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Channel State Information Accuracy and its Impact on mMIMO Performance in 6G Industrial Networks

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Keywords

mMIMO, 6G, 5G, Electromagnetic Field (EMF) etc.

Abstract

The implementation of 5G technology paves way for major changes in terms of wireless communications, these applications are; robots, self-driving cars and even medical equipment. This technology that is based on higher frequency bandwidths and efficient modulation techniques hold the possibilities of enhanced capacities, less latency and better connected network. Nevertheless, there are some contentious issues that should be discussed while talking about 5G networks, one of them is the electromagnetic radiation and its possible influence on health. There are still controversies on whether it is safe to expose people to more RF, though regulatory bodies dismissed this as a concern arguing that the amounts found to be carcinogenic are much higher than RF-EMFs. This paper describes the complex interactions of mMIMO systems for large scale indoor industrial settings, and explores the outcomes of CmMIMO and DmMIMO arrangements. For such an environment, we substantiate a wireless channel model using the collected measurement data and theoretical modeling and analyze the large scale fading behavior and the interplay between different device types and APs. The analysis focuses on evaluating the signal quality identification, which may include aspects such as avg channel gain and also signal to interference plus noise ratio (SINR). Furthermore, we also evaluate the outage probability to determine the effect of this parameter on the execution success ratio and the latency of MTC communication in the concerned network environment. It also evaluates the economic and needs for adopting the mMIMO technologies in certain industries and their operations, which are essentials in today's industrial world. By simulating the channel coefficients using Monte Carlo simulations, we determine and compare the mMIMO deployment scenario outcomes during regular and emergency traffic. Thus, it has been noticed that DmMIMO configurations provide better signal strength and reliability in most of the cases that are beneficial for application in controlling and processing real-time data. From the general comparison table, it is evident that DmMIMO setups, in general, yield better results regarding the network and different settings of the grid and linear deployments yield different results in terms of spectral efficiency and outage probability. This study not only provides insights into the technical and operational aspects of mMIMO systems but also contributes to the ongoing standardization efforts for future wireless communication technologies. It highlights the transformative potential of 5G in supporting the demands of the Industrial Internet of Things (IIoT) and sets a precedent for future advancements in 6G technologies.

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I. INTRODUCTION

As we are living in a period of communication wherein, we can undoubtedly move any type of data (video, sound, and other data) as electrical signals to some other gadget or foreordained territory. Despite the fact that it is common we would say that imparting or accepting signs or data is basic, however it includes very perplexing strategies, potential outcomes, and included situations inside the communication frameworks. Thus, in the extent of communication frameworks, modulation plays hold vital obligation in the communication framework to encode data carefully in the simple world. It is vital to adjust the signals prior to sending them to the collector segment for bigger distance move, accurate data move, and low-noise data reception. Modulation is an interaction of changing the attributes of the wave to be sent by superimposing the message signal on the high-frequency signal.

As 5G wireless innovation is gradually advancing across the globe, numerous administration offices and associations counsel that there is no motivation to be frightened about the impacts of radiofrequency waves on our wellbeing. However, a few specialists unequivocally oppose this idea. Offer on Pinterest Why do a few people accept that 5G innovation may hurt our wellbeing? The term 5G alludes to the fifth generation of portable innovation. With guarantees of quicker perusing, streaming, and download speeds, just as better network, 5G may appear to be a characteristic advancement for our undeniably tech-dependent society. In any case, past permitting us to stream the most recent films, 5G has been intended to build capacity and lessen inactivity, which is the time that it takes for gadgets to speak with one another.

For integrated applications, for example, advanced mechanics, self-driving vehicles, and clinical gadgets, these progressions will have a major impact in how rapidly we receive innovation into our regular daily existences. The backbone of 5G innovation will be the utilization of higher-frequency bandwidths, directly across the radiofrequency range. In the United States, the Federal Communications Commission has sold the main bandwidth 28 gigahertz (GHz) that will shape the 5G organization, with higher bandwidth barters planned for the near future. Yet, what does 5G have to do with our wellbeing? In this Spotlight, we take a gander at what electromagnetic radiation is, what it can mean for our wellbeing, the contention encompassing radiofrequency organizations, and how this affects the coming of 5G innovation.

What is electromagnetic radiation? An electromagnetic field (EMF) is a field of energy that outcomes from electromagnetic radiation, a type of energy that happens because of the progression of power. Electric fields exist any place there are electrical cables or outlets, if the power is turned on. Attractive fields are made just when electric flows stream. Together, these produce EMFs. Electromagnetic radiation exists as a range of various frequencies and frequencies, which are estimated in hertz (Hz). This term signifies the quantity of cycles each second. Electrical cables operate somewhere in the range of 50 and 60 Hz, which is at the lower end of the spectrum. These low-frequency waves, along with radio waves, microwaves, infrared radiation, noticeable light, and a portion of the bright spectrum which bring us into the megahertz (MHz)‖, GHz, and terahertz spectra make up the thing is known as nonionizing radiation. Over this falsehood the pet hertz and exahertz spectra, which incorporate X-beams and gamma beams. Lennart Hardell, from the division of oncology at Örebro University, in Sweden, is a frank pundit of the WHO's choice not to embrace the IARC's arrangement of RF- EMFs as perhaps cancer-causing. High portions of RF-EMFs can prompt an ascent in the temperature of the uncovered tissues, prompting consumes and other harm.

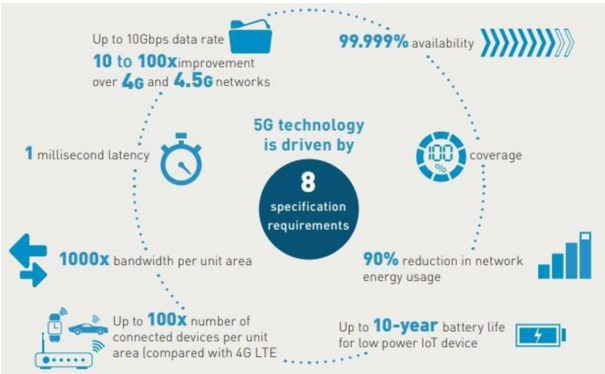

Figure 1 5G Technology

II. LITERATURE REVIEW

Mamta Agiwal (2019): Simultaneously, 5G wireless guarantees another associated environment with possible innovations, as massive Multiple-Input and Multiple-Output (MIMO), Cloud Radio Access Network (C-RAN), Heterogeneous-CRAN (H-CRAN), mmWave, programming characterized organizing, data (substance or data)- driven communication, Multi-RAT, and novel multiplexing. Since arising 5G organization is relied upon to change the method of communication, its plan and normalization ought to think about IoT as one of the significant rules. To this respect, we present specialized subtleties of arising 5G organizations inline with squeezing IoT necessities,

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fundamental for a definitive forming of an associated living.

Muhammad Mateen Hassan (2020): This work presents a novel two-component multiple input multiple output (MIMO) reconfigurable receiving wire that can be exchanged among 600 MHz, 1.8, 2.4, 3.5, and 5.5 GHz groups. The proposed receiving wire comprises of two semi-round ring-formed strip-lines and a rectangular opening on the top directing layer of the substrate and a U-molded space, carved on the base side of the substrate. Frequency reconfigurable attributes have been accomplished utilizing single shaft four toss radio frequency miniature electro-mechanical framework switch. The switch has been introduced in the ground opening. The elements of the proposed MIMO receiving wire are $32 \times 98 \times 1$ mm3.

A. S. Rachini (2019): The primary point of ongoing examination exertion based on 5G versatile innovation is to build the bandwidth for all clients, huge bandwidth, more effective and effectively reasonable and uninterrupted uniform availability. A critical viewpoint to this development has been the improvement of novel signal transmission procedures and progressed signal handling beneficiary that permit huge expansions in wireless capacity without chaperon increments in bandwidth or force prerequisites. To accomplish this objective, a few transmission strategies are tried like FBMC, F-OFDM, UFMC and WOLA. In this, we mimic the exhibition of the transmission procedures recorded above against OFDM innovation utilized for 4G regarding BER versus SNR.

A. Hammoodi (2019): There is a developing interest for 5G applications in all fields of information. Current applications, for example, the Internet of Things, shrewd homes, and clean energy, require modern types of 5G waveforms. Analysts and engineers are exploring the prerequisites of 5G organizations for better waveform types, which will bring about high spectrum efficiency and lower inertness with less multifaceted nature in frameworks. This work proposes an appraisal of different 5G waveform competitors [filtered orthogonal frequency-division multiplexing (OFDM), all-inclusive sifted multicarrier (UFMC), channel bank multicarrier (FBMC), and summed up frequency- division multiplexing] under the key execution pointers (KPIs). This work evaluates the fundamental KPI factors (computational multifaceted nature, top to-average-power ratio, spectral efficiency, channel length, and dormancy).

A. S. Ovsyannikova (2018): This work gives correlation of polar codes and super codes applicated to ideal Faster-than-Nyquist signals. The efficiency of the joint utilization of these coding methods and ideal signals is assessed as far as moving toward as far as possible. For various cases, the base distance between the Shannon bend and the point which directions are the estimations of the spectral and energy efficiency is determined. The utilization of polar codes permits to draw nearer to the Shannon furthest reaches of 11%. Contrasted with "exemplary" BPSK signals, ideal signals with polar coding think of the increase about 86%. In this, we present the aftereffects of utilizing a super decoder to recover a sequentially encoded data stream, which has been sent over an aeronautical channel.

J. Wang et al (2018): Three 5G empowering innovations, i.e, inadequate code multiple entrance (SCMA), Polar codes and sifted OFDM (f-OFDM), are actualized into a massive MIMO framework in the field preliminary led by HUAWEI and NTT DOCOMO to examine their effects on the framework spectral efficiency. Taking massive MIMO with OFDMA and Turbo codes as the baseline, we see about 30% downlink spectral efficiency improvement in the preliminary. Results from test field are summed up and investigated, which checked that SCMA, Polar codes and f-OFDM are additionally achievable for massive MIMO frameworks regarding spectral efficiency improvement.

S. K. Goudos (2017): Fifth generation (5G) wireless innovation is a promising answer for multi-Gbps data rates in future versatile communications. The new gadgets are relied upon to operate at millimeter wave frequencies. To address the 5G necessities novel reception apparatuses must be created. In this work the Teaching-Learning-Optimization (TLBO) calculation is applied to plan a double band E-molded fix radio wire. The mathematical boundaries of the gap coupled reception apparatus are the inputs of the enhancement calculation. The technique gives satisfactory plan arrangements accomplishing all the while S11 minimization and low VSWR at the frequencies of interest (25GHz and 37GHz).

J. Wang et al (2017): Spectral efficiency is consistently a critical factor to be improved and streamlined along versatile communication networks developing generation by generation. 5G empowering innovations should contemplate spectral efficiency. In this, we show the exhibition of three key 5G advancements in feeling of spectral efficiency improvement. Scanty code multiple entrance, polar codes, and sifted orthogonal frequency-division multiplexing are novel multiple entrance innovation, channel coding plan, and waveform, individually. The blend of them is executed in a 5G field preliminary testbed by NTT DOCOMO and Huawei unexpectedly.

C. Mei (2020): Network cutting (NS) is perceived as a critical innovation for the 5G versatile organization in empowering the organization to help multiple differentiated vertical business sectors over an imparted actual framework to efficiency and adaptability. A 5G NS example is made out of a bunch of virtual organization work (VNF) occasions to shape the start to finish (E2E) virtual organization for the cut to operate autonomously. The organization of a NS is a regular virtual organization implanting (VNE) issue. We consider a situation wherein VNF occurrences can be shared across multiple cuts to additional improve the usage ratio of the basic actual assets. For NSs with sharable VNF cases, the sending of the cut examples is basically the inserting of multiple virtual organizations coupled by the VNFs divided between cuts. Subsequently, we define this sharable-VNFs-based multiple coupled VNE issue (SVM- VNE) through a number direct program (ILP) definition, and plan a back-following composed virtual organization planning calculation. Reenactment results demonstrate that VNF-sharing can upgrade the cut acknowledgment ratio with a similar actual organization, which addresses higher actual asset use. Additionally, our methodology accomplishes higher acknowledgment ratio by contrasting with a baseline calculation.

B. B. Haile (2020): The preliminaries and rollout of the fifth generation (5G) network advancements are progressively heightening as 5G is situated as a stage that obliges detonating data traffic as well as opens a large number use cases, administrations and sending situations. In any case, the requirement for hyperdense 5G arrangements is uncovering a portion of the impediments of preparation moves toward that heretofore demonstrated satisfactory for pre-5G frameworks. The hyperdensification imagined in 5G organizations not just adds intricacy to arrange arranging and improvement issues, however underlines need for more reasonable data-driven methodologies that think about expense, changing requests and other relevant credits to create attainable geographies. Besides, the journey for network programmability and computerization including the 5G radio access organization (RAN), as showed by network cutting advances and more adaptable RAN models, are likewise among different components that impact arranging and streamlining structures.

Wang et al (2020): Dynamic and adaptable optical systems administration joined with virtualization and softwarisation empowered by network work virtualization (NFV) and programming characterized organizing (SDN) are the key innovation empowering agents for supporting the dynamicity, bandwidth, and idleness necessities of arising 5G organization administrations. To accomplish the start to finish availability objective of 5G, network administrations (NSes) should be frequently sent straightforwardly over multiple authoritative and mechanical areas. Such situation frequently presents security chances since an average NS 11 Network administration is a blend of multiple virtual and actual organization capacities made to understand an ideal organization usefulness. may include a chain of organization works, each executed in various distant areas, and altering inside the organization framework may bargain their communication. To keep away from such dangers, quantum key appropriation (QKD) has been recognized and proposed as a future-verification strategy insusceptible to any algorithmic cryptanalysis based on essential quantum-material science systems to disseminate symmetric keys.

III. OBJECTIVES

1. **Evaluate m\MIMO Configurations**: To analyze different mMIMO architectural configurations, including centralized mMIMO (CmMIMO) and distributed mMIMO (DmMIMO) with grid and linear deployments, in terms of their performance in an indoor industrial environment.
2. **Signal Quality Assessment**: To measure the impact of these configurations on signal quality, focusing on factors like average channel gain and signal-to-interference-plus-noise ratio (SINR).
3. **Outage Probability Determination**: To determine the outage probability and understand its implications on the reliability and latency of machine-type communication (MTC) within the network.
4. **Channel Model Validation**: To validate a wireless channel model tailored for indoor industrial scenarios using empirical data and analyze large scale fading effects caused by path loss and shadowing.
5. **Impact of Deployment Schemes**: To compare the effectiveness of different deployment schemes of APs on the overall network performance, specifically looking at macro diversity and signal spatial diversity.

Scope of Research

- **Geographic and Environmental Context**: The study is confined to an indoor industrial setting with specific dimensions, simulating a factory hall

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scenario.

- **Technological Focus**: The research exclusively focuses on m\MIMO technologies, assessing various deployment strategies under a single frequency band and analyzing their implications on network performance.
- **Temporal Aspects**: While not explicitly mentioned, the study likely considers transient dynamics by examining different time slots and the activity of multiple machine-type devices (MTDs).
- **System Components**: The scope includes the examination of antenna configurations, the spatial distribution of access points (APs), and the interaction between MTDs and APs through detailed mathematical modeling and simulations.

Application of Research

- **Industrial Internet of Things (IIoT)**: Insights from this study can directly influence the design and optimization of IIoT networks in industrial settings, enhancing connectivity and reliability.
- **mMIMO System Design**: The findings can aid in the architectural design of mMIMO systems, providing guidelines on AP deployment for optimal coverage and performance.
- **Network Planning and Management**: Network engineers and planners can use the research outcomes to improve the planning and management of wireless networks in industrial environments.
- **Standardization Efforts**: Contributions to the ongoing standardization discussions for future wireless communication technologies, particularly in refining models and specifications for mMIMO setups.

Educational and Training Programs: The detailed analysis and methodologies employed can serve as educational material for advanced learning and training in wireless communication technologies.

IV. PROPOSED METHODOLOGY

Centralized mMIMO (CmMIMO)

- A single Base Station (BS), carrying M antenna elements, is centrally positioned at the height h within the factory hall:

$$(x_{BS}, y_{BS}, z_{BS}) - \left(\frac{l}{2}, \frac{l}{2}, h\right) \quad (4.1)$$

Distributed mMIMO, Grid Deployment

- The factory hall's ceiling uniformly distributes Q APs, each with $S - M/Q$ antenna elements. The spatial coordinates for the q-th AP in the grid are defined as:

$$(x_q, y_q, z_q) - \left(q_z - \frac{1}{2}\frac{l}{Q}, q_y - \frac{1}{2}\frac{l}{Q}, h\right) \quad (4.2)$$

Distributed mMIMO, Linear Deployment

- APs are sequentially positioned around the factory hall's perimeter as specified in the layout from equation (4.3). B. Signal Model

The aggregated signal vector y in $M \times 1$ dimension is expressed as:

$$\mathbf{y} = p_u \mathbf{G}\mathbf{x} + \mathbf{n} \quad (4.3)$$

Where p_u represents the uniform uplink transmit power for all MTDs, $\mathbf{G} \in \mathbb{C}^{M\times K}$ is the channel matrix between the M antenna elements and the K active MTDs, $x \sim \mathcal{CN}(\mathbf{0}_{M\times 1}, \mathbf{I}_K)$ denotes the vector of symbols transmitted by the KMTDs, and $\mathbf{n} \sim \mathcal{CN}(\mathbf{0}_{M\times 1}, \sigma^2\mathbf{I}_M)$ is the vector of Additive White Gaussian Noise (AWGN). The noise power is quantified by:

$$\sigma^2 - N_0 B N_{F^*} \quad (4.4)$$

The matrix $\mathbf{G}$, encapsulating the channel vectors from the KMTDs, is structured as:

$$\mathbf{G} - [\mathbf{g}_1, \mathbf{g}_2, \dots, \mathbf{g}_K] \quad (4.5)$$

Wireless Channel Model

We utilize a 3GPP-validated channel model suitable for indoor industrial settings, assuming a non-line-of-sight (NLOS) scenario between the MTDs and the APs. The channel vector for the k-th MTD and the q-th AP is modeled as:

$$\mathbf{g}_{k,q} \sim \mathcal{CN}\left(\mathbf{0}_{S\times 1}, \beta_{kq}\mathbf{I}_S\right) \quad (4.6)$$

The large scale fading is determined by:

$$\mathrm{PL}_{kq}[\mathrm{~dB}] - 32.5 + 20\log_{10}(f_c) + 10\eta\log_{10}(d_{kq}) \quad (4.7)$$

Where the total attenuation combining path loss and shadowing is:

$$\mathrm{PL}[\mathrm{dB}]_{kq} - \mathrm{PL}_{kq}[\mathrm{~dB}] + X_{\sigma_s}[\mathrm{~dB}] \quad (4.8)$$

Here, $X_{\sigma_s}[\mathrm{~dB}] \sim N(0, \sigma_S^2)$ represents the log-normal shadowing term, and the large-scale fading coefficient β_{kq} is calculated as:

$$\beta_{kq} - \frac{1}{\mathrm{DT}_{k_{kq}}(d_{kq})} \quad (4.9)$$

These theoretical components and operational specifics comprehensively describe the mMIMO deployments and signal processing strategies in an industrial setting,

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emphasizing the importance of spatial configurations, channel modeling, and noise considerations.

We explore the signal framework for a singular active entity within the network. The received signal at the array, represented as a vector y of dimension $M \times 1$, is described by:

$$\mathbf{y} - \mathcal{P}_T \mathcal{G} \chi + \eta(1) \qquad (4.10)$$

Here, $\mathcal{P}_T$ denotes the transmission power of the Mobile Terminal Device (MTD), $\mathcal{G} \in \mathbb{C}^{M\times 1}$ indicates the channel vector encompassing the M antenna elements and the device's antenna, $\chi \in \mathbb{C}$ is the transmitted symbol satisfying $\mathbb{E}\{|\chi|^2\} - 1$, and $\eta \in \mathbb{C}^{M\times 1}$ is the Additive White Gaussian Noise (AWGN) vector, modeled as $\eta \sim \mathcal{CN}\left(\mathbf{0}_{M\times 1}, \sigma_\eta^2 \mathbf{I}_M\right)$ with σ_η^2 being the noise variance.

The set of wireless channel coefficients linking the device and Q Access Points (APs) is given by:

$$\mathcal{G} - \left[\mathcal{G}_1^T, \mathcal{G}_2^T, \ldots, \mathcal{G}_Q^T\right]^T \in \mathbb{C}^{M\times 1} \qquad (4.11)$$

where each

$$\mathcal{G}_q - \alpha_q \mathbf{h}_q^T \in \mathbb{C}^{S\times 1} \qquad (4.12)$$

represents the channel vector from the device to the q-th AP, α_q is the large scale fading coefficient, and $\mathbf{h}_q \in \mathbb{C}^{S\times 1}$ denotes the small scale fading coefficients. B. Large Scale Fading

The large scale fading effect in an indoor industrial setup is modeled based on empirical data from a 3.5 GHz measurement campaign in varied industrial environments. In scenarios like "dense factory clutter" with "embedded APs," characterized by harsh channel conditions due to non-line-of-sight (NLOS) paths and metallic reflectors, the channel exhibits Rayleigh fading:

$$\mathcal{G}_q \sim \mathcal{CN}\left(\mathbf{0}_{1\times S}, \alpha_q \mathbf{I}_S\right) \qquad (4.13)$$

where $\alpha_q < 1$ accounts for path loss and shadowing. The path loss in decibels is modeled as:

$$\mathrm{PL_{dB}} - 32.5 + 20\log_{10}(f_c) + 10\nu\log_{10}(d_{aD}) \quad (4.14)$$

with f_c as the carrier frequency in GHz, $\nu - 3.19$ as the path loss exponent, and d_{3D} as the 3 - dimensional distance between the AP and MTD.

The overall attenuation due to path loss and s owing is:

$$\mathrm{PL_{dB}} - \mathrm{PL_{dB}} + X_{\mathrm{dB}} \qquad (4.15)$$

where $X_{\mathrm{dB}} \sim \mathcal{N}(0, \sigma_X^2)$ represents the log-normal shadowing component with $\sigma_X - 7.56$ dB. The linear model for large scale fading coefficient between the device and q-th AP is represented by:

$$\alpha_q\left(d_q, \sigma_X\right) - \frac{1}{P_{L-1} - 10^{x_{d=1}\pi^{10}\mathrm{P}_{L_{L_f}}}} \qquad (4.16)$$

where PL is the total attenuation in linear scale.

Macro Diversity Gain Analysis

The macro diversity gain in distributed and centralized mMIMO setups quantifies the benefit of distributing APs over centralizing them. For distributed setups, the average channel gain across Q APs is determined as:

$$\mathbb{E}\{\| \mathcal{G} \|^2\} - \sum_{q-1}^{Q} \mathbb{E}\{\|\mathcal{G}_q\|^2\} - \sum_{q-1}^{Q} \mathbb{E}\{\alpha_q\}\mathbb{E}\{\|\mathbf{h}_q\|^2\}$$
(4.17)

using the expression for $\mathbb{E}\{\alpha_q\}$ derived from equation (4.7) and recognizing $\mathbb{E}\{\|\mathbf{h}_q\|^2\} - S$ as the gain from S antennas at each AP. This summation denotes the macro-diversity gain due to spatial distribution of antenna elements.

Comparative Analysis of CmMIMO and DmMIMO

CmMIMO Setup:

- Involves a central base station equipped with multiple antennas that serve all devices within its range. This traditional setup is prone to issues like signal degradation at the edges of the cell and significant inter-cell interference.

DmMIMO Setup:

- Features multiple antennas distributed across the coverage area, each linked to a central processing unit. This configuration aims to enhance signal quality across the entire environment, mitigating the limitations observed in centralized setups.

The study employs a theoretical framework based on a factory hall modeled as an indoor industrial scenario. It compares CmMIMO and DmMIMO systems under various deployment strategies:

- **CmMIMO:** A single base station with multiple antennas centrally located to cover the entire hall.
- **DmMIMO:** Multiple APs distributed either on the ceiling or walls to ensure thorough coverage without centralization drawbacks.

The signal model incorporates transmission power, antenna configurations, and noise factors to evaluate performance, focusing on path loss, shadowing, and fading relevant to indoor environments.

Performance Metrics:

- **Spectral Efficiency:** Assesses the network's throughput per unit of spectrum, indicating bandwidth utilization efficiency.
- **Outage Probability:** Evaluates the likelihood of a connection failing to meet the required signal threshold, crucial for reliability.

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- **Latency and Reliability:** These metrics are vital in environments requiring real-time data processing and control.

Traffic Models:

- **Regular Traffic:** Represents steady and predictable network load with devices sending updates at scheduled intervals.
- **Alarm Traffic:** Entails high-priority data transmissions triggered by specific events, creating sudden spikes in network demand.
- **Macro Diversity Gain and System Reliability**

Distributed setups inherently offer macro diversity advantages by dispersing antenna elements throughout the deployment area, enhancing signal strength and reliability. This contrasts with centralized setups where signal quality can degrade significantly at the cell edges.

- **Signal Variability**

DmMIMO reduces the variability of received signal strength, which is particularly advantageous in URLLC scenarios where predictability and reliability are paramount. The study uses statistical measures like the Coefficient of Variation (CV) to quantify signal strength variability under different deployment strategies. This comprehensive theoretical analysis elucidates the potential of CmMIMO and DmMIMO in supporting the demands of machine-type communication in industrial environments. Insights from this study highlight the importance of adopting distributed architectures to overcome the limitations posed by centralized systems, particularly in complex and dynamic industrial scenarios. This research paves the way for future advancements in 6G technologies, aiming at optimizing network performance and reliability in support of industrial IoT applications.

V. RESULTS & DISCUSSIONS

In this section, we utilize Monte Carlo simulations to evaluate the performance of various mMIMO deployment strategies under normal and emergency traffic conditions. The simulation settings are detailed in Table . Specifically, during alarm traffic scenarios, we simulate a single alarm incident within the factory hall and exclude normal traffic for simplicity.

Table 5.1: Simulation Parameters Overview

Parameter	Value
Total number of antenna elements (M)	18-98
Antenna elements per AP (S)	4
Total number of APs (Q)	5-17
Active MTDs count (K)	18-66
Dimension of the square area (l)	260 m - 1.01 km
Height of Base Station or AP (h)	6 m
Height of the MTDs (h_MTD)	1.5 m
Target data rate (R)	1 bit/s/Hz
Carrier frequency (f_c)	3.5 GHz
Transmit power of MTDs (p_u)	20 dBm
Power Spectral Density of noise (N_0)	-174 dBm/Hz
Bandwidth (B)	20 MHz
Noise figure at the receivers (N_F)	7 dB
Number of simultaneous alarm events (A)	1
Epicenter of the alarm event (x_a, y_a, z_a)	l/4, l/4, 0
Intensity of the alarm event (ν)	50

This table summarizes the adjusted simulation settings used in the Monte Carlo analyses to evaluate mMIMO deployments under regular and alarm traffic conditions in an industrial setting.

Our objective is to calculate the system's outage probability. To do this, we simulate N={10}^2 different scenarios, each with a unique distribution of random locations for the active mobile terminal devices (MTDs). Figures display the empirical and theoretical probability density functions (PDFs) of the locations of active MTDs on the x and y axes during an alarm event, and Figure 4c presents a heatmap of the triggered MTD locations for a specified area with dimensions l=250l=250 meters and an epicenter at (xa,ya,za)=(l/4,l/2,0)(xa,ya,za)=(l/4,l/2,0). The simulation involves v=25v=25 alarm events, Ktotal=103Ktotal=103 active MTDs, and N={10}^3 network scenarios.

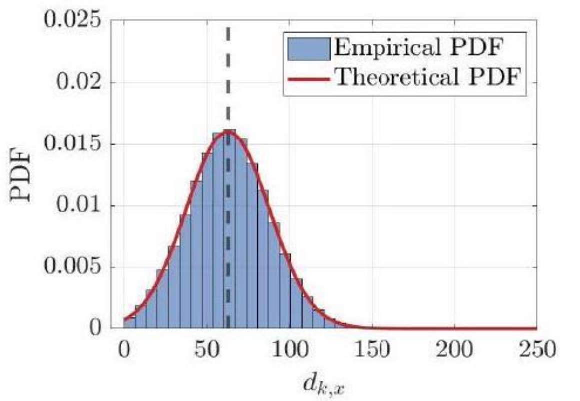

Figure 2 Analysis of Empirical and Theoretical PDFs of Position

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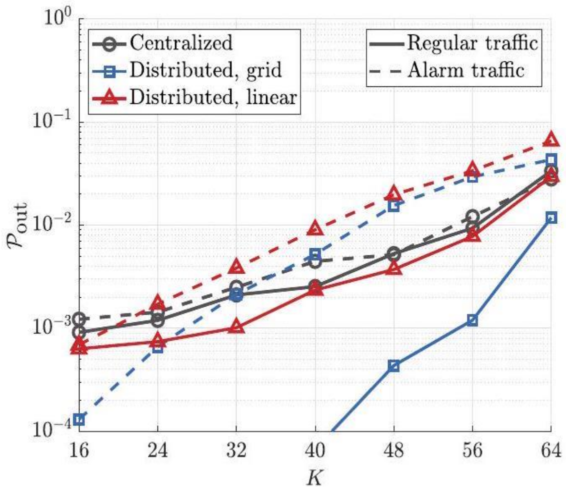

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Figure 3 Outage Analysis with respect to MTD

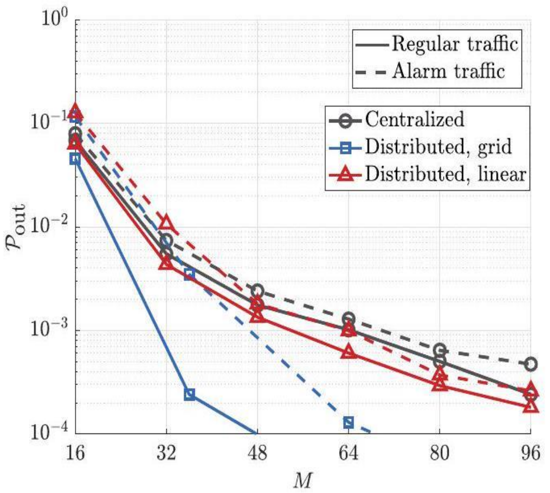

Figure 4 Outage Probability with respect to Antenna

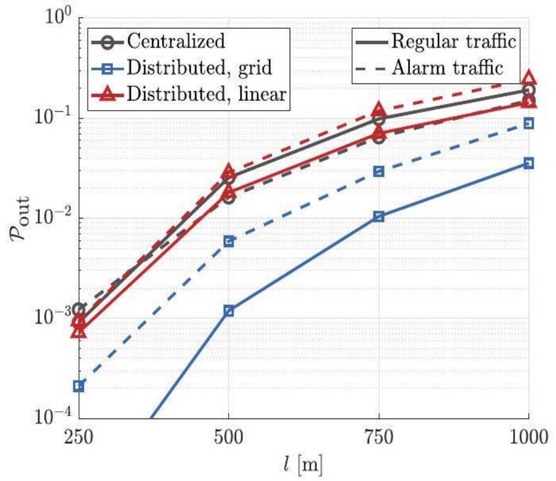

Figure 5 Comparative Analysis of Outage

Figures offer snapshots of the network during normal and alarm traffic within an indoor industrial setting with dimensions $l=250l=250$ meters.

Figure illustrates the outage probability as a function of the number of active MTDs KK for $M=64$antennas and $l=250l=250$ meters. Figure 7 charts the outage probability relative to the number of antenna elements MM for $K=16K=16$ MTDs and the same area size. Figure 8 analyzes the impact of the area size ll on outage probability for $M=64M=64$ antennas and $K=16K=16$ active MTDs. From the data associated with regular traffic, we reaffirm established results: Distributed mMIMO (DmMIMO) configurations generally surpass Centralized mMIMO (CmMIMO), especially when APs are arranged in a grid. This arrangement offers superior macro-diversity gains, although it demands increased fronthaul connectivity compared to a linear setup, where a single fronthaul link suffices.

Interestingly, the findings from alarm traffic conditions reveal that CmMIMO might surpass DmMIMO under certain conditions (varied combinations of MM, KK, and ll). This is primarily because during an alarm, most active MTDs cluster near the alarm's epicenter. Consequently, in a DmMIMO configuration, many antenna elements are positioned far from the epicenter, providing suboptimal coverage. In such scenarios, CmMIMO can provide better performance due to the central location of the base station (BS), which reduces the average distance to the MTDs, as depicted in Figure 7. Thus, DmMIMO can only outperform CmMIMO in alarm conditions if the total number of antenna elements is sufficiently large to ensure adequate coverage near the alarm site.

In summary, our simulations compare the performance of CmMIMO and DmMIMO under two traffic conditions in an indoor industrial environment. The results confirm that under regular conditions, DmMIMO configurations, especially those with a grid layout, consistently outperform CmMIMO, albeit at the cost of higher fronthaul requirements. During alarm conditions, the proximity of most active devices to the alarm's epicenter can advantageously position CmMIMO for better performance, depending on the spatial distribution and number of antennas. The studies provided a granular look at how different mMIMO configurations perform under a variety of conditions. Detailed metrics like average channel gain, standard deviation, and coefficient of variation were scrutinized for typical and worst-case scenarios within a factory setting.

- **Channel Gain Metrics:** In typical scenarios, DmMIMO with grid configurations showed higher channel gains compared to other setups, reflecting their efficiency in a controlled environment. Conversely, in worst-case scenarios where variables such as interference and physical obstructions play a more significant role, the

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flexibility of DmMIMO configurations helped maintain more consistent service quality.

- **Signal Stability:** Stability of the signal, as reflected by lower standard deviations in channel gains, was notably better in DmMIMO setups, particularly those using radio stripes. This stability is crucial in industrial applications where sudden drops in signal quality can disrupt operations.
- **Adaptability in Dynamic Environments**

Industrial environments are highly dynamic, with varying equipment layouts and operational states that can affect wireless communications. The adaptability of mMIMO, particularly DmMIMO, allows for dynamic recalibration of network parameters to maintain optimal performance. This adaptability was evident in the studies' findings:

- **Reconfiguration Capabilities:** DmMIMO systems can dynamically adjust their configurations based on real-time data about device locations and traffic patterns, optimizing both coverage and power efficiency.
- **Reduced Interference:** By using advanced beamforming techniques and leveraging the distributed nature of antennas, DmMIMO can significantly reduce interference, a common challenge in densely populated industrial environments.
- **Economic and Operational Efficiency**

The economic implications of deploying mMIMO technologies are significant, especially considering the scale and complexity of modern industrial operations. The studies touched on several key aspects:

- **Cost-Effectiveness:** Although initial installation costs for DmMIMO configurations, particularly grid and radio stripe setups, can be higher than traditional systems, they offer long-term savings through improved energy efficiency and reduced need for frequent upgrades.
- **Maintenance and Scalability:** The modular nature of DmMIMO systems facilitates easier maintenance and scalability compared to CmMIMO. This is crucial as industrial facilities often need to expand or modify their IoT infrastructure with minimal disruption to ongoing operations.

The evolution from 5G to 6G is set to redefine the landscape of industrial wireless communications, with mMIMO technologies leading the charge. The detailed studies reviewed underscore the transformative potential of these technologies, particularly DmMIMO, in meeting the complex demands of modern industrial environments. As we move forward, the insights from these studies will not only guide technological deployments but also influence policy-making and strategic planning in the telecommunications sector. The future of industrial communication is bright, with mMIMO technologies at its core, promising unprecedented levels of connectivity, efficiency, and scalability.

VI. CONCLUSION

Both studies utilized Monte Carlo simulations to assess performance metrics such as signal strength variability, outage probability, and spectral efficiency under different mMIMO setups. The studies revealed:

- **Superior Performance of DmMIMO:** Particularly, grid configurations of DmMIMO tend to offer better average signal strengths and reduced signal variability, enhancing reliability and coverage uniformity.
- **Cost-efficiency of Radio Stripes:** While radio stripes provide lower variability in signal strength, they do not always achieve the average gains seen in grid deployments. However, they blend cost-efficiency with effective performance, presenting a viable option for certain industrial applications.
- **Spatial and Spectral Efficiency:** DmMIMO systems, due to their distributed nature, adapt more efficiently to various industrial layouts and user densities, supporting a vast array of IoT devices with minimal latency and maximal throughput.
- **Comparative Analysis**

The studies consistently demonstrate that DmMIMO configurations, especially those using grid patterns, significantly enhance the reliability of wireless communications in challenging environments. By eliminating cell boundaries and increasing the density of access points, these systems provide uniform coverage essential for critical Machine-Type Communications (MTC) where interruptions may cause significant operational disruptions.

- **Challenges and Economic Considerations**

While DmMIMO systems show considerable promise, the studies also highlight logistical and economic challenges associated with their deployment. The radio stripes configuration, in particular, emerges as an intriguing solution by potentially lowering installation costs and simplifying maintenance. However, the performance trade-offs compared to traditional grid setups must be carefully considered, especially in scenarios demanding ultra-reliable communications.

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