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Performance Optimization of 5G NR Technology for Industrial Automation

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Abstract: Communication via remote means has evolved significantly, now capable of supporting the essential control mechanisms of high-definition digital industrial processes. The fifth-generation (5G) mobile networking, known as New Radio (5GNR), boasts flexible control and sub-bandwidth transmission capabilities, particularly suitable for efficiently managing small data packets crucial for industrial automation. While the minimum process duration serves as a reliable metric for assessing robustness in modern wireless communication, its exploration within the framework of 5G technology remains limited. This thesis explores 5G-enabled industrial automation control through wireless networking, employing a delay optimization strategy integrated with database channel control. Leveraging the Ant Colony Optimization (ACO) method, this study proposes a reliable minimum cycle time evaluation for 5G network communication, addressing the associated challenges effectively.

Keywords: 5G, ACO, 5GNR, Mobile Networking

1. Introduction:

A functional area of movement is remote correspondence for key control in computerization structures. Major control applications establish unbending requirements for the mystery correspondence organization s in terms of benefit and unwavering quality, which vary depending on the use case. For instance, the automation of the information trade generation line demands process terms in the sales for 1to 10milliseconds and consistency more than 99.9999% [1]. The use cases presented by the power structure field are inherently extremely taxing, requiring process times of less than 1 ms and consistent nature of 99.9999999%. [2], [3].

The likelihood that fundamental current control applications will be aided by two or three distant techniques is demonstrated in [1], [3]–[7]. One of these levels of development is the far-off relationship for current robotization creation line mechanisation (WIA-FA), which has actually been normalised as IEC 62948. In various taking care of plant computerization conditions, it appears to have empowering execution [1]. For time-sensitive modern applications, the new Wi-Fi specification IEEE 802.11ax is regarded as a respectable remote characteristic of concerted effort [7]. The USA has supported IEEE 802.11ax extension in the unlicensed 6 GHz band, and the 1200-MHz move speed with negligible resistance is predicted to increase transmission rate and reduce idleness [8]. The use of wireless high performance (WirelessHP) has been suggested to support today's ultra-critical applications and deliver performances comparable to those of cutting-edge wired networks [3]. It is clear that the fifth time frame (5G) is rapidly evolving in terms of common transports and product development. Progress line robotization is one of the key applications that 5G Ultrareliable and Low Laziness Communications (URLLC) aims to work with [9].

Another real layer (PHY) known as 5G New Radio (NR) has been normalised in 5G movement 15 (R15). To encourage laziness execution and facilitate unconventional opening transmission for short bundles, 5G NR adopts a flexible numerology and bundling upgrade [10]. Up until this point, the majority of research on 5G NR for URLLC has focused on examining start to finish idleness and dependability introductions over the air interface, as seen in [11] and [12], for example. The base cooperation length (MCT) may be a crucial signal for modern applications. With each slave community point in the affiliation, the MCT provides the bottom bound of the optimum possible entryway for the expert [13]. The main goal of every modern correspondence network is to achieve adequate MCT for the delegated application with a set level of information sent and a given number of slave focus points [14]. Unlike wired current correspondence movements, which have nearly constant transmission cutoff points and consistent steadiness performance, analysing the MCT of 5G under a given determined quality execution is challenging due to the vast array of options available and the inconsistent behaviour of the remote channel with time and place. The MCT using 5GNRwas broken down in [15] assuming existing sporadic transmission. The structure to modify 5G NR assets and transmission restrictions with varying current remote channel characteristics to achieve what is referred to as consistent execution is not evaluated in [15]. The main concern of the top level associates has always been the reliability execution of distant correspondence. Furthermore, as execution in the time domain will also be impacted by the asset distribution close to the PHY, it seems sense to specify MCT execution close to a reliability guarantee. Due to the 5G delay, it isn't possible to finish the primer underwriting, which increases the strain on the inflexible quality show evaluation. In order to meet the demand for high constant quality, the streamlined channel portrayal (CCDO) in [16] offers to plan the PHY farthest reaches of the even recurrent division multiplexing (OFDM)system using an information-driven modern channel portrayal. However, such effort is not taken into account for 5G NR. It is essential and significant to research 5G NR limit setting and asset scattering in the present circumstances to assure consistency need given the adaptable numerology restrictions and a combination of PHY transmission limits maintained. Such an analysis will provide the correspondence suppliers and current assistants with basic info tidbits.

In this study, we employ ACO to organise an asset piece of 5G NR to achieve consistent quality fundamentals. We choose the fundamental data transmission, balancing, and coding requirements while simultaneously orchestrating the pack sections of varying numbers of OFDM pictures to send one group, taking into consideration the reliable quality essential and contemporary channel credits. Additionally, we take the aforementioned result as a duty to resolve a solid MCT of 5G NR with a trustworthy immovability execution.

2. Related Work:

[11] Ashraf, N., and Haraz (2017) proposed a circular inset microstrip patch antenna for future fifth-generation (5G) cellular communications. The antenna is designed on a compact FR-4 substrate with dimensions of 5 x 5 x 1.6 mm^3 and a relative permittivity (εr) of 4.4. Simulations using HFSS software indicate that the antenna operates at 28 GHz, with a return loss (S11) below -10 dB and a strong directional pattern. This work presents a compact curved antenna for future 5G cellular communication on an FR-4 substrate, which is not extensively covered in current literature. Simulated results show a resonance at 28 GHz with an impedance bandwidth ranging from 26.6 to 31.2 GHz.

Universal connectivity is a primary advancement enabling data sharing among components of an industrial Internet of Things (IIoT) framework. The increasing pressure to open the mobile market for location-specific networks has led to new regional licensing and sharing-based models for spectrum access, allowing the emergence of local networks to serve various verticals. While the development of technical solutions for network performance is advancing, less attention has been paid to spectrum management policies for new industrial networks and location-specific services. [12] Pekka Ojanen et al. (2019) examined solutions to current industry challenges in acquiring spectrum to support the IIoT and proposed a framework for assessing the viability of spectrum management approaches. They assessed how spectrum is currently allocated and how it meets IIoT needs in six selected countries: Canada, Finland, France, Germany, the Netherlands, the UK, and the US.

The ongoing deployment of fifth-generation mobile network (5G) technology is bringing higher speeds, greater capacity, lower latency, and improved reliability, facilitating data sharing among components of industrial systems. The opportunity for private industrial networks to serve various verticals largely depends on the timely availability, quality, and cost of spectrum. The increasing pressure to open the wireless market for location-specific networks has resulted in new regional licensing and sharing-based models for spectrum management. [13] Pekka Ojanen et al. (2020) discussed private industrial network requirements for spectrum management through a framework used to assess the feasibility of spectrum management approaches. They specifically explored recent sharing concepts over 5 GHz in the US, Europe, and four selected countries: Australia, Hong Kong, Japan, and the UK, highlighting unique approaches to making wideband spectrum available for network providers other than traditional mobile network operators (MNOs).

[14] Gilberto Berardinelli et al. (2022) presented a vision for a Beyond 5G Wireless Isochronous Real-Time (WIRT) system for industrial control networks, designed to support fast closed-loop control applications. WIRT aims at ultra-reliable short-range wireless links with 0.1 ms latency and wired-like 10^-9 reliability. Utilizing a large spectrum and frequency/interference diversity are considered fundamental components for WIRT. Ultrawideband (UWB) spectrum access and unlicensed transmission at millimeter-waves (60 GHz band) are identified as potential solutions for ultra-reliable, ultra-low latency communication. The feasibility and challenges of these approaches are discussed in detail, along with future directions for WIRT design.

3. Methodology:

Smallest resource unit consists of one OFDM symbol in the time domain and one subcarrier in the frequency domain, which is defined as a resource element (RE).

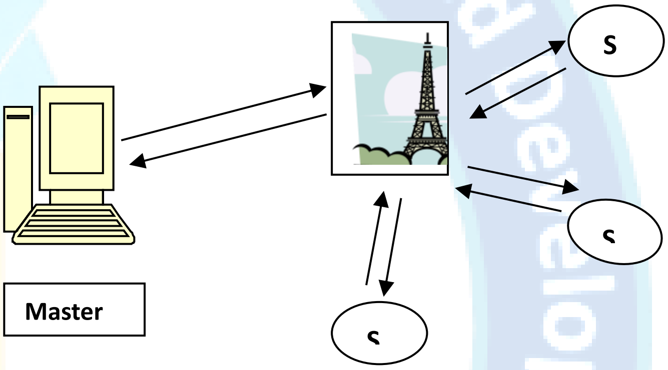

Fig. 1: Industrial communication network based on 5G NR.

Orthogonal Frequency Division Multiplexing (OFDM), as a multi-carrier modulation technique, has been widely adopted by 5G NR communication systems, as well as LTE and Wi-Fi(R). It offers several advantages: robustness to channel delays, single-tap frequency domain equalization, and efficient implementation. However, its drawbacks, such as loss in spectral efficiency due to higher side-lobes and strict synchronization requirements, are often overlooked. To address these issues, new modulation techniques are being considered for 5G NR communication systems.

For instance, an LTE system with a 20 MHz channel bandwidth uses 100 resource blocks of 12 subcarriers each, with an individual subcarrier spacing of 15 kHz. This configuration utilizes only 18 MHz of the allocated spectrum, leading to a 10 percent loss. Additionally, the cyclic prefix of 144 or 160 samples per OFDM symbol results in another ~7 percent efficiency loss, culminating in an overall 17 percent loss in potential spectral efficiency.

With the ITU requirements now defined for 5G NR systems, applications demand higher data rates, lower latency, and more efficient spectrum usage. This work focuses on a new modulation technique known as ACO-based Multi-Carrier OFDM and compares it with traditional OFDM within a conventional framework.

ACO OFDM 5G NR Multi-Carrier Modulation

The ACO (Ant Colony Optimization) optimization problem determines the minimum reliable bandwidth to transmit one packet while varying the number of OFDM symbols in the time domain. Since the Packet Error Rate (PER) is linked to the packet bandwidth, modulation, and coding scheme, we use MATLAB simulations to validate the PER requirement. For each site and various parameters and payloads, the combination of M and C varies from high to low order, and the corresponding required bandwidth (Wt) is determined.

ACO OFDM 5G NR is considered an extension of Filtered OFDM with FBMC (Filter Bank Multi-Carrier) modulations. In filtered OFDM, the entire band is filtered, and individual subcarriers are filtered in FBMC, while groups of subcarriers (sub-bands) are filtered using ACO OFDM 5G NR. This subcarrier grouping reduces the channel length compared to FBMC. Additionally, ACO OFDM 5G NR can still use QAM, retaining complex symmetry, which facilitates existing MIMO schemes.

The full band of subcarriers (N) is divided into sub-bands. Each sub-band has a fixed number of subcarriers, and not all sub-bands need to be used for a given transmission. An N-point IFFT is computed for each sub-band, inserting zeros for unallocated carriers. Each sub-band is filtered by a filter of length L, and the responses from different sub-bands are added. Filtering is done to reduce out-of-band spectral emissions. Different filters per sub-band can be applied; however, in this model, the same filter is used for each sub-band. A Chebyshev window with defined side-lobe attenuation is used to filter the IFFT output per sub-band.

The result showcases the ACO fundamental processing of OFDM, which is FFT-based. The sub-band filtering extends the reception time window to the next power-of-two length for the FFT operation. Each frequency value corresponds to a subcarrier's main lobe. Typically, per-subcarrier equalization is used to balance the joint effect of the channel and the sub-band filtering.

4. Result and Discussion:

The optimization problem (2) determines the minimum reliable data transfer capability to convey one packet while varying the number of OFDM symbols in the time domain. Since the Packet Error Rate (PER) is associated with the packet data transmission, modulation, and coding scheme, we use MATLAB simulations to validate the PER requirement (2c). For each site and different numerology parameter μ and payload, we vary the combination of M and C from high order to low, and the corresponding required Wt is determined by (2a) and (2b). Simulations are used to check if the chosen parameters satisfy (2c); if they do, the minimum reliable data transfer capability to transmit one packet is found; if not, the combination of M and C is adjusted to a lower order and the process is repeated. To achieve PER < 10^-6, 10^8 packets are simulated for each parameter set.

The tapped delay line model and the clustered delay line (CDL) model from the 5G specification [20] are used to describe omnidirectional transmission at FR1 and transmission with clustered delays at FR2, respectively. Transmission power PTX is set at 20 dBm, in line with 5G specifications. Due to the lack of channel estimation at 5G NR frequency bands, path loss and delay spread values in FR1 are derived from results at two industrial sites at 2.25 and 5.4 GHz [21]. The steam generation plant represents a medium-sized site with a maximum connection distance of 35 m and several boilers and piping causing significant multipath fading. The device acting as a base station (BS) is positioned at a height of 3.364 m, with other devices at 1.94 m above the ground. The maximum path loss and delay spread in the steam generation plant are 90 dB and 55 ns, respectively.

The other site is an automotive assembly (AA) plant, including machining areas, assembly cells, and stacked storage areas, with a maximum connection distance of 110 m. The device acting as a BS is placed at a height of 3 m, with other devices at 1.917 m above the ground. The maximum path loss and delay spread in the AA plant are 115 dB and 180 ns, respectively. At FR2, the parameters for the CDL channel are set by empirical results from a machine hall at 28 GHz [22]. The device acting as a BS is positioned at a height of 7 m, with other devices at 4 m above the ground. The maximum distance between the transmitter and receiver is 42 m, with maximum path loss and delay spread of 94 dB and 112 ns, respectively, and azimuth angle spread of arrival and departure at 41° and 80°, respectively. Beamforming is not used in the simulation. For an industrial site with longer communication ranges and higher path loss, beamforming can be employed to achieve the best SNR. The Doppler shift in each site is set according to a speed of 2.5 m/s.

The minimum required Wt to achieve PER < 10^-6 in both sites at FR1 is plotted in Fig. 3(a) and (b). To meet the reliability requirement, M = 2 (QPSK) and C = 349/1024 are used to modulate the payload in the AA plant, while M = 4 (16QAM) and C = 658/1024 achieve the desired reliability in the steam generation plant. For each μ, the minimum required Wt decreases with Nsymb and increases with L, consistent with (2a). The minimum required Wt with each μ is lower-bounded by the corresponding smallest BWP, approximately 5 MHz with μ = 0 and 1, and approximately 10 MHz with μ = 2. Fixing Nsymb, the minimum required Wt increases with μ as the subcarrier spacing (SCS) increases with μ. Compared to the steam generation plant in Fig. 2(a), the minimum required Wt is greater in Fig. 3(b) of the AA plant because smaller values of M and C are needed to compensate for greater path loss in the AA plant and achieve the same PER performance, leading to a larger Wt by (2a). In Fig. 2(b), with a 100-byte payload size, for Nsymb < 2 with μ = 1 and Nsymb < 4 with μ = 2, no Wt value can satisfy the PER requirement. Fig. 2(c) shows the minimum required Wt to achieve PER < 10^-6 in the machine hall at FR2, using M = 6 (64QAM) and C = 567/1024. The smallest BWPs at FR2 with μ = 2 and 3 are both approximately 50 MHz, accommodating a large number of RBs, and this value can satisfy constraints (2a)-(2c) with both 10- and 100-byte payload sizes and varying Nsymb..

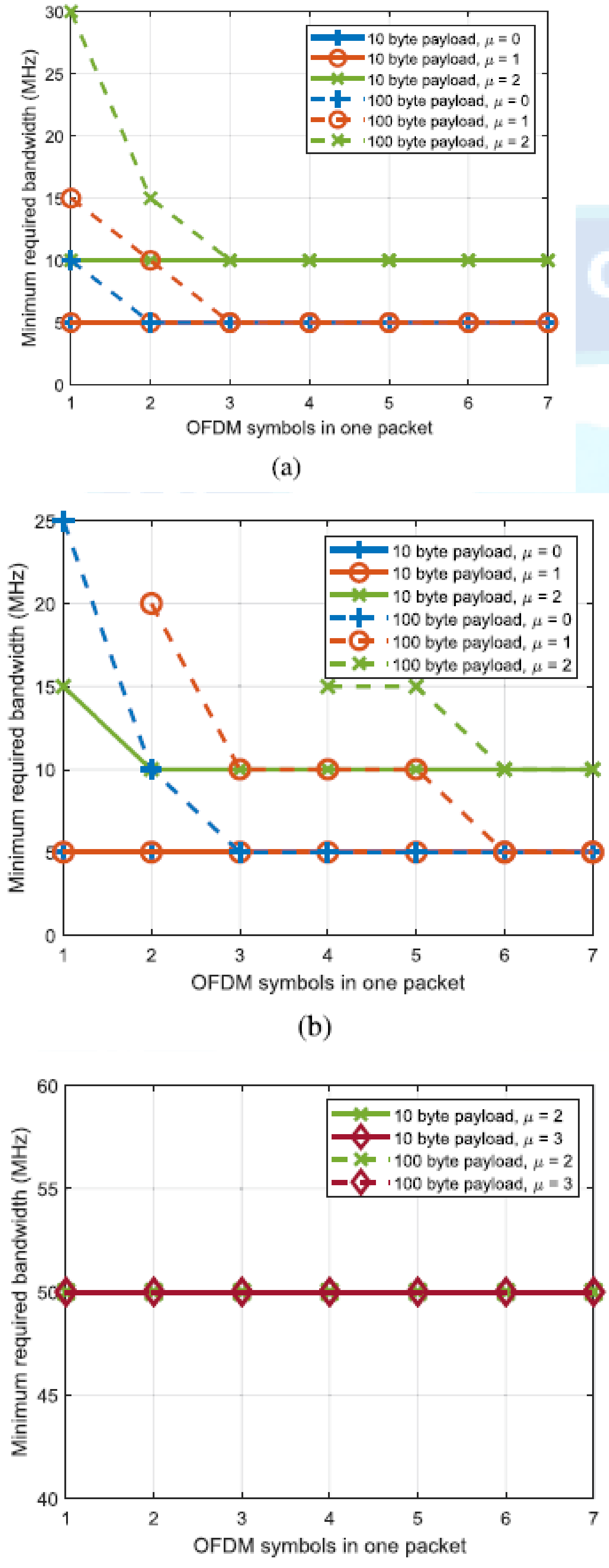

Fig. 2. Least required bundle transmission transfer speed Wt, got by tackling (2), for PER< 10−6 as a component of the OFDM images in a single parcel. The PHY payload sizes are 10 and 100 byte. The numerology boundaries at FR1 $\mu = 0, 1, 2$ and at FR2 $\mu = 2, 3$ are utilized. (a) Steam age plant. (b) Car get together plant. (c) Machine shop. Process duration Model In 5g-Based Modern Control Frameworks

5. Conclusion:

5G URLLC (Ultra-Reliable Low-Latency Communication) is designed to support industrial scenarios with stringent reliability and low-latency requirements. A method was proposed to evaluate the reliable Maximum Cycle Time (MCT) of 5G NR Release 15 by formulating an optimization problem with a reliability constraint that takes industrial channel characteristics into account. The assessment results indicate that in three representative industrial sites, covering both FR1 and FR2 of 5G NR, a few milliseconds of cycle time with a PER of 10^{-6} can be achieved, comparable to other non-cellular wireless technologies. To implement the proposed method in this article with 5G NR-capable devices, a monitoring table can be used to record various channel characteristics, including path loss and signal angles, along with the corresponding minimum required bandwidth, modulation, and coding when using different numerologies. ACO-based OFDM in 5G is considered superior to traditional OFDM due to its enhanced spectrum efficiency. This strategy is promising for short bursts because sub-band allocation reduces the size of the FFT and the guard intervals between sub-bands. Compared to other optimization methods, which typically have a much longer FFT length, this characteristic is particularly advantageous..

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