is up/down converted in a later stage.

- **RF transceiver Pi-Radio board:** The IF signal generated by the RFSOC 4×2 Kit is up/down converted by a Pi-Radio TRX board, which translates the fixed-frequency IF to a configurable frequency in the 6-24 GHz range, enabling the frequency sweep. The up and down conversions are performed coherently, ensuring consistent phase measurements. More details of the board can be found in [53].
- **Vivaldi wideband antenna:** The measurements are performed over a bandwidth of over 15 GHz centered around 14 GHz, which constitutes a fractional bandwidth greater than 100%. Such a fractional bandwidth is difficult to achieve with standard antennas such as patches or dipoles, which usually provide a percentage fractional bandwidth in the order of units to a few tens. To address this, we use a wideband Vivaldi antenna which, thanks to its exponentially tapered structure, can operate across the whole 6-24 GHz band.

To validate our experiments and obtain reference data to be used as a sanity check, we also adopt a VNA configured to operate in the 6-24 GHz and connected to the same Vivaldi antenna used on the SDR platform. The device is calibrated, so it does not introduce phase distortion due to non-idealities of the hardware. The VNA is a N9952B FieldFox Handheld Microwave Analyzer from Keysight, and can operate coherently over 50 GHz of bandwidth. We collect the majority of our measurements in a laboratory environment where we cover walls, furniture, and the support of the targets with panels made of RF absorbing material, as shown in Fig. 18. To evaluate the impact of multipath components and unequal RCS of the targets, as discussed at the end of the [Multitarget resolution](#) section, we remove the absorbing panels and turn the Pi-Radio front-end towards the other end of the room. In this scenario, furniture and other people working are present, causing multipath reflections and scattering, as shown in the rightmost picture in Fig. 18.

- **Transmitted signal details:** The transmitted signal consists of Zadoff-Chu pilot sequences with 1024 subcarriers. 768 subcarriers are used to contain the pilot sequence and 256 are used for the OFDM cyclic prefix. 1 subcarrier at 0 Hz and 11 subcarriers at the edges of the OFDM spectrum are left empty and do not contain pilot signals. The subcarrier spacing is set to 976 kHz. The sampling frequency of the ADC is 983.04 MHz.

In our experimental results, we consider the following three types of targets.

- **Corner reflector:** We use a corner-cube reflector with 15 cm side length, as shown in the middle picture in Fig. 18. The corner reflector is calibrated for radar applications.
- **Metal plate:** We use a flat metal plate of dimensions 25×10 cm (Fig. 18). The thickness of the plate is a few millimeters.
- **Static human:** Human targets are instructed to stand as still as possible in front of the measurement device. To mitigate the impact of respiration on the phase measurements, they are asked to hold their breath for 2-3 seconds during the data collection, which lasts 150 ms for the full frequency sweep.

To obtain coherent CFR estimates over the bandwidth 6-22 GHz, we use the Pi-Radio FR3 board to implement a frequency sweep across the full bandwidth. This is done by transmitting random OFDM pilot signals from a 4-Quadrature Amplitude

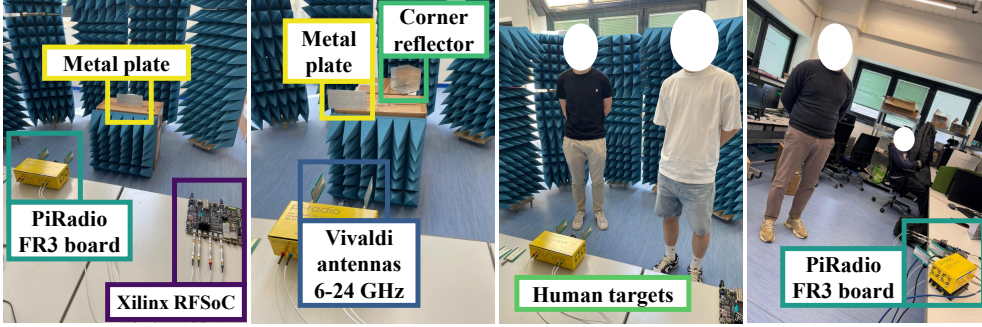


Fig. 18: Experimental testbed and considered targets. The Xilinx RFSoc generates the base-band signal and sends it to the Pi-Radio board for FR3 upconversion. The Vivaldi antennas enable wideband signal transmission. The different types of considered targets, namely the corner reflector, metal plate, and humans, are further described in the [Measurement system and experimental protocol](#) section. In the rightmost figure, we show the scenario with multipath from background objects, considered in the [Multitarget resolution](#) section.

Modulation (QAM) over a configurable bandwidth centered around a configurable carrier frequency. The carrier frequency is changed in subsequent OFDM symbols. The switching between different carrier frequencies requires $t_{\text{switch}} = 10$ ms in the Pi-Radio board, so this is the minimum timing between OFDM symbols that can be configured in our measurements.

In our experiments, we use two different bandwidth values 0.5 or 1 GHz, depending on the specific experiment. We select the carrier frequencies to obtain a *contiguous* set of CFR estimates. When using 0.5 GHz, we select the set $\{6.5, 7, \dots, 22\}$ GHz, with 32 subbands, while using 1 GHz we select $\{6.5, 7.5, \dots, 21.5\}$ GHz, with 15 subbands. The different cardinality of the two sets has the important consequence that the total duration of the frequency sweep using 0.5 GHz is $32t_{\text{switch}} = 320$ ms, while using 1 GHz it is $15t_{\text{switch}} = 150$ ms. For this reason, we use 1 GHz in the measurements involving human targets since a shorter total measurement time is preferable to avoid incoherence due to small involuntary movements of the person.

Data availability. The dataset used to obtain the results presented in this work is available on Zenodo at [\[10\]](#).

Code availability. Code to load and handle the data used in this work is available on Zenodo at [\[10\]](#).

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Supplementary. Supplementary material is provided in a separate file.

Author Contributions. J. P. carried out the data analysis, algorithm design, code implementation, and contributed to the writing of the experimental results, discussion, and methodology sections of the manuscript. G. V. contributed to the data analysis and results, as well as to the writing of the results section. A. B. performed the supporting measurements with the VNA device and contributed to the writing of the experimental results section. D. T. and M. M. carried out the dataset collection and contributed to the writing of the introduction and methodology sections. M. R. and J. W. supervised the research and contributed to the writing of the manuscript. All authors reviewed the manuscript.

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