Validation of a CommSense Based ISAC System Using In-Situ mmWave Propagation Model

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***Abstract*—With the imminent arrival of sixth-generation (6G) wireless networks, conventional communication-centric systems face challenges in meeting future demands. As transformative technologies need real-time and reliable sensing capabilities, Integrated Sensing and Communication (ISAC) emerges as a comprehensive framework, integrating communication and sensing functionalities in one system. Sensing the environment using the information from channel equalization, called Communication based Sensing (CommSense), has been an area of investigation by the authors for more than a decade. In this work, we validate a CommSense-based ISAC system using in-situ mmWave propagation models. To do this, firstly, we verify the accuracy of our real-world measurements by validating the measured Received Signal Strength Indicator (RSSI) against a standard path loss model for the 60GHz band. Secondly, we derive an in-situ Cluster Delay Line (CDL) channel model by simulation, leveraging real map data to accurately represent dynamic wireless environments. Finally, we apply CommSense using the derived CDL channel and observe that it achieves good accuracy in real-time environmental sensing. The result is the facilitation of adaptive and context-aware communication strategies, enabling transformative applications such as intelligent traffic management, environmental monitoring, and IoT. Through our contributions, we demonstrate the potential of CommSense in achieving accurate sensing performance, opening avenues for the future of wireless networks.**

***Index Terms*—5G, 6G, Integrated Sensing and Communication (ISAC), Joint Communication and Sensing (JCAS), Communication based Sensing (CommSense), mmWave Communication, Machine Learning (ML)**

I. Introduction

With the advent of the upcoming sixth generation (6G) of wireless networks, there is an increasing awareness that conventional communication-centric systems may not suffice to meet the future's challenging demands. As we embrace the Internet of Things (IoT), autonomous vehicles, smart cities, and other emerging technologies, the importance of real-time and dependable sensing capabilities becomes more evident [1], [2], [3]. This necessity led to the emergence of ISAC, a framework that seamlessly integrates communication and sensing functionalities into an unified ecosystem. Among the emerging solutions that leverage the potential of ISAC, one noteworthy approach is CommSense system.

CommSense [4] represents a data-driven implementation with a communication-centric focus, utilizing the reference signals integrated into the 5G resource grid to extract channel state information (CSI). By employing machine learning (ML) methodologies, CommSense estimates environmental changes in real-time [5], [6]. This data-driven approach enables adaptive and context-aware communication strategies, fostering transformative applications such as intelligent traffic management [7], environmental monitoring [8], and immersive augmented reality experiences.

The significance of millimeter-wave (mmWave) technology in the context of ISAC cannot be overstated. The utilization of mmWave frequencies provides substantial bandwidth, facilitating high data rates and meeting the extensive connectivity demands envisioned in 6G networks. Additionally, the short wavelength of mmWave signals enables the implementation of sophisticated beamforming techniques, which not only enhance spatial resolution but also address propagation challenges in densely populated urban areas [9].

The role of mmWave technology is pivotal in enabling precise and high-resolution environmental sensing, a critical aspect of context-aware communication and resource optimization in ISAC scenarios. By fully harnessing the potential of mmWave, CommSense can achieve unmatched accuracy in identifying and interpreting environmental conditions. This capability facilitates seamless adaptation of communication strategies, ensuring superior performance and high-quality service delivery within 6G networks.

To lay the foundation for our research, we validate the measured Received Signal Strength Indicator (RSSI) against a standard model for 60GHz band. This validation serves to demonstrate the accuracy of our real-world measurements, ensuring that they somewhat align with the expected path loss characteristics. By providing empirical evidence of the correspondence between our measurements and the theoretical model, we establish the reliability of our experimental setup and data collection methodology.

Building upon the validated real-world measurements, we proceed to derive an in-situ CDL channel model. This model is tailored to capture the unique characteristics of dynamic wireless environments and incorporates real map data to enhance its realism and accuracy. The in-situ CDL channel model is crafted to offer a comprehensive representation of multipath propagation, channel fading, and spatial clustering effects,

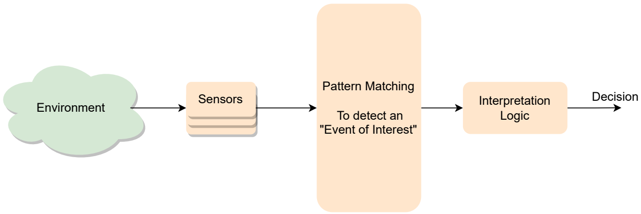

Fig. 1. A simplified block diagram of an ASIN instrument

making it well-suited for the simulation of 6G communication scenarios.

With our in-situ CDL channel model in hand, we apply CommSense, to explore its performance in dynamic wireless environments. Through our experimentation, we observe that CommSense effectively leverages the in-situ CDL channel model, achieving a good level of accuracy in sensing performance. The performance evaluation of the CommSense system using the 5G standard CDL channels can be found in [10].

To summarize,

- We present a comprehensive investigation of ISAC in 60GHz band. By validating our real-world measurements and path loss model, we establish the reliability of our data collection.
- The derivation of an in-situ CDL channel model, tailored to the dynamics of wireless environments, enables us to explore the power of CommSense: a communication-centric data-driven implementation of ISAC.
- Our findings highlight the potential of CommSense in achieving good sensing accuracy (over 84%) in 6G communication scenarios, opening doors to transformative wireless applications and laying the groundwork for the future of wireless networks.

II. Background Theory

A. CommSense System Model

CommSense incorporates the Application Specific Instrumentation (ASIN) framework, as introduced in [11], which employs low-resolution sensors and artificial intelligence (AI) algorithms for specialized tasks, as illustrated in Fig. 1, minimizing computational overhead. This novel approach revolutionizes sensor design, tailoring them to specific tasks. Utilizing channel impulse response (CIR) or impulse radio (IR) based sensing, CommSense systems extract environmental features using the reference symbols employed in communication.

In conventional communication standards, pilot symbols are transmitted to estimate the channel. Subsequently, channel state information (CSI) is extracted from channel equalization blocks at the receiver or user equipment (UE). CommSense first captures relevant event information and then utilizes stored phenomenological data and extracted CSI for training and pattern classification. A simple illustration of this process can be seen in Fig.2. This fusion of phenomenological data and communication related information enables CommSense

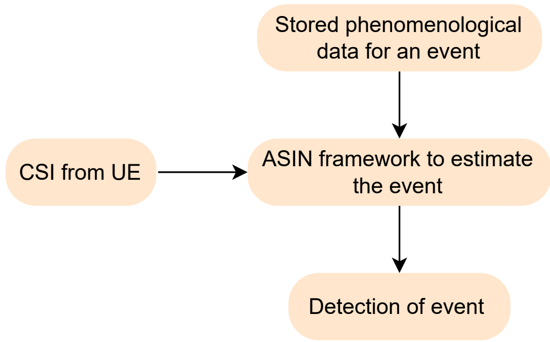

Fig. 2. CommSense's flow diagram for identifying events of interest.

to achieve context-awareness and adaptive communication strategies effectively.

B. Propagation in mmWave channel

- Free Space Path Loss (FSPL) : FSPL occurs when a signal travels through an unobstructed wireless medium without encountering any obstacles or reflections. The free space path loss is calculated by the following formula:

$$\text{FSPL} = \left(\frac{4\pi d}{\lambda}\right)^2 \tag{1}$$

  d : Distance between transmitter and receiver
  λ : Wavelength of propagating signal.
  e.g. For distance of 200m, The FSPL will be approximately 110dB at $60GHz$
- Atmospheric Attenuation: Compared to sub-6GHz bands, mmWave signals are more susceptible to atmospheric effects like water vapor and oxygen absorption, rain attenuation, and building material penetration [12]. These attenuating effects pose challenges to mmWave signals, leading to shorter transmission ranges. A detailed descriptions of these contributions can be found in [13].

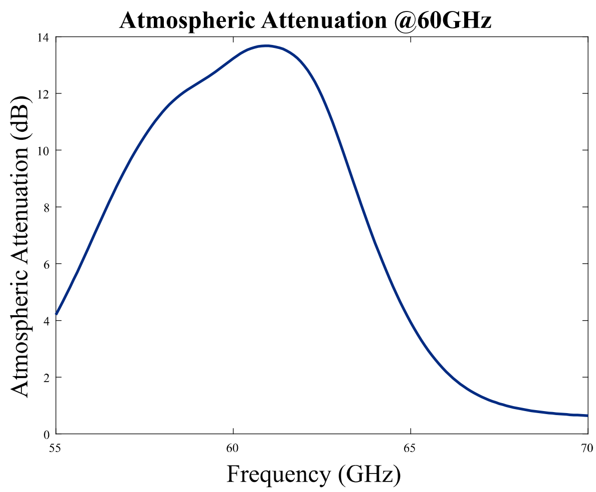

Fig. 3. Atmospheric attenuation in $60GHz$ band

We utilized a MATLAB app, "Vaayu" [14], to get the atmospheric attenuation profile as a function of frequency. This app follows the ITU standard to calculate the atmospheric attenuation, the plot is illustrated in Fig.3.

C. Channel model using Ray Tracing

Ray tracing serves as a prominent channel modeling technique employed to simulate diverse wireless communication environments [15]. This method meticulously considers the interactions of propagating waves with various objects and structures along the propagation path. By tracing individual rays from the transmitter to the receiver and accounting for reflections, diffraction, and scattering effects, the ray tracing model offers in-depth insights into signal strength, coverage, and multipath characteristics as depicted in Fig.4. This helps to optimize wireless network designs, strategically deploy base stations, and assess communication system performance in complex real-world scenarios. By exclusively considering the attenuation and delay associated with each path, as depicted in Fig.4, we can express the channel as $\sum_i \alpha_i \delta(t - \tau_i)$, where each (α_i, τ_i) pair represents the attenuation and delay for the i^{th} path, respectively. For the purpose of our experiment, we will normalize the delay of the initial path to zero.

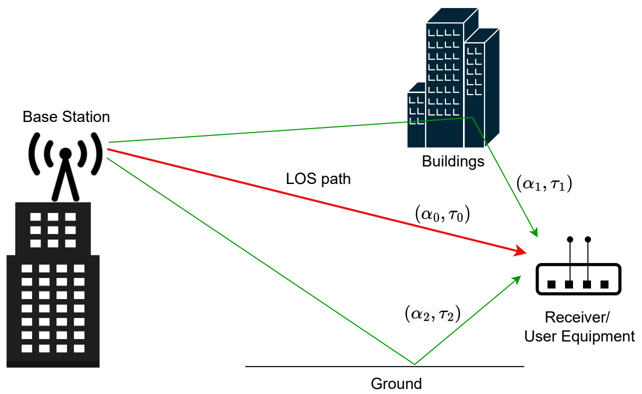

Fig. 4. A ray tracing model is a powerful tool in wireless communication, employing geometric optics to simulate electromagnetic signal propagation. By accounting for reflections, diffractions, and scattering effects, it offers insights into signal strength and coverage, aiding network design, base station deployment, and performance assessment in complex scenarios, pivotal in advancing future wireless technologies.

D. Data generation and Evaluation of Comm Sense System

In this setup, the derived channel is put to practical use. The base station transmits signals, and at the receiver, the channel estimation process helps to get the CSI, which is high-dimensional. To assess the system's performance in real-world scenarios, For a particular channel, the process of data generation incorporates the addition of additive white Gaussian noise (AWGN) to the received signal with that channel, then we estimate the CSI. This high-dimensional channel CSI represents the characteristics of that particular wireless channel and that environment.

To effectively analyze and interpret this information, Principal Component Analysis (PCA) is applied, which is one of the dimensionality reduction tool [16], [17]. PCA transforms the high-dimensional data into a lower-dimensional space, capturing the most significant features while reducing the computational complexity. With the reduced-dimensional CSI in hand, the next step involves employing Support Vector Machine (SVM) as a classification algorithm. SVM is used to measure the accuracy of the sensing process, enabling the system to distinguish between different environmental conditions. By training the SVM with labeled data representing known environmental states, it becomes capable of predicting and categorizing new and unseen data.

Overall, this comprehensive approach combining Channel modelling and validation, Channel estimation, data generation, PCA, and SVM allows CommSense to effectively detect and interpret environmental conditions based on the wireless channel's characteristics.

III. Results and Discussion

A. Validation of the derived channel

Our work revolved around conducting an In-situ experiment, which involves performing measurements and data collection in the actual environment of interest. To ensure accuracy, we meticulously set up the experiment using detailed mapping of the area under investigation as illustrated in Fig.5. The objective of the experiment was to derive the channel characteristics of the 60GHz band, focusing specifically on the line of sight path and the path resulting from the 1^{st} order reflection, which corresponds to the non-line of sight path received from a single bounce.

To validate our measurements and evaluate the channel's performance, we conducted a series of RSSI measurements using Cambium Networks' cnWave $60GHz$ radios [18], utilizing a V5000 as transmitter and a V1000 as receiver with center frequency of $64.8GHz$ and $2.16GHz$ bandwidth. The $22.5dBi$ Receiver was moved incrementally from Location 1 to 15, with a 2-meter step size between each location, as illustrated in Fig.5. Subsequently, the obtained RSSI values were juxtaposed with those projected by a standardized model [13], as illustrated in Fig.6. We incur Root Mean Square Error (RMSE) of $2.082dB$ and $1.046dB$ when we compare the theoretical prediction with the actual measured data and smoothed data respectively. This comparative analysis not only confirmed the precision of our real-world measurements but also validated the reliability of our setup.

The key contribution of our work lies in the precise measurement of the in-situ Cluster Delay Line (CDL) channel by ray tracing as discussed in Section II-C, and it is shown in Table I. This table presents crucial information, including Path delays, Average path gains, Angles of Arrival at the UE, and Angles of Departure from the Base Station. The CDL model is a critical component in the field of CommSense, which is communication-centric data-driven implementation of ISAC system. CommSense leverages the potential of mmWave technology and advanced data analytics to enable real-time environmental sensing, adaptive communication strategies, and context-aware applications.

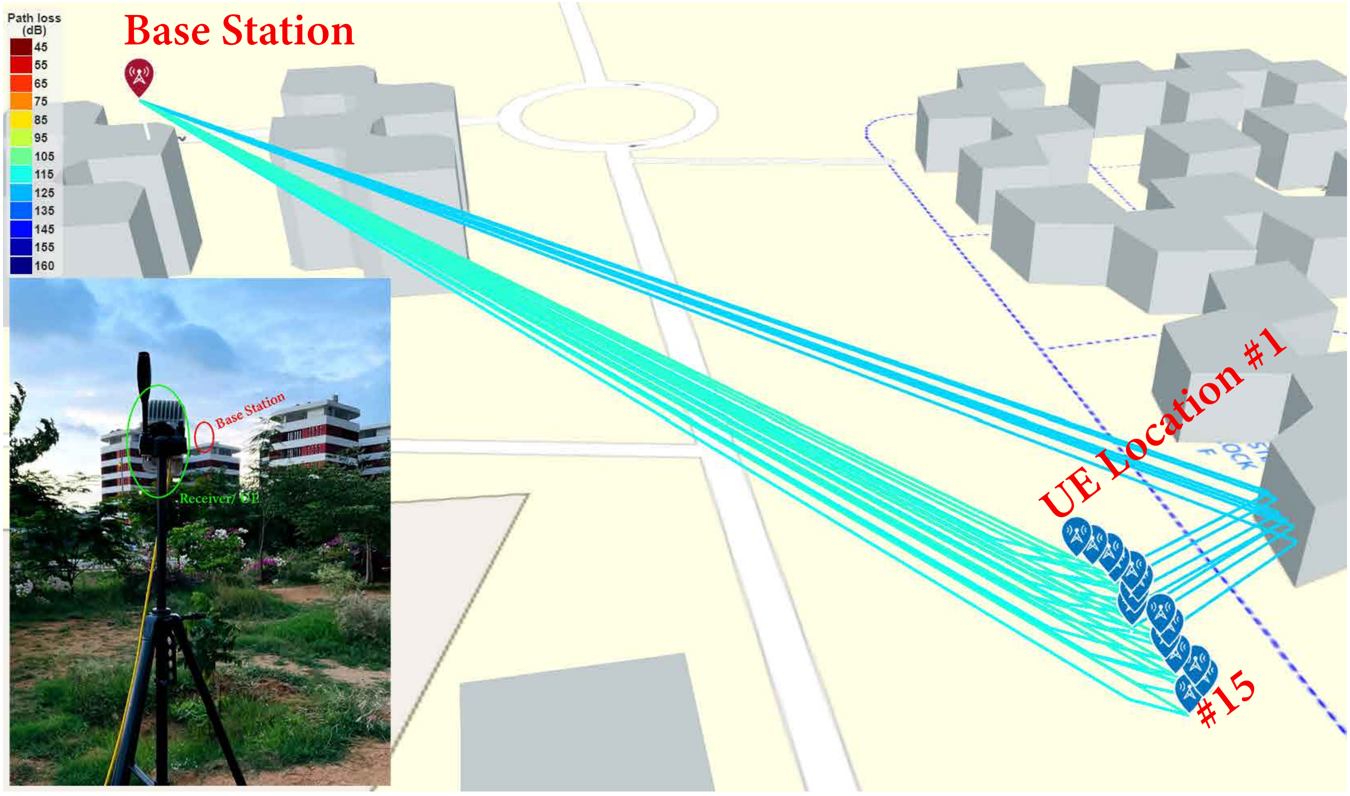

Fig. 5. An In-situ experiment set up using detailed mapping, to derive the 60GHz band based solely on the line of sight path and the path from the 1^{st} order reflection(s) (i.e. non-line of sight path received from a single bounce). To validate our measurements and measure path loss, we relocated the Receiver/UE from Location 1 to 15, recording the Received Signal Strength Indicator (RSSI) and comparing it with a standard model. The highlight of our endeavor was the precise measurement of the In-situ CDL channel from our carefully designed setup, offering invaluable insights in the field of CommSense using mmWave technology.

TABLE I
DERIVED IN-SITU CDL CHANNEL FROM FIGURE 5

Location #	*Path Delays (ns)*	*Path Gains(dB)*	*Angle of Departure (degrees)*	*Angle of Arrival (degrees)*
1	[0 1.64]	[-111.51 -115.66]	[45.80 46.00]	[-134.19 -137.12]
2	[0 1.63]	[-111.62 -115.69]	[45.66 45.45]	[-134.33 -130.92]
3	[0 1.57 113.85]	[-111.73 -115.80 -121.56]	[45.52 45.45 52.58]	[-134.47 -133.55 107.87]
4	[0 1.59 111.95]	[-111.79 -115.78 -121.58]	[45.10 44.92 52.03]	[-134.89 -131.82 107.64]
5	[0 1.53 103.98]	[-111.89 -115.88 -121.56]	[44.97 44.92 51.62]	[-135.02 -134.35 109.42]
6	[0 1.56 102.09]	[-111.96 -115.83 -121.59]	[44.55 44.49 51.07]	[-135.44 -133.95 109.12]
7	[0 1.58 1.62 106.16]	[-111.98 -115.96 -115.85 -121.66]	[43.86 44.08 43.64 51.07]	[-136.13 -138.88 -131.57 112.03]
8	[0 1.55 109.93]	[-112.01 -115.99 -121.74]	[43.11 43.23 50.52]	[-136.88 -138.35 111.22]
9	[0 1.62 96.20]	[-112.15 -115.91 -121.68]	[43.27 43.21 50.11]	[-136.72 -134.98 114.47]
10	[0 1.485]	[-112.22 -116.09]	[42.83 42.80]	[-137.16 -136.73]
11	[0 1.58 1.52]	[-112.25 -116.00 -116.11]	[42.16 42.37 41.95]	[-137.83 -142.51 -135.21]
12	[0 1.49]	[-112.33 -116.08]	[41.66 41.52]	[-138.33 -135.80]
13	[0 1.43]	[-112.44 -116.19]	[41.53 41.52]	[-138.46 -138.37]
14	[0 1.51]	[-112.50 -116.13]	[41.16 41.09]	[-138.83 -136.93]
15	[0 1.53]	[-112.49 -116.12]	[40.20 40.24]	[-139.79 -140.91]

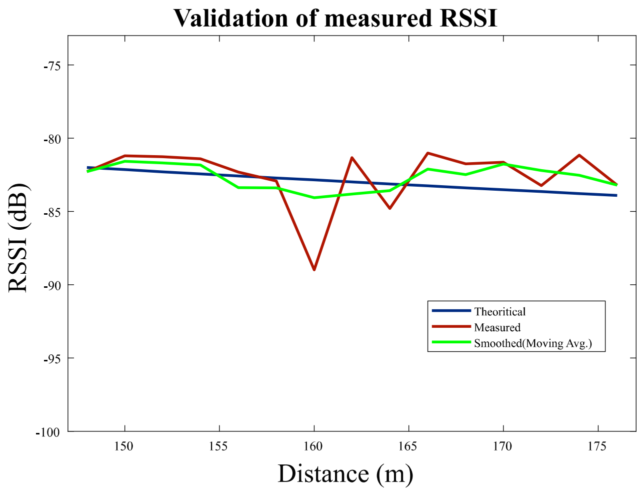

Fig. 6. To validate the channel measurements, we conducted RSSI measurements while moving the Receiver from Location 1 to 15 (Fig. 5). Comparing the measured RSSI values with those from standard model confirmed the accuracy of our real-world measurements and verified the expected path loss characteristics.

Our carefully designed setup and the precise measurement of the In-situ CDL channel provide invaluable insights for the implementation of CommSense using mmWave technology. Understanding the characteristics of the channel, including multipath propagation and path loss, is essential for optimizing the design and deployment of wireless communication systems, particularly in the development of advanced networks.

B. Sensing Performance

We are using $60GHz$ band with a wavelength of $5mm$, and our step size for each location is approximately 2 meters (which is 400 times the wavelength), we can reasonably assume that the channels for each location are uncorrelated. Therefore, our primary goal is to leverage the CommSense principle to distinguish these channels effectively. In other words, we aim to discriminate between each receiver location or UE, based on the unique characteristics of their channels.

For simulation, we generated 100 data points for each of the channels by transmitting $1.4MHz$ OFDM signal at $60GHz$ center frequency, as detailed in Section II-D. For each location, we utilized the derived in-situ channel models specified in Table I. These channel models allowed us to recreate realistic wireless propagation scenarios. To handle the high-dimensional channel state information obtained from the simulations, we employed PCA to project the data into a lower-dimensional space. This process reduced computational complexity while retaining essential features.

To evaluate the performance of our sensing system, we applied Support Vector Machine (SVM) with Gaussian kernel on the projected data. An example of such analysis can be found in Fig.7, where we successfully discriminated between channels at Location 1 and Location 2 with 84% accuracy. The results demonstrate the effectiveness of our approach in distinguishing different channel conditions.

Furthermore, we present the overall accuracy of the sensing system with respect to Location 1 as the reference, as illustrated in Fig.8. The figure shows that, on average, we achieved a sensing accuracy of over 80% for all the channels, despite being only 2 meters apart. These results indicate the reliability and robustness of our CommSense implementation in accurately detecting and interpreting environmental conditions in dynamic wireless environments.

IV. Conclusion

In conclusion, mmWave technology plays a vital role in enabling precise and high-resolution environmental sensing, a critical aspect of context-aware communication and resource optimization in ISAC. CommSense effectively harnesses the potential of mmWave, achieving good accuracy in identifying and interpreting environmental conditions.

This research laid a strong foundation by validating the measured Received Signal Strength Indicator (RSSI) against a standard model for the 60GHz band, ensuring the accuracy of real-world measurements and establishing the reliability of the experimental setup and data collection methodology.

Building upon the validated measurements, this study derived an in-situ CDL channel model, tailored to capture the unique characteristics of dynamic wireless environments. CommSense effectively utilized this model in dynamic wireless environments, resulting in a good level of accuracy in sensing performance.

In summary, this study on ISAC in the 60GHz band, incorporating validated measurements and a customized in-situ CDL channel model, demonstrates the effectiveness of CommSense as a communication-centric data-driven implementation. The findings underscore CommSense's potential in achieving accurate sensing in 6G communication scenarios, paving the way for transformative wireless applications and advancing the future of wireless networks.

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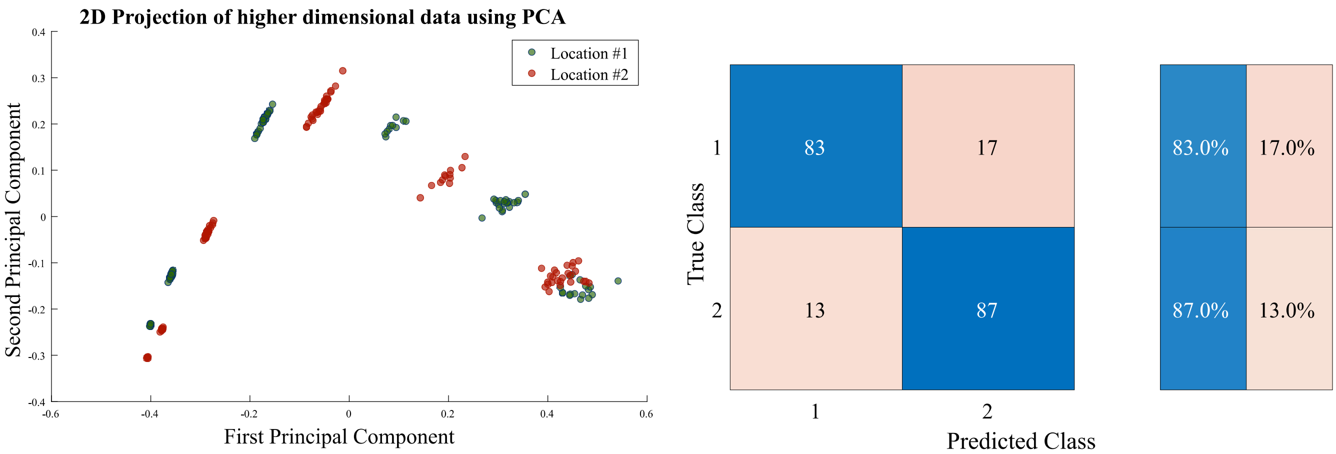

(a) 2D Projection using PCA

(b) Output from SVM on the PCA projected low dimensional data

Fig. 7. By utilizing Principal Component Analysis, the high-dimensional channel state information was projected into lower dimensions, reducing computational complexity while retaining crucial features. To evaluate sensing accuracy, SVM was applied to discriminate channels at different locations. Here we present one instance where we successfully discriminated between channels at Location 1 and Location 2 with 84% accuracy.

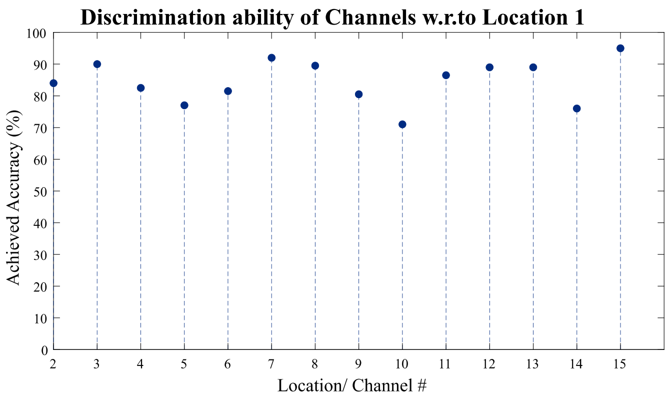

Fig. 8. Results showcased CommSense's effectiveness, achieving an average accuracy of over 84%, making it a robust and reliable approach for accurately detecting and interpreting environmental conditions in dynamic wireless environments.

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