CSI-based Sensing with NOMA of Multiple Sensing Users for ISAC

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***Abstract*—As wireless technology continues to evolve, the integration of sensing and communication layers is becoming increasingly necessary. However, this integration presents significant technical and commercial challenges. The main challenges are the issues of coexistence, scheduling, and interference which arise due to the increase in the number of signals transmitted over networks. Transmitting signals orthogonally may not be spectrally efficient, hence the need for non-orthogonal multiple access (NOMA) technology is increasing in the future wireless technology. This paper proposes the use of integrated sensing and communication (ISAC) with iterative channel estimation (ICE) to overlap sensing and communication signals, for multiple sensing users (SUs). To assess the effectiveness of this approach, we compared the bit error rate (BER), mean square error (MSE), and spectral efficiency of sending both sensing users (SUs) and communication users (CUs) using non-orthogonal and orthogonal techniques.**

***Index Terms*—Integrated sensing and communication (ISAC), non-orthogonal multiple access (NOMA), channel state information (CSI), iterative channel estimation (ICE), multi-user.**

I. INTRODUCTION

Emerging applications are expected to greatly benefit from the implementation of future wireless networks such as beyond fifth generation (5G) and sixth generation (6G) [1]. These applications require dependable and precise sensing capability, in addition to high-quality communication. Therefore, sensing and communications have been acknowledged as vital components in creating and executing widespread future devices such as self-driving cars, wearable gadgets, Wireless Fidelity (Wi-Fi), drones, and satellites [2].

Rather than seperation, the integration of sensing and communication layers is anticipated to become more prevalent, as technical and commercial factors continue to drive the convergence of these two domains [2]. The emergence of integrated sensing and communication (ISAC) is providing several benefits such as reduced hardware costs, lower power consumption, decreased signaling latency, improved spectral efficiency, and smaller product sizes. By integrating sensing and communication capabilities into a single device, hardware costs can be reduced by reducing the number of components required, simplifying system design, and eliminating the need for physical connectors and cables [2]. Integrated sensing and communication can improve spectral efficiency by reducing the amount of interference in the wireless spectrum. In a traditional wireless communication system, separate sensors and communication modules may operate on different frequencies or use different wireless protocols, resulting in more radio frequency (RF) signals being transmitted in the wireless spectrum. This can lead to interference and reduced spectral efficiency. However, in an integrated sensing and communication system, the sensing and communication functions are combined into a single device that uses a unified wireless protocol and operates on a single frequency. This reduces the amount of RF signals in the wireless spectrum and minimizes the potential for interference, which can improve spectral efficiency [3]. Although ISAC can increase a system's hardware, spectral, temporal, signaling, and energy efficiency, which resources can be saved depends on the precise areas where integration is used.

Although significant benefits of ISAC have been predicted, there is still a long way to go until sensing and communication are fully integrated [4]. As wireless sensing applications become more prevalent, the number of signals transmitted over networks will rise, leading to a rise in network traffic [5]. This increase in traffic will cause issues with coexistence, scheduling, and interference.

The idea of multi-access technology has encouraged the notion that these issues can be resolved by utilizing orthogonal resource allocation techniques like time, frequency, or spatial division [2]. In [6] and [7], the orthogonal spectral sharing for ISAC has been proposed. Taking it a step further, a fully integrated waveform design is considered more advantageous as it can effectively utilize wireless resources and enhance integration gain [2]. However, incorporating information signaling in the probing waveform for target sensing results in low data rate can pose challenges related to information security [8]. Similarly, the sensing capability present in communication-centric waveform causes poor, scenario-dependent, and difficult-to-tune sensing performance. Also, even if a new waveform is designed, there will possibly be a trade-off between the transmission rate and sensing performance.

On the one hand, it is crucial to enhance the spectral efficiency (SE) even further to meet the demanding communication needs of future wireless networks [9]. Considering this, non-orthogonal multiple access (NOMA) is considered a promising approach for enhancing communication performance. NOMA allows multiple users to share the same frequency and time resources and distinguishes them at the receiver [3], [9]. A NOMA empowered ISAC framework is investigated in [10]. In this study, a base station with dual functionalities can support multiple communication user (CU)s through NOMA, and at the same time, the superimposed NOMA communication signal can be utilized for target sensing. The goal of the beamforming design problem in this study is to maximize the weighted total of the communication throughput and the effective sensing power. Nevertheless, power-domain NOMA can experience performance deterioration under certain circumstances, including imperfect successive interference cancellation (SIC) and strict power control [11]. Considering this, a novel concept on NOMA, which is the coexistence of different waveform structures in the same resource elements, is introduced in [12]. Orthogonal frequency division multiplexing (OFDM) and frequency modulated continuous wave (FMCW) signals are overlapped in this study. The letter [13] presents a proposal for an ISAC scheme that utilizes multi-domain NOMA using orthogonal time-frequency space (OTFS) modulation. The scheme transmits data streams non-orthogonally in both the time-frequency and delay-Doppler domains. Furthermore, the receiver has been designed to effectively mitigate non-orthogonal interference through an iterative process.

A novel NOMA-ISAC scheme for channel state information (CSI) based sensing is proposed in [3]. There is just one sensing user (SU) and one CU and the transmitted OFDM signals are fully overlapped at the receiver. By applying an iterative channel estimation (ICE) method, CSI and communication signal are extracted from the received signal. The suggested ISAC-ICE method permits the sharing of spectrum by the sensing and communication signals, and results in both satisfactory bit error rate (BER) and mean squared error (MSE) for communication and sensing performance, respectively. This is different from conventional orthogonal ISAC (CO-ISAC) systems that separate these signals in time or frequency domains. Therefore, there is an enhancement in the spectral efficiency.

Although ISAC-ICE method is spectrally efficient compared to CO-ISAC, the effects of multiple SUs has not been investigated in [3] . In this study, the scenario that has multiple SUs for ISAC-ICE method will be examined. In the uplink transmission of multiple SUs, the BER and MSE metrics with different number of iterations and channel taps are considered for performance degradation, and the performance gain is shown with the spectral efficiency performance. Therefore, this study investigates the multiplexing of multiple SUs and analyzes its performance for the ISAC-ICE method.

II. System Model

We take into consideration an uplink ISAC system, as depicted in Fig. 1, where one CU and L SU simultaneously transmit wireless signals. The OFDM communication symbols contain data symbols, and the OFDM sensing symbols contain pilot sequences. Also, it is assumed that the communication channel is perfectly known. A multiple accessing method where the CU and SUs share the same time and frequency

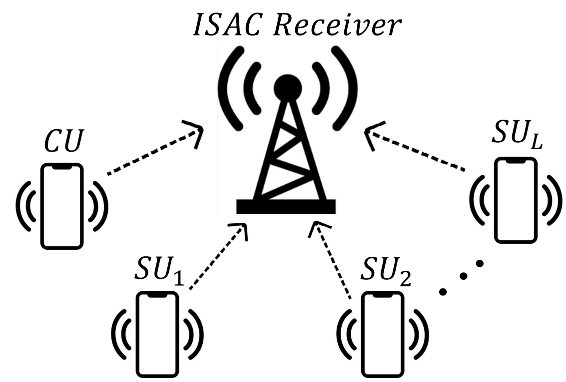

Fig. 1: The uplink L sensing users and one communication user scenario.

resources, but SUs are assigned to orthogonal specific frequencies which are obtained by dividing frequency resources as seen in Fig. 2 is considered in this paper to simultaneously execute sensing and communication. Also, there could be a method like the CU and SUs share the same time and frequency resources, but SUs are assigned to orthogonal specific time slots which are obtained by dividing time resources as seen in Fig. 3. It is assumed that the communication and sensing transmitters are properly synchronized in the time and frequency domains with the receiver for parallel transmission.

For the CU, the discrete time-domain OFDM symbol is produced as [3], [14]

$$x_m(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} \sqrt{P_{n,m}} X_m(n) e^{j2\pi n(k-N_{cp})/N} \times rect\left(\frac{k - mN_{sym}}{N_{sym}}\right), \tag{1}$$

where $X_m(k)$ specifies the m-th data symbol, $x_m(k)$ denotes m-th cyclic prefix (CP)-OFDM symbol in time domain, N_{cp} denotes the CP length, $P_{n,m}$ represents the transmit power, N indicates the fast Fourier transform (FFT) size where $N_{sym} = N + N_{cp}$, n denotes sub-carrier index and k denotes sampling index. Also, $rect(k)$ in (1) is defined by

$$rect(k) = \begin{cases} 1, & \text{if } 0 \le k \le N_{sym} \\ 0, & \text{otherwise} \end{cases}. \tag{2}$$

A generalized discrete multi-carrier OFDM communication signal equation in the time domain can be written as [14]

$$x(k) = \sum_{m=0}^{M-1} x_m(k). \tag{3}$$

where M gives total number of symbols.

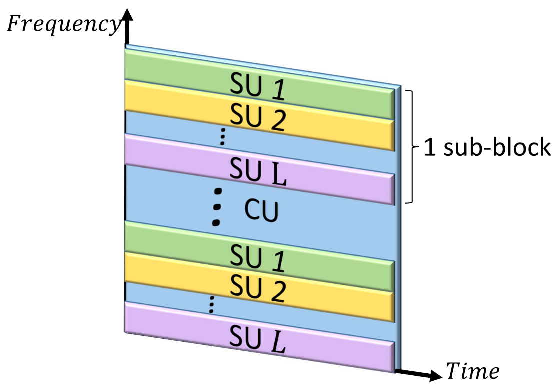

Fig. 2: Frequency divison multiplexing for SUs in ISAC-ICE.

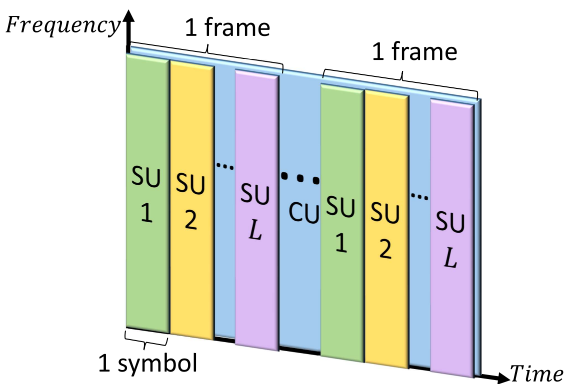

Fig. 3: Time divison multiplexing for SUs in ISAC-ICE.

For the SU, the discrete time-domain OFDM symbol is generated in a similar way:

$$s_m(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} \sqrt{P_{n,m}} S_m(n) e^{j2\pi n(k-N_{cp})/N} \, rect\left(\frac{k - mN_{sym}}{N_{sym}}\right), \tag{4}$$

where $S_m(k)$ specifies the pilot sequence for the m-th symbol, and $s_m(k)$ denotes the m-th CP-OFDM symbol for pilot sequences in time domain. A generalized discrete multi-carrier OFDM communication signal equation in time domain can be written as

$$s(k) = \sum_{m=0}^{M-1} s_m(k). \tag{5}$$

After that, the signals are converted from digital to analog. The analog signals are transmitted through different wireless channels. Even though the same CP is utilized here for both the production of communication and sensing symbols, other CP values may be used as long as they are more than the maximum excess delay of the communication and sensing channels.

At the ISAC receiver side, firstly the analog received signal is converted to digital to obtain $y(k)$. After getting $y(k)$, the signals are separated with equation (6) to get $y_m(k)$.

$$y_m(k) = y(k) rect\left(\frac{k - mN_{sym}}{N_{sym}}\right), \tag{6}$$

where $y_m(k)$ is the received signal for m-th OFDM symbol. After that, CP is removed and discrete Fourier transform (DFT) operation is performed. Eventually, the obtained signal in the frequency domain can be written as

$$Y_m(n) = \sqrt{\rho_c} H_{m,c}(n) X_m(n) + \sqrt{\rho_s} H_{m,s}(n) S_m(n) + W(n), \tag{7}$$

where ρ_c and ρ_s denote the received signal powers of communication and sensing signals. $H_{m,c}(k)$ and $H_{m,s}(k)$ represent Rayleigh fading channel samples for communication and sensing with the distribution of $\mathcal{CN}(0,1)$ respectively. $W(k)$ represents noise sample with the distribution of $\mathcal{CN}(0,\sigma_0^2)$. After all, an iterative channel estimation method for the communication and sensing channels is performed. Then, equalization is achieved and the received symbols are demodulated.

III. Multiple Access Schemes for CSI Based NOMA

The pilot symbols are utilized to estimate the channel in conventional OFDM systems [3]. Then, the data symbols are demodulated using the obtained CSI. In the NOMA-ISAC situation, the communication and sensing signals are totally overlapping in both the time and frequency domains, and they cannot be separated with conventional channel estimation methods. In [3], a channel estimation method is proposed but this method provides a solution only for one SU. The contribution of this work is to be able to estimate the sensing channels when there are multiple SUs. To allow access of multiple SUs, frequency resources are shared between SUs as shown in Fig. 2. In this work, the case where time resources are shared between SUs as shown in Fig. 3 is not considered because if the channel does not change during one frame, the performance is not affected by the number of SUs.

In frequency division method, each SU sends pilot with sub-carriers that are assigned for itself and does not send anything with sub-carriers that are assigned for other SUs. For example, if there are 4 sensing users and 256 sub-carriers, each user will use 64 sub-carriers and will not transmit signal in the other sub-carriers. The CU sends data using whole frequency resources. Sensing pilots are produced as follows:

$$S_l(n) = \begin{cases} r, & \text{if } mod(n-l, L) = 0 \\ 0, & \text{otherwise} \end{cases}, \tag{8}$$

where L is the total number of SUs and r is sensing symbol.

Equation (7), the received signal for the m-th symbol in frequency domain, is obtained. All of the SUs data are embedded to one symbol in this method. To separate the sensing signals, firstly least-square (LS) estimation method is applied to the received signal for sub-carriers that belong to each SU separately. To do this, indices that belongs to l-th user should be defined firstly.

$$n_l = l + aL. \tag{9}$$

Then LS estimation method is applied as:

$$\tilde{H}^i_{l,s}(n_l) = S_l(n_l)^{-1} Y^{(i-1)}_{l,s}(n_l), \tag{10}$$

here $\tilde{H}^i_{l,s}$ is estimated channel of l^{th} user for i^{th} iteration and its size is equal to N. Initial value of $\tilde{Y}^0_{l,s}$ is equal to $\tilde{Y}_m$ and finally L shows number of SUs. After (10), DFT based channel estimation is applied for each user as:

$$\tilde{h}^{(i)}_{l,s}(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} \tilde{H}^{(i)}_{l,s}(n) e^{j2\pi nk/N}, \tag{11}$$

$$\tilde{H}^{(i)}_{l,s,DFT}(n) = \sqrt{N} \sum_{k=0}^{N_{cp}-1} \tilde{h}^{(i)}_{l,s}(k) e^{j2\pi nk/N}, \tag{12}$$

Now, N channels ($\tilde{H}^{(i)}_{l,s,DFT}$) are obtained. After this step, subtraction of sensing signals for each SUs is applied:

$$\tilde{Y}^{(i)}_{m,c} = Y_m - \sum_{l=1}^{L} S_l \tilde{H}^{(i)}_{l,s,DFT}. \tag{13}$$

The communication signal ($\tilde{Y}^{(i)}_{m,c}$) is obtained after this step. To estimate communication data, channel equalization is done with known communication channel:

$$\tilde{X}^{(i)}_{m,c}(n) = H_{m,c}(n)^{-1} Y^{(i)}_{m,c}(n). \tag{14}$$

Next, the estimated communication signal is subtracted from the received signal to obtain total sensing signal:

$$Y^{(i)}_{m,s} = Y_m - H_{m,c} \tilde{X}^{(i)}_{m,c}. \tag{15}$$

Then, the process is repeated I times, beginning with equation equation (10).

IV. Simulation Results

This section includes simulation results for multiple SUs with FDMA. The BER and MSE performances are analyzed using Monte Carlo simulations. Both communication and sensing systems use binary phase-shift keying (BPSK) modulation. For the communication system, the perfect channel is assumed and communication system uses signal parameters $N = 256$, $N_{cp} = 16$ and $\rho_c = \rho_s = 1$ for the simulations.

In this study, the performance of multiple SUs with FDMA for 4 tap channel is analyzed and presented in Fig. 4. The results show that CO-ISAC outperforms ISAC-ICE in terms of BER for different numbers of SUs. However, the performance of ISAC-ICE improves with an increase in the iteration number. It is observed that with a higher number of SUs, the BER

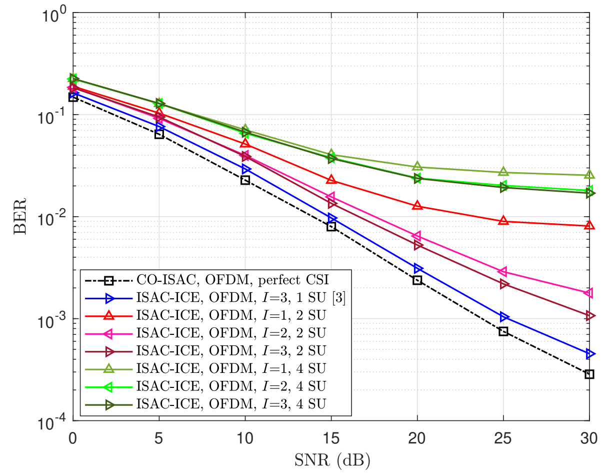

Fig. 4: The BER performance of multiple SUs with frequency division multiple access (FDMA) for different number of SUs.

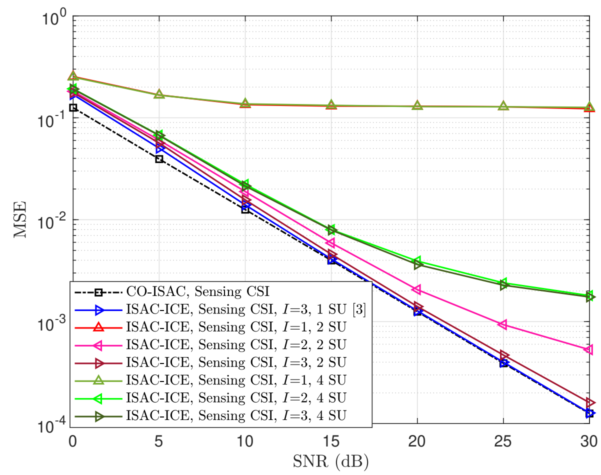

Fig. 5: The MSE performance of multiple SUs with FDMA for different number of SUs.

performance of ISAC-ICE deteriorates. The reason behind this can be attributed to the non-orthogonal interference caused by the overlapping signals. The coexistence of multiple SUs in the same frequency and time slots results in a high level of interference, which negatively impacts the performance of ISAC-ICE. To mitigate this, further improvements can be made by introducing advanced interference management techniques.

In addition to the BER performances, the MSE performances of multiple SUs using FDMA for a 4 tap channel are also evaluated, as shown in Fig. 5. The MSE is calculated by taking the expected value of the square of the difference between real channel coefficients and estimated channel coefficients. It can be observed that the MSE performances of ISAC-ICE are consistently worse than those of CO-ISAC, regardless of the number of SUs. Furthermore, the

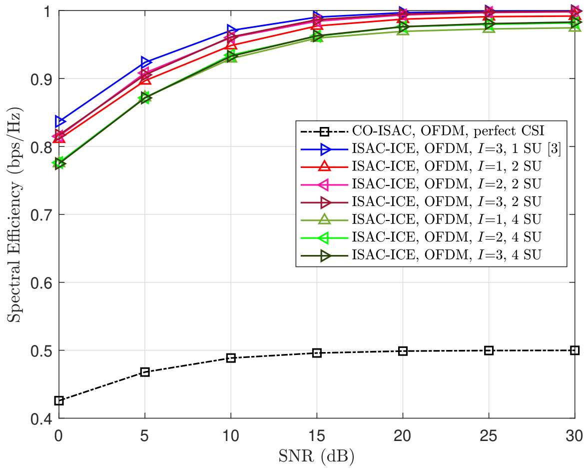

Fig. 6: The spectral efficiency of integrated sensing and communication with iterative channel estimation (ISAC-ICE) for different number of SUs.

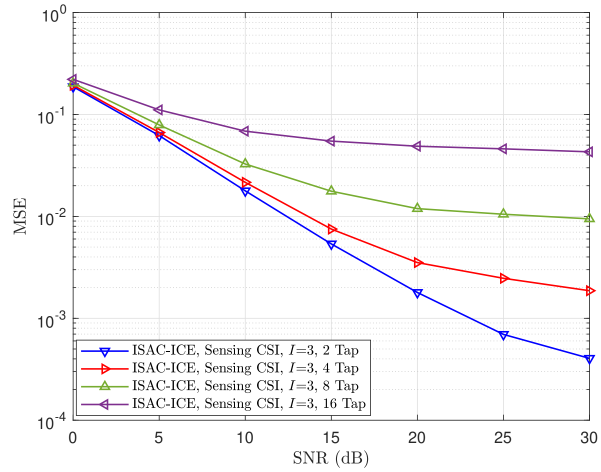

Fig. 8: The MSE performance of multiple SUs with FDMA for different number of channel taps.

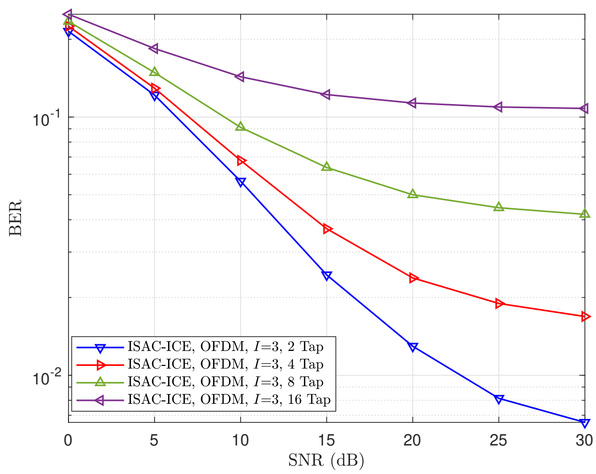

Fig. 7: The BER performance of multiple SUs with FDMA for different number of channel taps.

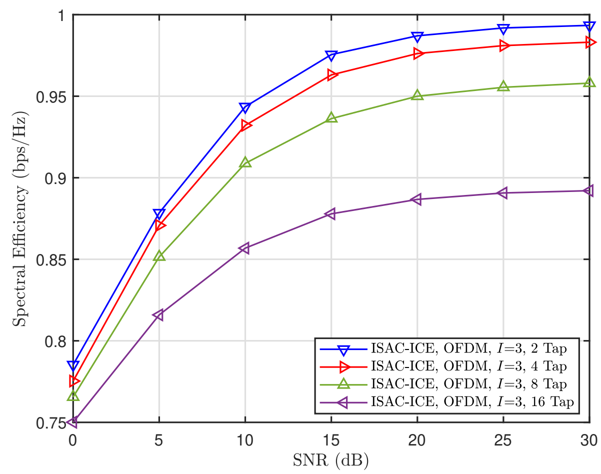

Fig. 9: The spectral efficiency of ISAC-ICE for different tap values.

performance of ISAC-ICE deteriorates as the number of SUs increases, which indicates that the interference among the SUs becomes more severe. However, it is worth noting that the MSE performances improve with an increasing number of iterations, leading to a better estimation of the channel and the separation of the SUs signals.

While the BER and MSE performances of ISAC-ICE are found to be worse than those of CO-ISAC, the spectral efficiency of ISAC-ICE is significantly better, as evidenced by Fig. 6. Spectral efficiency refers to the number of correctly transmitted bits over a given bandwidth, divided by the total duration of transmission. This indicates that, despite the worse BER and MSE performance, ISAC-ICE can achieve better utilization of the available bandwidth. However, as the number of SUs increases, the spectral efficiency of ISAC-ICE decreases, indicating a fundamental trade-off between spectral efficiency and the number of SUs.

The BER performances of multiple SUs with FDMA for 4 SUs are given in Fig. 7. The performance of ISAC-ICE for different numbers of channel taps is compared in the figure. As seen from the plot, the BER performances of ISAC-ICE degrade as the number of channel taps increases. This is due to the increasing complexity of the channel as more taps are added, which makes it harder to estimate the channel and thus degrades the system's overall performance

The MSE performances of multiple SUs using FDMA for 4 SUs are shown in Fig. 8. As seen in Fig. 8, the MSE performance of ISAC-ICE degrades as the number of channel taps increases, indicating a decrease in accuracy of the channel estimation process. This decrease in performance with increasing channel taps can be attributed to the increased complexity and variability of the channel, which makes it harder to accurately estimate the channel response.

The spectral efficiency is an important metric for evaluating the performance of communication networks. Fig. 9 shows the spectral efficiency performances of ISAC-ICE for different numbers of channel taps. It can be observed from the Fig. 9 that the spectral efficiency of ISAC-ICE decreases as the number of channel taps increases.

V. Conclusion

In conclusion, our study proposes a novel approach for managing multiple SUs using ISAC-ICE. The results demonstrate that as the number of SUs increases, the BER and MSE also increase, while they decrease with an increasing iteration number. Furthermore, the spectral efficiency achieved with ISAC-ICE is nearly twice as high as that of CO-ISAC. However, the spectral efficiency decreases with an increasing number of SUs. Additionally, it is observed that the overall system performance deteriorates as the number of channel taps increases. These findings highlight the effectiveness of our proposed approach in managing multiple SUs, while also shedding light on the impact of various factors such as the number of SUs and channel characteristics on system performance.

For future directions, further research and optimization efforts are warranted. Specifically, exploring techniques to enhance the scalability of the system when accommodating a larger number of SUs is crucial. Additionally, investigating methods to mitigate the performance degradation caused by an increasing number of channel taps would be beneficial. Furthermore, evaluating the proposed approach in realistic deployment scenarios and considering practical constraints and implementation challenges would provide valuable insights. Addressing these future directions will contribute to the advancement and practical applicability of integrated sensing and communication systems.

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