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WWRT

Wireless World Research and Trends Magazine

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From the Desk of the Editor-in-Chief

Dr Sudhir Dixit
Editor-in-Chief

Welcome back to the second issue of the Wireless World Research and Trends (WWRT) magazine. It gives me immense pleasure to share that the launch of the first issue for the magazine was a tremendous success. We continue to march forward to providing interesting articles on a diverse range of topics related to next generation communication systems and enabling technologies. Not only do we endeavor to provide opportunities to innovators and researchers to disseminate their latest results, we also include articles from experts to write about their experiences and trends in the industry that will shape our future. Additionally, we provide major happenings in standards around the world, and key points and takeaways from the annual huddle event organized by WWRF in different continents of the world.

This issue of the magazine contains seven interesting articles. The central themes of the first two articles are federated learning applied to energy efficiency in 6G networks and the enhancements of machine learning techniques. The third article looks at the impact of mobility, beam sweeping and smart jammers on security vulnerabilities of 5G networks. Since *Rate adaptation* in a wireless channel utilizes the periodic determination of the channel quality indicator to select the optimal modulation and coding scheme (MCS), the authors, in the forth article, propose Bayesian Learning based rate adaptation technique to decide on the MCS that delivers better performance in 802.11ax WLANs. The fifth article delves into spectral sampling and signal decomposition (SSSD) for improved spectral efficiency and reduces the required bandwidth and simplifies the receiver design. The sixth article is about how to make cross-walks safer with vehicle-to-everything communications technology. Finally, the last article discusses the importance of multi-disciplinary approach to 6G from technology, business, regulation, and sustainability perspectives.

I hope you find these articles interesting, and please do continue to send me your comments and feedback. As we are an open access journal, we welcome articles for publication in future issues of the magazine and any proposals to guest edit and organize a special issue on a topic of current interest.

The Need for an Innovation Friendly Climate in 6G – Learnings from 2G to 5G

Hakan Eriksson

Introduction

In this discussion we will review the development of the wireless industry over the past four decades, and extrapolate this development into the coming decade, leading to a few possible scenarios. We will also look into the role of the regulator, and what is needed to create an innovative environment in the era of 6G.

The Telecom Stack used in this Discussion

We will look at the telecom industry as a stack in four layers, from top to bottom as the

1. Application Service Layer
2. Consumer Device Layer
3. Connectivity Service Layer
4. Network Infrastructure Layer

If we go back to the 80s, before 2G, and look at this stack from a Fixed Line perspective, in most countries the stack was totally controlled by the Operator, the PTT. There was not much of an *Application Service Layer*, but by using * and # on your phone, you could order wake up calls etc.

Often the PTT also owned the phone on the *Consumer Device Layer*, and of course they owned the *Connectivity Service Layer,* and in addition usually had a national monopoly.

In some countries they even owned or had a joint venture with somebody on the *Network Infrastructure Layer*. The operator was a very powerful player. I once met a CTO of one operator, reflecting on that period, saying "It's interesting times, now we have to call them customers, I remember when we used to refer to them as network signalling termination points".

The Creation of a Global Access Technology

With GSM in the 90s, Europe created a common 2G standard, that showed the power of a well-designed multinational standard. Leading into 3G in the 00s, the standardisation body 3GPP was formed, with roots in the GSM framework, having more countries outside Europe joining, and finally with 4G in the 10s, we arrived at a Global Standard for cellular access, a feat that can not be underestimated in its importance. Now a user could move across the world using the same handset.

Global Scale for Network Vendors and Handset Manufacturers

However, it is not only the users that benefit from a global standard. Both the Network Infrastructure Vendors, such as Ericsson, and Handset Manufacturers, such as Nokia, benefitted from the global standard by now enjoying global scale for their R&D investments.

Also the Operators get to benefit in two ways. Firstly, the global scale for infrastructure and handsets offers lower cost for investments, whilst secondly, the roaming between countries that is now enabled, offers very profitable roaming revenues.

Operators Deregulated, But Still Owning SMS and Roaming

With the introduction of 2G, many countries also start deregulating the operator monopoly, by introducing a 2nd or 3rd Service Provider in the national market, to create competition.

However, the operators still enjoy the profitable message service SMS, since this service is based directly on the connectivity. Another profitable business is of course the roaming.

If we go back and reflect on what has happened to the stack we introduced in the beginning, we can see that the operator now has an increased power on the *Application Service Layer*, with the introduction of SMS and Roaming. However, they no longer own the device on the *Consumer Device Layer*, even though the device is still often bought from the Operator, often as part some multi-year plan.

They have also lost the monopoly on the *Connectivity Service Layer* and are often no longer involved on the *Network Infrastructure Layer*.

In spite of the loss of the monopoly, with SMS and Roaming it is still a good time to be an operator, and with healthy operators, the infrastructure vendors are also doing well.

Introduction of the Internet

Whilst 3G, and its later variant HSPA, were the introduction of Mobile Broadband or Mobile Internet, it was really with the introduction of 4G that the internet took off in cellular. We went from feature phones to smartphones, from "connecting people" to connecting to the internet, or via the internet.

The former changed the landscape on the *Consumer Device Layer*. People no longer wanted phones to connect to people, they wanted handheld computers to connect to the internet. Smartphone vendors such as Apple and Samsung took over what until then had been Nokia's layer in the stack.

But connecting to the internet also had drastic consequences for the operators. Firstly, with the possibility to stream and browse, consumers now wanted more data, and in the now deregulated environment, the war was on for offering the most data for the lowest consumer cost.

Secondly, with the option to now connect via the internet, global OTT players could take over the Application Service Layer, with services such as iMessage, Skype, FaceTime, just to mention a few.

The operator that used to own basically the entire stack, is now left with being a highly regulated national player, in fierce domestic competition in the *Connectivity Service Layer* alone.

If we look at the rest of our stack, we have arrived at a situation where players such as Google and Facebook own the *Application Service Layer*, Apple and Samsung own the *Consumer Device Layer*, above the operator, and Ericson and Huawei own the *Network Infrastructure Layer*, below the operator, just to mention two large players on each layer.

However, owning the layers above the operators, with consumers and advertisers as your customers, has proven much more valuable from a market capitalisation point of view, than owning the layer below the operators, with the operators as your only customer.

From a Luxury Product to a Human Obligation

Over 20 years, say from 1995 to 2015, cellular went from being a luxury product, where operators could charge what the market allowed, to being regarded basically as a human right, or at least something each government realised would be a necessary tool in the hands of each citizen, for society to function. In fact, one could almost look at it as not only a human right, but as a human obligation. During Covid we often saw the sign "Please scan the QR code to enter."

Industry Quest for Higher Spectral Efficiency and Network Capacity

The industry response to this challenge has been an impressive increase in spectral efficiency, an increase in available spectrum, and also the introduction of smaller cells. This has enabled a total traffic increase in cellular networks of a factor 300 over the last decade. At the same time subscribers are now also offered about 100 times more GBytes of data for the same monthly cost, sometimes even an unlimited amount. Cellular access has become the ubiquitous connectivity. When was the last time you saw a coffee shop trying to attract customers by advertising "Free Wi-Fi"?

Regulators Drive for Consumer Affordability

With cellular connectivity becoming in many cases the only way many citizens can access the network, and consequently, becoming and integrated part of many processes in government, banking, education, healthcare, etc, it has become critical for each government regulator to ensure cellular access is as affordable as possible. If having and using a smartphone is a human obligation, the society has to ensure that people can live up to that obligation.

As we have seen, this has been achieved by ensuring strong national competition between the service providers, but also by allowing global players to come in and offer the traditional services such as SMS and international voice calls, over the top, OTT. In Europe the regulator also removed the opportunity for roaming revenues. If we continue down this path there is a scenario where roaming revenues could also globally soon be a thing of the past.

This regulator approach to strive for highest possible affordability, through all means available, makes it very challenging to be an operator. And for the network infrastructure vendors, having the challenged operators as their only customers, it has resulted in a dramatic consolidation within the industry, and still, even they are challenged.

In the coming decade, as we will discuss later, there is a built-in conflict resulting from this approach. Each society will become completely dependent on a secure cellular network, and its platform of associated services, for its survival.

At the same time, driving the quest for affordability so hard, it can be questioned if the industry can afford the investments needed to deliver on the necessary requirements, that will be put on this network and platform. It is a conflict of short-term affordability versus long term safety and security.

Operator Separation into a ServiceCo and a NetCo, Basically a Layer 3.1 and 3.2

But for now, let's look at some initial responses within the service provider to these challenges. One option is to allow other service providers, that do not have a network, to use your network, so called MVNOs. This way you can make more revenue from your made investment, given these subscribers would otherwise have gone to a competitor.

Next step could be to make your own "internal MVNOs" to create sub-brands to differentiate in the market. From this follows that you divide the company into a ServiceCo, that interact with the customers, and compete with the MVNOs. The rest becomes the NetCo, that both the ServiceCo and MVNOs basically are customers of.

Going back to our stack we have split the *Connectivity Service Layer* into two parts, a 3.1 ServiceCo and a 3.2 NetCo.

From a Human Right to an Industry Automation Enabler

With the introduction of 5G the focus shifted from people to industry applications. As a result, low latency and concepts such as network slicing became more important. The view of the cellular connectivity as a human right expanded even further, into becoming the enabler for industry automation, and in fact even society automation.

Many operators already have a separation in a consumer sales side and an enterprise sales side, but put simply, that is more a differentiation in who you sell to, not really a differentiation in what you sell.

With 5G and the concept of various industry verticals, the requirements on the enterprise part of the ServiceCo increases dramatically. Now it is no longer about selling connectivity to an enterprise, it is about understanding how these respective industry verticals work.

The Industry Version of the Stack

If we go back to our stack and look at it from the industry perspective, the *Application Service Layer* could now be players such as AWS and Microsoft, while the device layer maybe should be called *Industry Equipment Layer*, with players such as ABB, GE and John Deere.

The operator will still in most cases own the *Connectivity Service Layer*, separated into the Enterprise ServiceCo and the NetCo, while the players on the *Network Infrastructure Layer* are still the same, possibly with the addition of HW related to AWS and Microsoft on the service layer.

A Three-party Play

Another change coming from this focus on the industry automation is that in some places industries get their own local spectrum allocations, mainly at manufacturing plants. This means that network infrastructure vendors now have a new customer besides the operators to sell to, the industry vertical itself, thereby basically bypassing the operator. It is a small start to a new structure we will likely see more of.

But this is not only about industry verticals. There is also a need for a secure national platform for other services such as banking, but even more importantly, all government related services, including police, fire brigade, health monitoring, defence, etc.

However, unless there is a change in the current regulatory model, it will be very difficult for operators to afford the investment needed to build the competence required to effectively interact with all these user verticals. The operator, mainly the Enterprise ServiceCo, will likely not be able afford to build competence in mining, agriculture, manufacturing, defence, etc.

As discussed earlier, this is a result of lacking global scale as a domestic operator, combined with the pressure from the national regulator in the effort to optimise consumer affordability.

Instead, operators will focus on creating an API to their network, under the assumption that all these verticals will be able to use and address the various functions of the network that they need to optimise their respective use cases.

The Need for a Global Player that Understands the Network

With the operator in this scenario unable to build the necessary competence needed, and the situation that e.g. the police force in each country will not have the capacity to program the network API, there will be a need for a player with global scale between the vertical user and the network API. It will even be challenging for industry verticals with global scale to build the competence needed to program the API of each operator in each country.

The global players that best understand the functionality behind the API are the network infrastructure vendors. In addition to providing the infrastructure equipment to the NetCo of the operator, they are also best positioned to offer global use case know-how to the Enterprise ServiceCo. In the case of some manufacturing plants, as discussed above, where the operators in practice are already bypassed, the infrastructure vendors are offering this service to the industry vertical. Other players that are well positioned to take a role here are System Integrators, already working with the service providers to increase the efficiency in their operations.

But as said, the scope is larger than the industry, it is about building a secure national service platform for the digitisation and automation necessary to effectively serve the society.

The Consumer Side, Your Phone in the Cloud

It is not only on the enterprise side of the ServiceCo there could be big changes ahead. Today many of us own a smartphone, and with that a subscription of some form of a cloud service where all our data and pictures are stored, and all other phone data is backed up. In fact, you can see this as having your actual phone in the cloud. What you carry in your hand is only a physical representation of this cloud-based phone.

Add to this the possibility you often now have to trade in your old phone when buying a new phone, to physically represent your phone in the cloud. The step from this trade-in and buy, to just pure leasing a physical phone is not big. We are then back where we started, with the consumer no longer owning their phone, but the new owner owns so much more than just your phone, they are the guardians of your life's history.

The eSIM and the Future of Roaming

Another concept introduced in modern consumer devices is the eSIM, and with the eSIM there are no physical limitations to how many SIM cards you can have in a phone. Nor are there any restriction on where and how to physically buy them.

This offers an opportunity for the smartphone industry to negotiate say a pool of eSIM subscriptions in each and every country, based on their customer base and the travel patterns of this base. Then they can offer the use of these eSIMs to their customer. This could of course be offered even in the country where the customer lives.

This effectively means that there is a scenario where I as a consumer no longer subscribe to a service from any of my local operators. I subscribe to being part of this pool of eSIMs, and my subscription is with my smartphone provider. And when I'm roaming, I'm just offered a local eSIM in the country I'm in. I don't have to know which operator it is, and this can vary by time, location, traffic load, and other dynamic parameters. And this could be the same even in my home country.

The Future of Subscription

Combining these trends there is a future scenario where consumers have a subscription from a smartphone vendor, including three main components, comprising of cloud storage of my data, leasing of a physical representation of my cloud phone, and a subscription to a pool of eSIMs giving me national and global connectivity without any roaming cost.

Roaming, even nationally, is in this scenario managed by your device subscription, and operators have to prove who can deliver the most competitive connection at any given time and location, basically through a constant live auction. This would also be completely in line with how national regulators have acted so far, so unless something changes, there is little indication that this would not be allowed.

What regulators might have to do, should the smartphone industry try to overcharge for this “all-in-one” subscription, is to force the possibility to port at least a user’s data, such as photos, from one smartphone cloud to another. Again, this would be in line with current regulator models, to protect user data. It will become a question about who owns the phone in the cloud.

The Need for a Neutral Global Player also Here?

There might be a role for a non-partial player with global scale also in this real time bidding competition, this time being a middleman between the smartphone provider and the Consumer ServiceCo of the operator. It is less obvious that it is a role for the network vendor, or a system integrator, but given the position they would likely take on the industry vertical side, they could be well positioned to take also this role. If this has been a requirement from say the car industry on the industry vertical side, the extension over to the consumer side is very obvious.

Leading into the Era of 6G

Going back over the generations there seems to be a trend that even though a new cellular generation comes every decade, it takes two decades for each new substantial use case to develop.

1G and 2G was about mobile telephony, with the success during the second decade. 3G and 4G was about mobile internet, again with its hay days during the second decade.

5G and 6G is about automation and digitisation of all aspects of society. We are still in the learning decade of 5G, but there is no doubt in my mind that we will see the pattern repeated again in the second decade, with 6G becoming a monumental milestone, on par with 2G and 4G. It takes the odd generation to mature the use case, on which we harvest in the even generation.

It is impossible to see how a future with automation and AI could be feasible without a secure and safe connectivity and service platform, often with a desire for national control. 6G will be a key component in this development.

The Role of the Regulator Going Forward

As we have seen in this discussion the regulator has been instrumental in the development towards consumer affordability as we took the mobile phone from a luxury product to a human obligation.

However, the fact that the mobile phone is now an obligation is because we have built a society where the mobile network is the backbone of all we do. Going forward into the era of 6G this dependency on the mobile network will only increase.

In the discussion above we have played out a few realistic scenarios following the trend of the past decades. However, it must now be up to each and every regulator to evaluate if these scenarios are in the best interest of the domain they are set to regulate.

If you want a national safe and secure backbone for all aspects of society, on which also innovation will thrive, maybe consumer affordability is not the only parameter to guide you.

Summary

Following the reasoning in this discussion it is easy to see the challenges for the operator ServiceCo going forward, should these scenarios evolve, mainly due to the consequences coming from being a heavily regulated domestic player, and the focus on consumer affordability.

On the Enterprise side, they lack the global scale needed to build up the necessary resources to add value in the interaction with the User Verticals.

On the Consumer side the role could be a connectivity bidding exercise towards the device industry, with little need for local operator brand recognition by the consumer.

However, the operator NetCo would be more important than ever, in a service provider world that will no longer be measured on ARPU, Average Revenue Per User, but on lowest cost per produced GB.

Also, on both the Enterprise side, as well as on the Consumer side, it would be unlikely that the Industry Verticals and Device industry respectively, would want to deal with each and every operator in each and every country directly.

There could thus likely be a need for a player with global scale and network competence to come in and take this role, and on the industry vertical side the network vendors are well positioned, and by pure extension they could fill this role also on the consumer side.

It is thus very important that the national regulators reflect on their role. If the desire is a secure and safe national service platform for the nation’s various functions, such as police, health, governance, defence, etc, and where innovation could thrive, it must be feasible for the involved players to make the investments needed and build the competence required.

Biography

Hakan Eriksson holds a Master of Science in Electrical Engineering after studies at Linköping University, Sweden, and Stanford University, USA. He also received an honorary Doctorate in Technology from Linköping University.

With nearly four decades of experience in the wireless industry, Hakan began his career at Ericsson’s research organization in 1986. He went on to serve as Group CTO of Ericsson from 2003 to 2012 and as President of Ericsson Silicon Valley from 2010 to 2012.

In 2012, Hakan relocated to Australia to assume the role of CEO for Ericsson Australia and New Zealand, a position he held until 2016. He then served as Chief Strategy Officer for Ericsson Southeast Asia and Oceania. In 2017, Hakan joined Telstra as Group CTO.

After four years at Telstra, Hakan founded his consultancy business, Fifth Tee, where he assists large companies and start-ups in navigating 5G technologies. He also holds directorships in several companies, including Chairman of the Australian start-up Zetifi, and is active in the venture capital industry.

Throughout his career, Hakan has seen the development of cellular from many perspectives, having been instrumental in the development of 2G and 3G technologies as CTO at Ericsson, the selling of 4G as CEO of Ericsson Australia and New Zealand, and the acquisition of 5G for Telstra as CTO. He now leverages his expertise to help organizations explore and implement 5G use cases through his consultancy.

Summary From the Mini-huddles in Berlin

The WWRF held a successful 10th edition of the Huddle in Berlin with the theme, "Implementing the 6G Framework: Terrestrial and Beyond," on 17–18 April. During the Huddle, 4 mini huddles, i.e., breakout sessions were organized to focus on key challenges facing the development of 6G. In this article, we summarize some of the key outcomes from those sessions. The views expressed are the personal views of the participants and not those of their organizations.

(1) Sustainability

(Chaired by Sudhir Dixit and Vinod Kumar)

Sustainability is considered to be a very broad term. In the broadest sense, sustainability **implies the ability to maintain or support a process continuously over time**, and encompasses societal, environmental and financial aspects. The debate/discussion on "Sustainability" in 6G seems to follow quite a similar trend as during the introduction of 4G and 5G. It is a debate on how to achieve more, such as higher bit rate, smaller latency and faster response time for multimedia applications, e.g, AR, VR, with less energy consumption and higher density of usage. It was felt that more clarification is needed on whether we need to design "Sustainable 6G" or use "6G for Sustainability", or both.

A similar question arises about the introduction of AI based solutions. Should the 6G design and implementation be driven by "Sustainable AI" or rather we have to check the impact of AI based solutions on the successful achievement of UN Sustainable Development Goals (SDGs). In fact, on the one hand the introduction of AI based solutions should be helpful in improving the spectral efficiency and response time for services but it would work against the improvement of network energy efficiency, on the other hand. The training of data intensive AI models is very heavy on energy consumption. The complexity of quantum technology based mechanisms needed for accrued information and network security in future networks would call for such considerations too.

Studies have shown that 80% of the UN-SDG's would be positively impacted by the introduction of AI based solutions. The relative negative impact on the remaining 20% SDG's is difficult to evaluate, especially in view of the constantly evolving geo-political situation. The political objectives of the governments and the social structure in the developing countries may be quite different from the ones in the developed world whereas the requirements of the users worldwide may be quite similar. Moreover, the "sustainability requirements" for the developing world may be more stringent due to the higher user density and the need for low-cost equipment and services. Consequently, it is felt that it is important to keep some control on the introduction of new generation technologies and services through regulation and standardization.

Although it is good to adopt the approach of distributed cloud and mobile edge for improving performance, but they also increase energy consumption.

The group recommended that: (1) Sustainability related KPI's be introduced right in the beginning of the definition of 6G technology standards, (2) Definition of Sustainability criteria should take into account the geopolitical/social situation and the equipment life cycle management, (3) An ESG (Environmental, Social, Governance) framework should be developed to define basic principles to drive the development of 6G and ICT, (4) The economy of scales achieved through the introduction of standardized technologies is expected to have a positive impact towards the achievement of UN-SDG's, and (5) It is essential that joint goals and objectives should be agreed through collaboration and cooperation amongst all the stakeholders, including regulators and standards bodies.

Security/Privacy/Resilience

(Chaired by Nuwan Weeransighe and Knud Erik Skouby)

The security break-out session served as an extension of the session on "Security & Privacy Requirements and Challenges of 6G." Experts from the initial session joined the break-out session to further discuss and elaborate on the topics presented earlier. The session began with a summary of the main points covered in the "Security & Privacy Requirements and Challenges of 6G" session. Enhancing consumer trust and transparency in security protocols was highlighted as essential for building user confidence that must be upheld and developed as an important precondition for broader 6G adaption. Strategies to provide customer visibility into security measures without compromising security were explored.

The discussion on regulatory issues focused on the implementation of current security standards, particularly the evaluation of 3GPP security standards implemented in 5G. Participants analyzed the successes and shortcomings of these standards and emphasized the need to ensure more satisfying and covering security measures in 6G. The implications of adopting zero-trust networks versus network performance indicators (KPIs) on system security were also considered. There was a consensus that regulators are often lagging in adapting security regulations, and steps must be taken to ensure faster regulatory responses as new technologies emerge.

Vendor responsibilities and security guarantees were another key area of discussion. The group examined how telecommunications companies can ensure that 6G hardware and software vendors meet stringent security requirements and the role of vendors in maintaining and updating security measures was seen as crucial. Measuring and ensuring security in real-time emerged as a critical challenge. Effective methods for this were debated, along with strategies for gracefully degrading services without significant security compromises. The responsibility for managing the new types of data generated by 6G networks was also discussed, with a focus on the roles of network operators and other stakeholders.

From a design perspective, the importance of integrating "Privacy by Design" principles into 6G development was underscored. Participants discussed key design principles and lessons from 5G and earlier technologies that should be integrated from the onset of 6G development. Lessons from other IT and cloud infrastructures were also considered, comparing the telecommunications stack with other IT stacks and identifying security lessons from cloud computing that could enhance telco security in 6G. Privacy and anonymity features were addressed, including the security and privacy implications of anonymous calls in 6G and the feasibility of implementing digital twins in secure environments. The session also examined the security of current backhaul communications and how this influences the choice between distributed and centralized models in 6G, impacting system resilience and security. Preparing for future challenges, such as the potential threats posed by quantum computing to current cryptographic methods, was also a focal point, with discussions on when and how to prepare for these challenges in the development of the 6G system. Strategies for ensuring quick, seamless security updates and bug fixes without system downtime were explored, along with the role of open-source in enhancing system security and update responsiveness.

Addressing social engineering threats specific to 6G technologies was another significant topic. During the discussion, the impact of optional 3GPP security standards was critically analyzed. While many excellent security mechanisms are defined in the standards, the fact that they are optional creates security vulnerabilities as operators, manufacturers, or countries may not implement these optional features or implement different aspects. The accidental switch-off of optional features was also highlighted as a concern. The reasons behind making these security features optional were discussed, emphasizing the consensus required among various parties involved in designing 5G. The session stressed the importance of highlighting this issue in the 6G design process to reduce the number of optional security features. The convergence of telecommunications, IT, and AI was acknowledged, noting the severe lack of experts with knowledge across all three domains. This could make 6G systems vulnerable, so there is a need to involve engineers with expertise in all three areas and to get IT and AI domain experts more involved in 6G design.

The session concluded with several recommendations. Regulators need to be more proactive in updating security regulations to keep pace with technological advancements. There should be a reduction in optional security features in 6G standards to minimize vulnerabilities. Vendors must be held accountable for meeting stringent security requirements and continuously updating security measures. Transparency in security should be enhanced to build consumer trust. It is crucial to incorporate "Privacy by Design" principles from the beginning of the 6G development process and foster collaboration between telecom, IT, and AI experts to strengthen 6G security. Future-proofing security by investing in quantum-resistant cryptographic methods and developing strategies for seamless security updates and maintenance was also recommended. By implementing these recommendations, the industry can ensure robust security and privacy for 6G networks, fostering trust and confidence among users and stakeholders.

Unraveling the Future: Intelligence in 6G Networks

(Chaired by Gordon Johnson and Seshadri Mohan)

The primary objective of the session was to foster a vibrant exchange of ideas, exploring the implications of intelligence within the context of 6G networks. Through interactive deliberations, participants contemplated on driving business innovation and digital transformation across diverse industries while aligning with the overarching theme of implementing the 6G framework, both terrestrial and beyond. A fundamental aspect that permeated the discussions was the integration of Artificial Intelligence (AI) and Machine Learning (ML) with 6G networks. The discourse traversed through various domains where AI/ML could catalyse transformative changes, including edge computing, network core, applications, and cloud infrastructure. In particular, the role of AI in the Radio Access Network (RAN) garnered significant attention. AI's imprint on RAN operations extends to network planning, optimisation, and energy management. Participants underscored AI's pivotal role in optimising base station placement, frequency planning, and radio resource allocation, all in real-time response to dynamic channel conditions. Moreover, intelligent beamforming techniques were hailed for enhancing spectral efficiency, while self-organisation and fault tolerance mechanisms were deemed indispensable amidst the burgeoning complexity of integrated access systems.

The Edge Use Case emerged as a focal point, especially in the context of the Internet of Things (IoT). While the proliferation of IoT devices promises a deluge of data, ensuring data reliability emerged as a paramount concern. Challenges such as spatio-temporal data fusion, heterogeneous sensor formats, and communication constraints necessitate sophisticated data curation and machine learning techniques for meaningful insights extraction. During the discussions on AI's transformative potential, a pivotal topic that captured the attention of participants was energy management within 6G networks. Emphasising the need for sustainability and efficiency, experts delved into innovative strategies for optimizing energy consumption. One notable approach highlighted during deliberations was the adaptation of energy usage, based on fluctuating traffic patterns throughout the day. By dynamically adjusting the capacity while maintaining essential network operations, significant energy savings could be achieved. This nuanced approach not only ensures operational continuity but also minimises the environmental footprint, by conserving energy during periods of reduced demand. However, amidst these deliberations, concerns surfaced regarding the balance between green power consumption and the energy costs associated with AI operations. Participants engaged in a nuanced discourse, weighing the potential environmental benefits against the computational demands of AI algorithms. While AI's training phase may incur substantial energy costs, inferencing (the process of making predictions or decisions based on the trained model) typically requires less computational intensity, and therefore consumes less energy.

The implications of AI in connected and autonomous vehicles (CAVs) were also explored, ranging from intelligent traffic routing to data storage and mining for network performance enhancement. Further discussions delved into a myriad applications of AI in network security, privacy, sustainability, and automated frequency band management. From predicting network failures to optimising antenna positioning and propagation planning, the consensus was clear: the advent of 6G necessitates a paradigm shift towards AI-driven network intelligence. As the session concluded, it became evident that the journey towards 6G transcends mere technological advancement; it embodies a collective endeavour to harness the power of intelligence in shaping a more connected, efficient, resilient, and sustainable future. The exponential growth of AI was emphasised, echoing the sentiments of turning today's dreams into tomorrow's reality, underscoring the inexorable march of technological progress.

Ubiquitous Communications to Connect the Unconnected

(Chaired by Bharat Bhatia and Gary Clemo)

The breakout session on CTU/ubiquitous connectivity consisted of the following Structure:

- Technology – what are the technologies that will enable ubiquitous connectivity? Where will the challenges be in developing, standardising, commercialising and managing networks based on these technologies? Will 6G be a revolution or an evolution?
- Business models – what uses do we think will drive late 5G and early 6G deployments? Will 6G finally unlock the untapped use cases envisaged for the industrial, agricultural sectors, etc? What are the barriers to these currently unconnected users benefiting from 6G?
- Collaborations and partnerships – what has worked to date? What hasn't worked and why? What new collaborations and partnerships do we think will be necessary to deliver ubiquitous communications? What role will governments have?

Following is the summary of discussions during the breakout session

1. We should understand the use cases (including digging into the detail in the 6G Framework)
   a. What are you seeking to achieve?
   b. Who or what are you seeking to connect?
   c. What existing infrastructure (broadly) is there, such as the opportunities to co-locate power and communications?
   d. What are the constraints (e.g. power availability and consumption, population density, affordability etc)?
2. Mobile technology and 6G will play an important role, but how are they part of the bigger picture
   a. There's some merit in being technology neutral when considering what we're trying to achieve. For example, there are cases where local connectivity is provided using satellite, backhauled Wi-Fi, which may meet requirements
   b. There's a question, and potentially a worry, about how complex 6G might become and whether we need a 'slimmed down' 6G that could be deployed cheaply and be easily upgradeable
   c. General view is that technology is important in providing solutions, but this fundamentally isn't a technology problem
3. We need flexible models of spectrum management
   a. Once we understand the use cases, we should understand spectrum requirements
   b. It should be recognised that traditional licensing approaches don't (easily? At all?) allow for sharing or reuse
   c. It could mean that spectrum can't be used in certain areas or at certain times
   d. Regulators should explore and implement flexible frameworks for spectrum management and develop tools (e.g. sandboxes) to allow organisations to experiment and innovate
   e. Operators (MNOs, satellite, HAPs etc.) should explore options for using spectrum more flexibility, and regulators should explore ways of incentivising those options
4. The market has an important role to play
   a. Market driven approaches have been successful in giving us technologies based on common standards
   b. Market leads to economies of scale and cheap devices - ecosystem
   c. Even if we have flexible spectrum management, we still need standards, for example in Mexico a band was allocated but equipment wasn't available to use it. The implications are that future devices will need to be more agile in their use of spectrum and better perform in a shared spectrum environment. Nevertheless, there are some use cases that will never be commercially viable
5. Where the market does not deliver governments and regulators will need to step in
   a. Whether through flexible spectrum licensing
   b. Setting regulations around competition (noting that some parts of the world with poor coverage also have sub-optimal competitive markets)
   c. Setting targets for coverage, measures of connectivity quality, results-driven investment
   d. Trials and PoC - could adopt a tech neutral approach and just focus on specifying success in terms of broader society outcomes
6. Collaboration is important, but meaningful, successful collaboration is difficult
   a. Tech people are good at speaking to tech people
   b. Solving challenges involves bringing in new players and taking collaboration seriously
   c. But it's often uncomfortable, and one needs to be willing to be curious and go beyond his/hercomfort zone
   d. In summary, complex challenges like thiese will be solved by a diverse set of people coming together as we are already doing.

Standards Update

INDIA

1. India to host World Telecom Standards Organisation India hosted ITU's prestigious World Telecom Standardization Assembly Delhi 2024 (WTSA 2024) from 15th–24th Oct 2024. It was a momentous occasion that India brought WTSA to Asia for the very first time where 190+ Countries will participate. Scheduled every four years, the World Telecommunication Standardisation Assembly (WTSA) serves as the governing conference of the ITU Standardisation Sector. Alongside WTCA, India's premier annual mobile event India Mobile Congress 2024 (IMC 2024) was held on 15–19 Oct 2024 at the same location

2. TSDSI completed 10 years as India's Telecom SDO in January 2024 Telecommunications Standards Development Society, India (TSDSI) came into being on January 7th, 2014, as an outcome of the Govt. of India's resolve to setup an Indian Telecommunication Standard Development Organisation (TSDO). This resolution was embodied in the text of the India's National Telecom Policy 2012 (NTP 2012). As India's Telecom SDO, TSDSI has the mandate to develop, promote, contribute and maintain India centric requirements, besides actively working with 3GPP, ITU and other institutions in the advancement of telecom technologies. As an organizational Partner of 3GPP, TSDSI now makes available globally harmonised releases of 3GPP standards regularly through a streamlined process of transposition, consultation, and approval of our members to TEC for eventual adoption as national standard. Likewise, through our agreements with global institutions and SDO's like IEEE-SA, ETSI, ATSC et al., recently TSDSI also transposed the ATSC 3.0 standards and made the same available to TEC for its adoption as national standard, in response to industry needs. TSDSI swiftly embarked on 6G development following the ITU-R's completion of 5G recommendations. Contributions encompassing IMT-2030, including use cases, performance indicators, future tech trends, and IMT in frequencies surpassing 100 GHz, have been submitted to the ITU-R. As part of our 10th anniversary celebrations, TSDSI is launching a series of "Standards Awareness Workshops" in various cities of the country to raise awareness of the crucial role of Standards in innovation and success in today's digitally driven ecosystem. The goal is to encourage companies and R&D organizations to establish dedicated internal structures for adoption and contribution to the development of standards. The series will also act as an ideation platform to discover locally relevant use cases/topics that have a potential for standardization. These workshops will cover the local industry, startups, R&D and academia, relating the standardization opportunities to the organic ICT activity in the region. TSDSI is also hosting 3GPP SA meetings in Hyderabad from 14 to 18 October 2024 to positions India as a key player in global telecommunications standards, promoting local innovation and collaboration with international experts.

3. IAFI hosted national spectrum conference in November 2024 IAFI hosted the India Spectrum Management Conference (ISMC-24) on 7 and 8 November 2024 at Hotel Le Meridien in New Delhi, India. Throughout this important 2 day conference, Spectrum experts from all over the world had the opportunity to be involved in discussions on the key spectrum topics for India and beyond, through interactive sessions, networking opportunities, an exhibition area and much more.

4. Bharat 6G Alliance (B6GA) The Bharat 6G Alliance (B6GA) has been set up in India as a Not-for-profit Society to promote, inter alia, the ecosystem for research, design, development, IPR creation, field testing, security, certification and manufacturing of telecom products and solutions in India. The B6GA is an initiative of Indian industry, academia, national research institutions and standards organizations facilitated by the Government. It envisages India to be a front-line contributor in design, development and deployment of 6G technology by 2030. One of the key goals of B6GA is to identify priority areas for research by involving all stakeholders including industry, academia, and service providers, spanning theoretical and simulation studies, proof-of concept prototypes and demonstrations, and early market interventions led by start-ups; and to facilitate market access for Indian telecom technology products and services, enabling the country to emerge as a global leader in 6G technology and build coalition with like-minded 6G Global Alliances. Bharat 6G Alliance has recently signed Memorandum of Understanding with NextG Alliance of USA, 6G SNS IA of EU and 6G Flagship of Finland. The B6GA is working closely with MoU partners for aligning research and development priorities that support a common 6G vision and creating secure and trusted telecommunications as well as resilient supply chains. Bharat 6G Alliance has participated in various national and international global 6G events organised by USA, Japan, 3GPP, UK, South Korea etc.

KOREA

In Korea, as of 1Q 2024, 5G network is already deployed nationwide by 3 mobile operators using 3.5 GHz band. 5G penetration is higher than 58% and average monthly user data consumption by 5G is around 28 GB which is more than 4 times of 4G LTE data consumption. 5G geographical coverage is more than 75% of territory and population coverage is more than 95%. In addition to public 5G services focusing on eMBB, private 5G networks, so called "eUm-5G", targeting URLLC and mMTC services were deployed by 31 players on 59 sites using 4.7 GHz and 28 GHz. In rural Areas, MOCN type network sharing was adopted jointly by 3 mobile operators.

Regarding 6G preparation, Korean government has already funded 150 million USD for 6G core technologies R&D for 5 years from 2021 and recently started to fund additional 300 million USD for 5 years from 2024 for 6G system technology R&D. If both programs are successful, Korean consortium may demonstrate pre 6G system technologies in 2026 before official draft standard is available by 3GPP and ITU-R around 2029–2030.

JAPAN

The XG Mobile Promotion Forum (XGMF) held its inaugural meeting on 7th June 2024 in Japan.

Considering the centralization of human resources and the unification of international contact points, the 5G Mobile Promotion Forum (5GMF) and the Beyond 5G Promotion Consortium

(B5GPC) were discussed to be integrated and to establish the new "XG Mobile Promotion Forum (XGMF)" in April 2024 in Japan.

The forum has been discussing the organizational structure, terms of reference, and other issues. The XG Mobile Promotion Forum held its inaugural meeting online on 7th June 2024. The purpose of the forum is to contribute to the enhancement of the growth potential of the information and telecommunications industry by promoting the diffusion of mobile services and the development of mobile businesses in order to meet the changing needs of mobile communications.

NORTH AMERICA

Canada

Innovation, Science and Economic Development Canada (ISED) is initiating a consultation on a policy, licensing and technical framework for the use of certain bands allocated to flexible use and/or commercial mobile services to support the expansion of coverage via satellite, which is referred to hereafter as supplemental mobile coverage by satellite (SMCS). Better known to us as Non-Terrestrial Network (NTN). This consultation closed on September 13, 2024. Anyone can reply to it. https://ised-isde.canada.ca/site/spectrum-management-telecommunications/en/learn-more/key-documents/consultations/consultation-policy-licensing-and-technical-framework-supplemental-mobile-coverage-satellite

United States

(1) The FCC released changes to CBRS standards in June 2024, a Notice of Proposed Rulemaking (NPRM). This proceeding seeks comments on a range of potential rule changes to improve the CBRS (Citizen's Broadband Radio Service) band for current and future users. The 3.5 GHz CBRS band is unique to the U.S. and uses a three-tiered model to protect Navy radar while allowing commercial use of the spectrum. Title of the document is: WIRELESS TELECOMMUNICATIONS BUREAU AND OFFICE OF ENGINEERING AND TECHNOLOGY ANNOUNCE MODIFIED AGGREGATE INTERFERENCE MODEL USED BY SPECTRUM ACCESS SYSTEM ADMINISTRATORS, GN Docket Nos. 17-258 and 15-319, https://docs.fcc.gov/public/attachments/DA-24-553A1.pdf?ref=broadbandbreakfast.com

(2) On October 21, 2024, **IETF published a document** on "Security and Privacy Implications of 3GPP AI/ML Networking Studies for 6G." The document outlines key application areas and proposes modifications to the architecture to address the issues related to security and privacy with the objective to initiate new work at the IETF. Not only does the document describe the architecture, it goes into the role of training and federated learning and what AI/ML can do in radio access networks.

(3) Recently, **IEEE announced a collaborative Innovation 5G/6G testbed** (https://testbed.ieee.org/about/our-mission/). Collaborative testing allows for a more comprehensive and accurate evaluation of 5G/6G networks, addressing key challenges related to interoperability, performance, and security. As highlighted on the testbed website, "IEEE created the 5G/6G Innovation Testbed to foster collaborative experimentation and advancement among stakeholders in the 5G and 6G ecosystem." The IEEE FNTC project held a Connecting the Unconnected (CTU) Summit where several awards were announced for best projects around the world (https://ctu.ieee.org/) and the IEEE Future Networks World Forum in Dubai, U.A.E. (https://fnwf2024.ieee.org/). Both the events were held between the dates of 14–18 October, 2024.

ITU(R) SG5 & WP5D

The 46th meeting of WP 5D was held as a physical meeting with remote participation from June 25 to July 2, 2024 in Geneva. The work is organized into three working groups: General Aspects, Spectrum Aspects and WRC Preparations, and Technology Aspects. The Ad Hoc Work Plan group meets on an as needed basis.

A decision was reached in the opening plenary by the Chairs of the Working Groups (WGs) as follows: (a) Spectrum Aspects and WRC-preparations – Mr. Michael Kramer from Intel, (b) Technology Aspects – Mr. Hu Wang from China (Huawei), (c) General Aspects – Mr. Bharat Bhatia from India (IAFI). Bharat is also Vice Chair of the WWRF for Asia Region. He also represents WWRF in WP5D together with WWRF Chair, Nigel Jefferies.

After prolonged discussions, the WP Vice-Chairs reached an agreement in the closing plenary that the following individuals would be appointed in acting capacity, such as the 5D chairs: (a) Mr. Ven Sampath from Canada, (b) Mr. Rauno Ruismäki from Finland, and (c) Mr. Stuart Cooke (GSMA). This is due to geo political deadlock at SG 5 level.

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Federated Learning for Energy Efficiency in 6G

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Abstract: This paper presents a multi-tier Federated Learning (FL) architecture designed to optimize energy efficiency in 6G, with particular emphasis on compliance with the Network Data Analytics Function (NWDAF) standards defined by 3GPP. Unlike existing FL architectures that often overlook energy efficiency and lack full integration with network functions like NWDAF, our proposed architecture integrates AI-driven strategies across multi layers. This multi-tier approach dynamically adjusts computation and communication rounds, reducing energy consumption while maintaining high model accuracy and network performance. By addressing challenges such as data heterogeneity and personalisation through adaptive training, intelligent routing, and advanced model aggregation, the architecture significantly enhances energy efficiency. Initial simulations, aligned with NWDAF processing requirements, underscore the architecture's suitability for deployment in 6G , offering a scalable, energy-efficient, and privacy-preserving solution that aligns with industry standards and addresses key challenges in distributed learning.

Keywords: 6G, energy efficiency, federated learning, multi-tier architecture, NWDAF, AI-driven strategies.

1. Introduction

The advent of 5G has led to a significant increase in data generation and the need for real-time analytics. In response, the Third Generation Partnership Project (3GPP) introduced the Network Data Analytics Function (NWDAF) in Release 17, 18 and 19 [1–3] to manage, optimize and automatise network operations through data-driven insights. NWDAF facilitates the collection and analysis of network data to enhance performance, reliability, and user experience. However, the distributed nature of data and the requirement for privacy-preserving mechanisms present substantial challenges that need to be addressed.

As we move towards 6G, the focus extends beyond enhancements in data throughput and connectivity. A critical aspect of 6G development is the integration of advanced intelligence to ensure sustainable and efficient network operations [4–6]. Energy efficiency and sustainability have emerged as paramount concerns, particularly as networks become increasingly complex and data-intensive [7]. Consequently, optimizing energy consumption in communication networks is a central priority in 6G technologies.

Edge computing has emerged as an effective strategy to address these energy challenges. By utilizing a combination of platforms, Internet of Things (IoT) devices, and software, edge computing systems efficiently manage computational resources, distributing processing tasks according to workload requirements. By offloading computational demand from centralized servers, edge architectures conserve bandwidth, alleviate cloud infrastructure load, and reduce latency. This approach is critical for real-time applications like autonomous vehicles and smart cities, where immediate processing is essential.

Despite its advantages, edge computing introduces challenges such as increased security risks due to its distributed nature, bandwidth management complexities, and hardware heterogeneity. Managing these issues is essential to ensure consistent performance and secure data processing across devices.

Federated Learning (FL) has emerged as a promising approach to address some of these challenges by enabling local model training on devices and aggregating updates centrally. This method preserves user privacy and reduces the need to transmit sensitive raw data, aligning with the privacy requirements of modern networks. However, FL faces issues like communication overhead from frequent model updates, dependence on a central server for aggregation, and performance degradation when client devices hold non-independent and identically distributed (non-IID) data.

Combining edge computing with FL creates a synergistic relationship that enhances the capabilities of both technologies. Edge computing provides the necessary infrastructure for FL to operate more efficiently, reducing latency and communication costs. This synergy leads to a more robust and scalable system for managing distributed data.

Several FL architectures have been proposed, leveraging the benefits of edge computing to improve privacy preservation, reduce communication overhead, and enhance scalability [8, 9]. However, these architectures often overlook energy efficiency and do not fully integrate with network functions like NWDAF [10, 11]. Additionally, challenges related to data heterogeneity and personalisation remain inadequately addressed [9].

To bridge these gaps, we evaluate how a previously proposed multi-tier FL architecture [12], designed to handle data heterogeneity and personalization, fits within 6G while aligning with the NWDAF framework defined by 3GPP standards [3]. By integrating AI-driven strategies across its Client, Edge, Fog, and Cloud layers, the architecture dynamically adjusts computational resources to reduce energy consumption while maintaining

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model accuracy and network performance. This design effectively manages data heterogeneity and personalisation while minimizing redundant computations and communication overhead.

In this paper, we evaluate the energy efficiency of the proposed multi-tier FL architecture, particularly highlighting how it seamlessly integrates with NWDAF in accordance with 3GPP standards, making it a well-aligned solution for optimizing 6G. We demonstrate how adaptive training, intelligent routing, and advanced model aggregation contribute to significant energy savings. Initial simulations highlight the effectiveness of these strategies in 6G, suggesting substantial improvements in energy efficiency for real-world applications.

The remainder of this paper is organized as follows: Section II details the proposed multi-tier FL architecture, discussing the specific roles and contributions of each layer in enhancing energy efficiency and aligning with NWDAF. Section III presents the results of our simulations, demonstrating the framework's effectiveness in reducing energy consumption while maintaining model accuracy. Section IV discusses the AI-driven strategies employed across the layers to optimize energy efficiency. Finally, Section V concludes the paper and outlines potential areas for future research and real-world implementation in diverse 6G scenarios.

2. Multi-Tier Federated Learning Architecture and its Integration with NWDAF

The multi-tier FL architecture, originally proposed in [12], comprises four hierarchical layers: **Client**, **Edge**, **Fedge**, and **Cloud** as shown in Figure 1. This architecture is designed to manage data and model training effectively in distributed networks, addressing challenges related to data heterogeneity, personalisation, and energy efficiency in 6G environments. In this section, we review this architecture from the perspective of the NWDAF, highlighting how it aligns with 3GPP standards and can be seamlessly integrated into existing network infrastructures.

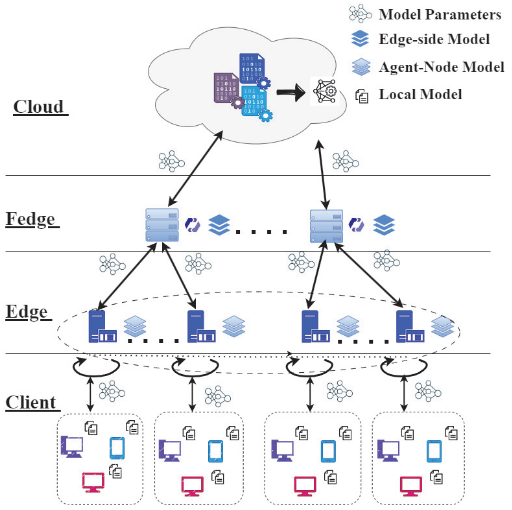

Figure 1.

Proposed multi-tier federated learning architecture.

2.1. Overview of the Architecture

The proposed architecture combines the capabilities of edge computing and FL to distribute computational tasks and data processing efficiently across different layers of the network. This approach reduces communication overhead and redundant computations, improving energy efficiency and performance in model training. NWDAF plays a crucial role in this architecture by enabling distributed data analytics and optimizing network operations, ensuring privacy and network efficiency.

In this architecture, NWDAF facilitates both vertical (North/South bound communication) and horizontal (East/West bound communication) data flow to support real-time analytics across various network functions such as Application Function (AF), Session Management Function (SMF), Access and Mobility Management Function (AMF), (Network Exposure Function) NEF, and Policy Control Function (PCF), as depicted in Figure 2. The Hyperscaler provides additional computational power, allowing NWDAF to leverage machine learning (ML) models embedded across the network for optimizing resource allocation and reducing latency. This interaction ensures that the FL system operates efficiently in compliance with 3GPP standards and effectively adjusts to varying network conditions.

2.2. Client layer

The Client layer consists of end-user devices, such as smartphones and IoT devices, where local model training occurs using the client's own data. This allows for privacy-preserving operations, as raw data remains on the device, which aligns with 3GPP privacy requirements.

Regarding NWDAF integration, clients primarily interact with the network through standardized interfaces. These devices share aggregated model updates, not raw data, with the higher network layers, particularly the Edge layer, to support distributed analytics. In line with NWDAF's objective of safeguarding privacy, these communications are carried out securely, ensuring that the data is handled in compliance with privacy regulations.

Energy efficiency is enhanced by minimizing data transmission to the Edge Layer. Clients send only critical model updates, which reduces redundant communications. Additionally, clients utilize adaptive training techniques to optimize learning and minimize resource consumption. By dynamically adjusting learning parameters, the Client Layer ensures that training is both energy-efficient and aligned with NWDAF's goals for reducing overhead in real-time analytics.

2.3. Edge Layer

The Edge layer operates as an intermediary between the Client layer and higher-tier layers like the Fedge layer and Cloud layer. Its primary function is to collect and process model updates from the clients before passing them upwards in the network. The Edge layer uses NWDAF to optimize the flow of data and manage network functions such as AMF and SMF by ensuring that relevant, context-aware information is processed efficiently.

The interaction with NWDAF allows the Edge Layer to perform distributed analytics, reducing latency and network load by processing data closer to its source. For instance, by using ML models within the Edge Layer, the system can make real-time decisions about what data is important and should be sent to the Fedge layer or NWDAF for further analysis. This selective forwarding of information conserves energy and ensures that the Edge layer operates efficiently within the NWDAF framework.

Furthermore, this layer ensures that communication between client devices and the network is optimized for energy savings, avoiding redundant data aggregation. The edge nodes also facilitate secure and efficient communication of aggregated model updates from multiple clients to the Fedge ayer, aligning with NWDAF's objective of streamlining distributed analytics across the network.

2.4. Fedge Layer

The Fedge layer acts as the aggregation and coordination layer in this architecture. It serves as a crucial point for managing and optimizing the flow of data between Edge and Cloud layers. This layer aggregates model updates from multiple Edge layers, performing complex tasks such as clustering and aggregation to improve scalability and efficiency in the FL process.

In this architecture, the Fedge layer closely integrates with NWDAF to ensure that the aggregated data from various network functions (like AF, SMF, AMF, NEF, and PCF) is analyzed efficiently. As depicted in the diagram, Fedge plays a key role in facilitating horizontal (East/West) communication between NWDAF instances, enhancing network-wide coordination and distributed analytics. This coordination is crucial for managing data from different network segments and ensuring consistent and efficient learning processes across the system.

By aggregating model updates before they are sent to the Cloud layer, the Fedge layer minimizes computational redundancy and energy consumption, which aligns with the energy efficiency goals of the system. This hierarchical aggregation also prevents unnecessary re-training of models across different edges, further reducing the system's computational burden.

2.5. Cloud Layer

The Cloud layer serves as the top tier in the architecture, where global model synchronization and storage occur. It is responsible for aggregating insights from lower layers, including the Fedge Layer, and coordinating network-wide optimization strategies.

The Cloud layer interacts with NWDAF by handling centralized analytics functions and ensuring that the insights gathered from the Fedge layer are used for system-wide optimization. This interaction allows the Cloud Layer to update models and analytics functions across the network based on real-time feedback from NWDAF, ensuring that the system remains scalable and energy-efficient.

The Cloud layer focuses on maintaining model synchronization while minimizing communication overhead with the lower tiers. By optimizing when and how updates are pushed to the lower layers, the Cloud layer ensures that the system remains responsive and aligned with energy-efficient operations. Additionally, by interacting with the Network Repository Function (NRF), the Cloud Layer ensures the discoverability and integration of analytics services across the network.

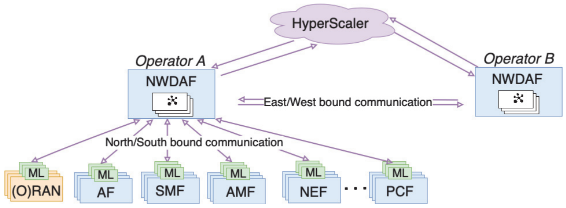

Figure 2.

Proposed multi-tier FL architecture within 3GPP

2.6. Integration with NWDAF

The integration of the multi-tier FL architecture with NWDAF is achieved through several key mechanisms, ensuring compliance with 3GPP standards and seamless operation within 5G and beyond networks.

1. **Standardized interfaces and protocols:**
   The architecture utilizes standardized interfaces defined by 3GPP, such as the NWDAF interface, to ensure compatibility and interoperability with existing network functions. This allows for efficient communication between NWDAF and other network functions, facilitating data exchange and analytics reporting.
2. **Security and privacy compliance:**
   Adhering to 3GPP security frameworks, the architecture ensures secure communication and data handling across all layers. Secure protocols are used for transmitting model updates and analytics data, protecting user privacy and data integrity. By preserving user privacy and minimizing the transmission of sensitive data, the architecture complies with data protection regulations and user expectations.
3. **Support for network slicing:**
   The hierarchical design of the architecture supports NWDAF's role in managing network slices by providing analytics tailored to specific slice requirements. Each layer can process and aggregate data relevant to particular network slices, enabling more efficient and customized network management. This capability enhances the network's ability to provide specialized services and optimizes resource allocation, aligning with 3GPP standards.
4. **Energy efficiency optimization:**
   By minimizing redundant data processing and optimizing computational resource allocation across layers, the architecture contributes to NWDAF's objectives for energy efficiency. Techniques such as adaptive training at the Client Layer, intelligent forwarding at the Edge Layer, and efficient model aggregation at the Fedge Layer collectively reduce energy consumption, which is crucial for sustainable network operations in 6G.
5. **Real-time analytics and scalability:**
   Integration with NWDAF enables real-time analytics, which is essential for applications requiring low latency and immediate responsiveness. The multi-tier design allows for scalable deployment, supporting a growing number of devices and services in 6G. This scalability aligns with NWDAF's need to accommodate increasing network complexity while maintaining high performance.

3. Results Analysis

In this section, we assess the effectiveness of the multi-tier FL architecture, emphasizing its ability to handle data heterogeneity and its implications for energy efficiency and integration with the NWDAF. The evaluation leverages results from our previous study [12], focusing on findings that are particularly pertinent to energy efficiency in 6G.

3.1. Methodology

The architecture's performance was evaluated using the Federated Averaging (FedAvg) algorithm on the MNIST dataset under non-Independent and Identically Distributed (non-IID) conditions. Two scenarios were designed to test the architecture's capability to manage data heterogeneity:

Generalisable non-IID scenario: The dataset was evenly divided among three clients, each receiving a balanced mix of all digit classes. This scenario serves as a baseline to evaluate performance under typical non-IID conditions.

Non-generalisable non-IID scenario: One client received images of only two digit classes, while another received images of eight classes, creating an extreme imbalance. This scenario challenges the architecture's ability to handle significant data skew, which is critical for real-world applications where data distributions are often uneven.

A Simple Convolutional Neural Network (SimpleCNN) model was used across all clients to maintain consistency. The primary focus was on measuring model accuracy and convergence speed, metrics that directly impact computational load and energy consumption.

3.2. Results and Analysis

In both scenarios, the multi-tier FL architecture outperformed the standard FL model in terms of convergence speed and final accuracy:

Faster Convergence: The multi-tier FL model reached higher accuracy levels in fewer training rounds compared to the standard FL model. This reduction in training rounds implies fewer communication cycles and less computational effort, leading to energy savings.

Robustness to Data Heterogeneity: In the non-generalisable non-IID scenario, the multi-tier FL architecture maintained consistent accuracy across clients, effectively mitigating the adverse effects of extreme data imbalance. This robustness is essential for NWDAF's ability to provide reliable analytics in diverse and dynamic network conditions.

These results demonstrate the architecture's efficiency in handling non-IID data distributions, a common challenge in federated networks. Detailed figures and quantitative results are provided in our previous work [12].

3.3. Implications for Energy Efficiency and NWDAF Integration

The observed improvements have significant implications for energy efficiency and NWDAF integration:

1. **Energy Efficiency:** Faster convergence and reduced training rounds translate directly into lower energy consumption. By minimizing the computational workload and the frequency of communication between clients and servers, the multi-tier FL architecture conserves energy—a critical consideration for battery-powered devices and large-scale networks in 6G.
2. **Optimized Resource Management:** The architecture employs AI-driven strategies that adapt to varying network conditions and data distributions. By focusing computational efforts where they are most needed and avoiding redundant processing, it reduces unnecessary energy expenditure.
3. **Alignment with NWDAF:** The architecture's ability to handle heterogeneous data while maintaining high accuracy aligns with NWDAF's objectives of efficient and privacy-preserving analytics. Its hierarchical structure maps onto NWDAF's distributed analytics framework, facilitating seamless integration and enhancing overall network performance.

These findings underscore the suitability of the multi-tier FL architecture for deployment in energy-sensitive and data-intensive environments characteristic of 6G.

4. Conclusion & Future Directions

In this paper, we evaluated the proposed mult-tier FL architecture for the energy efficiency demands of 6G, integrating seamlessly with the NWDAF as defined by 3GPP standards. Initial simulations demonstrated the framework's potential in reducing energy consumption while maintaining high model accuracy, even with non-IID data distributions. However, as this is a preliminary proposal, several challenges need to be addressed. Real-world evaluation is required to validate the architecture's effectiveness across diverse and complex datasets representative of 6G scenarios. Additionally, issues related to security and the heterogeneity of edge devices must be overcome to ensure robust and scalable deployment.

Future work will focus on conducting extensive trials in practical settings, refining AI algorithms for better adaptability, and testing with more complex and larger-scale datasets. Addressing these challenges is crucial for advancing towards energy-efficient, high-performance networks in the 6G era. By overcoming these obstacles, the proposed multi-tier FL architecture can significantly contribute to sustainable and intelligent 6G networks, enhancing distributed learning capabilities and optimizing network operations in compliance with industry standards.

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Federated Learning Enhancement Through Transfer and Continual Learning Integration: Analyzing Effects of Different Levels of Dirichlet Distribution

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Abstract: Machine learning plays a pivotal role in modern technology, driving advancements across various domains such as healthcare, finance, and autonomous systems. Federated Learning (FL) offers a significant advantage over traditional machine learning by enabling decentralized model training without requiring data to be centralized, thereby enhancing privacy and security. With the advent of 6G networks, which promise ultra-reliable low-latency communications (URLLC) and massive machine-type communications (mMTC), FL can be significantly enhanced. 6G's improved bandwidth and latency characteristics will enable more efficient data exchange and model updates, further enhancing the adoption of FL. However, the performance of FL can be significantly affected by data distribution, particularly in non-IID (non-Independent and Identically Distributed) scenarios, where FL tends to perform poorly. This paper proposes a novel approach to enhance FL by integrating Transfer Learning (TL) and Continual Learning (CL), named Integrated Federated Transfer and Continual Learning (IFTCL). TL can extract features from client training samples to benefit subsequent clients, while CL mitigates catastrophic forgetting caused by heterogeneous data across clients. This integration improves FL performance under varying degrees of heterogeneous data distributions simulated by Dirichlet distribution, enhancing accuracy, convergence speed, and reducing communication overhead. The proposed method's feasibility is validated using a publicly available radar recognition dataset.

Keywords: federated learning, transfer learning, continual learning, Dirichlet distribution.

1. Introduction

With the advent of sixth-generation (6G) technology, the significant increase in data volume has brought considerable attention to machine learning, which is expected to play a crucial role in the development of 6G wireless networks. These networks, offering ultra-reliable low-latency communication (URLLC) [1] and extensive machine-type communication (mMTC) [2], are poised to revolutionize technology and convenience. Machine learning influences a wide range of applications that are closely tied to daily activities such as: healthcare [3], finance [4], and transportation [5]. Its ubiquity in everyday applications underscores its significance in the contemporary digital landscape. However, it also gets access to vast amounts of personal data that require protection from unauthorized access and misuse.

These advancements facilitate more efficient data exchange, seamless real-time applications, and improved performance of various digital services. However, as 6G bandwidth and connectivity improve, the accompanying surge in data volume and increased network complexity have made privacy issues more severe [6]. The potential for data breaches and unauthorized access is greater than ever, making privacy protection a top priority. Traditional centralized machine learning methods, which aggregate data from multiple sources into a central repository, pose significant privacy risks.

Federated Learning (FL) addresses these concerns by enabling decentralized model training. In FL, the data remains on local devices, and only model updates are shared with a central server, thus ensuring that personal data is not exposed or transmitted [7]. This method not only preserves privacy but also complies with stringent data protection regulations, making FL a compelling solution for privacy-conscious applications. However, the performance of FL is highly dependent on the distribution of the dataset. When the samples in each client are uniformly distributed across each training client, the training results are generally excellent [8, 9]. However, in real-world scenarios, data is often non-IID (non-Independent and Identically Distributed), meaning that data distributions can vary significantly between clients [10, 11]. This heterogeneity can lead to substantial challenges in model convergence and accuracy [12]. For instance, certain clients may have data that is biased or skewed towards specific classes or features, causing the global model to perform poorly when aggregated from these disparate local models. This imbalance can slow down the convergence rate, reduce overall model accuracy, and increase the communication burden due to the need for more frequent synchronization and updates to achieve acceptable performance.

To address these challenges, this paper proposes a novel approach that combines FL with Transfer Learning (TL) and Continual Learning (CL) to enhance FL under varying degrees of Dirichlet distribution. TL facilitates the extraction of useful features from a set of clients [13], which can then be utilized by subsequent set of clients to form a complete feature extractor, thereby promoting knowledge transfer to remaining clients and improving overall learning efficiency by freezing the feature extractor layers of FL network to reduce communication

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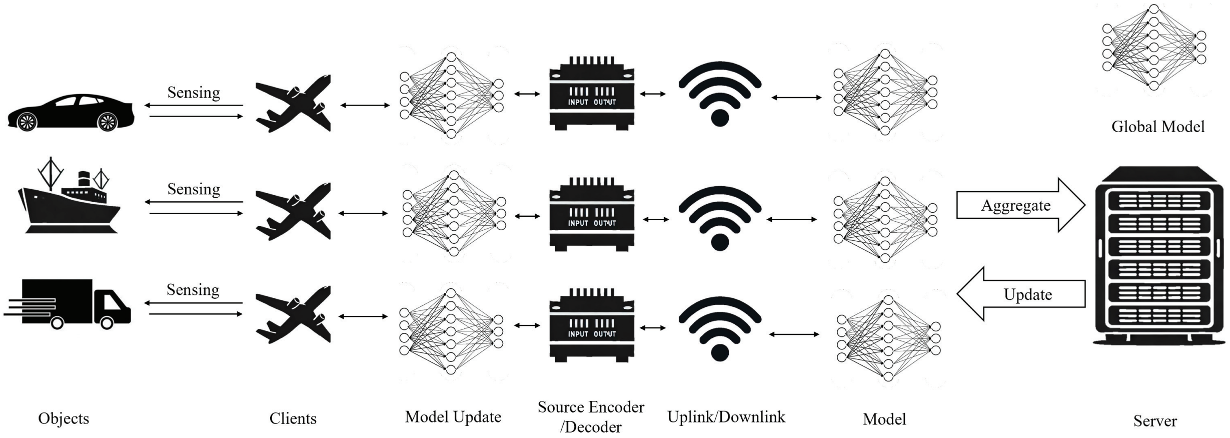

Figure 1.
System model demonstration.

burden [14]. Meanwhile, CL helps to mitigate the issue of catastrophic forgetting [15], which occurs when a model trained on new data overwrites previously learned information, especially reduce the impact of heterogeneity between different sets of clients.

By leveraging these two techniques, our approach aims to enhance the training performance of FL in non-IID environments, modelled by Dirichlet distribution [16], improving accuracy, convergence speed, and reducing communication overhead.

The contributions of this paper are as follows:

(1) *Investigation of FL and FTL performance*: We explore the performance of federated learning and federated transfer learning under different levels of non-IID data distributions, providing insights into its weakness under non-IID condition.
(2) *Introduction of IFTCL*: IFTCL approach by integrating TL and CL with FL is introduced, which demonstrate its ability to enhance training accuracy, accelerate convergence, and reduce communication overhead in non-IID environments.
(3) *Empirical validation*: We validate the practicality and effectiveness of FL, FTL and IFTCL algorithms on a publicly available radar recognition dataset, highlighting its potential for real-world applications.

2. System Model

In this section, the basic system models are presented, representing the context to carry out the data collection, communication and federated training process. A simple demonstration of the system model is shown in Figure 1. The clients are responsible for collecting radar images from different geographical locations and various objects. After the data is collected, the collected raw data is stored in each client. Communication between the clients and the server is conducted via wireless communication. Through multiple rounds of aggregation and updates between clients and the server, federated learning is eventually completed.

In this experiment, in order to simulate different levels of non-IID, each FL client is assigned a portion of the whole dataset with varying quantities and distributions of data according to a Dirichlet distribution, simulating a non-IID environment for FL. Every client utilizes a Convolutional Neural Network (CNN) with the same architecture to train for object recognition tasks.

2.1. Data Distribution

The non-IID nature of data is a challenge in FL. The Dirichlet distribution can effectively model such data distributions, which is a multivariate probability distribution used to describe the distribution of probability vectors. The probability distribution function for this distribution is:

$$P(p \mid \alpha) = \frac{1}{B(\alpha)} \prod_{m=1}^{M} p_m^{\alpha_m - 1} \tag{1}$$

where p is an M-dimensional vector representing the probability of each object's tag m for each client, and α_m is a positive parameter that determines the concentration of the generated distribution.

From this, we can conclude that the smaller the value of α, the more uneven the distribution of different tags across different clients which is caused by bigger variation of different objects in each client. Especially, when α is particularly small, it is highly possible that not all tags will be included on each client.

2.2. Basic FL Model

Federated learning involves a set of K clients, each with its local dataset D_k, and a central server. The goal is to train the global model w in the server by aggregating locally computed parameters without sharing the actual data. The optimization problem can be formulated as the minimization of loss function:

$$\min F(w) = \sum_{k=1}^{K} \frac{n_k}{n} F_k(w) \tag{2}$$

where: $F_k(w)$ is the local loss function for client k, n_k is the number of data points in client k, n is the total number of data points.

Each client k performs local updates by minimizing its local objective function using gradient descent:

$$w_k^{t+1} = w_k^t - \eta \nabla F_k \left(w_k^t \right) \tag{3}$$

where η is the learning rate.

After a certain number of local updates, clients send their local models to the server, which aggregates them to update the global model:

$$w^{t+1} = \sum_{k=1}^{K} \frac{n_k}{n} w_k^{t+1} \tag{4}$$

The algorithm above is called the Federated Averaging algorithm (FedAvg).

2.3. Wireless Communication Model

The communication process includes the formation of the local parameter in each training iteration in each client, the uplink of the trained model parameters to the server, the aggregation of the encoded parameters, decoding of the parameters, and the downlink of the parameters back to each client.

Hence that the communication system need source encoding and some kinds of encryption. The overall process of encoding can be represented as:

$$\theta_k^t = \phi(w_k^t) \tag{5}$$

Therefore, after the procedure of encoding, each client will uplink its encoded parameters. The transmission process can be denoted as the following algorithm:

$$\mu_k^t = \beta(\theta_k^t) \tag{6}$$

After the transmission, the server will begin to aggregate the coefficient by the conditional distribution of samples in each client. Finally, the fusion of the coefficient will be decoded, and gain the aggregated weight.

3. IFTCL Algorithm

This section delves into the structure of CNN, transfer learning and continual learning, providing an understanding of their definitions and mechanisms. It discusses why traditional Federated Transfer Learning (FTL) alone struggles to achieve optimal training outcomes under highly non-IID conditions. Finally, we introduce the Integrated Federated Transfer and Continual Learning (IFTCL) method, and explains its operational principles.

3.1. Composition of CNN

When it comes to tasks such as object recognition, speech recognition, image segmentation, and natural language processing, we often use Convolutional Neural Networks (CNNs). A CNN is a deep learning model composed of multiple layers, each responsible for different functions. A CNN can be roughly divided into two parts:

(1) Feature Extraction Part: Comprising multiple convolutional and pooling layers, this part is responsible for extracting feature information of the object, including shapes, contours, textures, colors, and spatial relationships. These layers gradually extract increasingly abstract features, transforming the input data into high-dimensional feature representations. It can be expressed as: w^f.

(2) Classification Part: Mainly composed of fully connected layers, this part inputs the high-dimensional features generated by the feature extraction part into a classifier to make the final classification decisions. The output layer of this part is usually a softmax layer, which produces a probability distribution over the various classes. It can be expressed as: w^c.

3.2. Transfer Learning

Transfer Learning (TL) is a machine learning technique where a model developed for a particular task is reused as the starting point for a model on a second task. By leveraging the knowledge gained from the first task, TL can significantly improve the performance and efficiency of the model on the new task.

Based on the information above, in FL, if clients can be divided into two subsets, we can pre-train one subset first and then use transfer learning to transfer the pre-trained biases gradients to the remaining subsets for further FL. At this point, if the pre-trained model parameters can fully represent the object's features, we only need to freeze the feature extraction parts of the CNN on these remaining clients and directly train the classification parts to obtain the specific object labels. However, this method, known as Federated Transfer Learning (FTL), is less effective in scenarios where the data is highly non-IID.

3.3. Continual Learning

Continual Learning (CL), also known as lifelong learning, is a significant concept in machine learning aimed at enabling models to retain and accumulate knowledge over a continuous learning process without forgetting previously learned information. Unlike traditional machine learning models that are trained on a fixed dataset, continual learning models are designed to adapt and learn from data that arrives incrementally.

There are many methods of CL, such as: (1) replaying a small portion of stored old data along with new data; (2) incorporating additional terms into the loss function to ensure that learning new tasks does not interfere significantly with previously learned tasks; (3) isolating or partitioning the model parameters to prevent interference between tasks. Among all three methods, the first method that using replaying mechanism is the easiest to carry out, and it can retain the same network structure as FL and FTL for later comparision. Therefore, we utilize the replaying strategy in our new approach.

3.4. Integrated Federated Transfer and Continual Learning

Since traditional FL and FTL has its limitations, we propose an Integrated Federated Transfer Continual Learning (IFTCL) approach. This method combines the advantages of federated learning (transferring parameters instead of the entire model), transfer learning (leveraging learned knowledge), and continual learning (avoiding catastrophic forgetting).

The procedure of IFTCL can be described as follows: First, we partition N clients into $M + 1$ subsets $S_1, S_2, \ldots S_M, S_R$ rather than only two sets. Initially, federated learning is used to train on the data of first set S_1. At this time, a rough feature extractor $w^f_{S_1}$ can be trained.

Then, using transfer learning, the feature extraction parts are transferred to the second subset through the server, where federated learning continues. At this point, because the model parameters are not frozen, due to the nature of transfer learning, the second set start learning based on the first rough feature extractor. The second client set will form a relatively complete feature extractor.

However, due to the non-IID nature in each client, the composition of data in each client is highly different. The knowledge learned by the previous subset will gradually be forgotten by the next subset during training. To address this, after training on S_2, CL will enable experience replay strategy by transfering parameters to previous trained set S_1 for continual learning for a certain round.

The following scenario is quite similar to the one described above. After CL, its feature extraction parts will undergo TL on S_3. Once TL is completed, it will go through a certain number of CL rounds on S_1 and S_2. This process will continue in the same manner until reaching S_M. In order to balance the training iterations in each client and compare the performance of FL and FTL later, we make the iterations in each client are the same in total.

Compared to the FTL method mentioned earlier, this approach aims to train the feature extractor more effectively. In traditional FTL, clients are divided into two groups, S and S_R, with the clients in S participating in federated training independently to obtain the feature extractor. However, in our IFTCL method, the set S in FTL is further subdivided into M smaller subsets, which first learn individually and then leverage transfer learning to pass knowledge to the next client.

The advantage of this approach lies in the fact that the ultimate goal is to minimize the global loss function through the aggregation phase of federated learning by minimizing the loss function of each client during local training. In scenarios where data among clients is highly heterogeneous, each client contributes differently to the global model during aggregation when minimizing its local loss function. This contrasts with IID data scenarios where each client's gradient descent direction is generally consistent. The multiple rounds of transfer learning in IFTCL reduce the aggregation process among clients, significantly mitigating this issue. Additionally, due to the substantial heterogeneity of client data, continual learning is employed to ensure that the previous training results are not forgotten during subsequent federated learning stages, necessitating the use of replay.

After all these procedures, a well optimized feature extractor is trained, we can continue the procedure in FTL, transfer the feature extractor to S_R and freeze it for further classification.

4. Simulations and Results

4.1. Experiment Setup

In this experiment, the MSTAR dataset was utilized, which is widely recognized in Synthetic Aperture Radar (SAR) imagery. For the purposes of this study, radar images of eight distinct objects were selected from the MSTAR dataset. The data distribution among clients was modeled using a Dirichlet distribution with parameter α set to 0.3 and 1. The α parameter controls the degree of non-IID distribution, allowing the evaluation of the performance of federated learning methods under various non-IID conditions.

The experimental configuration involved $K = 6$ clients, each equipped with a convolutional neural network consisting of two convolutional layers. These two layers are selected to be the feature extraction part for pre-training in FTL and IFTCL. In the process of transfer learning, three clients are selected for pre-training and the remaining three clients are chosen for classification. Meanwhile, in IFTCL, the selected three clients are designed to be three subsets, which means that local training is carried out in each client, which greatly decreases the communication burden. In this experiment, the total number of training rounds was set to 100, with 3,318 out of 4,459 samples being utilized for training.

4.2. Data Distribution

According to the Dirichlet distribution, data is allocated among six clients, as illustrated in Figure 2. Notably, different clients

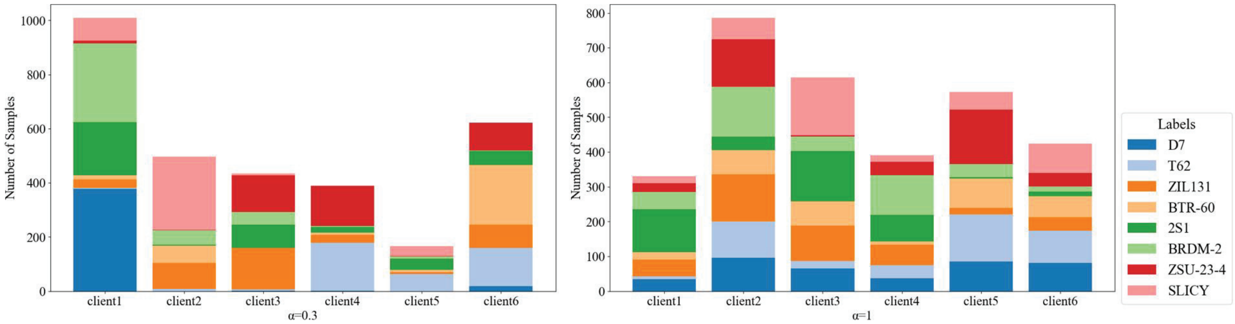

Figure 2.

Visual presentation of different parameters in non-IID data for each client.

receive varying quantities of data, with smaller values of α resulting in more imbalanced distributions. When $\alpha = 1$, we can clearly tell the distribution is uneven and unbalanced, but there are still eight kinds of objects in each client. In cases where the non-IID coefficient α is particularly small, as $\alpha = 0.3$, certain clients may receive very few samples for specific categories, or even none at all.

4.3. Training Performance

The evaluation of these scenarios is based on four critical metrics: communication overhead, convergence speed, accuracy.

4.3.1. *Training Accuracy*

As shown in Figures 3 and 4, these graphs illustrate the training performance of FL, FTL and IFTCL under different Dirichlet parameters α. From a broader perspective, comparing the two graphs, it is evident that all three methods demonstrate that as the Dirichlet parameter α increases, the training process converges faster, and the final training results become more accurate. Specifically, when $\alpha = 1$, the data is most evenly distributed compared to $\alpha = 0.3$, leading to a higher overall accuracy, with the fastest convergence rate.

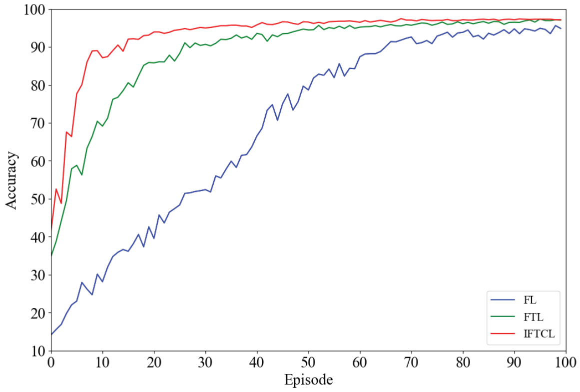

Figure 3.
Three algorithms training results comparison when $\alpha = 1$.

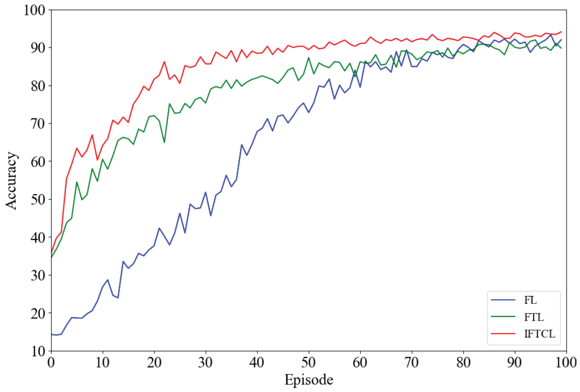

Figure 4.
Training performance when $\alpha = 0.3$.

Table 1.

The overall communication overhead comparison	
	Communication Overhead
FL	315.64MB
FTL	263.55MB
IFTCL	36.92MB

We can observe from the graph that regardless of the value of α, the initial accuracy is highest for IFTCL, followed by FTL, and then FL. This is because the pre-training step in transfer learning inherently boosts accuracy. However, the final accuracy may not always follow this pattern. When $\alpha = 1$, the results align with this trend, but when α is smaller, the significant differences in data across clients can cause issues. Specifically, in FTL, the pre-trained feature extractor may not sufficiently capture all the features, and the frozen feature layer could negatively impact subsequent classification. From the graph, it can be seen that when $\alpha = 0.3$, the accuracy of FTL slightly lags behind that of traditional federated learning. In contrast, IFTCL, having developed a more comprehensive feature extractor through training, consistently maintains higher accuracy than both federated learning and federated transfer learning.

4.3.2. *Convergence Speed*

In terms of convergence speed, when α is relatively large, such as $\alpha = 1$, it is obvious that the standard FL has the slowest convergence, only approaching convergence after 75 iterations. In contrast, FTL converges after 27 iterations, while IFTCL achieves convergence even faster, in just 18 iterations. On the other hand, when $\alpha = 0.3$, FL converges after about 82 iterations, FTL after around 50 iterations, and IFTCL after 25 iterations.

4.3.3. *Computation of Communication Overhead*

The communication overhead is defined as the volume of uplink and downlink data required for the communication process until the training reaches convergence. The results are shown in Table 1, We can see that traditional FL has the most communication overhead. FTL mitigates the burden greatly, because it needs fewer rounds than FL to achieve convergence, IFTCL results in a even lower communication overhead of 36.92 MB, which is much smaller than that of FL.

5. Conclusion

The Dirichlet distribution effectively models varying levels of non-IID conditions by adjusting its parameter, α. When α is small, some clients may lack certain labels from the dataset. In studying the impact of federated learning under different degrees of non-IID conditions, it has been observed that as distribution variation increases, the training accuracy and convergence speed of federated learning decreases. Federated transfer learning, known for reducing communication overhead and speed up convergence, can outperform traditional federated learning when the degree of non-IID is high (e.g., $\alpha = 1$). However, when α is small (e.g., $\alpha = 0.3$), the high heterogeneity causes FTL to underperform compared to FL due to an inadequately trained feature extractor in the pre-training stage.

To address this issue, the proposed integration of federated transfer and continual learning trains and transfers feature extractors multiple times, using replay mechanisms to avoid forgetting caused by highly non-IID data. This reduces aggregation challenges during the pre-training stage. It consistently outperforms both FL and FTL across varying α values, achieving higher training accuracy, faster convergence, and lower communication overhead. These results have been validated using the MSTAR dataset.

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Biographies

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The Impact of Mobility, Beam Sweeping and Smart Jammers on Security Vulnerabilities of 5G Cells

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Abstract: The vulnerability of 5G networks to jamming attacks has emerged as a significant concern. This paper contributes in two primary aspects. Firstly, it investigates the effect of a multi-jammer on 5G cell metrics, specifically throughput and goodput. The investigation is conducted within the context of a mobility model for user equipment (UE), with a focus on scenarios involving connected vehicles (CVs) engaged in a mission. Secondly, the vulnerability of synchronization signal block (SSB) components is examined concerning jamming power and beam sweeping. Notably, the study reveals that increasing jamming power beyond 40 dBm in our specific scenario configuration no longer decreases network throughput due to the re-transmission of packets through the hybrid automatic repeat request (HARQ) process. Furthermore, it is observed that under the same jamming power, the physical downlink shared channel (PDSCH) is more vulnerable than the primary synchronization signal (PSS) and secondary synchronization signal (SSS). However, a smart jammer can disrupt the cell search process by injecting less power and targeting PSS-SSS or physical broadcast channel (PBCH) data compared to a barrage jammer. On the other hand, beam sweeping proves effective in mitigating the impact of a smart jammer, reducing the error vector magnitude root mean square from 51.59% to 23.36% under the same jamming power.

Keywords: Cybersecurity, connected vehicles, jamming detection, 5G NR.

1. Introduction

The susceptibility of 5G NR to external attacks, particularly jamming, is a significant concern given its inherent nature of wireless radio frequency transmission [1,2]. Jammers have the potential to deplete substantial resources and disrupt critical applications, posing serious risks to areas like national defense, self-driving technology, public safety, and healthcare, as 5G and beyond infrastructures become increasingly essential for government agencies and commercial businesses [3]. The rise in electronic attacks on 5G networks, with jamming being a predominant method, has been noted [1].

Jamming attacks including proactive, reactive, barrage, function-specific, and protocol-specific [4, 5] manifest at various levels, including physical, network, and application layers, ranging from radio frequency interference that blocks wireless transmission to the distortion of packets in legitimate communications. These attacks range from blocking wireless transmission through radio frequency interference to distorting packets in legitimate communications. Notably, the synchronization signal (SS) block is a crucial component of the 5G waveform, and attacks on this block can lead to denial of service, increased overhead in terms of re-transmission, and heightened power consumption [6]. In comparison to barrage jammers, which apply jamming signals across the entire 5G resource grid, attackers can enhance the impact and efficiency of their attacks by specifically targeting the SS block.

To address these concerns, we investigate the characteristics of barrage jamming and protocol-specific jamming attacks, utilizing the spatio-temporal parametric stepping (STEPS) mobility model [7]. Our specific contributions are outlined as follows:

1. Study the impact of multi-jammer attack scenarios on 5G cell metrics, including throughput and goodput.

2. Examine the impact of mobile user equipment (UE), particularly utilizing the STEPS mobility model, along with the spatial placement of jammers to achieve maximum disruption of cell metrics..

3. Investigate jamming attacks on the 5G synchronization signal block (SSB), various reference signals such as primary synchronization signal (PSS), secondary synchronization signal (SSS), and demodulating reference signal (DM-RS) in the physical broadcast channel (PBCH). This exploration encompasses the extraction of the physical cell identity (PCI) and master information block (MIB).

The paper is organized as follows: Section 2 introduces related works, while Section 3 discusses the network, mobility, channel, and jammer models. Section 4 presents the performance analysis of the network under jamming, including the vulnerability of the SSB concerning jamming power. Finally, Section 5 provides the conclusions.

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2. Related Work

Several studies have explored jamming attacks in 5G networks, categorizing them based on their strategies to disrupt legitimate signals [8–13]. While individual jamming attacks have been extensively studied, there is a need to investigate the impact of multiple simultaneous jamming attacks on 5G networks [14]. Understanding this scenario is crucial for developing more robust detection and localization algorithms tailored to critical 5G scenarios. Simultaneous attacks can lead to severe consequences, with longer jamming durations and reduced resource usage, posing challenges for detection and localization techniques.

Tague et al. [15] investigated flow-jamming attacks in simple wireless networks, focusing on metrics such as jamming impact, efficiency, and resource variation using linear programming. In a flow-jamming attack, adversaries strategically place multiple jammers within a network to disrupt the flow of communication. This type of attack is categorized into two forms based on their attack control entity: a centralized flow-jamming attack, where a central control entity is involved, and a distributed flow-jamming attack, where jammers operate autonomously without centralized control. Cheng et al. [16] investigated the impact of multi-jammer attacks in wireless sensor networks (WSNs) and proposed two localization algorithms: M-cluster and X-ray. In their proposed topology, sensor nodes in the network are categorized as jammed, unaffected, or boundary nodes. The increasing number of jammers leads to broader jammed regions, amplifying the jamming effect and posing challenges for network defenders. While studies like [15] and [16] establish the foundation to understand the impacts of jamming in simpler network scenarios, and proposed preliminary models for jammer localization, recent developments focus on the complex dynamic 5G network configuration. For instance, Liu et al. [17] introduced a localization method to locate multiple jammers in wireless networks by computing jamming signal strength (JSS) using ambient noise floor (ANF). Also, Atya et al. [18] implement a jamming mitigation technique for wireless networks based on the 802.11a standard. This technique aims to preserve the network's throughput even in the presence of a jamming attack. The paper evaluates the performance of the mitigation technique in the presence of multiple jammers in a network with 50 nodes.

In addition to the number of jammers in a jamming attack scenario, the impact of the attack can be amplified by targeting vulnerable and critical control signals in the 5G resource grid. Some works that investigate the vulnerability of critical 5G NR channels include [8, 9, 19]. Wang et al. [19] propose a scheme to detect an intelligent jammer attacking the PBCH using principal component analysis. This attack disrupts the MIB recovery and cell connection process. The proposed method's advantage is its independence from any attacker information, as it employs adaptive thresholding computed from statistics. The vulnerability of PBCH and the physical downlink control channel (PDCCH) in 5G new radio (NR) to selective jamming attacks is discussed in [8]. This design flaw becomes particularly alarming when higher-frequency carriers are considered, requiring the jammer to be in close proximity to the mobile station for an effective attack. Lichtman et al. [9] emphasize the vulnerability of 5G NR channels, including PDCCH, PBCH, and physical downlink shared channel (PDSCH), to jamming attacks. They introduce PBCH jamming and PSS jamming as potential high-impact attacks, underscoring the need for specific considerations to enhance the security of 5G NR. This study investigates vulnerabilities arising from the connection between implementations of the 5G NR and long term evolution (LTE) protocols. These works emphasize the need for specialized countermeasures to protect against both broad and targeted jamming attacks.

Although localization techniques can identify the jammer's location, mobile jammers remain a significant threat, particularly in vehicular networks and unmanned aerial vehicular networks, where rapid transmission restoration is crucial [4, 20]. Consequently, localizing the jammer is imperative for implementing security measures against the jammer and restoring transmission in such mobile environments. Rani Dey et al. [21], propose a real-time mechanism for detecting and localizing denial of service (DoS) attacks in vehicular networks. Their approach utilizes data packet counters and average packet delivery ratio (PDR), augmented with a supervised machine learning-based solution to enhance robustness and consistency. By leveraging PDR and triangulation-based methods, they successfully localize both intentional and unintentional DoS attacks.

The interaction between mobility and jamming is explored in [22, 23], where the authors examine the influence of movement patterns on the effectiveness of jamming and the strategies for its mitigation. Balakrishnan et al. [22], analyze the impact of mobility on physical layer security using an analytical model for secrecy metrics, focusing specifically on mmWave users under the random waypoint mobility model. Meanwhile, Malebary et al. [23], investigate the effects of jamming attacks under mobility and behavior in IEEE802.11p networks. Their study evaluates jamming effectiveness under different mobility patterns and proposes a jammer detection scheme tailored for IEEE802.11p networks. Additionally, et al. [24], conduct an extensive investigation into interference mitigation techniques, assessing the impact of reaction delay and interference signal length on car-to-car communications. These studies provide valuable insights into mitigating interference and enhancing security in vehicular networks. We summarize and compare our contribution with existing studies in Table 1.

This study delves into the intricate aspects of 5G networks when subjected to jamming attacks. It incorporates a mobility model to illustrate the movement of UEs across the network and areas affected by jamming. Signal attenuation is considered in the jammer models to simulate the impact of jammer locations in the network. Additionally, the study accounts for multi-jammer scenarios, discussing the positions of jammers, their overlapping areas, and the effective number of jammers. This investigation contributes to a deeper understanding of the susceptibility of 5G networks to jamming attacks and provides insights that can inform the development of robust jamming detection and mitigation techniques.

3. System Model

3.1. 5G Network Model

We employ multiple UEs and multiple gNodeBs (gNBs) to simulate multi-user scenarios in 5G networks. To comprehensively assess the impacts of inter-cell interference and user mobility, our study establishes a dynamic network configuration that allows UEs

Table 1.

Gap analysis and contributions of this work with respect to the existing studies in the literature

Contributions	This work	[25]	[26]	[27]	[19]	[20]	[28]	[22]	[23]	[24]
Detection Algorithm	✓	✓	✓	✓	✓	✓	✓		✓	
Mobility	✓		✓	✓		✓		✓	✓	✓
Presence of Multi-Jammers	✓									
Attacks on Different Reference Signals	✓									

to move freely within their designated cell areas, introducing a layer of complexity reflective of real-world scenarios. Each gNB is configured to cover a distance of R_{cell} with a transmit power of P_{gNB}^{Tx}. Within the coverage area of each cell, n_{UE} UEs are randomly positioned to capture the heterogeneity and distribution of users in 5G networks. UEs are equipped with a single antenna for communication, enabling them to receive digitally modulated transmitted signals.

In addition, n_{RB} physical resource blocks are considered for data transmission and reception. Each resource block comprises 12 subcarriers with a spacing of Δf for frequency separation between neighboring subcarriers. Furthermore, n_{RB}^{ssb} resource blocks, as per the standard, are assigned to the SSB. Parameters such as downlink carrier frequency F_c^{DL}, downlink bandwidth BW_{DL}, uplink carrier frequency F_c^{UL}, and uplink bandwidth BW_{UL} define the central frequency and spectral space for both downlink and uplink transmissions. The downlink application data rate C_{app}^{DL} quantifies the total amount of data reliably transmitted from the gNB to the UEs within a given timeframe.

3.2. Mobility Model

To address the challenges associated with traditional mobility models like random waypoint and random walk in the context of user mobility, this study adopts the STEPS model [7]. The STEPS model offers a versatile framework for simulating diverse human mobility patterns, allowing manipulation through a concise set of parameters. Incorporating the principles of preferential attachment and location attraction, the STEPS model captures intrinsic spatio-temporal correlations in human mobility behaviors. Notably, the model leverages a power law distribution to govern both spatial attraction and temporal preference, enhancing adaptability. The probability density function (PDF) of this power law distribution is defined as

$$P[D = d] = \frac{\beta}{(1+d)^{\alpha}}, \tag{1}$$

where d represents the distance from the preferred zone, β is a normalizing constant ensuring the PDF integrates to 1 at all distances, and α is the power law exponent determining the intensity of zone attraction. The power law also dictates the duration a node stays in its preferred zone, expressed as

$$P[T = t] = \frac{\omega}{t^{\tau}}, \tag{2}$$

where τ and ω are parameters that model the staying time T of a node in a particular zone within the mobility model. τ denotes the temporal preference level of the node, reflecting the degree to which the node prefers to remain within a specific zone and ω is the normalization factor ensuring the PDF integrates to a total of 1. Adjusting the power law factor allows for the generation of diverse mobility patterns, ranging from completely random to highly localized.

3.3. Channel Model

This study explores multipath propagation in urban environments by employing the widely adopted clustered delay line (CDL) model. The CDL model amalgamates paths with distinct delay spread (DS) and angle-of-arrival characteristics, effectively capturing complex signal interactions within urban settings, encompassing both line-of-sight (LOS) and non-line-of-sight (NLOS) components. The received signal, traversing the CDL channel, accounts for signal intensity variation caused by clusters' impairments in the environment. Additionally, the channel model includes the fundamental free space path loss (FSPL), which factors in the decrease in signal intensity due to distance. Based on the FSPL model, the received signal power is expressed as follows,

$$P_r = P_t + G_t + G_r - 20\log\left[\frac{\lambda^2}{4\pi^2 d^2}\right], \tag{3}$$

where P_t represents the transmitted power, G_t and G_r denote transmitter and receiver antenna gains, and λ and d represent wavelength and transmitter-receiver distance, respectively. The incorporation of the CDL model and FSPL contributes to the understanding of interference and channel attenuation dynamics.

3.4. Jammer Model

A barrage jammer emits Gaussian noise across the entire 5G downlink bandwidth. The FSPL model is employed to consider signal attenuation and distance-related propagation effects. To simulate a real-world jamming attack more accurately, the jamming signal undergoes transmission through the CDL channel model, accounting for the time-varying nature of wireless communication and incorporating precise signal distortions. Similar to the received signal power in (3), the power received by the user equipment (UE) from the jammer (P_j^{rx}) is expressed as

$$P_j^{rx} = P_j + G_j + G_r - 20\log\left[\frac{\lambda^2}{4\pi^2 {d_j}^2}\right], \tag{4}$$

where P_j denotes the jammer's transmit power, and G_j and d_j represent the gain of the jammer antenna and the distance of a node to the jammer, respectively.

Table 2.

Simulation settings			
Parameter	Value	Parameter	Value
n_{UE}	20	R_{cell}	500 m
P^{Tx}_{gNB}	32 dBm	n^{ssb}_{RB}	20
n_{RB}	51	n_{RE}[1]	12 n_{RB}
Δf	30 kHz	F^{DL}_{c}	2.635 GHz
BW_{DL}	20 MHz	C^{DL}_{app}	16 kbps
Duplex Mode	FDD	F^{UL}_{c}	2.515 GHz
BW_{UL}	20 MHz	RLC SDU Size	9 kb
Channel Model	CDL-A	DS	30 ns

[1] n_{RE} represents the number of resource elements.

Moreover, a smart jammer in this context is defined as a jammer that strategically transmits its power on a specific portion of the resource grid (RG), thereby making its actions more energy-efficient.

4. Performance Analysis of Mobility, Jammer Position, and Targeted Reference Signals

In this study, the MATLAB 5G Toolbox is employed to assess the impact of a jamming attack within the dynamic context of a multi-user 5G network. The evaluation takes into account factors such as UE mobility, jammer position, and targeted reference signals. The simulation inputs are determined based on parameters outlined in 3rd generation partnership project (3GPP) specifications [29–32], while the transmit power[1] of the gNB is adapted from the findings in [33]. The simulation is operated on the 5G NR n7 band with a center frequency of 2.635 GHz based on the 3GPP specifications. For clarity, Table 2 provides a comprehensive list of parameters and assumptions utilized in the simulation scenario, as discussed in Section 3.

4.1. Cell Network Metrics Under Jamming

The movement of UE induces changes in path loss values and received signal strength (RSS), directly influencing the received signal quality. Signal strength variations, such as a decrease in signal strength, result in a diminished signal-to-noise ratio (SNR), thereby elevating the likelihood of errors and packet loss. In scenarios involving a jamming attack, where intentional interference disrupts the communication link, these fluctuations in signal intensity become critical.

As the signal strength of a UE diminishes due to path loss, its susceptibility to the effects of the jamming attack increases. Interference signals can further deteriorate the legitimate signal, making it challenging for the UE to accurately receive and decode data. The impact of the jamming attack can vary over time and space as the UE moves and encounters fluctuations in signal intensity. This dynamic nature underscores the importance of considering both spatial and temporal dimensions when assessing the effectiveness and consequences of jamming attacks on the communication system.

To comprehensively assess the impact of a jamming attack within a realistic multi-cell/multi-user UE 5G NR scenario, an end-to-end link-level simulation has been established. This simulation takes into account UE mobility and integrates all functions associated with the jamming scenario, spanning both the physical layer (L1) and the medium access control layer (MAC - L2). Key components, including the MAC scheduler, modulation and coding scheme (MCS), hybrid automatic repeat request (HARQ), and channel state information (CSI) configuration, are considered.

The evaluation of network metrics, cell throughput, and goodput provides insights into the performance of the communication system under the influence of a jamming attack. This holistic simulation framework enables a thorough examination of the interplay between various system functions and their collective impact on network performance in the presence of jamming-induced challenges.

The impact of network metrics in relation to the number of jammers is visually represented in Figure 1. To specifically investigate the influence of varying numbers of jammers, the distance is fixed at 224 meters. This approach ensures a focused examination of the effects of changing jammer quantities while minimizing distance-related factors' impact on the results. The goal is to avoid variations in jamming signal strength due to distance fluctuations.

With a single jammer present, both throughput and goodput experience a significant decrease, with throughput dropping by 46.78%. Introducing a second jammer further exacerbates the degradation of cell throughput, resulting in an additional 26.12% decline. However, the introduction of a third jammer leads to a marginal deterioration in cell metrics, approximately 8.16%, indicating an overlapping affected area. In a realistic scenario involving multiple jammers within a 5G cell, the throughput degrades even with the presence of a single jammer, as verified in Figure 1, until reaching a certain threshold of jammer density. This saturation

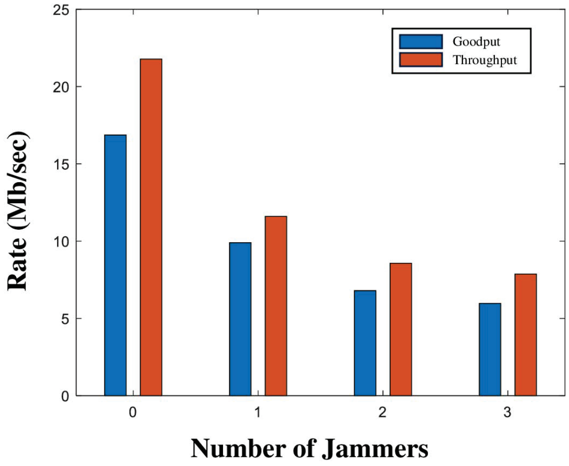

Figure 1.

Cell throughput and goodput vs. number of jammers with jammer distance of 224 m at jamming power of 20 dBm.

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[1] This power is correspondence to effective isotropic radiated power (EIRP).

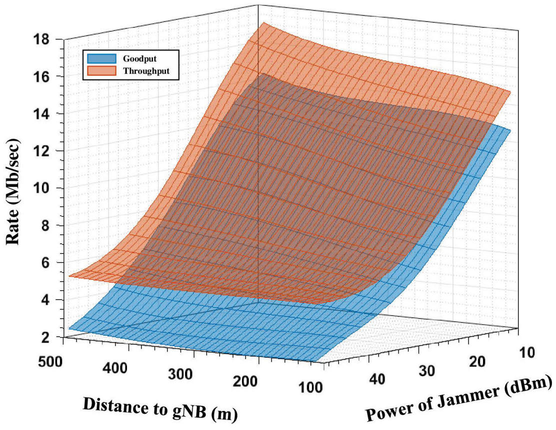

Figure 2.

Cell throughput and goodput versus transmit power of the jammer and jammer-gNB distance.

of jamming effects occurs because the network's inherent capacity and resilience mechanisms are severely compromised by the initial set of jammers. Operating near its interference threshold, the network has limited tolerance for additional jammers, diminishing the contribution room for further disruptions.

The relationship between 5G cell throughput and goodput concerning jamming power and jamming distance from the gNB is depicted in Figure 2. Clearly, higher jamming power corresponds to lower throughput and goodput. As the jamming power increases from 10 dBm to 40 dBm, both throughput and goodput experience a decrease. However, when increasing the jamming power from 40 dBm to 50 dBm, the throughput remains relatively stable, while the goodput continues to decrease. This observation arises because throughput is measured based on the total number of packets, including re-transmissions, while goodput is calculated solely based on new arrivals.

The conclusion drawn is that increasing jamming power affects more UEs, leading to a higher number of retransmitted packets through the HARQ process. Consequently, the total throughput remains relatively constant, but the goodput decreases due to the reduction in the number of new packets in the network. This distinction emphasizes the impact of jamming power on both retransmissions and new packet arrivals, influencing the overall performance metrics differently.

4.2. SSB Vulnerability To Jamming

In this section, we consider two types of jamming, namely, barrage and smart. Assuming P_{RE}^{Rx} as the received signal power per each resource element (RE) at the UE location, the signal-to-jamming-noise ratio (SJNR) in the presence of a jammer is expressed as

$$SJNR = \frac{P_{RE}^{Rx}}{P_j^{RE} + P_N^{RE}}, \tag{5}$$

where P_j^{RE} and P_N^{RE} are the jamming and noise powers per RE at the UE side, respectively. To disrupt the link, a barrage jammer needs to inject a minimum power of $P_{j,min}^{RE}$ at the UE side per each RE to bring the SJNR below the threshold of γ_{th}. In such a case, the total power of the barrage jammer at the UE side should be equal to $P_j^b = 12 \times n_{RB} \times P_{j,min}^{RE}$.

On the other hand, disrupting communication can be more straightforward for a smart jammer targeting the SSB, which provides UE with essential information for cell selection [34]. To prevent the initialization of any connection, a smart jammer can inject a portion of the power, denoted as

$$P_{j,min}^{RE} = \frac{P_{RE}^{Rx}}{\gamma_{th}} - P_N^{RE}, \tag{6}$$

on SSB bursts, thereby making the jamming process more energy-efficient[2]. In this case, the jammer searches for PSS and SSS to locate the position of SSBs and transmits the jamming signal only over the bandwidth of $n_{RB}^{ssb} \times 12 \times \Delta f$.

Furthermore, a smart jammer does not need to transmit power throughout the entire frame since the SSB bursts in 5G are periodically transmitted for a brief time interval in every two frames. Therefore, the total power of the smart jammer at the UE side is given by $P_j^s = 12 \times n_{RB}^{ssb} \times P_{j,min}^{RE}$. It is noteworthy that if one of the SSB signals (PSS or SSS) is not successfully extracted, the UE cannot establish any connection with the gNB [35].

A smart jammer can act more intelligently by specifically targeting the PBCH data or PBCH DM-RS signal. By extracting the PCI through decoding PSS and SSS, the jammer becomes aware of the location of DM-RS and PBCH. Hence, instead of targeting PSS and SSS, the jammer can transmit power at PBCH, focusing only on DM-RS and PBCH data, which is easier to disrupt than PSS and SSS since PCI extraction relies on auto-correlation, making it more robust to noise, interference, and jamming than decoding PBCH. From another perspective, under the same transmit power, a wider area is affected by the jammer.

To validate the aforementioned discussions and examine the vulnerability of PDSCH and SSB under a jamming attack, another simulation has been configured involving both barrage and smart jammers. Assuming the gNB is located at the origin, the jammer and UE are positioned on the x-y plane at (100, 100) and (60, 60), respectively. Figure 3 illustrates the equalized constellation of UE's downlink data modulated with 16-QAM, with a jamming transmit power of $P_j = 30$ dBm covering the entire RG. The root mean square (RMS) of error vector magnitude (EVM) is reported to be as high as 68.17%, as observed in the Figure 3.

Figures 4 and 5 depict the PSS and SSS correlation under the jamming power $P_j = 30\, dBm$. As it is shown, the peaks related to SSS cell ID ($N_{ID}^{(1)}$) and PSS cell ID ($N_{ID}^{(2)}$) are clear and the UE can successfully extract the PCI which has been set to 350. In the sequel, a smart jammer transmits its power only to the RBs corresponding to SSB.

Figures 6 and 7 illustrate the correlation of PSS and SSS under a smart jammer attack with transmit power equals $P_j = 27.5$ dBm. The peak related to PSS is not extracted anymore in this power which is 2.5 dBm lower than the barrage jammer case. Therefore, the smart jammer targeting SSB can disrupt the network with lower power, making the jamming process more energy-efficient, as discussed earlier. Note that since $n_{RB}^{ssb}/n_{RB} = 0.39$ (see Table 2),

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[2] Note that a smart jammer needs to be synchronized with the gNB through a limited over-the-air processing.

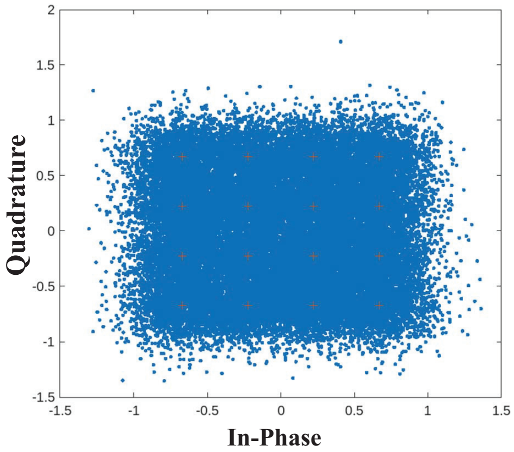

Figure 3.
Equalized PDSCH constellation – $P_j = 30\, dBm$.

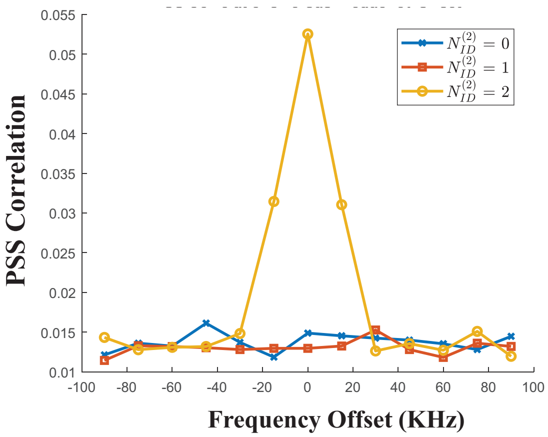

Figure 4.
PSS correlation with whole RG under jamming attack – $P_j^t = 30\, dBm$.

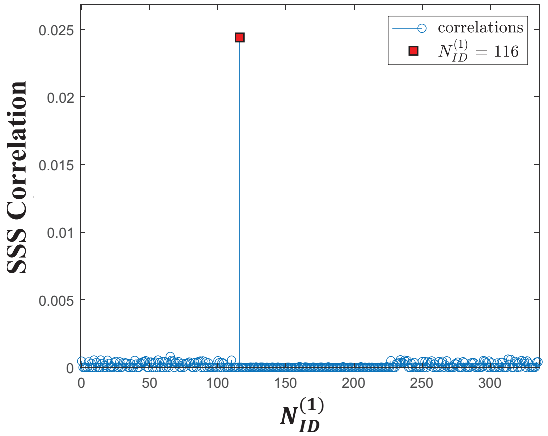

Figure 5.
PSS correlation with whole RG under jamming attack – $P_j^t = 30\, dBm$.

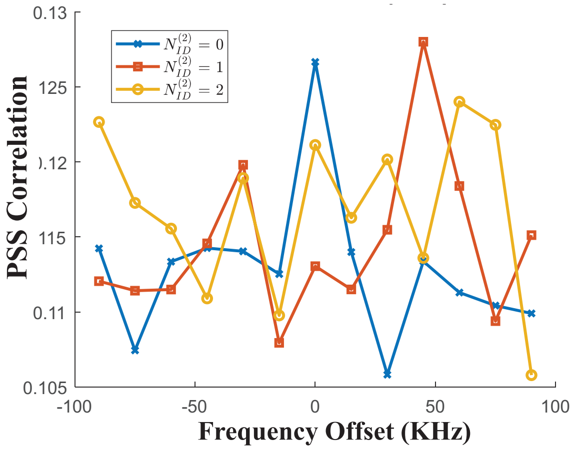

Figure 6.
PSS correlation, only SSB is under jamming attack- $P_j^t = 27.5\, dBm$.

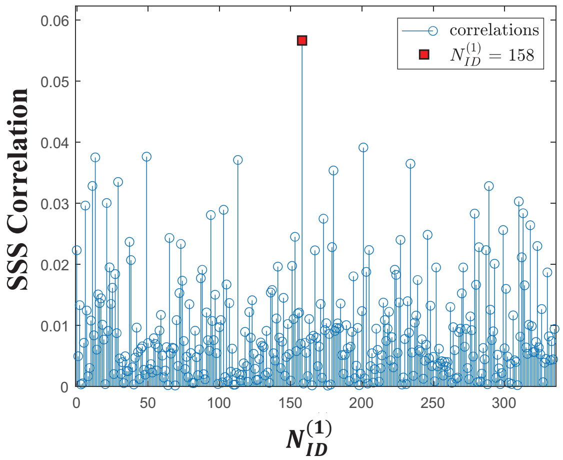

Figure 7.
SSS correlation, only SSB is under jamming attack- $P_j^t = 27.5\, dBm$.

the reduction in jamming power is expected to be $10\log(0.39) = -3.97$ dB, proportional to the bandwidth. However, PSS and SSS symbols are more robust to jamming compared to the PDSCH symbols[3].

The constellation of PBCH data is plotted in Figures 8 under jamming power of $P_j = 25$ dBm in which the PCI of 350 has been extracted. However, the RMS EVM for PBCH data is reported as 51.59% which is so high that the PBCH data cannot be decoded under such an attack. Since extracting PCI is based on correlation, it is more robust to impairments than PBCH data. Hence, with a jamming power of 25 dBm, the PCI is successfully decoded, but not the PBCH data. Thus, a smart jammer can reduce its power by targeting only the PBCH data.

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[3] The EVM reported for PSS symbols is 57%, which is even less than that for PDSCH.

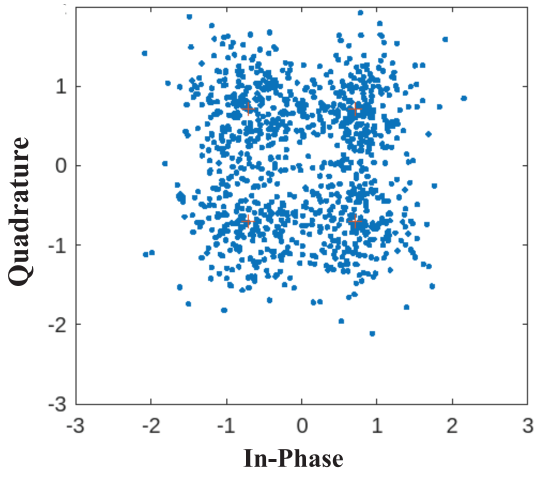

Figure 8.
Equalized PBCH constellation- $P_j^t = 25\, dBm$.

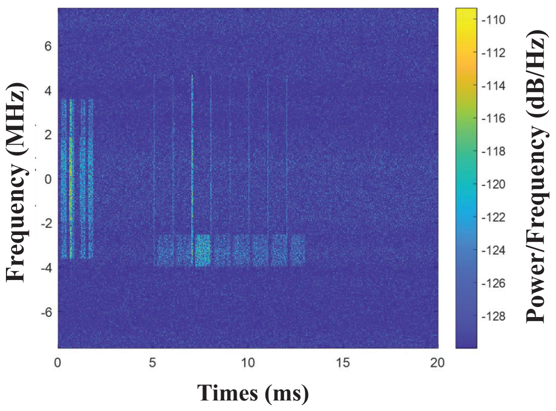

Figure 9.
Spectrogram of RG, SSB index #2 boosted due to beam sweeping- $P_j = 25\, dBm$.

The impact of beam sweeping on the smart jamming attack is considered in the following analysis. Eight SSB bursts are configured during two frames (20 ms), and the received spectrogram is plotted in Figure 9. As can be seen, the third SSB has higher power (brighter in color) which is the effect of beam sweeping.

The estimated received SJNR for DM-RS in PBCH is plotted in Figure 10 versus the SSB index which shows the third SSB burst is received with higher power. The equalized PBCH data constellation is depicted in Figure 11 under $P_j = 25$ dBm which shows beam sweeping can make the SSB burst more robust to the SSB jamming attack with the PBCH RMS EVM is reported as 23.36%.

This analysis demonstrated that the information contained in SSB (including PSS correlation, SSS correlation, and PBCH data) can be effectively utilized for detecting both smart and barrage jammers. Given the varying sensitivity of these features to jamming power, fusing them into a comprehensive detection model is anticipated to significantly enhance the accuracy of jamming detection in the radio frequency (RF) domain.

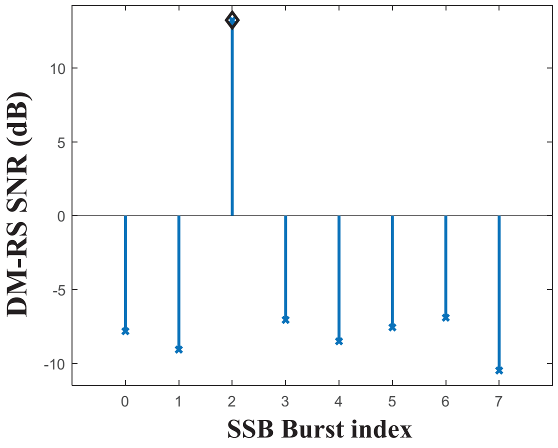

Figure 10.
DM-RS SJNR vs SSB bursts indices – $P_j^t = 25\, dBm$.

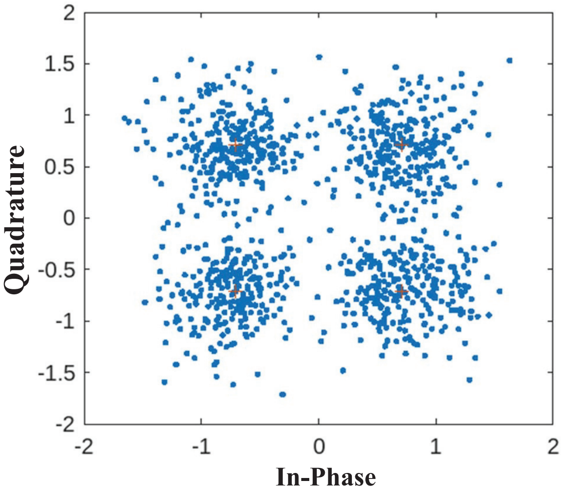

Figure 11.
Equalized PBCH constellation – $P_j^t = 25\, dBm$.

5. Conclusion

This work explores the susceptibility of 5G cells to both barrage and smart jamming attacks, particularly in scenarios where user equipments (UEs), such as connected vehicles deployed for a mission, follow the spatio-temporal parametric stepping (STEPS) mobility model. The assessment of network metrics, considering jamming power, location, and varying numbers of jammers, has been thoroughly examined. Furthermore, the impact of barrage and smart jamming attacks on different aspects of the synchronization signal block (SSB) has been investigated. The numerical results demonstrate that a smart jammer, particularly one targeting SSB, proves to be more efficient than a barrage jammer or a smart jammer aimed at primary synchronization signal (PSS) and secondary synchronization signal (SSS). Finally, the study highlights the efficiency of beam sweeping in enhancing the robustness of the cell selection process against such jamming threats.

Acknowledgement

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Bayesian Learning based Rate Adaptation in IEEE 802.11ax WLANs with a Target PER

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Abstract: The optimal modulation and coding scheme (MCS) selection in wireless transmission depends on the dynamically evolving channel state. Hence, *Rate adaptation* in a wireless channel relies on periodically reported channel quality indicator (CQI) values to select the optimal MCS. The latest 802.11ax, with a HE-sounding protocol, supports an explicit feedback mechanism where the client sends back a transformed estimate of the channel state information (CSI) in the HE CQI Report field. When generated more frequently, these reports can be expensive as they introduce unnecessary computational and protocol overhead. Also, the CSI feedback information is quantized, delayed, and noisy. To reduce the frequent CSI feedback (receiver to the transmitter) overhead, in our work, we obtain CSI statistically at the transmitter through Bayesian Learning (BL). Further, we propose a Bayesian Learning based Rate Adaptation (BLbRA) scheme at the transmitter. BLbRA throughput performance is consistent even with *reduced feedback overhead*. BLbRA can be implemented without any change in the standard frame format, and therefore, it is suitable for practical deployment.

Keywords: Rate adaptation, 802.11ax, Bayesian learning, channel gain, RBIR, Gamma distribution.

1. Introduction

One of the critical features in Radio Resource Management (RRM) for 802.11ax networks is deciding the Modulation and Coding Scheme (MCS) for packet transmissions. This is known as “Rate adaptation” since the choice of MCS impacts the rate of data transfer (throughput) achieved. Higher MCS would be suitable for improved throughput, but there is also a higher chance of packet errors. We study this trade-off. Ideally, one would like an algorithm that achieves maximum throughput while complying with application-imposed target Packet Error Rate (PER) values.

The Rate adaptation algorithms (RAA) at the transmitter depend on the feedback from the receiver to assess the impact of MCS choices. Many widely deployed RAA-s use only *implicit* feedback, observing MAC-layer acknowledgments [1–3]. Positive acks cause the transmitter to choose a higher MCS, while the absence of acks results in a lower MCS. This inherently reactive approach leads to slow adaptation to changing channel conditions, leading to a burst of packet errors and unsatisfactory throughput.

A natural approach is to consider not only MAC-layer feedback but also PHY-layer feedback – the latter provides direct information about channel conditions. While this idea has been pursued in the literature, proposed schemes require changes in packet formats to convey the PHY layer feedback. Because of this, available solutions cannot be implemented at scale [4,5]. We seek a *standards-compliant* way of including PHY layer feedback so that the transmitter can access both MAC and PHY information to choose the MCS code for the next packet.

Explicit feedback rate adaptation techniques rely on periodically reported channel quality indicator (CQI) values to dynamically adjust the MCS for transmitting physical-layer transport blocks [4–6]. The IEEE WLAN 802.11ax standard has a HE-sounding protocol to determine channel quality. The HE CQI report field carries an array of received per-RU average SNRs for each space-time stream. Each per-RU average SNR in dB is the arithmetic mean of the SNR computed over a 26-tone RU [7].

The signal-to-noise ratio (SNR) at the receiver is a good measure of the channel conditions and provides very useful PHY layer feedback [6]. We propose an efficient and fast offline link model-based Bayesian update scheme to refine the channel SNR probability distribution model. We explore how Bayesian learning can gradually gauge the prevailing channel conditions and thereby help judicious MCS selection. To the best of our knowledge, we are the first to propose the Bayesian Learning based channel feedback framework to update the SNR probability distribution.

A mixture gamma (MG) distribution is a more accurate model for composite fading, and it is a versatile approximation for any type of fading SNR. The SNR in a Nakagami-1 fading channel is modeled with a mixture having a single gamma density [8, 9]. We verified this fact by repeated simulations for different channel input parameters using the WLAN TGax channel model of MathWorks’s WLAN Toolbox. We found the empirical distribution of the channel fading coefficient to be Nakagami-1 or Rayleigh distributed and empirically observed packet SNR at the receiver to match the gamma distribution closely.

1.1. Contributions

We make the following primary contributions in this paper: (i) the design of a Bayesian Learning based Rate Adaptation (BLbRA) scheme that models the probability density function (pdf) of the channel SNR as a gamma distribution, (ii) the choice of the optimal MCS based on the SNR point estimates, obtained by

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sampling the posterior SNR pdf. The optimal MCS is chosen to maximize the throughput while keeping the average PER below a target value, (iii) Implementation and evaluation of the BLbRA scheme using standards-compliant MATLAB WLAN Toolbox, generating 802.11ax PHY layer waveforms, passing through the Indoor TGax channel model [7, 16] with LDPC channel coding and OFDMA receiver processing.

Other novel features included in packet processing much closer to real-time processing are as follows:

- In receiver processing, we do realistic Least squares (LS) channel estimation and perform time and frequency synchronization over the TGax frequency selective channel instead of the oversimplified ideal channel and synchronization assumptions. Channel estimation and synchronization are the unique features in our implementation compared to previous works and open TGax technical documents [11,20], wherein they assume perfect CSI and synchronization.
- The L-LTF and HE-LTF training fields of the packet preamble are used to estimate the channel gains, and these estimated channel gains are used to equalize the channel effects and decode the packet.
- PHY impairments such as carrier frequency offset (CFO) and symbol timing offset are considered to simulate more realistic situations. After packet detection, coarse CFO correction, timing synchronization, and fine CFO correction are done in the front-end processing of the receiver. This is yet another vital feature in the implementation of our algorithm. None of the earlier works considered these PHY impairments while evaluating their rate adaptation algorithms (RAA).

1.2. Organization

The rest of the paper is organized as follows. Section 2 presents the theoretical analysis of average SNR's probability distribution across a resource unit (RU) and the simulation settings. Section 3 lists the key implementation challenges and describes our proposed BLbRA algorithm. We evaluate BLbRA and compare its throughput with our earlier proposed Hybrid Channel-Dependent Rate Adaptation (HCDRA) algorithm [15] in Section 4. Finally, we conclude the paper in Section 5 and discuss future research directions.

2. System Model and Methodology

We consider packetized data transmission over an IEEE 802.11ax wireless link. Maximizing link throughput in a time-varying propagation channel due to multipath fading or movement of the surrounding objects requires a dynamic variation of MCS. At every transmission instant $t = 1, 2\ldots,$ the wireless transmitter selects a MCS $m(t)\epsilon\{1, 2\ldots M\}$. With MCS index $m(t)$, bits are packed into a transport block, then encoded with the forward error-correcting code and bit-interleaved to protect against stochastic noise and channel fading effects [10]. The encoded bits are mapped onto complex-valued modulation symbols prescribed by the MCS. The sequence of modulated symbols is either zero-padded or truncated to fill the time-frequency resources allocated for transmission. The channel estimation at the receiver is done using the known High-Efficiency Long Training Fields (HE-LTF) of the packet preamble to equalize the channel effects. The IEEE 802.11 standard does not provide any specification for a rate-adaptation scheme. However, the rate adaptation strategy must allow transmissions at rates that can be successfully decoded at the receiver [7].

2.1. SNR Per Packet

For a SISO system, the received SNR for the i^{th} sub-carrier is given [11] by

$$SNR_i = \frac{P_{tx}}{N\sigma_i^2}|H_i|^2 = \frac{P_{tx}}{P_n}|H_i|^2, \tag{1}$$

where $\sigma_i^2 = kB_{sc}T$ with $B_{sc} = 78.125$ KHz, sub-channel bandwidth in 802.11ax, k is the Boltzmann's constant, and T is the temperature in Kelvin. N is the total number sub-carriers in a bandwidth B, $|H_i|^2$ is the channel gain at i^{th} sub-carrier, P_n is the total noise power, and P_{tx} is the total transmit power across bandwidth 'B'. Considering the Rayleigh fading channel, the channel gain for each sub-carrier $|H_i|^2$ is exponentially distributed [12], as depicted in Figure 1a. Here, the subcarrier index ($i = 75$) is picked randomly. A histogram plot of 20,000 samples corresponding to 20,000 channel realizations follows the exponential distribution. We have $|H_i|^2 \sim \exp(\lambda_1)$. From Equation (1), with the total transmit power $P_{tx} = 1W$ across 20 MHz operating bandwidth, $SNR_i \sim \exp(P_n\lambda_1)$.

IEEE 802.11ax supports OFDMA, where multiple subcarriers are grouped to form a resource unit (RU). Each RU is assigned to a user for data packet transmission. Since packets are the entities we transmit and receive, SNR per packet is a quantity of interest. The WLAN channel varies slowly; hence, the SNR is assumed to be static over the entire packet duration. The SNR for each packet is computed using the channel and noise estimates at the receiver. The channel estimates are obtained using the HE-LTF samples of the packet preamble transmitted over N_d sub-carriers of the allotted RU. The average noise power is estimated using the pilot sub-carriers of the HE-data field. The SNR at the receiver over an RU of N_d sub-carriers with $P_{tx} = 1W$,

$$SNR_{RU} = \left(\frac{1}{N_d}\right)\sum_{i=1}^{N_d} SNR_i = \left(\frac{1}{N_d}\right)\sum_{i=1}^{N_d}\frac{|H_i|^2}{P_n}. \tag{2}$$

If sub-carrier SNRs, SNR_i, are ***iid***, since SNR_i are exponentially distributed, the average SNR over N_d sub-carriers of an RU (SNR per packet) is distributed according to a Gamma distribution [12, 13], $SNR_{RU} \sim \text{Gamma}\,(N_d, N_dP_n\lambda_1)$. N_d is the number of sub-carriers in a RU, P_n is the noise power, and λ_1 is the parameter of the exponentially distributed channel gains at the i^{th} sub-carrier.

2.2. Simulation Settings

We simulate a scenario of an Access Point (AP) transmitting to a user in a 20 MHz Bandwidth channel (OFDMA) at a carrier frequency of 5.25GHz using WLAN High Efficiency (HE) multi-user (MU) format packets as specified in IEEE 802.11ax [7].

MATLAB WLAN Toolbox of MathWorks is used to model 802.11ax multi-user OFDMA downlink transmission over a TGax

Table 1.

Simulation parameters	
General Parameters	
Distance (d)	12 m (NLOS)
Noise power (Pn)	−90 dBm
Transmit power per packet (P_{tx})	1W
Packet size (P_b)	500 bytes
Number of packets processed	40,000
Signal flow	Downlink
Target PER	0.1
Specific for IEEE 802.11ax	
Mode of transmission	OFDMA
RU allocation index	192
Number of RUs	1
Number of users	1
RU size (N_d)	242
Channel parameters	
Channel Bandwidth	20 MHz
Carrier frequency	5.25 GHz
Delay profile	Channel model-D
Environmental speed	0.089 km/hr
Channel coding	LDPC
No. of penetration walls	2
Wall penetration loss	2.5 dB
Pathloss	74.62dB

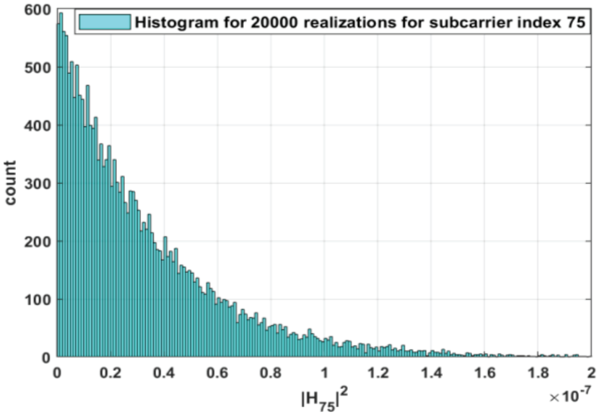

Figure 1a.

Histogram of a channel gain at $i = 75$, $|H_{75}|^2$.

indoor fading channel. Table 1 summarizes the simulation parameters to evaluate our proposed rate adaptation algorithm, BLbRA, and HCDRA algorithm.

The RU allocation index property defines the number of RUs, the size of each RU, and the number of users assigned to each RU. The AP transmits a burst of 40,000 packets, and the client demodulates and decodes the packets. An evolving TGax indoor Rayleigh fading channel with AWGN is modeled between the AP and client device.

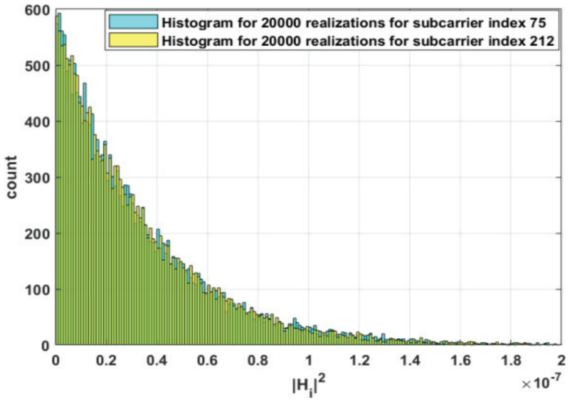

Figure 1b.

Histogram overlap of $|H_{75}|^2$ and $|H_{212}|^2$.

3. Key Implementation Challenges and Bayesian Learning

We mention some *challenges faced* during the experimentation, and the directions followed to overcome them.

- The initial plan was to use N_d, the number of subcarriers in an RU, as the shape parameter (α) of the SNR probability distribution and learn the rate parameter 'R' from the observed SNR measurements at the receiver. However, experiments showed that the learned distribution did not match the empirically observed SNR distribution. This resulted in overestimating the packet SNR, as shown in Figure 2.
- This observation made us suspect that the ***iid*** property among subcarriers could be assumed. We obtained the histogram plots of channel gains $|H_i|^2$ at sub-carrier indices $i = 75, j = 212$, as shown in Figure 1b. We further chose closely spaced sub-carrier indices to $i = 75, j = 72$ to obtain their histogram plots and then concluded that the sub-carriers are *identically* distributed.

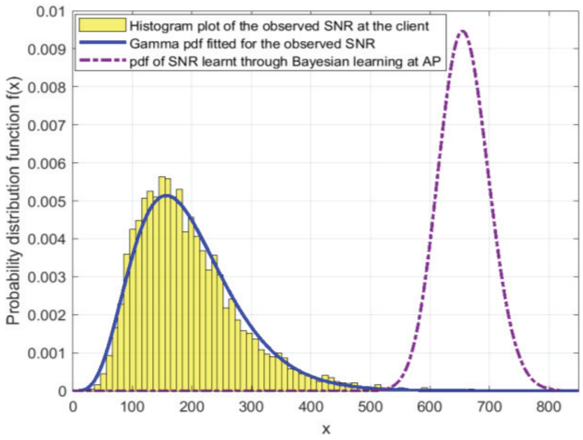

Figure 2.

Histogram plot and Gamma pdf fit of the observed SNR at the client, SNR pdf learned through Bayesian learning by fixing the shape parameter, $\alpha = 242$.

Table 2.

Experimental data to check for the independence of channel gains at sub-carrier indices 75 and 212

(A1, B1)	(A2, B2)	W	N1	N2	N3	P (X AND Y)	P(X)	P(Y)	P(X) P(Y)
[0.2e-7, 0.21e-7]	[0.6e-7, 0.61e-7]	0.01e-7	3	339	107	**1.50e-04**	0.01695	0.00535	**0.9069e-04**
[0.2e-7, 0.22e-7]	[0.6e-7, 0.62e-7]	0.02e-7	7	656	202	**3.50e-04**	0.03280	0.01010	**3.3128e-04**
[0.2e-7, 0.23e-7]	[0.6e-7, 0.63e-7]	0.03e-7	11	967	304	**5.50e-04**	0.04835	0.01520	**7.3492e-04**
[0.2e-7, 0.24e-7]	[0.6e-7, 0.64e-7]	0.04e-7	19	1273	386	**9.50e-04**	0.06365	0.01930	**12.2845e-04**

- To check the independence of channel gains over sub-carriers, we define two events for sub-carrier indices $i \neq j$. Event $X = \{|H_i|^2$ falling in the interval (A1, B1)$\}$ and Event $Y = \{|H_j|^2$ falling in the interval (A2, B2)$\}$. Let N1 = Number of occurrences of the joint event X AND Y, N2 = Number of occurrences of event X, and N3 = Number of occurrences of event Y, W = width of an interval. We check for the probability condition for the two events X and Y to be independent, P (X and Y) = P(X) P(Y). Table 2 summarizes the observed values.
- The experimentation suggested that subcarrier SNRs, SNR_i are not independent. This is because the channel gains at any two sub-carriers are *not independent*. The channel gains of sub-carriers are significantly correlated due to the channel coherence bandwidth. Therefore, multipath propagation has an impact on the channel gain or SNR statistics.

3.1. Probabilistic SNR Model

However, we found the empirical distribution of observed packet SNR at the receiver to match the Gamma distribution closely, as shown in Figure 2. Then, we wondered if the Gamma distribution could be "tuned" to match observed histograms by adjusting its parameters. Ideally, both parameters should be learned. However, the literature indicates that learning both parameters is hard. The conjugate prior for the Gamma rate parameter is known to be Gamma distributed, but no standard distribution behaves as the prior for the shape parameter [14]. So, we decided to keep the shape parameter, α, fixed and learn the rate parameter (R) through Bayesian learning.

The next question that arose was, what value to be chosen for α. We use the range of desirable SNR from past channel measurements as a piece of prior information to choose the shape parameter's value. We had two criteria: (i) we wanted the SNR pdf to cover the full range of possible SNR values from 0 to 28dB, modeling all possible channel conditions. (ii) we wanted the shape of the pdf not to become symmetric around its mean value. We did some experiments to study the effect of the shape parameter, α, on the gamma pdf by fixing the scale parameter β = 10, 20, 30, 40 and 50. The pdf spread is smaller than the desired range for lower values of α, up to 5. For larger values of α beyond 7, the mean of the distribution shifts towards the right, and the support of the distribution does not include lower values of observed SNR. Also, higher values of α, beyond 15, resulted in a more concentrated distribution around its mean. So, we prefer to choose $\alpha = 6$ and estimate R (=1/β) through Bayesian learning. This method yielded an excellent match with the experimentally observed receiver SNR histogram and the gamma distribution learned by Bayesian learning.

Bayesian Learning (BL) of the Rate Parameter of the Gamma Distribution

To find the posterior probability of the Gamma distributed rate parameter R, we use the Bayes rule,

$$\mathrm{p}(\mathrm{R}|\gamma) = \frac{\mathrm{p}(\gamma|\mathrm{R})\mathrm{p}(\mathrm{R})}{\mathrm{p}(\gamma)}, \tag{3}$$

where $\gamma = \{\gamma_1, \ldots, \gamma_n\}$ is a positive vector of observed SNR per packet. Since the denominator only depends on observed data, the posterior is proportional to the likelihood multiplied by the prior

$$\mathrm{p}(\mathrm{R}|\gamma) \propto \mathrm{p}(\gamma|\mathrm{R})\mathrm{p}(\mathrm{R}). \tag{4}$$

Obtaining analytical solutions for the rate parameter R requires using conjugate priors. A prior is called conjugate with a likelihood function if the prior functional form remains unchanged after multiplication by the likelihood distribution [14]. A well-known conjugate prior for the rate parameter R of the Gamma distribution is a Gamma distribution parameterized using shape d and rate e,

$$\mathrm{p}(\mathrm{R}) = \mathrm{gamma}(\mathrm{R}|\mathrm{d}, \mathrm{e}). \tag{5}$$

Given the observation vector γ, and multiplying its Gamma likelihood by the prior on the rate (5), we get its posterior [14], $\mathrm{q}(\mathrm{R}) = \mathrm{gamma}(\mathrm{R}|\widehat{\mathrm{d}}, \widehat{\mathrm{e}})$ with

$$\widehat{\mathrm{d}} = \mathrm{d} + \mathrm{n} \propto \quad \text{and} \quad \hat{e} = e + \sum_{k=1}^{n} \gamma_k, \tag{6}$$

where $\propto$ is the shape parameter of the Gamma likelihood distribution of the SNR per packet ($\alpha = 6$), γ_k is the measured SNR of the k^{th} packet, and n is the number of SNR observations. We call 'n' as the *rate parameter update window*.

3.2. SNR Point Estimates and Posterior SNR Distribution

Let the SNR probability density function (pdf) at the transmission time $t = 0$ be denoted by $P_{\gamma(t=0)}(\theta) = gamma(6, R_0)$. The initial rate parameter, R_0, is chosen based on past measurements from the expectation of the likelihood distribution of average SNR, γ. Initially, we generate an SNR sample using SNR pdf $P_{\gamma(t=0)}(\theta)$. Though several sampling techniques exist [10], we describe one such technique called *inverse CDF sampling*. It is computationally efficient and easily implementable.

- First, the cumulative distribution function (CDF) is calculated using (7).

$$F_{\gamma(t)}(\theta) = P(\gamma(t) \leq \theta) = \int_{x \leq \theta} P_{\gamma(t)}(x)dx. \tag{7}$$

- Generate a uniformly distributed random variable, $u[t] = \mathcal{U}(0,1)$.
- Finally, map $u[t]$ to an SNR sample through the inverse SNR CDF, $\widetilde{\theta}[t] = F^{-1}_{\gamma(t)}(u[t])$, where $\widetilde{\theta}[t]$ is the SNR sample or the SNR point estimate at the t^{th} transmission instant, and $\widetilde{\theta}[t] \sim P_{\gamma(t)}$.

The sampling of the updated SNR pdf is done for every packet transmission, so the MCS is selected based on the sampled SNR. The selected MCS is used for the next packet transmission. The client device measures the SNR per packet using the channel and noise estimates and computes the sum of the measured average SNR for 'n' packets. The sum, $\sum_{k=1}^{n} \gamma_k$ is fed back to the AP using the standards-compliant HE-CQI report field. The rate parameter R's hyperparameters are updated using (6) after every 'n' packets (rate parameter update window). The posterior expectation of the rate parameter is calculated using the recently updated $(\widehat{\mathrm{d}}, \widehat{\mathrm{e}})$ pair. The updated value of R_i is further used to update the pdf of the average SNR ~ gamma $(6, R_i)$.

3.3. Simulation Results

The Bayesian update channel SNR model simulation is done using the standards-compliant, credible link simulator MATLAB WLAN Toolbox of MathWorks. Fixing the shape parameter, α to 6, and learning the rate parameter, R, through Bayesian learning resulted in an excellent match with the experimentally observed receiver SNR histogram at the client and the SNR pdf learned through Bayesian learning at AP.

The pdf of SNR iteratively concentrates around the true channel SNR, i.e., assigns a higher probability density to the SNRs close to the true channel SNR. This is depicted in Figure 3a. Figure 3b shows the perfect overlap of the CDF of the observed SNR at the client and the CDF learned at AP through Bayesian learning.

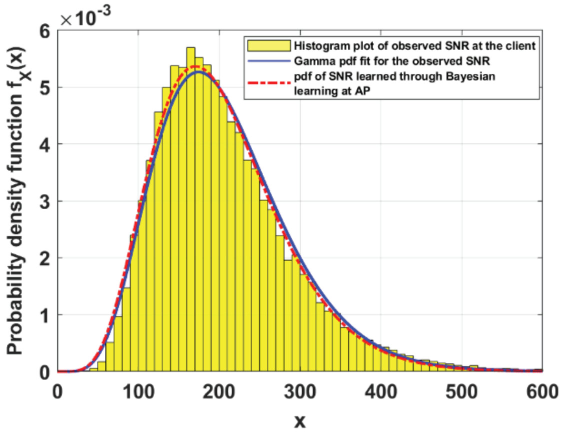

Figure 3a.

Histogram plot and Gamma pdf fit of the observed SNR at the client, and SNR pdf learned through Bayesian learning by fixing $\alpha = 6$.

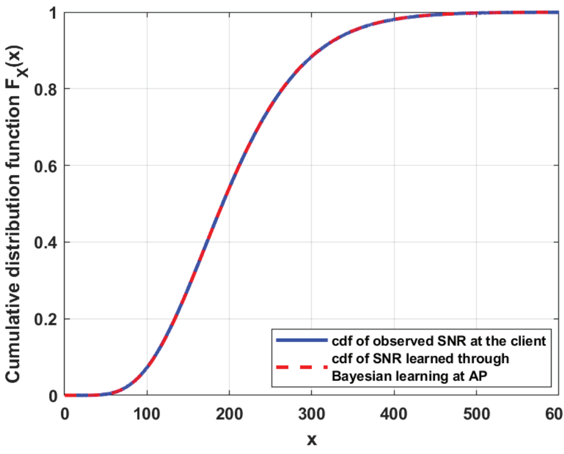

Figure 3b.

CDF of observed SNR and Learned SNR.

3.4. Optimal MCS Selection

The posterior SNR pdf learned through Bayesian learning is sampled for every packet transmission to get the SNR sample or the SNR point estimate. The SNR sample is mapped to the PER for all MCS (0–9) through a fast Received Bit Information Rate (RBIR) based offline link PLA model table lookup [15–17]. RBIR is described in detail in our previous work [15]. We select the highest MCS for which the estimated PER ≤ target PER (0.01).

For every successful packet transmission, there is some *link margin*. It is the difference between the instantaneous channel SNR (actual) and the minimum SNR (dependent on MCS) required for the successful decoding of the packet [18]. BLbRA addresses link margin by choosing the MCS for every packet transmission. BLbRA has lower computational complexity for computing the optimal MCS using RBIR table lookup and requires lower memory to store the SNR model. In our algorithm, the Access Point (AP) performs the Bayesian learning of the rate parameter of the SNR and decides the optimal MCS, taking off the computational load from the client device.

4. Throughput Performance Evaluation Using WLAN Toolbox

This section presents the throughput comparison of BLbRA and Hybrid Channel-Dependent Rate Adaptation (HCDRA), an algorithm we proposed earlier in [15]. Figures 4a, 4b and 4c show the throughput, PER and transmission time of both algorithms. For each presented results, we show the mean value over the 20 simulation runs with 95% confidence level.

HCDRA performs rate adaptation based on fresh channel estimates for every SNR feedback window. The per-RU average SNR derived from the channel estimates is fed back through HE Channel Quality Indicator (CQI) report field. The SNR feedback window (FBW) is set to 10, 50, and 100 packets. We observed that the throughput decreases in HCDRA as the FBW increases. This is because HCDRA uses the same MCS for all the packets transmitted for every SNR feedback window unless the probe

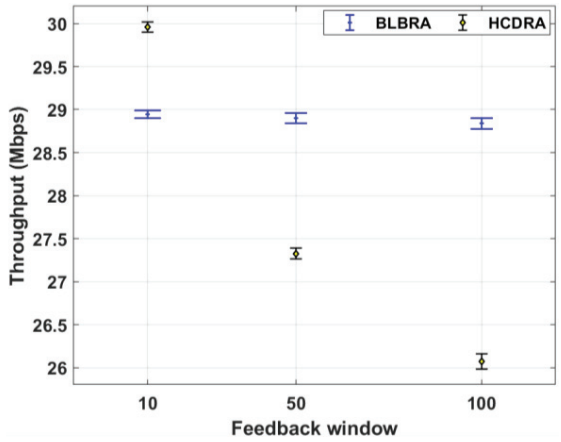

Figure 4a.

Throughput (Mbps) with 95% confidence level.

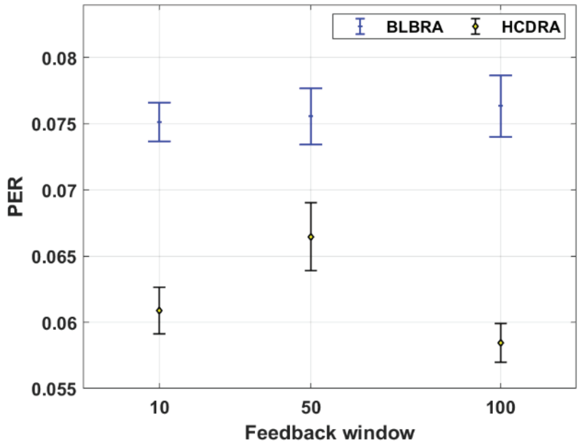

Figure 4b.

PER with 95% confidence level

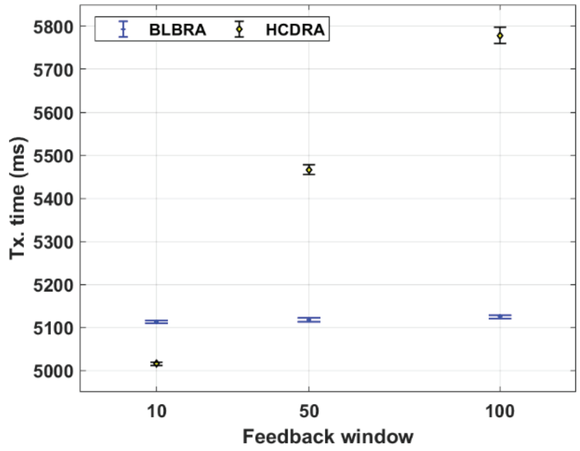

Figure 4c.

Transmission time (ms) with 95% confidence level with increasing feedback window.

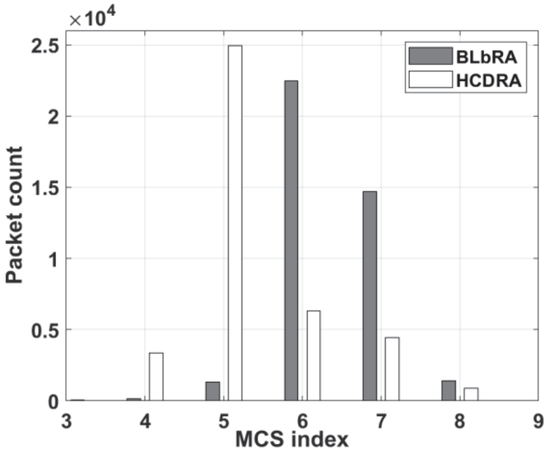

Figure 5.

Histogram of the MCS used in BLbRA (n=100) and HCDRA (FBW=100).

Table 3.

Performance of BLbRA (n = 100) within the window of N/4 packets

Packet Number	**1 to N/4**	**N/4 to N/2**	**N/2 to 3N/4**	**3N/4 to N**
Throughput (Mbps)	28.7458	28.8675	28.8256	28.7661
PER	0.0775	0.0769	0.0773	0.0761
Transmission time (ms)	1282.32	1280.31	1281.49	1282.47

packet fails or if two consecutive packets fail within the FBW (refer to Step. 5a of [15]).

In BLbRA, the rate parameter update window 'n' (of Equation (6)) is set to 10, 50, and 100 packets to compare the throughput performance with HCDRA. Here the sum of per-RU average SNR for 'n' packets is fed back to the AP using the standards-compliant HE-CQI report field. With the rate parameter update window of n = 10 packets, BLbRA throughput performance is close to HCDRA with FBW of 10 packets. However, we observed that throughput and PER performance of BLbRA with increased rate parameter update window of n = 50 and n = 100 remains on par with n = 10 packets.

HCDRA has a lower PER than BLbRA. This is because HCDRA becomes very conservative as feedback window increases compromising on the throughput gain. Unlike HCDRA, the transmission time in BLbRA is consistently smaller for n = 50 and 100, emphasizing the fact that BLbRA chooses a higher MCS for most of the packet transmissions.

Figure 5 shows the histogram plot of MCS used in BLbRA and HCDRA for a feedback window of 100. It is evident that the BLbRA uses higher order MCS larger compared to HCDRA, leading to a throughput gain.

Table 3 shows the performance metric for BLbRA (n = 100) within the transmission window of N/4 packets, with N = 40K packets. The throughput and PER are consistent within each transmission window. This is because the MCS in BLbRA is obtained by mapping the SNR point estimate for every packet transmission, as explained in section 3D. The BLbRA addresses the link margin for every packet transmission, thus transmitting the higher-order MCS whenever the channel supports it.

5. Conclusion

We designed the Bayesian Learning based rate adaptation to decide on the MCS for the next packet by sampling the learned SNR distribution at the AP and pretending that the sampled value is the SNR that the next packet will see. To evaluate both algorithms, we modeled the end-to-end link-level SISO transmit-receive link with IEEE standard-defined channel models [7,16]. BLbRA learns from the observed SNR feedback (after every rate parameter update window) to obtain the SNR estimate; the estimates closely match the true channel SNR. The rate parameter update window is increased to see the effect on throughput. BLbRA continues to perform well even with the reduced feedback overhead.

BLbRA is eminently implementable using the feedback mechanism recommended by the IEEE 802.11ax standard. Therefore, no customized mechanisms are needed to implement our proposed algorithm. Further, we would like to extend Bayesian learning to explore the possibility of learning both the parameters of Gamma distributed SNR and evaluate the throughput and PER performance of the link adaptation algorithm.

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Spectral Sampling and Signal Decomposition (SSSD) for Improved Spectral Efficiency

Basim H. Mohammed[*] *and Seshadri Mohan*

Abstract: Spectrally Efficient Frequency Division Multiplexing (SEFDM) aims to enhance spectral efficiency by compressing subcarriers in the frequency domain, thereby reducing the required bandwidth. This approach primarily focuses on minimizing Inter-Carrier Interference (ICI), which typically necessitates a complex receiver design. We propose a simpler receiver design based on Spectral Sampling and Signal Decomposition (SSSD) technique. This technique facilitates the receiver to process Orthogonal Frequency Division Multiplexing (OFDM) signals outside the conventional orthogonality points in the frequency domain. Unlike traditional SEFDM approaches, the SSSD receiver utilizes interfering carriers as useful signals. Through simulations, we showcase the SSSD receiver's performance in extracting SEFDM signals and accommodating various pulse shapes beyond the conventional sinc pulse. However, our results also highlight a significant challenge posed by severely ill-conditioned matrices, which can be mitigated by exploring alternative pulse types.

Keywords: Faster-than-Nyquist, frequency division multiplexing, inter-carrier interference (ICI), orthogonal frequency division multiplexing (OFDM), spectral efficiency, spectrally efficient frequency division multiplexing (SEFDM).

1. Introduction

The electromagnetic spectrum is becoming an increasingly scarce resource due to the rise in wireless communication traffic and the inherent limitations of the available spectrum in supporting radio communication. Global mobile data traffic forecasts indicate that this upward trend in traffic volume will continue, with significant growth expected in the coming years [1, 2]. By 2029, mobile data traffic is projected to triple compared to 2023 levels [3]. Various approaches have been proposed in the literature to increase 5G network capacity, including techniques for improving Spectral Efficiency (SE) [4, 5], acquiring wider spectral capacity [6], applying intensive spectral reuse [7, 8], and the use of better resource sharing to achieve higher utilization [9, 10]. While each approach has contributed to increasing 5G network capacity, enhancements in SE at the waveform level have made the least contribution. These improvements in SE primarily stem from the integration of Multiple-Input Multiple-Output (MIMO) technology rather than the waveform itself. The increase in SE from 4G to 5G is lower than that achieved during the transition from 3G to 4G [11, 12].

The Spectrally Efficient Frequency Division Multiplexing (SEFDM) proposed in [13] offers an alternative waveform that enhances SE at the waveform level. By reducing subcarrier spacing and violating the orthogonality conditions, SEFDM extends Faster-than-Nyquist (FTN) scheme into the frequency domain [14]. Figure 1 illustrates and compares the concept of SEFDM with OFDM and FDM. As a non-orthogonal multicarrier technique, SEFDM reduces required bandwidth by allowing subcarrier overlapping and utilizing non-orthogonal waveforms. However, SEFDM inherits FTN's complexities, particularly in receiver design [15]. The first SEFDM scheme, fast-OFDM, aimed to double OFDM's data rate [13]. Subsequent research established a mathematical framework for SEFDM, employing complex receiver structures. Performance analysis of SEFDM using linear detectors and Genetic Algorithm (GA) detectors revealed lower Bit Error Rates (BER) compared to OFDM, but with increased iterations for additional subcarriers [16].

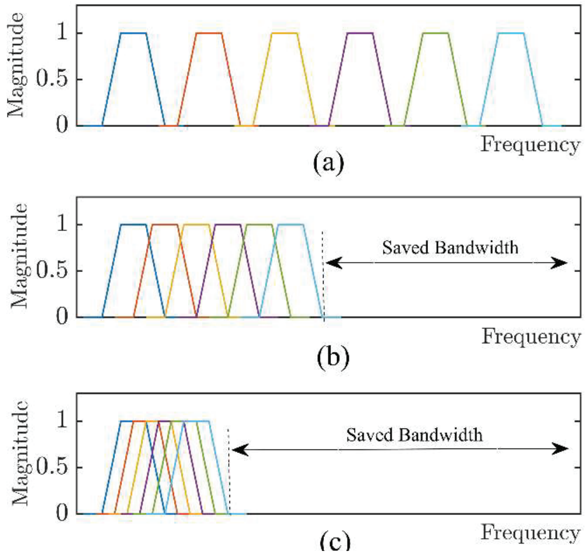

Figure 1.

Comparison of (a) FDM, (b) OFDM and (c) SEFDM in terms of savings in bandwidth.

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Moreover, system performance degraded significantly with higher modulation orders. Simple linear detection methods (zero-forcing, MMSE, and TSVD) yielded minimal BER improvements [17]. On the other hand, applying the non-linear detection techniques such as iterative detection (ID) [18], sphere decoding (SD) [19], and fixed sphere decoding (FSD) [20] leads to increased receiver complexity with more subcarriers or higher modulation orders [18–20]. A two-stage decoder combining iterative detection and sphere decoding has also been explored [18,19]. Notably, the Bahl-Cocke-Jelinek-Raviv (BCJR) decoder achieved 40% bandwidth savings compared to OFDM, albeit with minor performance loss (less than 2 dB) and iterative processing in multipath fading channels [21]. Furthermore, SEFDM has been extended to radio-over-fiber systems [22].

Since its introduction over twenty years ago [13], the SEFDM approach to achieve higher spectral efficiency is based on mitigating the Inter-Carrier-Interference (ICI) effect resulting from the overlapping of compressed subcarriers that violate the orthogonality condition. To address ICI, SEFDM employs two primary strategies: (i) Utilizing complex decoders to minimize interference effects; (ii) Applying robust and heavy coding to extract symbols embedded in interference. These approaches view overlapping subcarriers as undesirable interference to be canceled, necessitating complex receiver designs. However, the Spectral Sampling and Signal Decomposition (SSSD) receiver introduced in [23] offers a promising alternative. Initially designed for OFDM, SSSD can detect symbols beyond orthogonality points, making it potentially suitable for extracting SEFDM signals. This paper explores modifying the SSSD receiver for SEFDM signal extraction, achieving higher spectral efficiency through reduced bandwidth requirements. Notably, the SSSD approach contrasts with SEFDM's ICI mitigation strategy, instead offering a straightforward and simple receiver structure.

2. The Spectral Sampling and Signal Decomposition (SSSD) Principle

The frequency domain representation of the OFDM signal $R(f)$ at the receiver can be modelled as:

$$R(f) = \frac{T}{2}\sum_{n=0}^{N-1}\left[X_n V(f-F_n) + X_n^* V(f+F_n)\right] \qquad (1)$$

for $-\infty < f < \infty$, where $X_n = |X_n|e^{-j\theta_n}$ is the transmitted symbol, $F_n = f_0 + \frac{n}{T}$, and $V(f)$ is the pulse shape in frequency domain, while T is the symbol duration, N is the number of subcarriers, and f_0 is the frequency of the first subcarrier. As shown in [23], Equation (1) can be simplified for the sampled received signal and written in matrix form as follow:

$$\mathbf{X} = 2\mathbf{R}\mathbf{V}^{-1} \qquad (2)$$

Where $\mathbf{R}$ is the FFT of the received signal evaluated at $f_k = \pm(f_0 + k/T + p(1/T))$ for $k = 0, 1, \ldots, N-1$ and the matrix $\mathbf{V}$ is found by evaluating;

$$V(f) = \left[\frac{sin\left(\frac{\pi L}{F_s}f\right)}{sin\left(\frac{\pi}{F_s}f\right)}\right] e^{-j\frac{\pi(L-1)}{F_s}f},$$

at $f = f_k$. p is a parameter used to specify the spectral sampling point deviation from orthogonality points and it can take any value in the range $-1 < p < 1$ as shown in Figure 2. In other words, the spectral sampling points will experience a deviation of $p(1/T)$ Hz from the orthogonality points. The simulation results for the AWGN channel for $p = 0, 0.1, 0.2 \ldots 0.9$, shown in Figure 3 using the parameters listed in Table 1. It can be seen that SSSD can detect the OFDM symbols beyond the orthogonality point and

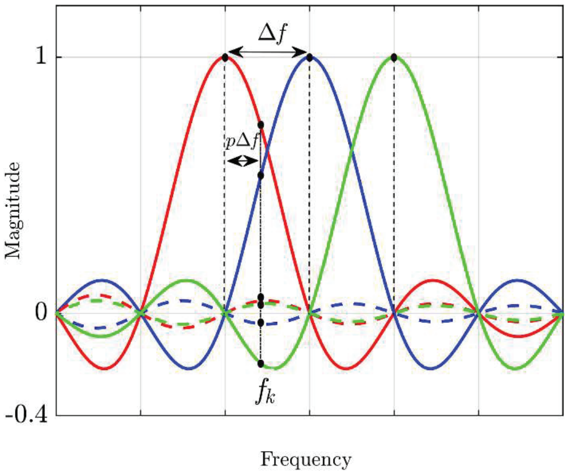

Figure 2.

The position of f_k in frequency domain and the role of p for an OFDM signal.

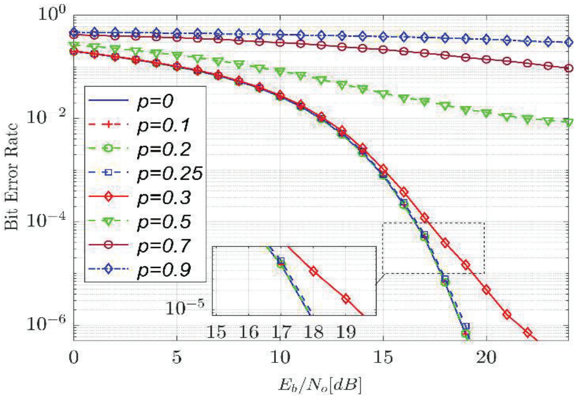

Figure 3.

BER Performance over AWGN channel with minimum number of 500 errors for each SNR value.

Table 1.

Simulation parameters	
Parameter	**Value**
Mapping	64-QAM
No. of subcarriers (N)	128
Subcarrier spacing (Δf)	15 kHz
Cyclic-Prefix length	16 samples
Delay spread for AWGN	1 sample

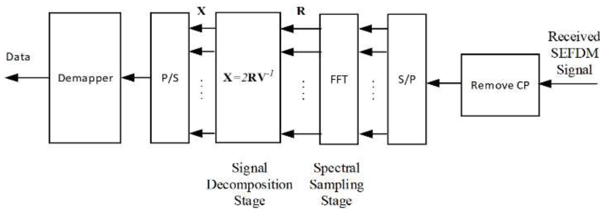

Figure 4.

The SSSD receiver for SEFDM signal.

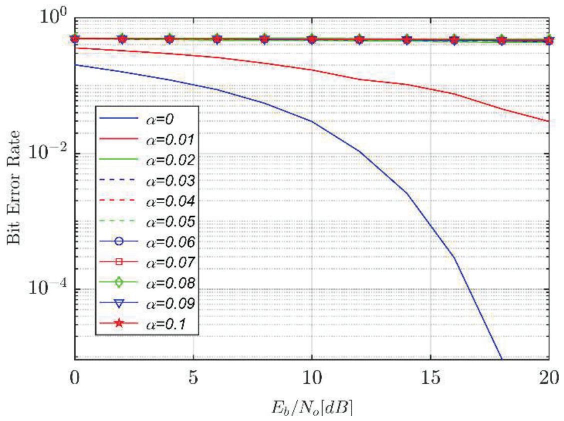

Figure 5.

BER performance using different values of α with minimum of 300 errors for each SNR value.

deliver the same performance for $p < 0.25$ and the performance degraded rapidly for $p < 0.25$. Since the SSSD has the capability to detect the OFDM signal in the presence of ICI, then the next logical step is to use it in receiving the SEFDM signal.

3. SSSD Receiver Performance for SEFDM Signal

The SSSD can be adopted to receive and extract the symbols carried by the SEFDM signal. The SEFDM signal is similar to the OFDM signal with the exception that the subcarriers frequency spacing (Δf) is less than the OFDM symbol rate; $\Delta f < \frac{1}{T}$, which produce non-orthogonal signal. While f_k is defined for all values of k to be: $f_k = f_0 + (1-\alpha)\frac{1}{T}$, where α is defined to be the compression ratio. By modifying the **V** matrix according to the desired α value, then, the SSSD receiver can be used to receive the SEFDM signal. Figure 4 depict the SSSD receiver for SEFDM signal. Figure 5 illustrates the BER performance of SEFDM signals utilizing the SSSD receiver for various values of α. Figure 6 show the impact of α on the noise power level per subcarrier, revealing that the noise coloration effect of α accompanied by a substantial increase in the noise level even with a minor increment in α. The simulation parameters shown in Table 2.

4. Using Raised Cosine and Triangular Pulses

The utilization of a rectangular pulse in OFDM and SEFDM yields a *sinc*-shaped subcarrier spectrum, which is sampled to construct the **V** matrix. The chosen pulse shape significantly influences the properties of the **V** matrix. To enhance the system performance, alternative pulses with diverse spectral characteristics can be explored to modify the **V** matrix.

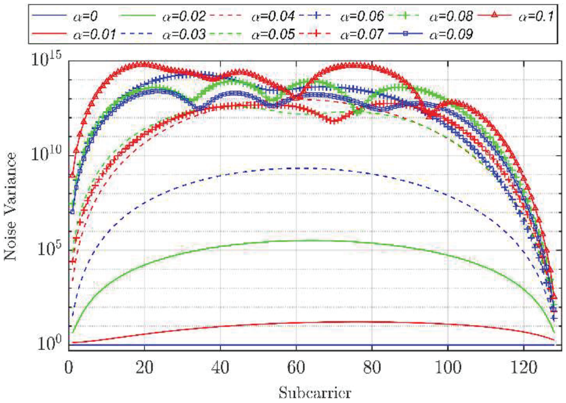

Figure 6.

Noise Power distribution per subcarrier for different values of α.

Table 2.

Simulation parameters for SEFDM	
Parameter	**Value**
Mapping	64-QAM
No. of subcarriers (N)	128
Subcarrier spacing (Δf)	15 kHz
Compression ratio (α)	0, 0.01, 0.02,...0.09, 0.1
Cyclic-Prefix length	16 samples
Delay spread for AWGN	1 sample

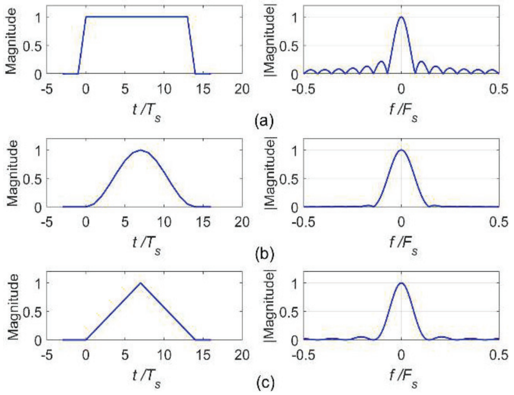

Figure 7.

The spectrum of (a) Rectangular (b) Raised Cosine and (c) Triangular pulse.

For the purpose of comparison, two pulses are selected with *sinc* or *sinc*-like spectrum: the Raised Cosine (RC) with a roll-off factor of one and the triangular pulse. Notably, both exhibit a distinctive main lobe in their spectra as displayed in Figure 7. The DTFT expressions for the RC and triangular pulses, respectively, for a symbol period of T, are:

$$\begin{aligned} V_{RC}(f) = {} & \frac{1}{2L}\left[\frac{sin\left(\frac{\pi L}{F_s}f\right)}{sin\left(\frac{\pi}{F_s}f\right)}\right]e^{-j\frac{\pi(L-1)}{F_s}f} \\ & -\frac{1}{4L}\left[\frac{sin\left(\frac{\pi L}{F_s}\left(f-\frac{1}{T}\right)\right)}{sin\left(\frac{\pi}{F_s}\left(f-\frac{1}{T}\right)\right)}\right]e^{-j\frac{\pi(L-1)}{F_s}\left(f-\frac{1}{T}\right)} \\ & -\frac{1}{4L}\left[\frac{sin\left(\frac{\pi L}{F_s}\left(f+\frac{1}{T}\right)\right)}{sin\left(\frac{\pi}{F_s}\left(f+\frac{1}{T}\right)\right)}\right]e^{-j\frac{\pi(L-1)}{F_s}\left(f+\frac{1}{T}\right)} \end{aligned} \tag{3}$$

$$V_{TRI}(f) = \frac{1}{2}\left[\frac{2}{L}\frac{sin\left(\frac{\pi L}{2F_s}f\right)}{sin\left(\frac{\pi}{F_s}f\right)}e^{-j\frac{\pi L}{2F_s}f}\right]^2 \tag{4}$$

Figures 8 and 9, respectively, depict the effect of α on the noise power level using RC and triangular pulses. Similarly, Figures 10 and 11, respectively, illustrate the BER performance of SEFDM receiver for various values of α using RC and triangular pulses. Additionally, Figure 12 compares the condition number of the **V** matrix for the rectangular, RC, and triangular pulses, revealing a significant increase as α increases. The results demonstrate

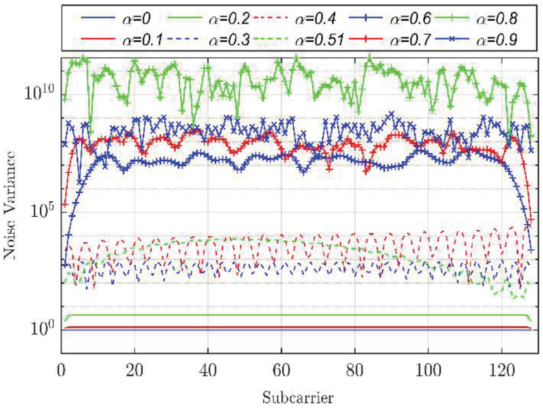

Figure 8.

Noise power distribution per subcarrier for the RC pulse using different values of α.

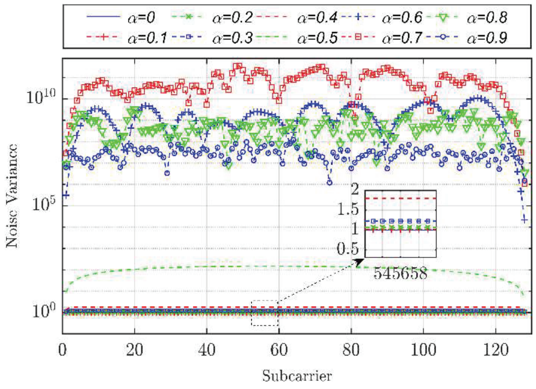

Figure 9.

Noise Power distribution per subcarrier for the triangular pulse using different values of α.

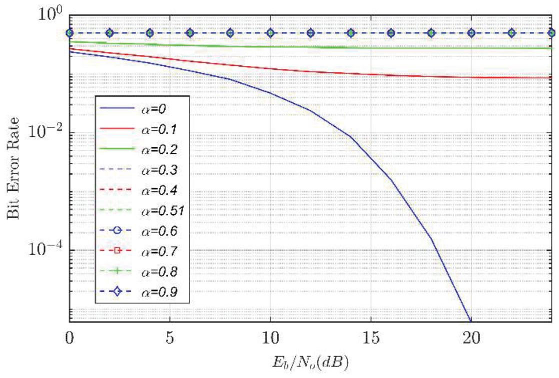

Figure 10.

BER Performance for RC pulse with minimum of 500 errors for each SNR value.

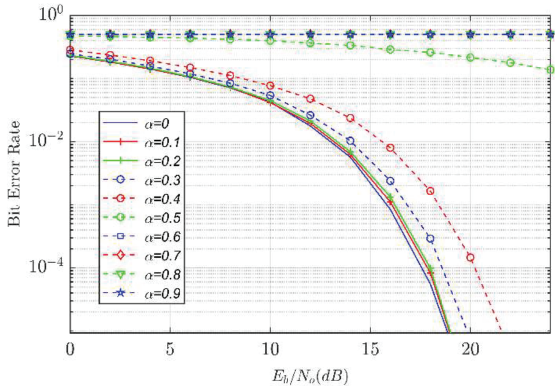

Figure 11.

BER Performance triangular pulse with minimum of 500 errors for each SNR value.

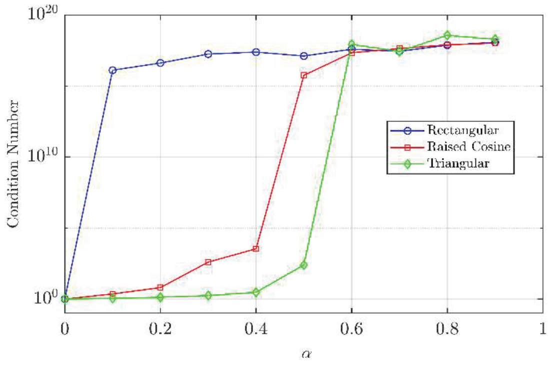

Figure 12.

The **V** matrix condition number comparison for the rectangular, RC and triangular pulses.

that increasing α severely ill-conditions the $\mathbf{V}$ matrix, leading to substantial increase in noise levels and performance degradation. The simulation parameters employed are identical to those summarized in Table 2, except the subcarrier spacing (Δf) is doubled to maintain orthogonality condition for the RC and Triangular pulses.

5. Simulation Results Discussion

The SSSD receiver's performance deteriorates rapidly as subcarriers are compressed in the frequency domain for non-zero values of α. Even a small α value of 0.01 causes the $\mathbf{V}$ matrix to become ill-conditioned, significantly increasing noise levels (Figures 5 and 6). Since the $\mathbf{V}$ matrix is derived from the spectral samples of the applied pulse, modifying the pulse shape alters the matrix properties. To compare performance, RC and Triangular pulses are evaluated alongside the conventional rectangular pulse.

Assuming preserved orthogonality at $\alpha = 0$, the SSSD receiver is tested with these pulses, requiring twice the frequency spacing used for the sinc pulse. Results show that the pure RC pulse yields relatively lower noise levels than the sinc pulse, though still high, leading to degraded performance due to the ill-conditioned $\mathbf{V}$ matrix (Figures 5 and 6). Notably, for the RC pulse, $\alpha = 0.51$ is used, as the $\mathbf{V}$ matrix becomes singular and non-invertible at $\alpha = 0.5$.

Figure 12 compares the condition numbers of the $\mathbf{V}$ matrix for three pulse shapes, revealing the Triangular pulse yields a better-conditioned matrix for $\alpha < 0.5$. This corresponds to lower noise levels and improved performance, as shown in Figures 9 and 11. Specifically, the SSSD receiver achieves near-orthogonal performance using the Triangular pulse for $\alpha < 0.2$, with gradual degradation beyond this threshold. The Triangular pulse offers enhanced performance relative to the RC pulse for $\alpha < 0.4$. The $\mathbf{V}$ matrix's condition significantly impacts noise levels, as its ill-conditioning amplifies noise power experienced by each subcarrier. Despite using different pulses, OFDM maintains better SE than the SSSD receiver for SEFDM signals, primarily due to OFDM's ability to maintain orthogonality at lower subcarrier frequency spacing.

6. Conclusion

The SSSD receiver can extract non-orthogonal SEFDM signals for various compression ratios, provided the $\mathbf{V}$ matrix is well-conditioned. However, as matrix condition deteriorates, noise level increases. Thus, the primary obstacle lies in the $\mathbf{V}$ matrix's condition, rather than inter-carrier interference (ICI). This study introduces a new perspective on the SEFDM problem, reframing it as an ill-conditioned matrix problem. Two approaches can be employed to address this: (i) Engineering approach: By designing pulses yielding well-conditioned matrices, and (ii) Mathematical approach: By modifying the matrix conditions.

To enhance SEFDM signal detection accuracy using SSSD receivers, we propose four research directions: (1) Pulse design: Create pulses yielding well-conditioned $\mathbf{V}$ matrices, (2) Diverse pulse sets: Employ varied pulses across subcarriers, (3) Non-uniform spacing and sampling: Explore non-uniform subcarrier spacing and spectral sampling, and (4) Matrix regularization: Utilize regularization or decomposition methods for invertible matrices with minimal error.

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Biographies

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Enabling Safer Crosswalks with State-of-the-Art Vehicle-to-Everything (V2X) Technology

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Abstract: Vehicle-to-Everything (V2X) communication is a technology that enables vehicles to communicate with other vehicles (V2V), infrastructure (V2I), cyclists, and pedestrians (V2P). V2X employs antenna technology that allows omnidirectional wireless data transmission between all nodes in the transportation ecosystem. This has strong implications for improving pedestrian safety, reducing traffic congestion, and enabling smart city applications. One area where V2X can have a tremendous impact is at pedestrian crosswalks. Currently, these are dangerous zones where vehicle-pedestrian collisions occur frequently due to blind spots, distracted driving/walking, and unclear right-of-way. V2X aims to eliminate these collisions by allowing vehicles and pedestrian smartphones to continuously share their real-time locations, trajectories, and analytics. This seamless connectivity is enabled by V2X antennas embedded in cars and mobile devices. The primary goal of this research is to increase the safety of pedestrians on and near crosswalks positioned on roadways. The Altair FEKO 2022.1 software is used in this study to create a symmetrical V2X communication scenario with intersecting highways. Cars, pedestrians, roads, and traffic lights are arranged in the Altair WallMan Computer-Aided Design (CAD) software. The Shooting Bouncing Ray (SBR+) solver in Altair ProMan is computed on a CAD-modelled database to simulate the power received at key prediction points on crosswalks in the path of each vehicle. Intelligent Ray Tracing (IRT) is utilized to animate the scene with moving cars and pedestrians over a three-second time interval while simultaneously counting the number of propagation pathways and rays used at each instant. At each prediction time instant and for every prediction point, power received is measured in decibel-milliwatts (dBm). The computed simulation results are analysed at 5.8 GHz, 6 GHz, and 28 GHz.

Keywords: Computer aided design (CAD), propagation manager (PROMAN), shooting and bouncing rays (SBR), vehicle to everything (V2X), safer crosswalks.

1. Introduction

Motor vehicle collision-related injuries and fatalities to pedestrians are a serious global public health concern. An estimated 400,000 pedestrians worldwide are killed in road crashes every year, with developing nations having the highest rates [1], emphasizing the need for creative solutions. As a solution to this problem, researchers have been investigating the ways in which V2X technology can improve crosswalk safety. V2X's integration with edge computing [2], sensors [3] offers a strong foundation for building an intelligent, networked traffic ecosystem.

A recent transition to V2X has raised safety applications beyond the vehicle network to lower the number of accidents. For instance, V2I systems warn cars and pedestrians of possible dangers by using crosswalk indications [4] and smart traffic signals [5].

State-of-the-art implementations leverage technologies like dedicated short-range communications (DSRC) [6], cellular V2X (C-V2X), and upcoming 5G networks, which enable low-latency and high-reliability communications. These systems can predict pedestrian behavior with high accuracy, allowing for proactive rather than reactive safety measures.

1.1. V2X Technology

Modern vehicles are equipped with multiple V2X antennas to ensure 360° coverage around the car. Typical configurations use various omnidirectional and directional antennas strategically positioned on the roof, side mirrors, rear bumper, and front bumper.

These include:

- Dedicated Short Range Communication (DSRC) Antennas: Operating in the 5.9 GHz band, DSRC antennas enable low-latency V2X communication up to 1000 m range. Omnidirectional "shark fin" antennas on the roof of a vehicle provide 360° coverage while directional patch antennas aim signals in specific directions.
- Cellular V2X (C-V2X) Antennas: Leveraging existing 4G/5G cellular networks, these antennas support longer range.

  V2X with cloud connectivity. These models use multiple embedded antennas or combine the cellular antennas with DSRC antennas [7].
- Radar/Lidar Antennas: Complementing V2X radio links, radar and lidar sensors act as another type of "antenna" using electromagnetic and optical signals to detect and track objects around the vehicle, enhancing perception capabilities [8].

In addition to hardware, vehicles utilize advanced antenna integration, beam steering, interference mitigation, and antenna

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diversity techniques to ensure reliable V2X links in challenging urban environments with obstructions and multipath interference [9].

1.2. SBR Solvers

Shooting and bouncing ray solvers provide an efficient and accurate way to model the electromagnetic radiation behavior of antennas in real-world environments. By tracing rays emitted from the antenna and calculating their reflections and interactions with surrounding objects and materials, SBR solvers can predict far-field radiation patterns, gain, and directivity.

Altair FEKO is a computational electromagnetics software that utilizes the shooting and bouncing ray (SBR) technique to launch several rays from the transmitter and calculate their paths [10]. This is an effective method for identifying potential signal interference and noise. Other SBR solvers include SIENT, CST A-Solver, Remcom XGTD, and Ansys HFSS SBR+ [11].

Full-wave simulation of the far-field radiation pattern accounts for complex effects like multi-path propagation, diffraction, and material properties that impact antenna operation [12]. SBR solvers allow engineers to virtually test numerous antennae designs and installation scenarios virtually before physical prototyping. Understanding this simulated performance is crucial for optimizing antenna designs to meet specified requirements.

1.3. Literature Survey

There is an increasing body of published literature available on the topic of pedestrian safety and emerging antenna technologies such as [13] which asserts *"that distractions by smart devices and reduced cognitive skills are major causes of accidents"* and suggests that *"there is a scope to assist pedestrians through amplifying cognitive skills using heterogeneous Internet of Things (IoT) and sensors."* A more recent study suggests that *"ensuring safety measures for the Vulnerable Road Users (VRUs) such as pedestrians, cyclists, and e-scooter riders remains an area that requires more focused research effort"* [9]. The following study presents a CAD scenario that is arranged and simulated over a three-second time interval with animated pedestrians and cars. The chosen time interval is where driver and pedestrian response time may not be sufficient to avoid a collision.

A similar electromagnetic simulation study to this paper is reported in [14] that considers 3D models of buildings in a line-of-sight (LOS) and non-line-of-site (NLOS) scenario to compute the multipath propagation of the signal geometrically using Matlab§Site View for ray tracing. The state-of-the-art Altair ProMan (WinProp) SBR solver is used in the following study to perform ray tracing with the maximum computing resources available to measure V2X antenna transmission and reflection across an active four-way intersection where LOS and NLOS is in constant flux.

1.4. Contribution

The 28 GHz FR2 frequency band was chosen for this study in addition to the 5.8 GHz and 6 GHz bands because of the higher channel capacity of smart-phone antennas available for integration into existing V2X systems [15, 16]. Performing an analysis of the 28 GHz frequency range in a time variant scenario while observing omnidirectional dipole antennas presents a helpful simulation environment and scenario for further study [17]. See Table 1 for a comprehensive overview of the gathered data.

2. Methods

2.1. Computer Assisted Design (CAD)

A general-purpose testbed environment for antenna testing, shown in Figure 1, is designed using Altair WallMan. The 3D cars, pedestrians, and traffic lights are placed in a V2X scenario to enable animated car and pedestrian movement over a three second time interval. The 3D models are sourced from libraries and training material included with the software license.

CAD models of pedestrians and cars are placed in a symmetrical configuration relative to the center of the intersection at zero. Exact coordinates are shown in Table 2. Note that the z-axis is raised 0.1 metres above the road to prevent overlapping topology.

2.2. Far-Field Propagation Pattern

The following far-field pattern is calculated for a finely meshed dipole antenna transmitting 5G-generation frequency bands designated by IEEE 802.11p for V2X to maximize render accuracy at 5.8 GHz, 6 GHz, and 28 GHz [18]. Computing the far-field radiation pattern produces a full wave, Method of Moments (MoM), and solution of Maxwell's integral equations in the frequency domain for the desired antenna [19]. Using a finely meshed matrix in the MoM implies a limit to the size of the problem that can be solved. Available computational resources and time determine this limit.

2.3. Computation Time

Simulations are computed with software-verified far-field radiation patterns placed on cars and pedestrians to calculate optimal transmission capacity at millisecond time intervals. The computation time required to calculate results for each animation increases as more dipole antennas are introduced. A short animation time and symmetrical design are utilized to reduce computational complexity, verify repeatability of the study, and increase precision.

Based on the observed computation times, a prediction rectangle is ultimately used for the dipole antennas transmitting at 5.8 GHz and 6 GHz. A set of four metre-by metre square prediction points are placed above every crosswalk for the 28 GHz omnidirectional antenna calculations. These computations were done without any explicit form of graphics processing unit (GPU) acceleration or algorithms to generalize the SBR calculations [20].

3. Results

3.1. Prediction Rectangles in 5.8 GHz to 6 GHz Range

This simulation is performed in the 5.8 GHz to 6 GHz range using the finely meshed far-field radiation pattern from a dipole antenna

Table 1.

Transmitters (Tx) and nearest receivers (Rx) are located relative to the true center (0,0,0) of the CAD environment. The power received at the nearest Rx dipole antenna placed directly in the path of the car and the pedestrian is shown

Vehicle to Crosswalk (SBR Prediction Rectangle): 5.8 – 6 GHz

Time (a)	Tx Location (x, y, z) [m]	Tx Power (dBm)	Nearest Rx Location (x, y, z) [m]	Rx Power (dBm)	Paths
0.0 – 0.5	(16.50, 5.50, 1.60)	30.0	(11.22, 7.50, 1.50)	−22.9	46
0.5 – 1.0	(10.79, 5.50, 1.60)	30.0	(11.22, 7.50, 1.50)	−10.5	21
1.0 – 1.5	(4.09, 5.50, 1.60)	30.0	(11.22, 7.50, 1.50)	−45.1	25
1.5 – 2.0	(−2.62, 5.50, 1.60)	30.0	(11.22, 7.50, 1.50)	−41.4	64
2.0 – 2.5	(−9.32, 5.50, 1.60)	30.0	(11.22, 7.50, 1.50)	−48.1	26
2.5 – 3.0	(−16.02, 5.50, 1.60)	30.0	(11.22, 7.50, 1.50)	−53.5	15

Pedestrian to Crosswalk (SBR Prediction Rectangle): 28 GHz

Time (a)	Tx Location (x, y, z) [m]	Tx Power (dBm)	Nearest Rx Location (x, y, z) [m]	Rx Power (dBm)
0.0 – 0.5	(−10.00, −11.00, 1.50)	30.0	(−10.00, −5.50, 1.50)	−45.0
0.5 – 1.0	(−10.00, −11.00, 1.50)	30.0	(−10.00, −5.50, 1.50)	−75.5
1.0 – 1.5	(−10.00, −11.00, 1.50)	30.0	(−10.00, −5.50, 1.50)	−45.0
1.5 – 2.0	(−10.00, −11.00, 1.50)	30.0	(−10.00, −5.50, 1.50)	−45.0

Vehicle to Crosswalk (SBR Prediction Rectangle): 28 GHz

Time (a)	Tx Location (x, y, z) [m]	Tx Power (dBm)	Nearest Rx Location (x, y, z) [m]	Rx Power (dBm)
0.0 – 0.5	(−16.50, −5.50, 1.60)	30.0	(−10.00, −5.50, 1.50)	−38.0
0.5 – 1.0	(−10.79, −5.50, 1.60)	30.0	(−10.00, −5.50, 1.50)	−52.0
1.0 – 1.5	(−4.09, −5.50, 1.60)	30.0	(−10.00, −5.50, 1.50)	−48.0
1.5 – 2.0	(2.62, −5.50, 1.60)	30.0	(−10.00, −5.50, 1.50)	−48.0

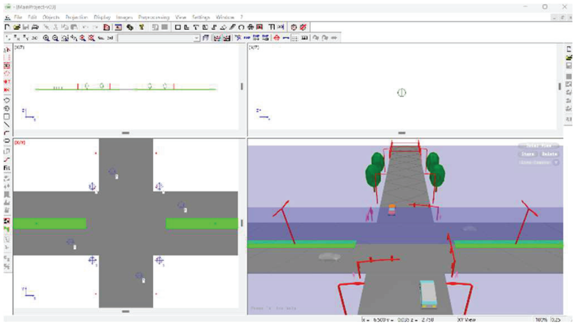

Figure 1.

This figure shows a four-way intersection with four cars, four pedestrians, and four traffic lights designed in Altair WallMan. WallMan is CAD design software used to create indoor and outdoor databases that are compatible with ProMan (WinProp).

Table 2.

Various car and human CAD models are placed in Wallman at the x, y, and z coordinates shown here

X-axis (meters)	Y-axis (meters)	Z-axis (meters)	Name
16.5	5.5	0.1	Car0 (Round)
−16.5	−5.5	0.1	Car1 (Mercedes)
−4.0	15.5	0.1	Car2 (Car)
4.0	−15.5	0.1	Car3 (Minibus)
10.0	11.0	0.1	Person4 (F)
10.0	−11.0	0.1	Person5 (M)
−10.0	−11.0	0.1	Person6 (F)
−10.0	−11.0	0.1	Person7 (M)

to yield results that verify the received power, in decibel-milliwatts (dBm), of current 5G-generation dipole antennas. The vehicles are animated to move at approximately 48.28 kilometres, or 30 miles, per hour and the pedestrians wait for the traffic to pass and cross the road at 4.82 kilometres, or 3 miles, per hour.

A transmitting antenna is placed just above the center of the Car0 roof at 1.6 metres. The received power is measured in a prediction rectangle placed directly in front of the vehicle at 1.5 metres above the crosswalk. This animation progresses from top to bottom in the left column and then the right column. The vehicle antenna remains attached to the animated car throughout the sequence.

The number of paths indicates the transmitted signal's reflections, and the subsequent calculations performed during computation. To reduce the overall number of computations, Shooting Bouncing Ray (SBR) solver reflections were limited to two bounces per angle of transmission.

The sequence from Figure 4 through Figure 9 illustrates how the received power decreases as the number of reflections increases

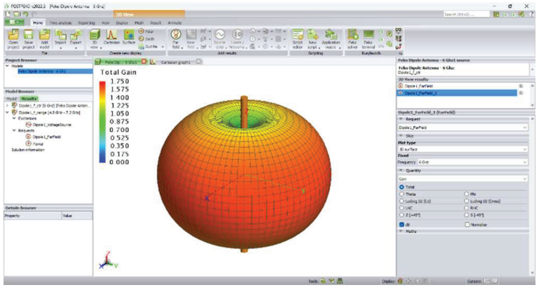

Figure 2.

Far-field propagation pattern for a dipole antenna capable of transmitting a maximum power of 1.750 dBm at 6 GHz. The dipole model is included as a template in Altair FEKO and finely meshed to maximize far-field computation accuracy.

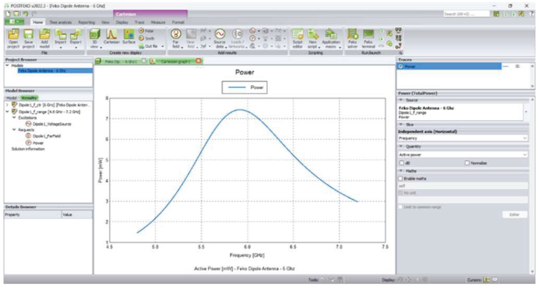

Figure 3.

The active power of the dipole antenna in Figure 2 is shown here to peak between seven and eight milliwatts (mW) within the 5.8 GHz and 6 GHz frequency bands.

Table 3.

List of ProMan (WinProp) computations cycles performed and the time required to complete with a 12th Gen Intel(R) Core (^{TM}) i9-12900 CPU operating on four threads within a Windows 11 Professional operating system. Each computation is identified by frequency, antenna type, number of antennas, and SBR method

Frequency	Antenna Type	# of Antennas	Method (SBR)	Time (hour)
5.8 GHz	Dipole	2	Prediction Rectangle	8
5.8 GHz	Dipole	2	Predication Point	2
6 GHz	Dipole	2	Prediction Rectangle	8
28 GHz	Omni	8	Predication Point	12
28 GHz	Omni	8	Prediction Rectangle	72+

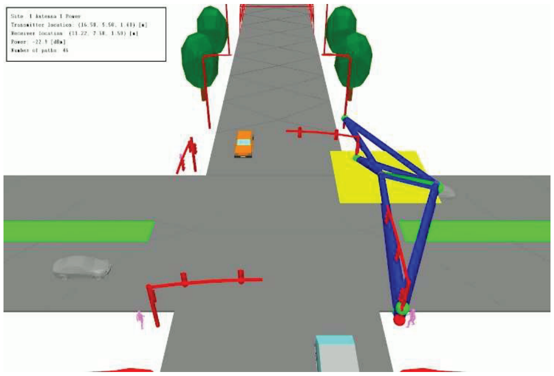

Figure 4.

Power received above the crosswalk from the Car0 dipole antenna is shown in the prediction rectangle.

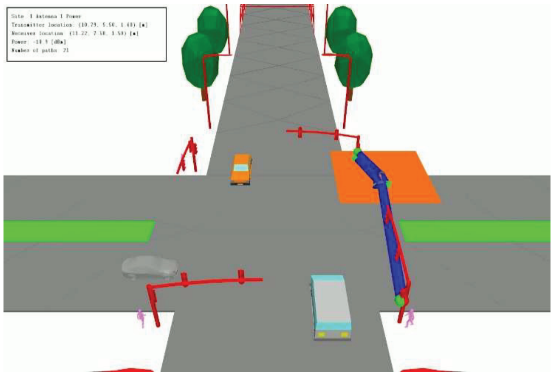

Figure 5.

Power received is maximum and interference is minimal when the crosswalk is within line-of-sight.

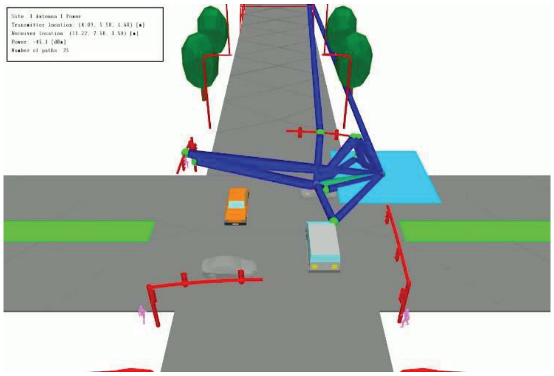

Figure 6.

Though number of paths are increasing, received power is sufficient.

and the car drives further away. The symmetrical movement of all the cars within this animation is a significant contributor to this clustering of propagation paths, which means that typical traffic patterns in an intersection will present less interference overall. Though antenna arrays and beam-steering techniques may be introduced to mitigate and reduce noise from these reflections, it is essential to verify that a sufficient level of performance is possible with simple dipole antennas before introducing further complexity to the far-field radiation patterns.

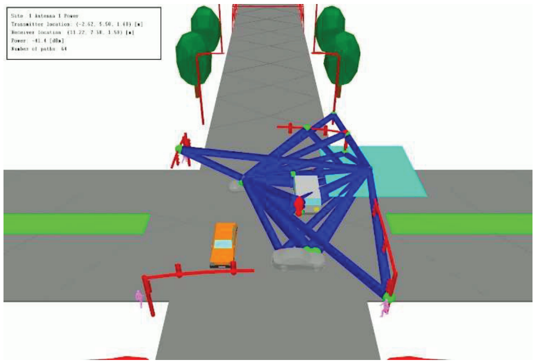

Figure 7.

The number of paths increase significantly with vehicle obstruction.

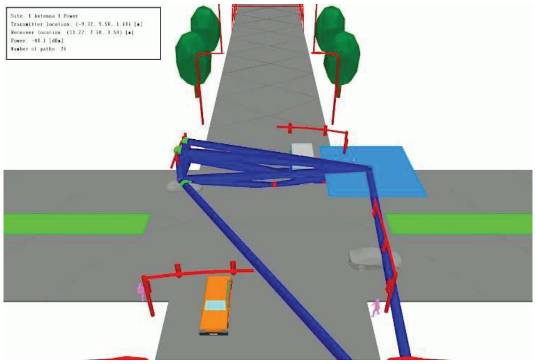

Figure 8.

Received power decreases dramatically once Car0 completes pass.

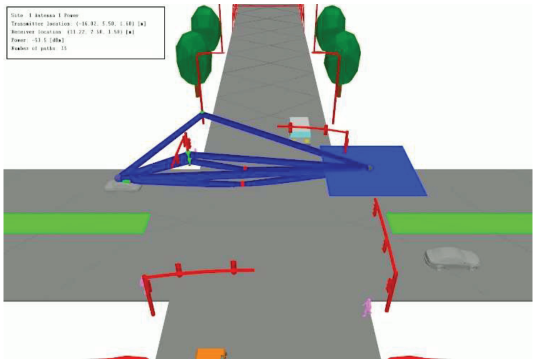

Figure 9.

Power received is the weakest here, far behind the vehicle.

3.2. Prediction Points at 28 GHz

Omnidirectional far-field radiation patterns included with and optimized in ProMan are used in the following 28 GHz simulation to reduce computational complexity further. This omnidirectional pattern is optimized for improved efficiency within the software. It reduces the chance of placement errors from importing finely meshed far-field radiation patterns from Altair FEKO. For this simulation, particular attention is placed on the received power at four square-metre prediction points placed at 1.5 metres above the intersection crosswalks.

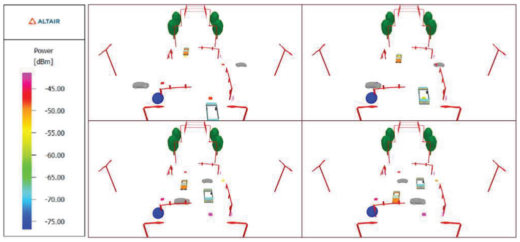

Figure 10.

Omnidirectional antenna placed at waist level in front of Person6 and transmitting at 28 GHz.

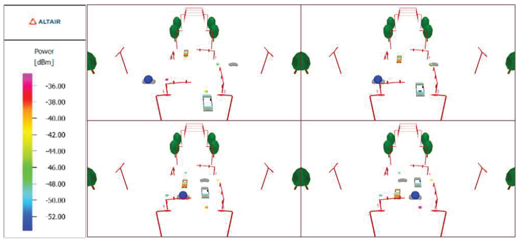

Figure 11.

Omnidirectional antenna placed above the roof of Car1 and transmitting at 28 GHz.

The power received at the propagation points in Figure 10 from the pedestrian antenna remains consistent while the pedestrian waits for the traffic to pass. Any power received that reaches or exceeds −100 dBm is deemed sufficient for low latency transmission of packets containing critical proximity information.

Notice how in Figure 11 the received power decreases where other vehicles obstruct the propagation path, though the crosswalk points within the line-of-sight of the vehicle remain optimal. It is also important to note that once the car has passed the prediction point, there is no longer a need to transmit to the path or proximity of the pedestrian.

4. Conclusion

Vehicle-to-Everything (V2X) is a crash avoidance technology that relies on communicating information between nearby vehicles and infrastructure to warn drivers about potentially dangerous situations that could lead to crashes. Strong carrier signal power is received above a crosswalk from car and pedestrian antennas within a 10-metre radius of a potential reception point in the critical path of a moving car. Transmission is not significantly affected by dipole antenna placement in terms of azimuth and phase. It, therefore, presents evidence to support the potential for pedestrian safety-aware antenna configurations in low and high traffic intersections to assist in crash avoidance. By iteratively simulating this performance in a time-variant scenario over a critical three second period, it appears possible to test and develop ideal antenna configurations along with existing and emerging V2X systems and 5G-generation smartphone devices. These iterative simulation techniques reduce the overall costs of hardware testing and deployment, empowering radio frequency engineers to think creatively about network design decisions.

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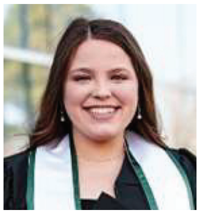

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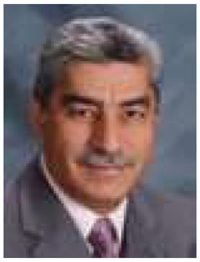

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Multi-disciplinary Approach to 6G: Technology, Business, Regulation, and Sustainability Perspectives

Marja Matinmikko-Blue[1,2,*], *Seppo Yrjölä*[2,3], *Petri Ahokangas*[4] *and Arturo Basaure*[2]

Abstract: 6G aims to address a number of societal challenges, while promising performance improvements over prior generations of international mobile communication technology. This calls for going beyond a traditional technology-driven approach in mobile communication system development and considering a wider set of values that are particularly driven by sustainability principles. In this 6G era, multi-disciplinarity, covering disciplines beyond telecommunications engineering, becomes an increasingly important approach to develop future-proof mobile communication technologies and services. This paper introduces a multi-disciplinary approach to 6G research and development (R&D) considering technology, business, regulation, and sustainability perspectives. Key topics and tools are introduced together with two case examples that illustrate how multi-disciplinarity, considering the proposed four perspectives, can bring new insights into practical topics relevant for 6G R&D.

Keywords: 5G, 6G, business, regulation, technology.

1. Introduction

6G is expected to play an important role in society in the 2030s, driving digitalization across different sectors and to address major sustainability challenges [1]. In particular, using information and communication technologies (ICTs) to solve sustainability challenges to maximize the positive handprint has become an important goal for digitalization, while ensuring that ICTs' own negative footprint impacts are minimized. Increasing attention in ICT and 6G research and development (R&D) is paid to values driven development [2], where the traditional performance driven technology design is complemented with values, spanning across a range of societal and business considerations. Yet, the topic of values driven technology design is in an early stage in telecommunications research [2], while the baseline concepts are more advanced in other fields of science including social sciences.

Multi-disciplinarity and inter-disciplinarity, i.e., bringing together expertise from different fields of science to different extent, are fundamental tools for addressing complex problems in 6G R&D. Mobile communication research has been traditionally conducted in disciplinary siloes, where most effort has been on developing techniques within engineering disciplines. Some exceptions have occurred, including business and regulation sides of 5G and 6G [3]. Finnish 6G Flagship's research agenda has included technical, business, regulation, and sustainability perspectives in the 6G R&D from the beginning in 2018 [1], presenting a multi-disciplinary approach to developing future communications [3]. This multi-disciplinary approach, however, is not mainstream in 6G, where studies typically focus on specific technology development, see [4]. Consequently, a major challenge in the new values driven 6G research arises from the engineering community's tendency to work in silos with limited collaboration within the same field, across disciplines and/or across stakeholders. In the era of sustainability, this is no longer adequate, but a multi-disciplinary approach is needed. Indeed, to ensure sustainability in the 2030s, new global 6G framework introduces four overarching design principles: sustainability, connecting the unconnected, ubiquitous intelligence, and security and resilience to guide the R&D in [5].

In the 6G era, mobile communication aims to link digital, physical, and biological worlds [6]. As a general-purpose technology (GPT) platform [7], 6G will become the backbone of digitalization, impacting innovation and transactions across downstream and upstream value chains in different sectors of society [8–10]. The traditionally vertically integrated mobile communications industry, where mobile network operators (MNOs) have control over communication infrastructure and end users, is evolving towards horizontalized service-oriented business models grounded on service-based architectures and common application programming interfaces (APIs) defined across architectural layers and technology domains [9].

This paper introduces a multi-disciplinary approach to 6G considering technology, business, regulation, and sustainability perspectives to help scholars, industries and public sector stakeholders in their 6G R&D related activities. The paper expands authors' prior work on business, regulation and technology perspectives [11] and sustainability perspective [12] to present specific topics and tools for the four perspectives together with two illustrative case examples in 5G and 6G. The presented themes are collected into a frame for holistic multi-disciplinary 6G R&D, whose applicability is demonstrated with two case examples of global IMT-2030 (6G) framework development at the ITU-R [5] and MNO business model for 6G [13].

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The rest of this paper is organized as follows. An overview of existing perspectives to 6G development is presented in Section 2. Section 3 presents our multi-disciplinary frame for 6G R&D. Case examples are presented in Section 4. Finally, conclusions are drawn in Section 5.

2. Overview of Perspectives to 6G Development

First, we review different perspectives relevant for 6G R&D including technology, business, regulation and sustainability perspectives, which are seen as important perspectives in [11,12].

2.1. Technology Perspective

Traditionally, research on mobile communication systems has focused on the development of new mobile communication technologies in a number of areas ranging from algorithm, service and hardware design to trialing and proof of concepts. In 5G, major technology developments took place in areas such as massive MIMO, beamforming, millimeterwave communications, cloud radio access network, energy efficiency, among others [14].

6G can be considered as a general purpose technology platform [9,10]. The way network services are being developed, delivered, and utilized in the 6G era will be increasingly built on open network architecture. In particular, the introduced exposure to network data, service, and transaction capabilities as northbound service application programming interfaces (APIs), operation APIs, and network APIs will allow developers to create new solutions and value via access to network capabilities, while providing the mobile network operators (MNOs) opportunities to capture value from their own network capabilities.

The vast majority of 6G R&D is around the technology perspective, similar to the prior generations of mobile systems. 6G technology development takes place around globally identified technology trends summarized in [4]. These trends and enablers include AI-native communications, integrated sensing and communications, device-to-device communications, convergence of communication and computing architectures, enhanced energy efficiency and lower power consumption techniques among others [4]. Significant research in these areas is ongoing, involving varying levels of multi-disciplinarity and collaboration within the same field, across disciplines and across stakeholders.

Mobile communication systems are typically defined in terms of minimum technical performance requirements, which for 6G are currently being defined at the ITU-R. For 5G (IMT-2020), the minimum technical performance requirements included peak data rate (bit/s), peak spectral efficiency (bit/s/Hz), user experienced data rate (bit/s), 5th percentile user spectral efficiency (bit/s/Hz), average spectral efficiency (bit/s/Hz), area traffic capacity (Mbit/s/m^2), latency (ms), connection density (number of devices per km^2), energy efficiency, reliability (success probability), mobility (mobility classes of km/h), mobility interruption time (ms), and bandwidth (MHz) [15].

6G discussions continue to use the same approach as prior generations and consider the 5G minimum technical performance requirements [15] as a starting point for improvements. Additionally, 6G work has introduced new values driven topics, including coverage, positioning, sensing-related capabilities, AI-related capabilities, sustainability, and interoperability [5]. The requirements for 6G will be defined by early 2026, setting requirements for the actual 6G technology development.

2.2. Business Perspective

Business perspective includes approaches to understand and characterize companies' business around mobile communication solutions and services and map and depict future business opportunities, use cases, and scenarios. There has been a growing interest in the telecommunications community to address the business aspects of mobile communications across the technology generations in terms of business models and business ecosystems, but still this research has remained limited.

Business model is a well-known but a debated concept for understanding and characterizing companies' operations, and it is widely used in different sectors. Business models describe how companies do business – by creating, delivering and capturing value – to exploit business opportunities. From the many definitions and approaches for business models, the approaches taken within mobile communication research are typically based on the original business model canvas [16].

More recently, platforms, ecosystems and stakeholders have gained attention in the business research on mobile communications for characterizing the complementing roles of different organizations in making business [6,11,17]. Stakeholders include individuals, groups, organizations or other entities that affect or are affected by a given theme such as 5G or 6G. Platforms – embodied in technologies, products, or services – form platform owner and complementor ecosystems that facilitate interactions between the supply and demand sides of a platform. Industrial digital platforms can be categorized into multisided transaction platforms that focus on facilitating exchange and interactions, and innovation platforms that help create value by enabling technological and service innovations. Ecosystems can be defined as value architectures based on value co-creation, delivery, and co-capture among ecosystem actors in co-specialized collaboration. For mobile communications, the delivery of services involves a number of stakeholders that form the ecosystem, especially when mobile communication is applied to a target environment in specific environments [6]. Research on 6G business models presents different options of value creation and capture in ecosystemic platform context for different stakeholders of the 6G ecosystem [3,13].

2.3. Regulation Perspective

Regulation perspective includes understanding and following of the laws, policies, rules, guidelines, and requirements governing the use of mobile communication technology to make business in different vertical sector application areas. Mobile communication sector is strictly regulated at national, regional and international levels. Spectrum regulation is a specific area within the telecommunication regulation with a lot of activity in different bodies having a big impact on the markets. Additionally, there are other generic regulations, such as AI, data, platform, cybersecurity and markets related regulations, as well as sector specific regulations in, e.g., healthcare, that need to be considered.

Regulation perspective involves analysis of existing and upcoming regulations and their impact on stakeholders, including for example AI, data and platforms. Additionally, regulation perspective involves identifying change needs developing new proposals for regulations, based on future predictions of the technology and markets. Yet, there is not much work on analyzing the regulatory landscape and the existing regulations specifically for mobile communications. There is even less research on how regulations should evolve in the mobile communications sector.

An example within spectrum regulation is frequency bands for mobile communications which are defined at international level in ITU-R, technical conditions, and finally access rights at the national level. For mobile communications, regulation for example defines the different ways to access spectrum and awards rights to do business for companies, including recent local spectrum licensing approaches [18].

2.4. Sustainability Perspective

The fourth considered perspective includes sustainability, which is the principle of ensuring that our actions today do not limit the range of economic, social and environmental options open to future generations. 6G R&D has adopted sustainability as a key driver early on in the world's first 6G White Paper [1] from the Finnish 6G Flagship. Sustainable development has been structured around triple bottom line of environmental, social and economic perspectives already decades ago, which continues to be valid [3, 6, 12]. These three perspectives are often conflicting and need to be optimizing together, leading to complex trade-offs.

Environmental sustainability in mobile communications covers topics such as energy efficiency, energy consumption, carbon and other green-house gas emissions, e-waste, device duration, etc. [19]. Organizations' environmental sustainability is often assessed with scope 1–3 emissions, where scope 1 covers direct green house gas emissions from the organization, scope 2 covers organization's indirect emissions and scope 3 covers the whole value chain's emissions. The degree to which countries collect environmental sustainability information from ICT sector's companies varies a great deal in Europe, see [19]. A lot of effort in mobile communication R&D has been on energy efficiency improvements with the goal to develop energy efficient techniques as well as lower power consumption devices to reduce the overall energy consumption and resulting green house gas emission.

Social sustainability in mobile communications addresses the human and societal aspects typically through topics of digital inclusion, security, and trustworthinesss [6]. A specific goal in 6G is to connect the unconnected aiming at bringing access to everybody everywhere in a trusted manner [5]. However social sustainability considerations have received less attention in mobile communications R&D than environmental sustainability.

Economic sustainability in mobile communications targets long-term economic growth while respecting the conditions for environmental and social sustainability [20]. Important concepts includesustainable business models at corporate, ecosystem and societal levels [6], calling for systemic change, cross-sectoral collaboration, policy engagement, and impact assessment among others [21]. Circular economy driven operational models with new business opportunities from sustainability footprint reduction and handprint improvements are essential parts of economic sustainability. Circular business models encourage minimizing of consumption and waste and maximizing societal and environmental benefit, rather than prioritizing economic growth [22], highlighting the interrelations of the three sustainability perspectives to optimize operations across the entire value chain over lifetime.

3. Proposed Framing for Multi-disciplinary Approach to 6G

We next present our proposed framing for multi-disciplinary approach to 6G R&D. The proposed framing consists of technology, business, regulation and sustainability perspectives expanding prior work in [11, 12] and identifies key themes within these four perspectives. The framing aims to help scholars, industries and public sector stakeholders in their 6G R&D to identify influential factors across disciplinary borders to facilitate better collaboration across stakeholders with conflicting goals. The framing aims to guide researchers to expand existing research to multi-disciplinarity. The framing is presented in Figure 1, where the technology, business, regulation and sustainability perspectives build on top of the notion of 6G as a general purpose technology platform.

Our technology perspective consists of two elements: (1) enabling techniques and technical solutions, and (2) technical performance requirements and assessments. Thus, the technology perspective includes the development of the technical enablers and technology components to meet the technical performance requirements and their assessment.

Business perspective consists of two elements: (1) business models, and (2) business ecosystems and stakeholders, which build on platforms. The proposed business perspective results in the notion of platform-based ecosystemic business models with ecosystem level and stakeholder level analysis. Business perspective is closely linked to the technology perspective since a proper development of business models requires understanding of the capabilities and limitations of technology solutions.

Regulation perspective consists of two elements: (1) understanding of the impact of existing regulations, and (2) defining regulations for future technology solutions. Understanding of the existing regulations is needed for contextual awareness for technology and business development and potential need for refinements in regulations. Regulation perspective is closely related to technology and business perspectives, as regulations govern the

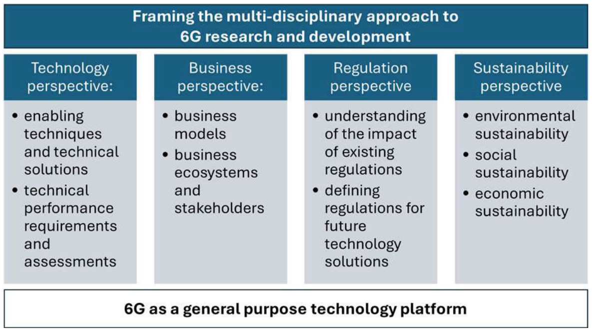


Figure 1.

Proposed framing for multi-disciplinary approach to 6G R&D.

use of technologies thus impacting their development and deployment, and ultimately business.

Finally, sustainability perspective consists of the triple bottom line: (1) environmental sustainability, (2) social sustainability, and (3) economic sustainability. These interrelated elements help to identify factors that influence 6G solutions' handprint and footprint effects over the life-cycle of end-to-end systems. The sustainability perspective is linked to technology perspective by driving sustainable technology development to solve major sustainability challenges. The sustainability perspective is linked to business perspective by redefining principles of making business around sustainability principles and circularity. Finally, the sustainability principle is closely linked to the regulation perspective as regulations on sustainability put requirements on organizations in terms of, e.g., green-house-gas reduction targets.

4. Case Examples

Next, we present two illustrative case examples of 6G, where several of the proposed perspectives are brought together to showcase the multi-disciplinary framing presented in Section 3. These examples include the global IMT-2030 framework for 6G developed at the ITU-R [5] and mobile network operator business model for 6G from [13]. The goal is to illustrate how a topic within mobile communications can be approached from the different perspectives in a coherent manner to discover interdependencies between the individual perspectives and how bringing them together helps to understand and further develop the entire concept.

4.1. Case Example 1: IMT-2030 Framework

The globally agreed framework for 6G is presented in ITU-R IMT-2030 framework recommendation [5]. At the high level, it consists of (1) trends and drivers including motivation and societal considerations and user and application trends, (2) usage scenarios, and (3) capabilities, which reflect performance and value related requirements, as shown in Figure 2.

When analysing the global framework for IMT-2030 (6G), presented in [5] and summarized in Figure 2, it is possible to distinguish that all four perspectives from our proposed framing presented in Section 3 are included, namely technical, business, regulation and sustainability perspectives.

Technical perspective is included in the IMT-2030 framework in the user and application trends, technology trends, usage scenarios, and capabilities parts, where enabling technologies as well as capabilities, which present performance requirements, are presented. In particular, a number of enabling technologies are presented in the technology trends part, which are further detailed in [4].

Business perspective is widely included in the motivation and societal considerations, user and application trends, and usage scenarios parts. Business perspective considers the potential benefits from the use of 6G and presents application areas for the new technology, including example use cases within the envisaged usage scenarios. Business perspective also considers stakeholders in the 6G ecosystem.

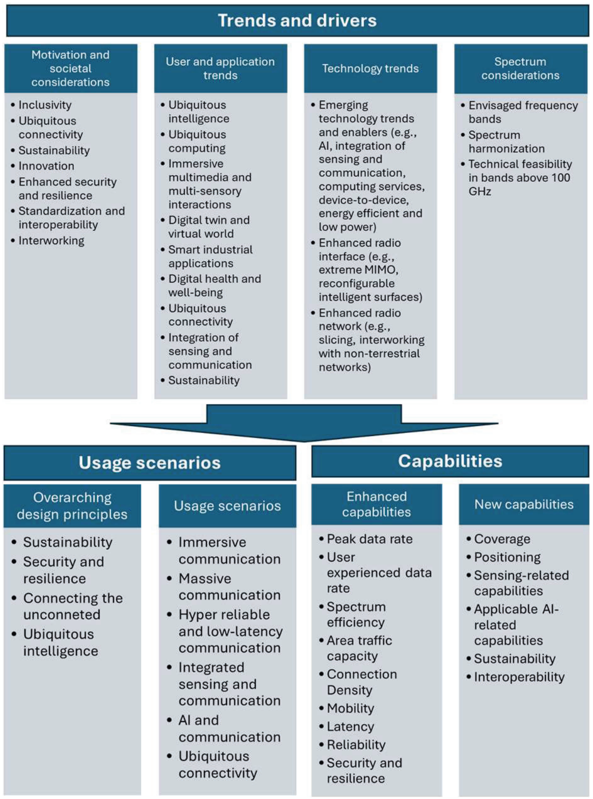
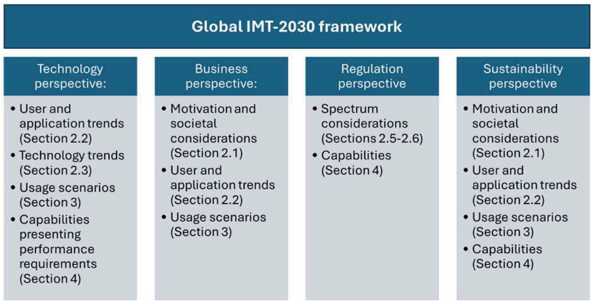


Figure 2.

Global framework for IMT-2030 (6G) based on [5].



Global IMT-2030 framework			
Technology perspective:	Business perspective:	Regulation perspective	Sustainability perspective
• User and application trends (Section 2.2) • Technology trends (Section 2.3) • Usage scenarios (Section 3) • Capabilities presenting performance requirements (Section 4)	• Motivation and societal considerations (Section 2.1) • User and application trends (Section 2.2) • Usage scenarios (Section 3)	• Spectrum considerations (Sections 2.5-2.6) • Capabilities (Section 4)	• Motivation and societal considerations (Section 2.1) • User and application trends (Section 2.2) • Usage scenarios (Section 3) • Capabilities (Section 4)

Figure 3.

Analysis of global framework for IMT-2030/6G from technology, business, regulation and sustainability perspectives.

Regulation perspective can be considered to be included in motivation and societal considerations, spectrum considerations and capabilities parts, showing what can be done and what cannot be done with the new technology. Furthermore, capabilities will be detailed in the future to present technical performance requirements for 6G as a requirement coming from regulation.

Sustainability perspective is included in motivation and societal considerations, user and application trends, overarching design criteria and capabilities, presenting a cross-cutting priority across the entire IMT-2030 framework. For example, in motivation and societal considerations, sustainability covers economic, social and environmental perspectives and highlights energy efficiency, low power consumption, reducing greenhouse gas emissions and use of resources under circular economy to address climate change and contribute towards the achievement of sustainable development goals. Thus, the sustainability perspective in [5] considers environmental, social and economic sustainability perspectives from our framing in Section 3. Additionally, sustainability is presented as an overarching design principle for 6G, spanning across different usage scenarios of 6G together with the need for connecting the unconnected, which is a form of social sustainability requirement for 6G.

As a result, the global 6G framework presented in [5] has captured all four perspectives proposed in our framing, indicating the importance of considering the different perspectives in developing a future-proof communications system.

4.2. Example 2: 6G Mobile Network Operator Business Model

Next, a case example of an envisioned 6G business model for mobile network operators presented in [13] is analysed with respect to our proposed framing from Section 3. The considered 6G MNO business model is a vertical business model (BM), where an enterprise such as the MNO takes control over its suppliers, distributors, or retail locations as part of its supply chain. To be competitive, the company needs to create value for its customers, thereby living in a value-creation economy and being grounded inside its selected verticals.

The considered 6G MNO business model presented in [13] is an evolution of existing MNOs and built on end-to-end value chain controlled by the 6G MNO and supported by specialized firms that are connected to the 6G MNO's connectivity-centered platform. The 6G MNO business model aims to capture value by 'matching' the needs or 'bridging' the customers via the 6G general-purpose technology connectivity platform. Technical features, such as automated network slicing, will be used to offer differentiated services and service levels to different customer segments including closed and open customer groups. The future 6G MNOs are also expected to offer connectivity from a multi-technology platform that consists of a selection of connectivity platforms that vary from low-earth-orbit, drone, and terrestrial 6G to hyper-local networks with a special focus on components and interfaces in the system. 6G MNOs will rely on their existing infrastructure assets on top of which 6G is built.

From the technology perspective, the 6G MNO business model is built on the general-purpose technology 6G platform whose development has followed a global define-standardize-develop-deploy-use cycle of technology commercialization [13]. For a half-century, all major mobile technology providers have relied on licensing as technology value capture mechanism through European Telecommunications Standards Institute (ETSI) third generation partnership project (3GPP) that brings together national standards development organizations to develop technical specifications for mobile communications. ETSI has orchestrated the development and governance of standards, allowing technology contributors to make licenses available on a fair, reasonable, and non-discriminatory (FRAND) basis for a wide variety of implementers globally. This nonexclusive licensing model has enabled a combination of technological co-development and widespread global adoption of mobile communications technologies.

From the business perspective, in the same way as with 5G, the 6G MNO business model considers vertical supply-side incumbent connectivity platform business model, which is represented by the 6G MNO with vertically structured business ecosystem configuration [13]. The vertical model builds on connectivity and cloud technologies with specialized partners that are tightly tethered to the connectivity platform with a deepened value proposition and with an exploration strategy. The model is connectivity-centric and the stakeholders adopting it aim to grow toward supporting content services or acting as a dealer of content such as media.

In the considered 6G MNO vertical business model, the MNO controls its suppliers, complementors, and retailers as part of its supply chain. In the 6G era, MNOs utilize end-to-end value chain controlled by it and supported by specialized firms tethered to MNO's connectivity-centered platform. This model monetizes interaction by matching customer needs with the platform. MNOs are expected to have a multi-technology platform comprising anything from low-earth-orbit, drone, and terrestrial 6G to hyper-local networks. The platform-based 6G ecosystem is expected to include new types of stakeholders, apart from the traditional MNOs and local operators, network constructors, system integrators, developer ecosystems, content owners and dealers, device, equipment, and technology vendors such as semiconductor technology vendors, operating system providers, application interface developers, or human–machine interface providers, cloud platforms and data centers and marketplaces prevalent already in 5G.

From the regulation perspective, the considered vertical 6G MNO business model is built on the existing regulations for mobile communications, where the strong position of incumbent MNOs stems from auction-based spectrum licensing. Additionally, the business needs to take into account not only the existing telecommunication regulations but also new general regulations on data, AI, and security among others, as well as vertical specific regulations when using 6G in different sectors of society. The business model is restricted by a number of regulations, whose impacts on the business are significant.

Finally, the sustainability perspective is considered in the analysed vertical 6G MNO business model covering primarily the economic sustainability perspective in business model elements such as value, costs and revenues. Environmental and social sustainability perspectives are considered only indirectly, noting that MNOs have increasing interest to reduce their energy consumption and other environmental footprints.

To conclude our analysis, the framing proposed in Section 3 can be found in both considered examples covering all proposed four perspectives: technology, business, regulation and sustainability. The IMT-2030 framework [5] has specific parts considering technology, business and sustainability perspectives, while the regulation perspective is more embedded in the framework. The 6G MNO business model [13] focuses on business perspective and has clear linkages to technology and regulation perspectives, while the sustainability perspective is more embedded in the model.

5. Conclusion

6G R&D calls for a multi-disciplinary approach that brings together different expertise areas across disciplinary boundaries representing different stakeholders to develop future-proof telecommunication solutions for the next decade. Our proposed multi-disciplinary approach to 6G consists of technical, business, regulation and sustainability perspectives, which were brought together to form a holistic multi-disciplinary framing for 6G R&D. This paper has further illustrated the key elements of these four perspectives through case examples of the global IMT-2030 framework and 6G mobile network operator business model. Both analysed case examples cover the four proposed perspectives to different levels of depth, indicating the importance of considering multiple perspectives in developing future proof communications systems. Future work is needed to promote multi-disciplinarity and inter-disciplinarity in 6G R&D integrating these four perspectives, especially to properly address sustainability challenges of different sectors of society as well as of 6G itself. In particular, research expanding future business cases is needed.

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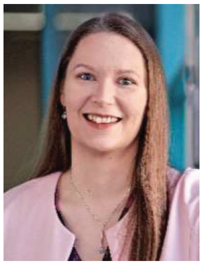
Biographies



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WIRELESS WORLD
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BITS Pilani Hyderabad Campus, Hyderabad, India
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As we transition toward the next generation of wireless systems, the world is facing unprecedented challenges that demand innovative and holistic solutions. The explosive growth of wireless data, the need for hyper-connectivity, and the push towards more intelligent systems have brought us to a pivotal moment. Emerging technologies such as 6G, AI-driven networks, and ubiquitous IoT hold immense potential for advancing societies, but they must be developed with sustainability at the forefront. The global emphasis on reducing carbon emissions and achieving environmental sustainability necessitates a shift toward greener communication systems. Wireless networks of the future must not only deliver higher speeds and lower latency, but must do so in an energy-efficient and environmentally conscious manner. Furthermore, the future wireless ecosystem must prioritize inclusivity, ensuring that the benefits of advanced technologies are accessible to communities worldwide, contributing to an overall collective prosperity.

The 53rd Wireless World Research Forum (WWRF) conference will serve as a hub for researchers, innovators, and thought leaders to exchange ideas, present latest findings, and collaborate on solutions that will enable smart wireless systems to drive both technological advancement for new business opportunities and social well being. In this spirit, the forum aims to bridge the gap between the development of future networks and the urgent need for sustainable, secure, and equitable solutions.

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- Standards: Current Roadmap and Future Progress
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- Intelligent applications for vertical industries
- Data analytics, AI, and machine learning for sustainability and network automation
- Edge Computing and Intelligence
- Software-defined infrastructures
- Advanced radio technologies
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- Tactile Internet
- THz communications
- Cyber-physical systems and networks
- Privacy and security
- Connected vehicles
- Holographic MIMO
- Reconfigurable intelligent surfaces
- Applications and impact of quantum-based technologies
- Semantic communications
- Spectrum sharing, issues and regulatory principles
- Social network-aware wireless
- Internet of Things and wearable technologies
- Quantum communications
- Cybersecurity in 6G and Future Networks
- AI/ML for wireless communications and networking
- Intent Based Networking

Authors are expected to be physically present at the meeting to present their contributions.

SUBMISSION INSTRUCTIONS

Contributors should submit an extended abstract by 15 December 2025 for review. Extended abstracts should preferably be at least two pages in length, either in plain ASCII text, MS Word or Adobe PDF. A template for abstract and submissions details are available in WWRF53 website (https://www.bits-pilani.ac.in/wwrf53). The following list shows the different working groups (WGs) and Vertical Industry Platforms (VIPs) to one of which the contributions should be directed:

- WG A/B – User Needs & Requirements, Services and Devices in a Wireless World
- WG C – New Directions in Communication Architectures and Technologies, including SON, NFV and MEC
- WG D – Radio Communication Technologies: Air Interfaces for 6G, advance wireless access techniques, MIMO, Reconfigurable Intelligent Surfaces, Radio Resource Management, SDR and Spectrum Sharing
- WG BM – Future Business Models supported and enabled by SG and Beyond wireless technologies
- WG HF – High-Frequency Technologies: mm Wave and THz Communications and Sensing
- VIP WG Digital Health
- VIP WG Connected Vehicles
- VIP WG Track-to-Train communications
- WG Cybersecurity
- WG6G
- New NTN WG

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Selected papers will be invited for a full paper submission in Springer as well as in the newly-launched WWRF journal Wireless World Research and Trends (WWRT).

IMPORTANT DATES

Abstract Deadline	**20th December 2025**
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Early registration	**25th January 2025**
Final Abstract and Copyright Licence Submission	**8th February 2025**
Event	**18th-20th February 2025**

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STUDENT GRANTS

Limited funding is available to support a number of students travelling and presenting papers at the meeting. Application for student funding must be provided with a paper submission. The level of the grant will depend on available funds and the student's country of residence. Priority will be given to students from WWRF member organizations.

Recent and Upcoming Events of Interest (Provided by WWRF Members)

No	Event	Date/Venue	Member	Website
1	International Mobile Telecommunications Forum South Africa IMT Forum SA	07–08 November 2024, Cape Town, Africa	Ramasela Matlou, ICASA	
2	FOKUS FUSECO Forum: Forward to 6G!	Nov. 7–8, 2024, Fraunhofer FOKUS in Berlin	Fraunhofer-Institut fuer Offene Kommunikationssysteme FOKUS	www.fuseco-forum.org
3	CGC 6G Briefing	12–13 November 2024, Sao Paulo, Brazil	Nigel Jefferies, HuaweiSudhir Dixit, Basic Internet Foundation	https://ctifglobalcapsule.org/event/5667/
4	Towards Network of Intellengence	November 14–15 2024 Abu Dhabi, UAE	Sudhir Dixit, Basic Internet Foundation	https: //www.6gsummitabudhabi.com/
5	WP5A	November 19–29, 2024, Geneva	Bharat Bhatia, ITU-APT Foundation of India	https://www.itu.int/en/events/Pages/Calendar-Events.aspx?sector=ITU-R&group=R23-WP5A
6	SG 5	2–3 December 2024, Geneva	Bharat Bhatia, ITU-APT Foundation of India	
7	Connected Vehicle Panel	December 15–18, 2024, IIT Guwahati, India	Seshadri Mohan	https://ants2024.ieee-ants.org/
8	Research Advancements in AI and Future Communication Technologies for Healthcare (RAFCATH)	January 13th 2025 Las Vegas, Nv, USA	Rehan Usman, Kingston University, UK	https://ccnc2025.ieee-ccnc.org/
9	WP5D	4–13 February 2025, Geneva	Nigel Jefferies, Huawei	https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/Pages/default.aspx
10	WWRF53	Febuary 18–20, 2025, BITS, Pilani, Hydrabad, India	Paresh Saxena, BITS Palani	
11	Satellite 2025 conference	March 10–13, 2025, Washington Convention Center Washington, DC		https://www.satshow.com/
12	IEEE DySPAN 2025	May 12–15, 2025 UK-Central London	Raviraj Adve and Ali Fazeli, University of Toronto, Publicity Chair, IEEE DySPAN 2025	https: //dyspan2025.ieee-dyspan.org/
13	WP5D	June 25th – July 02 2025, Japan	Nigel Jefferies, Huawei	https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/Pages/default.aspx

No	Event	Date/Venue	Member	Website
14	WP5D	7–16 October 2025, TBD	Nigel Jefferies, Huawei	https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/Pages/default.aspx
15	SG5	December 1st 2025, TBD	Bharat Bhatia, ITU-APT Foundation of India	
16	WTDC	November 17–28, 2025, Bako, Azerbaijan	Nigel Jefferies, Huawei,Bharat Bhatia, ITU-APT Foundation of India	
17	PP-26	November 9–27, 2026, Doha, Qatar	Nigel Jefferies, Huawei,Bharat Bhatia, ITU-APT Foundation of India	
18	IEEE Consumer Communications & Networking Conference	10–13 January 2025, Las Vegas, NV, USA	Nigel Jefferies, Sudhir Dixit, Rehan Usman	https://ccnc2025.ieee-ccnc.org/
19	WRC 2027	October 18 – November 12, 2027	Nigel Jefferies, Huawei, Bharat Bhatia, ITU-APT Foundation of India	

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