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Integrated Sensing and Communications: A Mutual Information-Based Framework

ABSTRACT

Integrated sensing and communications (ISAC) is capable of circumventing the limitations of existing frequency-division sensing and communications (FDSAC) techniques. Hence, it has recently attracted significant attention. This article proposes a novel framework for ISAC from a mutual information (MI) perspective. Based on the proposed framework, the sensing performance and the communication performance are evaluated by the sensing MI and the communication MI, respectively. Under this framework, the sensing and communication (S&C) performance metrics, i.e., the S&C MI, have similar physical and mathematical properties as well as the same unit of measurement, which could facilitate theoretical analyses and waveform design. This framework defines ISAC’s fundamental performance limits, which serves as an alternative candidate for evaluating the S&C performance tradeoffs. Based on this framework, the S&C performance of downlink and uplink ISAC systems is investigated and compared with that of FDSAC systems. Numerical results are provided to demonstrate the superiority of ISAC over conventional FDSAC designs. Finally, promising open research directions are provided in the context of MI-based ISAC.

INTRODUCTION

Next-generation wireless networks are envisioned to play a big part in shaping a connected, smart, and intelligent wireless world [1]. This will require a paradigm shift in future networks to support high-quality wireless connectivity as well as high-accuracy sensing capability [2]. To fulfill this dual-functional requirement, numerous potential technologies have been introduced over the last few years. Among them is integrated sensing and communications (ISAC), a technique to achieve dual-functional sensing and communications (DFSAC) via a single time-frequency-power-hardware resource [2–5]. Two fundamental ISAC models are illustrated in Fig. 1, where the DFSAC base station (BS) aims to serve uplink/downlink communication users (CUs) while simultaneously sensing the targets in its surrounding environment. Compared to the frequency-division sensing and communications (FDSAC) techniques, in which sensing and communications (S&C) require isolated frequency bands as well as hardware infrastructures, ISAC is capable of improving the spectral efficiency, reducing the hardware cost, and limiting the electromagnetic pollution [2–5]. In view of the above benefits, ISAC has attracted vibrant industrial and academic interest, which is anticipated to dominate the future wireless network market.

Recent years have witnessed a growing number of published papers around the ISAC theme. These works can be roughly categorized into two main topics, including S&C performance analysis and dual-functional beamforming design; see [5–8] and the references therein. Around these two topics, various S&C performance metrics have been exploited to unveil the fundamental limits in ISAC. Specifically, the authors in [5, 6] characterized the information-theoretic limits of ISAC by using the channel capacity and distortion function as the performance metrics. Moreover, the authors in [7, 8] discussed the fundamental S&C performance tradeoffs in Gaussian channels relying on the channel capacity and Cramér-Rao bound (CRB).

The previous works evaluated the communication and sensing performances by information-theoretic and estimation-theoretic metrics, respectively. One of the most classical information-theoretic metrics is channel capacity, which is the maximum communication mutual information (MI) between input and output. In contrast, typical estimation-theoretic metrics include CRB, mean squared error (MSE), and detection probability, which explicitly characterize either the estimation accuracy or detection reliability. Researchers have built a foundation for understanding the S&C performance limits in ISAC using these well-defined metrics to evaluate the sensing performance. Besides these estimation-theoretic metrics, the information-theoretic metric, i.e., sensing MI, is also a commonly used performance metric in radar sensing [9, 10]. As detailed later, the sensing MI provides a universal lower bound for the aforementioned estimation-theoretic metrics, which, thus, serves as an alternative candidate in defining the sensing performance limit. Moreover, the sensing MI has similar physical and mathematical properties as the communication MI. This might help simplify the S&C performance analysis and dual-functional beamforming design.

The above arguments imply that the sensing MI is a promising candidate performance metric for ISAC. However, it has received much less attention than other estimation-theoretic sensing
metrics in current ISAC literature; only a couple of works appeared recently [10–13]. Against this background, we propose a new framework for ISAC from the perspective of MI. Unlike existing ISAC frameworks, our proposed framework relies on MI to measure the S&C performance. As an application of this framework, we introduce several MI-related S&C performance metrics and exploit them to study the performances of downlink and uplink ISAC systems. Numerical results are provided to demonstrate the superiority of ISAC over conventional FDSAC designs. Finally, conclusions are drawn, and open research problems are highlighted.

**MI-Based Framework for ISAC**

**MI in ISAC**

We commence by introducing the basic concepts, properties, and operational meaning of the S&C MI.

- **Communication MI:** The objective of communications is to recover data information contained in the transmitted symbol from the received signal. To this end, the communication channel state is usually assumed to be known by the receiver, with which the data information can be successfully decoded. In Fig. 2, we illustrate the processing of communication signals in uplink and downlink ISAC over Gaussian channels to clarify this point. As shown, in the communication part of ISAC, the receiver leverages the channel state (H) to recover data information contained in the transmitted symbols (X_U or X_D) from the received signal (Y_U or Y_D). We define communication MI as the MI between the transmitted symbol and the received signal conditioned on the channel state. This metric evaluates the information-theoretic limit on how much data information can be transmitted without error. The communication MI has the well-known operational meaning of maximum achievable channel coding rate, which can be measured by bits.

- **Sensing MI:** The objective of sensing is to extract the environmental information in the target response (G in Fig. 1) that is treated as a deterministic function of the target parameter of interest, e.g., angle, range, and velocity [9–14]. To this end, the BS sends a predesigned sensing probing signal to the nearby environment and then recovers the target parameter from reflected echoes. Different from communications, the prior information at the sensing receiver is the transmitted probing signal instead of the channel response. To better show this, in Fig. 2, we illustrate the processing of sensing signals for uplink and downlink ISAC systems over Gaussian channels. As shown in the sensing part of ISAC, the BS leverages the predesigned sensing probing signal (X_D or X_U) to recover environmental information contained in the target response (G) from the reflected signal (Y_U or Y_D). To quantify how much environmental information can be extracted with a given probing signal, we define sensing MI as the MI between the reflected signal and the target response (or the target parameter) conditioned on the predesigned sensing probing signal, as depicted in Fig. 2.

Different from the communication MI, sensing MI has no explicit operational meaning. Yet, existing works have tried to establish the connection between sensing MI and other estimation-theoretic metrics. The authors in [9] proved that for a Gaussian channel with a Gaussian distributed target response, the sensing probing signal maximizing the sensing MI also minimizes the MSE in estimating the target response. The authors in [10] extended the result in [9] and showed that for any Gaussian channels, the sensing MI provides a universal lower bound for distortion metrics of sensing. More specifically, let the sensing MI be the input of the distortion-rate function for the to-be-sensed parameter, and the output serves as a lower bound of the corresponding distortion metric. Typical estimation-theoretic metrics, including MSE, CRB, and detection probability,
Having established the MI-based ISAC framework, we now move to explaining our motivation for establishing this MI-based framework.

can be treated as distortion metrics of sensing, because they may be induced by the distortion function between the parameter and its estimate in the context of rate-distortion theory. The sensing procedure can be interpreted as a virtual non-cooperative joint source-channel coding with the target parameter, target response, and sensing probing signal representing the source, channel input, and the virtual channel, respectively; see [10, Fig. 2] for more details. On this basis, the sensing MI bounds the rate-distortion function and thereby yields a lower bound for the well-defined distortion metrics. It is worth noting that the achievability of this lower bound is not guaranteed, and reference [9] provides one special case when this bound is achievable.

Based on the rate-distortion theory, the conclusion in [10] also applies to other non-Gaussian channels, i.e., the sensing MI bounds the rate-distortion function [15, Theorem 1]. Using the monotonicity of this function, we can improve the lower bound of our concerned distortion metric by designing the waveform to maximize the sensing MI. Although the achievability of this lower bound is not guaranteed, extensive research showed that using the sensing MI can improve the sensing performance; see [14] and the references therein.

The above arguments imply that the sensing MI not only defines the information-theoretic limit on how much environmental information can be extracted but also describes the estimation-theoretic limit on the distortion of the target parameter. This means that sensing MI is a promising alternative candidate metric of sensing.

**MI-Based ISAC Framework:** The previous statements suggest that the S&C MI satisfies the following properties:

- The sensing MI has a similar physical meaning to the communication MI, both being measured by bits and characterizing the information-theoretic limit.
- The sensing MI has similar mathematical properties to the communication MI, both satisfying the fundamental properties of MI.

We, therefore, establish an MI-based ISAC framework by using S&C MI as the S&C performance metrics. Under this framework, the S&C performance metrics have similar physical and mathematical properties and the same unit of measurement. This differs from most current ISAC frameworks, where different types of metrics are used to evaluate the S&C performances.

**Sensing MI vs. Other Estimation-Theoretic Metrics**

Having established the MI-based ISAC framework, we now move to explaining our motivation for establishing this MI-based framework. Since communication MI has been widely used in current research, our efforts will focus on sensing MI. We commence by comparing sensing MI with other estimation-theoretic metrics and summarizing its pros and cons.

We first list the potential advantages of sensing MI.

- Sensing MI is defined regardless of the estimator. Many estimation-theoretic metrics of sensing are based on specific estimation algorithms. For example, the detection probability depends on a statistical hypothesis tester. In contrast, the definition of sensing MI does not rely on any specific estimators, which provides a universal lower bound for distortion metrics of sensing. This fact reflects the generality of sensing MI in respect of estimation algorithms.
- Sensing MI can facilitate the dual-functional beamforming design. MI has been studied for over 70 years, and many optimization tools have been developed to improve it. Furthermore, sensing MI has similar properties and the same unit of measurement as communication MI. These two facts provide potential possibilities for using sensing MI to facilitate the dual-functional beamforming design.

**Limitations of Sensing MI**

- **Generality:** Sensing MI only applies when the target parameters are random with a prior known distribution (Bayesian setting). In contrast, the estimation-theoretic metrics, such as CRB, also apply when the parameters are treated as deterministic unknown (non-Bayesian setting). This fact reflects the limited generality of sensing MI.
- **Achievability:** Sensing MI has no explicit operational meaning. Though it provides a universal lower bound for distortion metrics of sensing, this bound is not guaranteed to be achievable. In contrast, most commonly used estimation-theoretic metrics can be achieved by specific estimation algorithms.
- **Tractability:** Sensing MI has a tractable expression for Gaussian channels with Gaussian distributed target response, which is the same as other estimation-theoretic metrics. Yet, sensing MI may involve an analytically intractable form for other settings, which could complicate both performance analyses and beamforming design.

After summarizing the pros and cons of sensing MI, we now elaborate on our motivation for establishing the MI-based framework. Despite limitations in some aspects, sensing MI can unveil the sensing performance limits and has potential advantages in waveform design and theoretical analysis. We do not mean to suggest that sensing MI is superior to other estimation-theoretic metrics.
The purpose of the above statements about the pros and cons of sensing MI is to show that in the Bayesian setting, sensing MI is also a promising alternative candidate metric for ISAC. Furthermore, as stated before, this metric has received much less attention in the current literature. These two facts thus motivate us to establish the MI-based ISAC framework. It is hoped that this framework could be an alternative candidate and provide new insights into future research about ISAC.

**Proposed MI-Related Performance Metrics for ISAC**

Leveraging the proposed MI-based framework, we can analyze the fundamental S&C performance to unveil important system design insights. Also, this framework enables us to compare the performances between ISAC and FDSAC techniques. In the sequel, we introduce several commonly used MI-related S&C performance metrics.

- **Sensing-Communication (Se-Co) Rate Region**: The communication rate (CR)/sensing rate (SR) is calculated by normalizing the communication/sensing MI with the time interval and bandwidth. It is clear that the CR and the SR explicitly characterize how much information can be transmitted and extracted in a unit time-frequency resource block, respectively. The Se-Co rate region defines a set containing all the achievable SR-CR pairs.

- **High-SNR Slopes**: The high-SNR slope is also known as the degree-of-freedom, the rate pre-log, or the multiplexing gain. The high-SNR slope of the CR/SR is calculated by taking the high-SNR limitation of the ratio of the CR/SR to the logarithm of the SNR. Thanks to its analytical tractability, this notion is an effective tool to evaluate the S&C performance in the high-SNR regime.

- **Other MI-Related Performance Metrics**: In addition to the Se-Co rate region and high-SNR slope, other MI-related metrics, such as the high-SNR power offset, outage probability, and diversity order, can be used to glean further insights.

**MI in Downlink ISAC**

The previous section laid a solid foundation for understanding the MI in ISAC systems. In the sequel, we exploit this framework to evaluate the S&C performance of ISAC with two MI-related metrics, i.e., the Se-Co rate region and high-SNR slope. Our hope is that this performance evaluation will contribute to a deeper understanding of the superiority of ISAC over conventional FDSAC. In this section, we focus on the MI in downlink ISAC systems, as depicted in the upper half of Fig. 1. Downlink ISAC refers to an ISAC scheme where the BS transmits data to downlink CUs while simultaneously sensing the targets in its surroundings [11, 12]. Moreover, our efforts focus on the Gaussian channels with a Gaussian distributed target response. In this case, the distortion lower bound provided by sensing MI is achievable.

**Rate Region Characterization**

Let us first study the Se-Co rate region of the downlink ISAC system. Notably, we characterize the rate region in two steps. In the first step, we assume that the BS uses a single transmit antenna to serve a single-antenna (SA) CU and to sense the targets. This scenario requires no beamforming design, and it is desirable to send at the maximum power to maximize either the CR or the SR. The above system settings enable us to generate a DFSAC signal that maximizes the CR and SR simultaneously. Using this signalling, both communications and sensing can enjoy all the power-spectrum resources and there is no inter-function interference as well as S&C performance trade-offs. This is in contrast to the FDSAC, in which both communications and sensing only benefit from partial power-spectrum resources. It is thus foreseen that ISAC is capable of achieving a broader rate region than FDSAC. To illustrate this point, we compare the rate regions achieved by ISAC and FDSAC under the SA case in Fig. 3. What stands out in this graph is that the rate region achieved by FDSAC is completely included in that achieved by ISAC. At the point \( P_o \), ISAC can attain both the maximum CR and the maximum SR; therefore, this point serves as supremum of the whole system.

The performance of ISAC can be further boosted in multi-antenna networks. Thus, in the second step, we discuss a multiple-antenna (MA) case where the BS exploits an antenna array to serve multiple CUs while simultaneously sensing the nearby targets. Besides, we assume that each CU is equipped with an antenna array to eliminate inter-user interference. More details about the system settings and the S&C performance. Thus, the pre-log term of the related CR/SR expressions and sensing only benefit from partial power-spectrum resources. It is thus foreseen that ISAC is capable of achieving a broader rate region than FDSAC. To illustrate this point, we compare the rate regions achieved by ISAC and FDSAC under the SA case in Fig. 3. What stands out in this graph is that the rate region achieved by FDSAC is completely included in that achieved by ISAC. At the point \( P_o \), ISAC can attain both the maximum CR and the maximum SR; therefore, this point serves as supremum of the whole system. The above argument implies that ISAC achieves larger high-SNR slopes. The high-SNR slope represents the slope with which the CR/SR curve increases with the SNR in the high-SNR regime. ISAC under the MA case, no point can simultaneously attain both the maximum CR and the maximum SR; therefore, this point serves as supremum of the whole system.

To fully understand this S&C performance trade-off, we propose three DFSAC beamforming design schemes, including the sensing-centric (S-C) design (maximizing the SR only), the communications-centric (C-C) design (maximizing the sum-CR only), and the Pareto optimal design (characterizing the Pareto boundary of the Se-Co rate region). The Pareto boundary of the rate region can be obtained by solving a standard convex problem [12]. Compared to FDSAC,
ISAC enables communications and sensing to use the entire power-spectrum resources. Due to this integration gain, ISAC is expected to achieve a broader Se-Co rate region than FDSAC. To better show this benefit, in Fig. 3, we compare the rate regions achieved by FDSAC and ISAC under the MA case. The points $P_1$ and $P_2$ are achieved by the S-C design and the C-C design, respectively. The black line segment connecting $P_1$ and $P_2$ is achieved by using the time-sharing strategy, namely applying the strategy corresponding to $P_1$ with probability $p$, while applying the strategy corresponding to $P_2$ with probability $1 - p$, which serves an inner bound of the rate region. Moreover, a green cure segment connecting $P_1$ and $P_c$ is achieved by using the high-SNR slope as a metric.

**High-SNR Slopes**

Having characterized the rate region, we now move to the high-SNR slopes. The high-SNR slope represents the slope with which the CR/SR curve decreases with the SNR in the high SNR regime. A larger high-SNR slope will lead to a better CR/SR performance in the high SNR region. This subsection aims to unveil the performance gap between ISAC and FDSAC by using the high-SNR slope as a metric.

FDSAC exploits isolated frequency bands for sensing and communications, respectively; therefore, a spectrum allocation factor smaller than one will appear in the pre-log term of the corresponding CR/SR expression. By contrast, ISAC can simultaneously use all the spectrum resources for communications and sensing. Thus, the pre-log term of the related CR/SR expression will not be decreased by a factor of less than one. The above argument implies that ISAC achieves larger high-SNR slopes than FDSAC in terms of both CR and SR. To quantify this benefit, in Fig. 4, we plot the CR and SR versus the SNR under the MA case. Notice that the high-SNR slope of CR/SR is determined by the slope of the asymptotic CR/SR curve. Hence, it can be concluded from Fig. 4 that ISAC brings in larger high-SNR slopes than FDSAC in terms of both CR and SR. This fact suggests that ISAC can provide more degrees of freedom than FDSAC in terms of both communications and sensing. Furthermore, based on the results in [12], the high-SNR slope is determined by the system parameters, such as the antenna number and the length of the DFSAC signal frame. This facilitates the discussion on the relationship between the system settings and the S&C performance.

**MI in Uplink ISAC**

Another fundamental ISAC model is termed the uplink ISAC, where the DFSAC BS aims to extract environmental information from the reflected sensing echoes while simultaneously detecting the data symbols sent by uplink CUs, as illustrated in the bottom half of Fig. 1. For brevity, we only consider the case of Gaussian channel with a Gaussian distributed target response.

**Rate Region Characterization**

To begin with, we characterize the rate region achieved in the uplink ISAC. In an effort to deal with the superposed sensing and communication signals, we establish a successive interference cancellation (SIC)-based framework [11]. Specifically, two SIC schemes are proposed, i.e., the S-C SIC and the C-C SIC, which correspond to two different SIC orders. In the S-C SIC scheme, the BS first decodes the communication signal by treating the sensing signal as interference. Then, the communication signal, subtracted from the superposed signal, and the remaining part will be used to sense the target response. As for the C-C SIC, the BS will first estimate the target response matrix by treating the communication signal as interference. Afterward, the sensing signal is subtracted from the superposed signal, and the remaining part will be used to recover the data information sent by the CUs. To characterize the performance upper bound, an ideal SIC condition is considered here, where the interference is assumed to be perfectly canceled. In the S-C SIC scheme, the communication signal does not influence the sensing procedure due to interference cancellation. In contrast, in the C-C scheme, the sensing signal does not affect the communication procedure.

The above argument suggests that the performance of uplink ISAC is influenced by the SIC order. To better illustrate this, in Fig. 5, we plot the rate region achieved by uplink ISAC. In obtaining Fig. 5, a minimum MSE (MMSE)-SIC decoder is used to detect the information bits sent by the uplink CUs, which is sum-rate capacity-achieving [11]. Let us now focus on the points $P_1$ and $P_2$ in Fig. 5. Particularly, to achieve point $P_1$, the BS should exploit the S-C SIC scheme, whereas to achieve point $P_2$, the BS must exploit the C-C SIC scheme. It is worth noting that $P_1$ and $P_2$ achieve the largest SR and CR, respectively, which reflects the influence of the SIC order. The line segment connecting $P_1$ and $P_2$ is achieved by using the time-sharing strategy, namely applying the strategy corresponding to $P_1$ with probability $\beta$, while applying the strategy corresponding to $P_2$ with probability $1 - \beta$. This line segment, essentially, represents a S&C performance trade-off. In a nutshell, the BS can use SIC to achieve any point...
in the ISAC’s rate region. As seen previously, SIC is at the heart of uplink ISAC, which achieves the best known Se-Co rate region in the uplink setting. For comparison, the rate region achieved by FDSAC is also presented in Fig. 5. As expected, it can be seen from Fig. 5 that ISAC can achieve a broader rate region than FDSAC.

**High-SNR slopes**

Having characterized the rate region, we now move on to the high-SNR slopes. Thanks to the SIC technique, the uplink ISAC makes full use of all the spectrum resources in both communications and sensing. In comparison with FDSAC, the pre-log term in the CR/SR expression of ISAC, will not be influenced by a spectrum allocation factor less than one. The uplink ISAC is therefore foreseen to enjoy larger high-SNR slopes than FDSAC. To show this benefit, in Fig. 6, we compare FDSAC with the S-C SIC-based ISAC by presenting the corresponding CR and SR. By observing slopes of the asymptotic CR/SR curves, we find that ISAC is capable of achieving larger high-SNR slopes than FDSAC. Furthermore, as Fig. 6 shows, in the low-SNR regime, ISAC achieves virtually the same CR and SR as FDSAC. By contrast, in low and moderate SNR regions, ISAC supports a higher CR as well as SR than FDSAC.

Putting the above results together, we conclude that ISAC can outperform FDSAC in terms of both the Se-Co rate region and high-SNR slopes. That is to say, under the same resources, ISAC can support the transmission of more data information as well as the extraction of more environmental information than FDSAC. This superiority, essentially, originates from ISAC’s integrated exploitation of spectrum and power resources.

**Conclusion and Promising Research Directions**

In this article, the performance of ISAC systems has been investigated from an MI perspective. We started by explaining the concept as well as the pros and cons of the MI-based framework. Then, two typical MI-related performance metrics, namely the Se-Co rate region and high-SNR slope, were highlighted. By using these two metrics as guidance, the performances of downlink and uplink ISAC over Gaussian channels were studied, followed by exploring the performance gap between ISAC and FDSAC. It is hoped that this article provides a promising alternative candidate framework for ISAC. There are still numerous open research problems in this area, which are summarized in three aspects.

- **MI-Based Information-Theoretic Limits:** Sensing MI provides a lower bound for distortion metrics of sensing, but its achievability is not guaranteed. Further efforts are required to explore the conditions for achieving this lower bound. Sensing MI also lacks any explicit operational meaning. Providing more insights into the relationship between sensing MI and other estimation- and information-theoretic metrics is another considerable thing.

- **MI-Based Performance Analysis:** The MI-based ISAC framework can be exploited to describe the S&C performance limit at both the system and network levels. Leveraging MI-related metrics to evaluate the performance gap between ISAC and FDSAC is a promising research direction that can unveil important system design insights. Moreover, existing literature on MI-based performance analysis focused on Gaussian channels, and further efforts are required to extend existing results to non-Gaussian channels.

- **MI-Based ISAC Waveform Design:** As stated before, the MI-based framework provides potential possibilities to facilitate the ISAC waveform design. Currently, this direction of research has received limited attention. The MI-based ISAC waveform design still constitutes an open area for ISAC application scenarios subject to practical resource and service constraints.

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