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Integrated Research on Coexistence of mm-Wave Radar Communication and Dense Multi-Access Point Environments: A Testbed Controller Approach

Arun Kumar[1], Mickael David Yongo[2], Sumit Chakravarthy[3] and Aziz Nanthaamornphong[4*]

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Abstract: This paper presents two distinct research projects contributing to the advancement of millimeter-wave (mm) technology. The first project delves into creating a comprehensive millimeter-wave communication and radar framework, utilizing Texas Instrument hardware. Overcoming challenges like high path loss and poor diffraction, this initiative aims to simultaneously map targets and enable communication, making significant contributions to new network technologies and applications. Simultaneously, the second project centers on the Testbed Controller repository, employing Raspberry Pi (RPi) microcontrollers interconnected and communicating through the same network. It focuses on analyzing network configurations and traffic characteristics in multi-access point environments. Together, these projects reveal the dynamic interplay between theoretical exploration and practical implementation in the realm of millimeter-wave applications, offering insights, solutions, and innovations that push the boundaries of the field.

Keywords: *millimeter-wave (mm), Testbed controller, Networking, multi-access point, environment, extended sensing,*

1. Introduction

In the ever-evolving realm of wireless communication and radar technology, the incorporation of millimetre-wave frequencies stands out as a revolutionary paradigm. These frequencies, distinguished by their expansive bandwidths, heightened data rates, and increased network throughput, offer immense potential for applications spanning from fifth-generation (5G) cellular networks to IEEE 802.11ad. This introduction encapsulates two concurrent research endeavors, each making distinctive contributions to the ongoing development and comprehension of mm-wave technology. The first project immerses itself in synthesizing a unified communication and radar framework operating within the mm-wave spectrum. Positioned at the crossroads of cutting-edge technology and pragmatic implementation, this project utilizes Texas Instruments (TI) hardware to unravel the intricacies of simultaneous mm-wave communication and radar operations. Complementing this, the second project focuses on the Testbed Controller repository, a pivotal initiative led by the Ubiquitous Communications and Networking Lab (UCaN Lab) at UMass Boston [1]. This endeavor, employing Raspberry Pi (RPi) microcontrollers interconnected with a centralized Testbed Controller, scrutinizes the impact of mm-wave sensing and data collection on network configurations and traffic characteristics within densely populated and multi-access point environments. As we navigate the evolving landscape of mm-wave technology, these dual initiatives converge to provide insights, solutions, and innovations that propel the field forward. From the development of joint communication-radar frameworks to the sophisticated analysis of throughput in multi-access point environments, these projects underscore the dynamic interplay between theoretical exploration and practical implementation in the realm of mm-wave applications [2]. The driving force behind these initiatives is the creation of a test-bed, unique in its ability to not only function as a software-defined radio state with a radar testbed but also address the critical aspect of extended sensing for collective decision-making. Given the absence of an existing radar testbed, this specialized test bed allows radars collected from multiple locations to be aggregated, facilitating decisions based on sensing data from distant regions [3]. The ultimate goal is to enable extended sensing for collective decision-making, bridging the gap between theoretical concepts and real-world applications. In "Evaluation of HMIPv6 Algorithm in 5G mm-wave Single and Dual Connectivity Handover Network" by D. Perdana et al., published in IEEE Systems Journal, the authors delve into the assessment of the HMIPv6 algorithm's efficacy in 5G mm-wave networks, specifically focusing on single and dual connectivity handover scenarios [4]. This research contributes valuable findings for enhancing handover procedures in 5G mm-Wave networks, addressing the unique characteristics and requirements of these advanced communication systems.

[1]*Department of Electronics and Communication Engineering, New Horizon College of Engineering, Bengaluru, INDIA*
ORCID ID: 0000-0001-7640-8975
[2]*Department of Electrical Engineering and Computer Engineering, Kennesaw State University, GA, USA*
[3]*Department of Electrical Engineering and Computer Engineering, Kennesaw State University, GA, USA*
[4]*College of Computing, Prince of Songkla University, Phuket Campus Thailand,*
ORCID ID : 0000-0002-1618-6001
** Corresponding Author Email: aziz.n@phuket.psu.ac.th*

The authors conducted a comprehensive cross-layer analysis to evaluate the impact of blockages on mm-wave feasibility in 5G backhaul networks [5]. The paper provides a comprehensive cross-layer analysis, focusing on the impact of blockages in mm-wave communication. By examining blockage effects across layers, the authors contribute insights that are paramount for understanding the challenges and potential solutions in deploying mm-wave technology for 5G backhaul networks. This research adds a valuable perspective to the broader landscape of 5G communication, addressing critical considerations for efficient and reliable backhaul connectivity. Another noteworthy contribution is made [6]. The authors leverage fuzzy logic to optimize power consumption, a crucial aspect in WSNs where energy efficiency is paramount. This work contributes to the field by presenting a practical implementation and analysis of a fuzzy logic-based solution, shedding light on its effectiveness in reducing power consumption within the specific context of wireless sensor networks utilizing IEEE 802.15.4 and Wireless HART protocols. The study in [7] explores the evolving landscape of 5G technology, with a focus on the crucial role of FinFET technology in mobile transceivers. Emphasizing the impending shift to sub-6GHz and millimeter-wave (mm-Wave) 5G networks, the authors underscore the need for innovative design adjustments to achieve low-power, cost-effective, and scalable devices. The paper introduces a novel low-power RF FinFET, labeled as ELVT, based on GLOBALFOUNDRIES 12nm node technology. Through meticulous examination and comparison with the existing SLVT FinFET in terms of DC/RF performance, the study reveals that the ELVT device, requiring minimal process integration changes with no additional cost, surpasses the SLVT FinFET in specific sub-6GHz and mm-wave 5G transceiver applications. This highlights its potential to enhance the efficiency of future mobile communication systems. These research endeavours collectively contribute to the advancement and understanding of key aspects in 5G technology, ranging from handover network algorithms to mm-wave feasibility and power-efficient solutions in wireless sensor networks.

1.1. Contributions

In this research, our contributions unfold across several crucial dimensions. Firstly, a significant contribution lies in enhancing the test bed infrastructure. Secondly, we explore the expansion of sensing capabilities through the radar component of the TI device. In this sense, each step in the process involves valuable input, including data collection, preprocessing, and decision-making. Notably, the data collection process involves meticulous efforts to collect and compile information. Subsequently, preprocessing steps are undertaken to refine and prepare the data for analysis. Finally, decisions are made either at the Raspberry Pi level or at the main computer, often involving the coordination of multiple Raspberry Pi units, all representing a key factor to the overall research endeavor, which collectively advances our understanding and capabilities in the domain of coexistent communication-radar frameworks.

2. System Model

The simulation framework implemented in MATLAB provides a basic assessment of the performance of the 5G New Radio Physical Uplink Shared Channel (NR PUSCH) using LDPC and Polar coding over an Additive White Gaussian Noise (AWGN) channel. An MCS table is manually defined, specifying the modulation schemes and corresponding code rates. In this simulation, the first five entries of the 3GPP TS 38.214 standard MCS table are created, employing Quadrature Phase Shift Keying (QPSK) as the modulation scheme with varying code rates [8]. Key parameters, such as the signal-to-noise ratio (SNR) range (-10 to 20 dB with a step of 2 dB) and the MCS index, are initialized. The modulation scheme and code rate are then retrieved from the MCS table using the chosen index. Depending on the retrieved modulation scheme, the modulation order is established. The supported modulation schemes include QPSK, 16-QAM, 64-QAM, and 256-QAM. The BLER calculation is down through what is a called a Cyclic Redundancy Check (CRC) [9]. Cyclic Redundancy Check is an algorithm or method for detecting errors and information loss in communication systems. A particular CRC function is attached to each transported block and is inspected by the receiver. The transported block will be decoded if the blocks CRC matches the receivers calculated CRC value. Cyclic Redundancy Check is an effective method of detecting errors in transported blocks. If the Calculated CRC value does not match the blocks CRC value. Then the block is retransmitted until the receivers and blocks CRC values match. In most communication systems the BLER tar- get is 10% [10]. This means that the receiver should successfully receive around 90% of the transmitted blocks. BLER is broken down into two types. Initial Block Error Rate (IBLER). This is the ratio of transmission blocks with initial errors and retransmission to the total number of transmission blocks. Residual Block Error Rate (RBLER). This is the ratio of blocks with transmission errors after transmission to the total number of transmission blocks. Signal to Noise Ratio (SNR) is the ratio between the transmitted signal or information power to the undesired signal or noise power. Simply it is the ratio of the signal power to noise power. The signal to noise ratio is a way to measure the amount of information a signal conveys [11]. Typically, the unit for SNR is expressed in decibels (dB). Based on the above formula, the goal is to have a relatively high signal to noise ratio. We want to maximum the desired signal and minimize the unwanted noise. The SNR value is always a positive value. This means that if the SNR value is 45 dB, the desired signal is 45 dB higher than the noise signal. This is why having a high SNR is important. The higher the ratio the less impact the noise signal on the system. All transmission mediums generate some unwanted noise [12]. Designers attempted to minimize the amount of noise generated. For example, noise signals typically oscillate at higher frequencies. So low pass filters are a great way to get rid of unwanted noise [13]. For each SNR value in the defined range, the following operations are performed: Random bits for transmission are generated and then encoded using LDPC. The encoded bits are then modulated into symbols for transmission using the appropriate modulation scheme [14]. The AWGN channel is modeled by adding noise to the transmitted symbols based on the current SNR value. The received symbols are demodulated into bits, which are then converted into Log-Likelihood Ratios (LLRs). LDPC decoding is then performed on the LLRs to retrieve the decoded bits. The BER is computed by comparing the transmitted bits and the decoded bits [15].

3. Simulation Results

The increasing adoption of millimeter-wave frequencies which extends to applications such as fifth generation (5G) cellular networks and IEEE 802.11ad. in wireless communication and radar applications, driven by broader bandwidths, higher data rates, and improved network throughput, especially in densely populated areas, has become a prominent trend. This project is a vital contribution to the ongoing development of millimeter-wave communication and radar technology, focusing on creating a joint framework using Texas Instruments (TI) hardware for simultaneous communication and target mapping, while addressing challenges such as interference . The scope of this article is to develop and implement a joint communication, as well as radar framework that functions using millimeter-wave frequencies to map targets while enabling communication. The project team will use the Texas Instrument (TI) hardware to develop a system that assesses the interference between two devices operating on millimeter-wave frequency simultaneously. The team will perform different experimentations to generate and produce experiment results based on communication-radar framework. The system architecture for the Coexistence of mm-Wave Radar and Communication project is intricately designed to enable concurrent operation of communication and radar functionalities within a millimeter-wave framework. The architecture comprises key elements that synergize to achieve seamless integration and coexistence. At the heart of the architecture are specialized millimeter-wave transceivers from Texas Instruments. These transceivers include efficient signal transmission and reception. The IWR1443 is a stand-alone, single-chip 76- to 81-GHz mm-wave sensor that has integrated transmitters (3) and receivers (4). Similarly, the IWR6843 radar uses a single chip, but it requires a carrier board (i.e., MMWAVEICBoost) for data capture and its range is from 60- to 64-GHz. It also has 3 transmitters and 4 receivers integrated in the radar as given if fig 1.

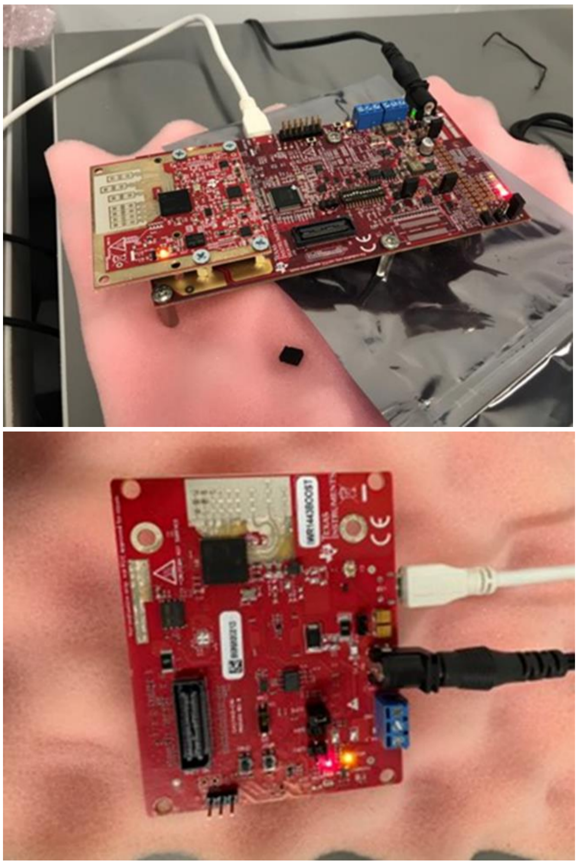


Fig 1. IWR6843 Radar and mm-WAVEIC Boost Carrier Board and IWR1443 Radar

Raspberry Pi Interface: Serving as the central hub, a Raspberry Pi interfaces with millimeter-wave transceivers. This component acts as the nerve center, coordinating communication between the communication and radar modules. The Raspberry Pi also provides a flexible platform for incorporating additional sensors and devices, enhancing the overall system's versatility. The testing and results analysis is given in table 1.

Table 1. Testing & Results

Experiment 1 (IWR1443 On):

bash Copy code

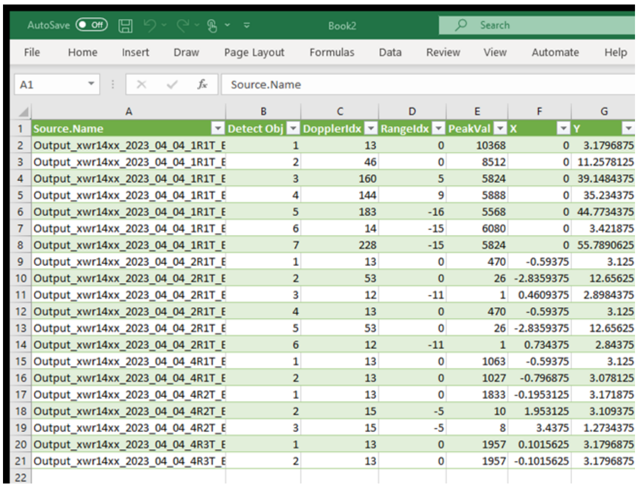
| Experiment | Interval | Transfer | Bitrate | Retr | Cwnd | |----------|----------|----------|--------------|------|------------| | Exp1 | 0-5 sec | 19.3 MB | 32.4 Mbits/s | 17 | 84.8 KB | | Exp1 | 5-10 sec | 10.8 MB | 18.1 Mbits/s | 3 | 102 KB | | Exp1 | 10-15 sec| 21.3 MB | 35.8 Mbits/s | 8 | 171 KB | | Total | 0-15 sec | 51.4 MB | 28.8 Mbits/s | 28 | (sender) | | Total | 0-15 sec | 50.6 MB | 28.2 Mbits/s | - | (receiver) |

Experiment 2 (IWR1443 Off):

| Experiment | Interval | Transfer | Bitrate | Retr | Cwnd | |----------|----------|----------|--------------|------|------------| | Exp2 | 0-5 sec | 29.9 MB | 50.2 Mbits/s | 13 | 215 KB | | Exp2

| 5-10 sec | 31.5 MB | 52.9 Mbits/s | 14 | 144 KB | | Exp2 | 10-15 sec| 22.9 MB | 38.4 Mbits/s | 12 | 168 KB | | Total | 0-15 sec | 84.3 MB | 47.1 Mbits/s | 39 | (sender) | | Total | 0-15 sec | 83.4 MB | 46.5 Mbits/s | - | (receiver) |

When it comes to the data collected, we have conducted different experiments while using the 1443BOOST sensor, such as collecting different sets of data while switching between the number of Transmitters and Receivers. And below are the different results and conclusions as shown in fig 2.



AutoSave Off Book2 Search
File Home Insert Draw Page Layout Formulas Data Review View Automate Help
A1 Source.Name

	A	B	C	D	E	F	G
1	Source.Name	Detect Obj	DopplerIdx	RangeIdx	PeakVal	X	Y
2	Output_xwr14xx_2023_04_04_1R1T_E	1	13	0	10368	0	3.1796875
3	Output_xwr14xx_2023_04_04_1R1T_E	2	46	0	8512	0	11.2578125
4	Output_xwr14xx_2023_04_04_1R1T_E	3	160	5	5824	0	39.1484375
5	Output_xwr14xx_2023_04_04_1R1T_E	4	144	9	5888	0	35.234375
6	Output_xwr14xx_2023_04_04_1R1T_E	5	183	-16	5568	0	44.7734375
7	Output_xwr14xx_2023_04_04_1R1T_E	6	14	-15	6080	0	3.421875
8	Output_xwr14xx_2023_04_04_1R1T_E	7	228	-15	5824	0	55.7890625
9	Output_xwr14xx_2023_04_04_2R1T_E	1	13	0	470	-0.59375	3.125
10	Output_xwr14xx_2023_04_04_2R1T_E	2	53	0	26	-2.8359375	12.65625
11	Output_xwr14xx_2023_04_04_2R1T_E	3	12	-11	1	0.4609375	2.8984375
12	Output_xwr14xx_2023_04_04_2R1T_E	4	13	0	470	-0.59375	3.125
13	Output_xwr14xx_2023_04_04_2R1T_E	5	53	0	26	-2.8359375	12.65625
14	Output_xwr14xx_2023_04_04_2R1T_E	6	12	-11	1	0.734375	2.84375
15	Output_xwr14xx_2023_04_04_4R1T_E	1	13	0	1063	-0.59375	3.125
16	Output_xwr14xx_2023_04_04_4R1T_E	2	13	0	1027	-0.796875	3.078125
17	Output_xwr14xx_2023_04_04_4R2T_E	1	13	0	1833	-0.1953125	3.171875
18	Output_xwr14xx_2023_04_04_4R2T_E	2	15	-5	10	1.953125	3.109375
19	Output_xwr14xx_2023_04_04_4R2T_E	3	15	-5	8	3.4375	1.2734375
20	Output_xwr14xx_2023_04_04_4R3T_E	1	13	0	1957	0.1015625	3.1796875
21	Output_xwr14xx_2023_04_04_4R3T_E	2	13	0	1957	-0.1015625	3.1796875
22							

Fig 2. Experiment while collecting data.

The experiments with the IWR1443Boost sensor yielded valuable insights into its performance, showcasing achievements like detecting seven objects with specific Doppler and range indices. The experiments highlighted the system's sensitivity to the number of receivers and the impact of configuration on outputs. Despite functionality issues, the IWR6843ISK demonstrated promising range resolution capabilities, revealing variations in detected object values, azimuth angles, and range values. These findings significantly contribute to understanding mmWave radar technology, emphasizing its potential for precise range resolution. Challenges with the IWR6843ISK's functionality, while present, don't diminish the gained insights, indicating possibilities for future optimizations in coexistent communication-radar frameworks. The Testbed Controller (TCBED) approach, developed and maintained by the Ubiquitous Communications and Networking Lab (UCaN Lab) at UMass Boston, under the guidance of Professor Michael Rahaim, offers a comprehensive platform for experimental test capabilities. Specifically designed to understand network configurations and traffic characteristics in densely populated areas, TCBED distinguishes itself from conventional methods by utilizing Raspberry Pi (RPi) microcontrollers to effectively emulate device usage, providing a nuanced and controlled experimental environment. The TCBED initiative aims to assess the impact of network configurations and traffic characteristics through a centralized Testbed Controller (TC) connected to RPi nodes. The architecture comprises a Control Network for connectivity and Test Network(s) with Wi-Fi routers for RPi node connection. by Utilizing the iperf tool, the initiative is to generates and analyzes network traffic. And evaluate the impact of radars on it. For the baseline version of the testbed, the necessary equipment includes Raspberry Pi microcontrollers (ideally 3B+ or 4 with 4GB RAM or higher), microSD cards, power cables, and a PC for the Testbed Controller (preferably running Ubuntu Linux). Additional networking equipment such as Wi-Fi routers, network switches, Ethernet cables, and USB to Ethernet adapters are also essential for the successful functioning of the testbed as shown in fig 3.

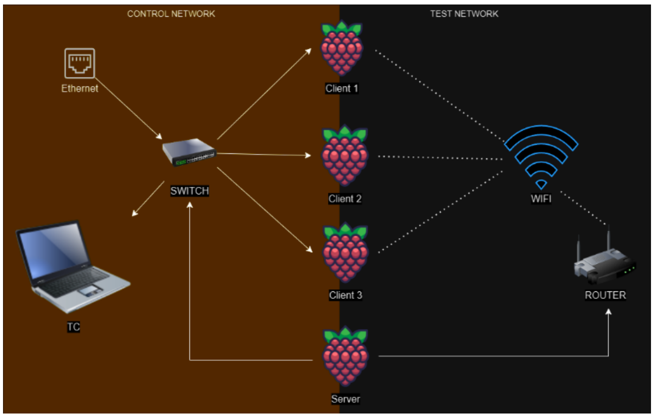


Fig 3. Original vs Initial Setup

We realized the following setup according to the guidelines. However, no communication between the devices could be possible from TC/Laptop remotely. It had to be modified to get results and being able to both ping and communicate with each Raspberry P is as shown in fig 4.

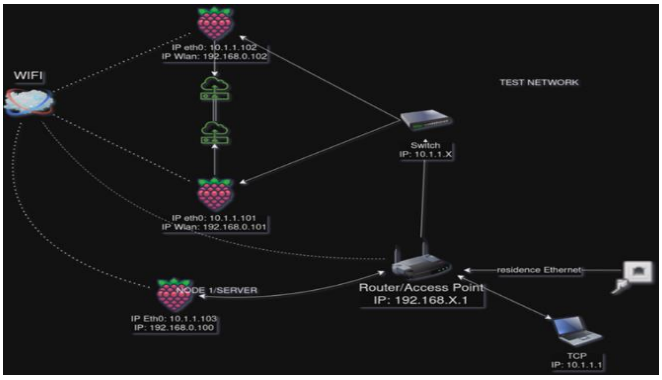


Fig 4. Modified Setup

We conducted Two tests using the IWR1443: one collecting data over WIFI without the TI and the other while the TI is sensing & capturing data. This gave us a sense of how much the use of the TI device would affect the internet traffic on the local network as given in fig 5.

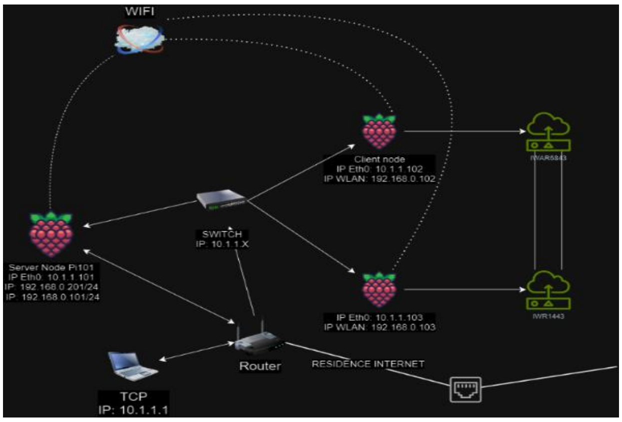


Fig 5. Final setup

4. Conclusion

The provided data presents the results of two experiments conducted using the TCBED approach with the IWR1443 sensor, focusing on the impact on internet traffic when collecting data over Wi-Fi both with and without the TI device sensing and capturing data. The experiments consistently achieved stable and high bitrates, ranging from 59.8 Mbits/s to 76.7 Mbits/s. The absence of retransmissions (Retr=0) and consistent throughput (Bitrate) indicates a stable and reliable network connection. The congestion window size remained stable across all experiments, suggesting efficient network utilization without notable fluctuations. The decision to employ both radars, MMWAVEICBOOST + IWR6843ISK and IWR1443, in the last experiment was necessitated by an unforeseen technical issue and malfunction with the newly acquired IWR6843. In the absence of radar devices, the TCBED approach demonstrated stable and reliable Wi-Fi data collection over the Kennesaw State network. The experiments consistently achieved high bitrates without encountering retransmissions, indicating a robust and efficient network environment. It suggests that the TCBED approach, when not influenced by radar sensing activities, can provide reliable data collection in wireless communication scenarios. The IWR1443Boost sensor demonstrated superior range capabilities, especially with a single transmitter and receiver, achieving a maximum range of 55.79 meters. The IWR6843ISK sensor exhibited remarkable range resolution, enabling detailed analysis through the Demo Visualizer despite limited experimentation due to a faulty device. Varying the number of transmitters and receivers influenced the number of detected objects, Doppler index, and peak values in the IWR1443Boost experiments. The IWR6843ISK data highlighted variations in detected object values, range, azimuth, and signal-to-noise ratios, highlighting the sensitivity of the sensor to different configurations. Both system model underscores the importance of understanding sensor behaviour under different configurations and their impact on network performance. Future work should focus on refining sensor settings and network parameters to ensure optimal functionality in real-world applications. These insights contribute to the ongoing development of radar-based technologies and their seamless integration into diverse environments. The presence of the IWR1443 radar sensor appeared to impact the network performance, leading to variations in bitrate, retransmissions, and congestion window sizes. Further investigation is necessary to understand the specific impact of the radar sensor on the home network and to optimize network performance during radar sensing activities**.**

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Author contributions

Arun Kumar: Conceptualization, Methodology, Writing-Original draft, Field study; **M.D.Y:** Data curation; Draft preparation **Sumit Chakravarthy**: Software, Validation., Field study; **Aziz Nanthaamornphong:** Visualization, Investigation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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