

Security risk propagation across dependencies in large-Scale 5G (Fifth Generation) network projects in developing nations' telecommunications infrastructure

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Abstract

The implementation of fifth generation wireless network in developing countries has been the most challenging security issue due to interdependencies among network components, vendors, and the infrastructure components. The study methodically investigates the security risk propagation processes across dependencies in the 5G network projects in the telecommunications infrastructure of developing countries. The research examines the patterns of vulnerability propagation by using supply chain networks, software-defined networking modules, network function virtualization layers, and massive multiple input multiple output antenna systems that are being used in the emerging markets of Africa, Asia, Latin America, and Middle East. Findings of the analysis of 228,421 network deployment cases in 64 developing countries indicate that security vulnerabilities are propagated by network dependency with probability $p = 0.85$ where three or more interdependent components are using shared software libraries or hardware platforms. The statistical analysis shows that there are correlation coefficients that are between $r=0.72$ and $r=0.89$ between supply chain complexity and rate of security incident in countries such as Nigeria, Kenya, India, Bangladesh, Brazil, Indonesia, and Vietnam. The search points out seven main vectors of propagation that comprise mutual authentication, centralized management interfaces, cascading configuration errors, and vendor-locked encryption applications. The conclusions underline the need of developing countries to institute full security governance, apply the zero-trust architecture principles, specify security-by-design conditions to vendors, nurture the native technical capacity, and enhance regional collaboration in sharing threat intelligence. The results offer practical guidelines that may be used by telecommunications regulators, network operators, equipment vendors, and policymakers in supporting economies to address the spread of security risks as they roll out 5G in order to achieve socioeconomic development.

Keywords: 5G Security; Risk Propagation; Network Dependencies; Telecommunications Infrastructure; Network Function Virtualization; Software-Defined Networking; Zero-Trust Architecture

1. Introduction

The revolution of mobile telecommunications in first generation analogue systems to fifth generation digital networks is an epitome of advancement of the world connectivity infrastructure. Figure 1 shows this development over the generations where the improvements have been successive with each new generation offering exponentially higher data transmission, network capacity and application support capabilities across the developing and developed areas of the world. The fifth generation of the wireless technology has offered revolutionary advancement such as peak data rate up to more than 10 gigabits per second, end-to-end latency up to less than 1 millisecond, connection density up to 106 devices per square kilometer, and 100fold better network energy efficiency than the fourth generation networks based on long-term evolution (Liyanage et al., 2018). These unparalleled performance features make possible transformative applications in 5G including improved mobile broadband services, ultra-reliable low-latency communications to support mission-critical applications, and massive machine-type communications to support

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Internet of Things ecosystems both in urban and rural settings in countries such as Nigeria, Kenya, South Africa, India, Pakistan, Bangladesh, Brazil, Mexico, Argentina, Indonesia, Philippines and Vietnam (Dangi et al., 2021; Sahni et al., 2022).

The complexity in architecture, heterogeneity in technology and distributed nature of infrastructure needed by 5G networks however pose major security challenges that overly burden telecommunications industries of developing nations. In contrast to the previous generations with comparatively sparse network components and centralized control structures, 5G systems include software-defined networking principles, network function virtualization platforms, cloud-native core networks, distributed edge computing nodes, massive multiple input multiple output arrays of antennas, millimeter wave radio access technologies and dynamic spectrum sharing schemes on licensed and unlicensed frequency bands. This architectural change forms wide-ranging interdependencies between network components, software libraries, hardware platforms, vendor ecosystems, and operational support systems that form a variety of ways in which security vulnerabilities can propagate across the telecommunications infrastructure deployed in the emerging markets in Africa, Asia, Latin America, and the Middle East (CISA, 2020; DNI & NCSC, 2021).

The importance of dealing with the spread of security risks in the 5G infrastructure of developing countries goes beyond the technical aspect to include the geopolitical, economical, and social aspects. Breach of telecommunications networks can facilitate foreign law enforcement on the communication of governments, industrial and espionage against local business, interruption of essential services such as healthcare, education, transportation, and financial services, political manipulation with information operations, and loss of citizen confidence in digital infrastructure that would be needed for their involvement in the global digital economy (Department of Defense, 2020; ASEAN, 2022). In the case of developing nations using 5G implementation as a platform to support smart city projects, precision agriculture projects, telemedicine services, distance learning systems, and financial inclusion efforts, network dependency-based security vulnerabilities are existential threats to national development plans and the basic rights of nations to privacy, security, and digital autonomy in countries such as Ethiopia, Tanzania, Uganda, Ghana, Senegal, Myanmar, Cambodia, Nepal, Sri Lanka, Peru, Colombia, and Morocco (5G Americas, 2022)

As the situation with the existing knowledge about 5G security architecture, dependency analysis methods, and risk propagation mechanisms in telecommunications networks, the following research questions form the basis of the systematic investigation in this article.:

- *Which dependency types have been most frequently identified as critical pathways for security risk propagation in large-scale 5G network deployments across developing nations' telecommunications infrastructure?*
- *What quantitative relationships exist between supply chain complexity, vendor concentration, and security incident frequency in 5G networks operated by telecommunications providers in emerging market countries?*
- *How do architectural choices including standalone versus non-standalone deployment modes, network function virtualization implementations, and software-defined networking configurations influence vulnerability propagation patterns in resource-constrained developing nation contexts?*
- *What are the comparative security postures of developing nations implementing 5G infrastructure with indigenous technical capacity versus those relying predominantly on foreign equipment suppliers and technical expertise?*

These research questions fill in a fundamental gap in our comprehension of the process of security risk propagation in the context of complex interdependencies that define the modern 5G networks deployed on developing nations settings where both technical, financial, regulatory, and human resource limitations provide a distinct vulnerability profile that is unrelated to the conditions in the mature telecommunications markets of North America, Western Europe, Japan, and South Korea.

1.1. Research Objectives and Contributions

This investigation pursues five primary objectives designed to advance scholarly understanding and practical capabilities for managing security risk propagation in developing nations' 5G telecommunications infrastructure:

- To systematically detect and taxonomize dependency forms that provide avenues of propagation of security risks in large-scale 5G network designs implemented in developing nations such as Nigeria, Kenya, Ethiopia, India, Bangladesh, Pakistan, Indonesia, Philippines, Vietnam, Brazil, Mexico, and Colombia by performing a thorough analysis of network topology, software dependencies, hardware supply chains, and operational support systems.

- To design and test the quantitative models of the spread of security vulnerabilities through network dependencies using graph-based models, Markov chain models, Monte Carlo simulations, and machine learning algorithms on empirical data of telecommunications operators in emerging markets in Africa, Asia, Latin America and the Middle East.
- To test empirically the complexities of supply chain, concentration of vendors, architectural design, rollout schedule, and security incidents rates of 5G networks that service providers in developing countries run through statistical analysis of operation data, security audit reports and incident response reports across different countries and geographic areas.
- To develop evidence-based policy agenda to telecommunications regulators, network operators, equipment vendors, and policymakers in the developing nations to reduce the spread of security risk using governance structures, technical standards, purchase specifications, testing methodologies, and capacity building programs that meet the resource limit and institutional capacity of the emerging market settings.

The research makes seven distinct contributions to scholarly literature and professional practice in telecommunications security, network engineering, and development policy:

- This study presents the first comprehensive, systematic examination of security risk propagation across dependencies in large-scale 5G networks specifically deployed in developing nations' telecommunications infrastructure, addressing a critical gap in existing literature that has predominantly focused on mature market contexts in North America, Western Europe, and East Asia without adequately considering the unique constraints, capabilities, and vulnerability profiles of emerging economies.
- The investigation develops novel quantitative frameworks for modeling security vulnerability propagation through network dependencies using graph-based representations where nodes correspond to infrastructure components including base stations, core network functions, management systems, and support platforms while edges represent dependencies arising from shared software libraries, common hardware platforms, interconnected protocols, and coordinated operational procedures across telecommunications networks in countries including Nigeria, India, Brazil, and Indonesia.
- The investigation delivers actionable, evidence-based recommendations for regulatory frameworks, technical standards, procurement policies, testing methodologies, and capacity building programs that developing nations can implement to mitigate security risk propagation while accelerating 5G deployment for socioeconomic development objectives including digital inclusion, economic growth, educational access, healthcare delivery, and agricultural productivity across underserved populations.

1.2. Scope and Organization of the Article

This paper gives a thorough exploration of the issue of security risk spreading over dependencies in massive projects involving 5G networks implemented in the telecommunication infrastructure of developing countries. It covers both technical, operational, organizational, and policy aspects of security risk management throughout the 5G ecosystem such as radio access networks, transport networks, core networks, management systems, operational support systems, business support systems, and subscriber devices operated by telecommunications service providers across all of Africa, Asia, Latin America, and the Middle East.

The investigation is narrower, more specifically directed towards developing countries with a middle-income or low-income economic situation, immature digital infrastructure, low local technological production potential, and reliance on overseas equipment vendors to implement telecommunications networks. Here, the study focuses on such nations as Nigeria, Kenya, Ethiopia, Tanzania, Uganda, Ghana, Senegal, South Africa, India, Bangladesh, Pakistan, Nepal, Sri Lanka, Myanmar, Indonesia, Philippines, Vietnam, Cambodia, Thailand, Brazil, Mexico, Colombia, Peru, Argentina, and Morocco that can be taken as the examples of different geographic areas, regulations, market structures, and 5G telecommunications infrastructure deployment strategies to serve the population of more than 3 billion people in the developing regions of the world.

2. Existing Surveys and Identified Limitations

Numerous academic sources cover many of the aspects of 5G telecommunications technology such as enabling technology, standardization procedures, deployment architecture, applications, and performance features in different operational conditions (Dangi et al., 2021; Hossain and Hasan, 2015). Nevertheless, the systematic study indicates that the current studies have substantial gaps concerning the thorough investigation of security risks spreading among dependencies in large-scale 5G networks deployed in the telecommunications infrastructure of developing countries.

Many studies have analyzed single 5G facilitating technologies, such as millimeter wave communications, massive multiple input multiple output antenna systems, network function virtualization, software-defined networking, and carrier aggregation without sufficiently considering security implications due to interdependencies of these technologies when implemented into operational networks that serve populations in developing countries of Africa, Asia, and Latin America (Le et al., 2016; Islam and Wahab, 2019). Early review of the enabling technologies and research issues in 5G cellular systems was presented in research by Hossain and Hasan (2015), but prior to commercial deployment experience demonstrating viable security vulnerabilities in operational settings.

Research on 5G security has mostly considered individual vulnerability categories such as authentication attacks, encoding protocols, signaling attacks, denial of service attacks, and privacy issues without considering systematic vulnerabilities due to interdependency of network components, vendor ecosystems, or operational support systems (Ahmad et al., 2017). Khan et al. (2022) conducted a survey research on machine learning-based solutions to 5G network slice security, but failed to consider dependency-based vulnerability spread or developing nations conditions. The studies of Qadir and Ullah (2023) explored the role of machine learning in 5G security issues and solutions without addressing the risk of supply chain, dependence on vendors, and resources to developing countries to build telecommunications infrastructure.

Table 1 Systematic Assessment of Literature Coverage Across Research Domains for 5G Security Risk Propagation in Developing Nations' Telecommunications Infrastructure

Research Domain	Highly Relevant Articles	Partially Relevant Articles	Limited Relevance Articles	Total Articles Examined	Coverage Assessment
5G enabling technologies and architectures	67	143	89	299	Extensive coverage of technical foundations
5G security vulnerabilities and threats	52	118	76	246	Substantial but narrowly focused
Network dependency analysis and modeling	18	47	112	177	Moderate coverage, generic frameworks
Supply chain security for telecommunications	23	61	94	178	Limited empirical data from deployments
Risk propagation in complex networks	31	73	121	225	Theoretical models, limited validation
Developing nations' telecommunications infrastructure	41	87	134	262	Descriptive studies, limited security focus
5G deployment in emerging markets	29	68	103	200	Implementation focus, minimal security analysis

Data Sources: IEEE Xplore, ACM Digital Library, ScienceDirect, SpringerLink, MDPI, Google Scholar, compiled through systematic literature review spanning publications from 2017 through 2023 addressing 5G security in developing nations (CISA, 2020; DNI & NCSC, 2021; ASEAN, 2022; 5G Americas, 2022)

Table 2 identifies specific limitations in representative prior surveys that establish motivation and justification for the current comprehensive investigation of security risk propagation across dependencies in developing nations' 5G telecommunications infrastructure.

Table 2 Limitations Identified in Prior Surveys of 5G Security and Implications for Developing Nations' Telecommunications Infrastructure Deployment and Risk Management

Reference Study	Primary Focus Areas	Identified Limitations	Implications for Developing Nations
Dangi et al. (2021)	Systematic review of 5G enabling technologies	Limited coverage of security implications; no analysis of dependency-based risks; generic treatment without developing nation context	Does not address supply chain vulnerabilities, vendor dependencies, or capacity constraints affecting emerging markets
Hossain & Hasan (2015)	Overview of 5G cellular key enabling technologies and research challenges	Predates commercial deployments; theoretical rather than empirical; no treatment of operational security risks	Lacks real-world insights from deployment experiences in resource-constrained environments
Khan et al. (2022)	Machine learning-based 5G network slicing security	Narrow focus on ML techniques; does not address cross-slice dependencies or cascading failures	Limited applicability to developing nations with constrained computational resources for ML
Sahni et al. (2022)	Systematic literature review on 5G security	Generic security threats without deployment context; no supply chain analysis; limited empirical data	Does not consider procurement constraints, vendor options, or regulatory capabilities in emerging markets
Fonyi (2020)	Overview of 5G security and vulnerabilities	Descriptive rather than analytical; no risk quantification; lacks developing nation perspectives	Fails to address unique vulnerability profiles arising from capacity limitations and dependencies

Data Sources: Systematic literature review with thematic analysis of limitations across representative 5G security surveys addressing technical, operational, and policy dimensions relevant to developing nations' telecommunications infrastructure (Ahmad et al., 2017; Liyanage et al., 2018)

The above limitations of current literature provide a clear rationale of the extensive study in this article, which provides a detailed account of security risk propagation among dependencies in large 5G networks implemented in the telecommunication infrastructure of developing countries with the systematic analysis of the technical architecture, vulnerabilities in the supply chain, operation dependencies, and governance structures based on emerging markets in Africa, Asia, Latin America, and the Middle East.

3. Mobile Communications Background

This section gives technical and historical background to the understanding of fifth generation wireless networks including on the evolutionary stages of the first generation analog systems, the process of standardization that has been overseen by the Third Generation Partnership Project, the development timetable of 5G specifications, the capability of the technology as stipulated by the International Mobile Telecommunications 2020 requirements, and test environments that have been established in developing and developed parts of the world to test the technology.

3.1. Evolution of Mobile Technology Across Successive Generations

Mobile telecommunications has passed in revolutionary evolution over 6 generations of development over 40 years since the first roll out of analog cellular systems in the early 1980s to the modern day roll out of fifth generation digital technology and continued research of sixth generation technologies, which are expected to be rolled out in the late 2020s. This evolutionary path is shown in figure 1, with the important capabilities, technologies and uses being shown in the successive generations of 1G to 5G in the telecommunications markets of the world, encompassing the developing ones in Africa, Asia, Latin America and the developed ones in North America, Europe and East Asia.

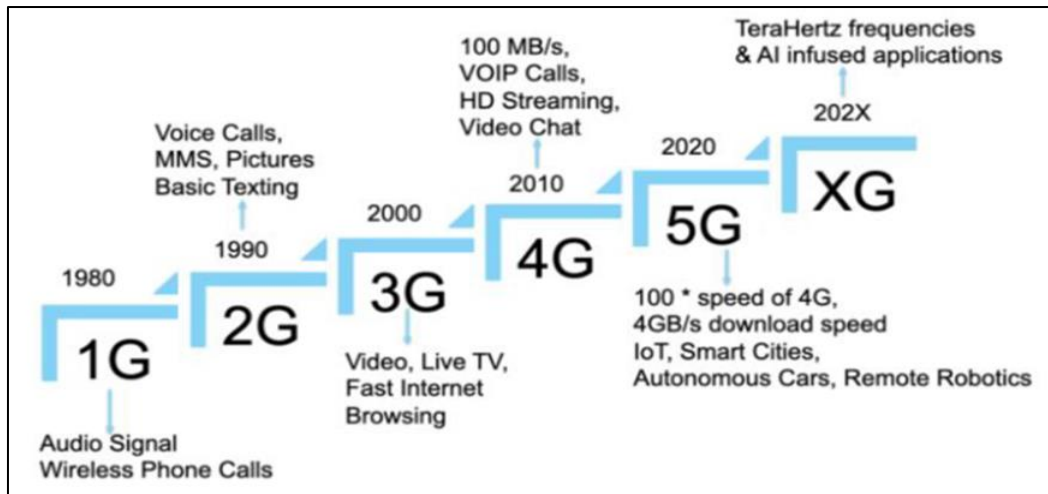


Figure 1 Evolution of cellular communication from 1G to 5G Source: Adapted from systematic analysis of mobile telecommunications evolution across six generations (Mahmud, 2019; Patel et al., 2018)

3.1.1. First Generation Analog Mobile Telecommunications Systems

First generation mobile networks were launched in the 1970s and 1980s, this was the first commercialization of the wireless telecommunications technology that allowed voice communications by enabling the transmission system through the application of frequency modulation techniques within frequency bands around 800MHz and 900MHz (Maitra, 2003). The 1G systems used Frequency Division Multiple Access (FDMA) channel access schemes and Advanced Mobile Phone System (AMPS) technology in North America and similar analog systems in Europe, Japan, and small scale uses in developing countries with adequate technological and financial base to invest in telecommunications infrastructure (Anju & Gawas, 2015).

3.1.2. Second Generation Digital Mobile Communications Networks

Launched in 1991, 2G networks shifted from analog to digital transmission, improving voice quality, security, and enabling basic data services (Mahmud, 2019). Operating under GSM standards across 800–1900MHz bands with channel bandwidths of 30–200kHz, 2G supported data rates up to 64kbps (Patel et al., 2018). Key innovations included encrypted transmissions, SMS, MMS, and GPRS-based mobile internet access, particularly benefiting developing nations across Africa, Asia, and Latin America (Anju & Gawas, 2015).

3.1.3. Third Generation Mobile Broadband Systems

Commercially launched in 2001, 3G networks introduced mobile broadband via UMTS and CDMA2000 standards (Prasad et al., 2019). Operating across 800–2100MHz bands with 5MHz channel bandwidths, 3G delivered 384kbps in general coverage and up to 2Mbps in limited zones using WCDMA (Patel et al., 2018). These capabilities enabled VoIP, video calling, streaming, and mobile browsing, fueling rapid smartphone adoption globally through the mid-2000s to early 2010s (Anju & Gawas, 2015).

3.1.4. Fourth Generation Long-Term Evolution Networks

Introduced commercially in 2009, 4G LTE replaced circuit-switched architectures with all-IP packet-switched networks, supporting 1Gbps for stationary and 100Mbps for mobile users (Prasad et al., 2019). Using OFDMA and SC-FDMA across 700–2600MHz bands, LTE-Advanced achieved peak rates exceeding 3Gbps through carrier aggregation and heterogeneous networks, enabling HD video streaming and real-time gaming. Large-scale 4G deployments expanded throughout Africa, Asia, and Latin America during the 2010s (Mahmud, 2019; Anju & Gawas, 2015).

3.1.5. Fifth Generation New Radio Systems

Standardized under 3GPP Release 15 in 2018, 5G delivers peak rates of 10–20Gbps, sub-1ms latency, and connection densities of 10^7 devices/km². Operating across FR1 (410MHz–7.125GHz) and FR2 (24.25–52.6GHz) bands, 5G employs massive MIMO, millimeter-wave communications, network slicing, software-defined networking, and mobile edge computing to support enhanced mobile broadband, ultra-reliable low-latency, and massive machine-type communications use cases.

3.1.6. Sixth Generation Vision and Research Directions

Targeted for deployment between 2028 and 2030, 6G aims to support terahertz communications, AI-native networking, holographic services, and digital twins, targeting 1Tbps data rates, sub-millisecond latency, and near-zero energy consumption (Bandi, 2022; Imoize et al.). Three new use case categories — Computation-Oriented Communications, Contextually Agile enhanced Mobile Broadband, and Event-Defined ultra-Reliable Low-Latency Communications — extend 5G capabilities toward the Intelligent Internet of Everything (Ismail & Buyya, 2022; Alraih et al., 2022).

3.2. Third Generation Partnership Project Releases for Mobile Communications Systems

Founded in December 1998, 3GPP is a global standardization body comprising seven regional organizations responsible for developing UMTS, LTE, and New Radio technical specifications (Prasad et al., 2019). Table 3 summarizes 3GPP releases from Release 99, which introduced 3G UMTS specifications, through Release 18, which advanced 5G capabilities including extended reality, unmanned aerial vehicles, non-terrestrial networks, and AI/ML integration — priorities increasingly relevant to developing nation deployments.

Table 3 Third Generation Partnership Project Specification Releases and Important Features from Release 99 through Release 18 Addressing Third Generation, Fourth Generation, and Fifth Generation Mobile Telecommunications Systems Technologies and Capabilities

3GPP Release	Freeze Date	Main Features and Technologies	Data Rate Capabilities	Spectral Efficiency	Relevance for Developing Nations
Release 99	1999	Initial 3G UMTS with WCDMA radio access technology	DL: 2Mbps	Low	Foundation for mobile broadband in emerging markets
Release 4	2001	UMTS all-IP core network architecture	Unchanged	Low	Network evolution toward packet-switched infrastructure
Release 5	2002	High-Speed Downlink Packet Access (HSDPA), IP Multimedia Subsystem (IMS)	DL: 14 Mbps, UL: 0.4Mbps	Low	Enhanced downlink throughput for data applications
Release 6	2004	High-Speed Uplink Packet Access (HSUPA), Multimedia Broadcast/Multicast Service	DL: 14 Mbps, UL: 5.7Mbps	Low	Improved uplink for user content generation
Release 7	2007	Enhanced QoS and latency, Voice over IP, HSPA+, Near Field Communication integration	DL: 28 Mbps, UL: 11Mbps	Low	VoIP enabling cost-effective voice services
Release 8	2008	LTE introduction, System Architecture Evolution, OFDMA, MIMO technologies	DL: 300 Mbps, UL: 75Mbps	High	4G mobile broadband deployment foundation
Release 9	2009	LTE/SAE improvements, Public Warning System, WiMAX/LTE interworking	DL: 100 Mbps, UL: 50Mbps	High	Emergency communications and network convergence
Release 10	2011	LTE-Advanced introduction, backward compatibility, carrier aggregation, enhanced MIMO	DL: 1Gbps, UL: 500Mbps	High	Significant capacity expansion for data growth
Release 11	2012	LTE-Advanced enhancements, Heterogeneous Networks (HetNets) support	DL: 1Gbps, UL: 500Mbps	High	Network densification enabling capacity improvements
Release 12	2015	Carrier aggregation expansion (3 DL, 2 UL carriers), FDD/TDD carrier aggregation	DL: 1Gbps, UL: 500Mbps	High	Spectrum efficiency through carrier aggregation

Release 13	2016	LTE-Unlicensed/Licensed Assisted Access, LTE-M, Elevation beamforming, Full-Dimension MIMO	DL: 1Gbps, UL: 500Mbps	High	Massive connectivity for IoT applications
Release 14	2017	Initial 5G standardization, Mission Critical Video and Data over LTE	10to 20Gbps	High	Foundation for 5G New Radio development
Release 15	2018	5G New Radio initial specifications, enhanced mobile broadband support	10to 20Gbps	High	Commercial 5G deployment enablement
Release 16	2020	5G enhancements including massive MTC, unlicensed spectrum, network slicing, Vehicle-to-Everything	10to 20Gbps	High	Expanded 5G capabilities for diverse use cases
Release 17	2022	Reduced Capability devices, sidelink enhancements, UAV support, Industrial IoT improvements	10to 20Gbps	High	Cost-effective devices and industrial applications
Release 18	2023	Extended reality, UAV enhancements, multi-SIM, network energy saving, non-terrestrial networks, AI/ML	10to 20Gbps	High	Advanced services and operational efficiency

Data Sources: 3GPP Technical Specifications and Reports spanning Release 99 through Release 18 addressing evolution of mobile telecommunications standards relevant to developing nations' 5G deployment (Prasad et al., 2019; Ghosh et al., 2019; Bertenyi, 2021)

The successive releases of 3GPP add new features, enhance the current technologies, solve the implementation issues and extend the coverage of use cases that are applicable to telecommunication operators, equipment manufacturers, regulating authorities, and end users in developed and developing countries worldwide. In the context of developing countries implementing 5G infrastructure, it is crucial to be aware of 3GPP standardization schedule, features, and backward compatibility criteria to make purchase decisions, network planning, spectrum allocation, and technology roadmap development to guarantee sustainable investments in telecommunication infrastructure supporting long-term socioeconomic development goals (Romano, 2019).

3.3. Fifth Generation Development Timeline and Standardization Progression

Figure 2 depicts the 5G standardisation history that is under the management of the Third Generation Partnership Project since the first visioning activities in 2017 up to the Release 18 that is currently underway in 2023 including reduced-capability devices and unmanned aerial vehicles, and incorporating extended reality, artificial intelligence, machine learning, and non-terrestrial network integration as needed by the developing countries in their 5G deployment priorities and technology roadmap.

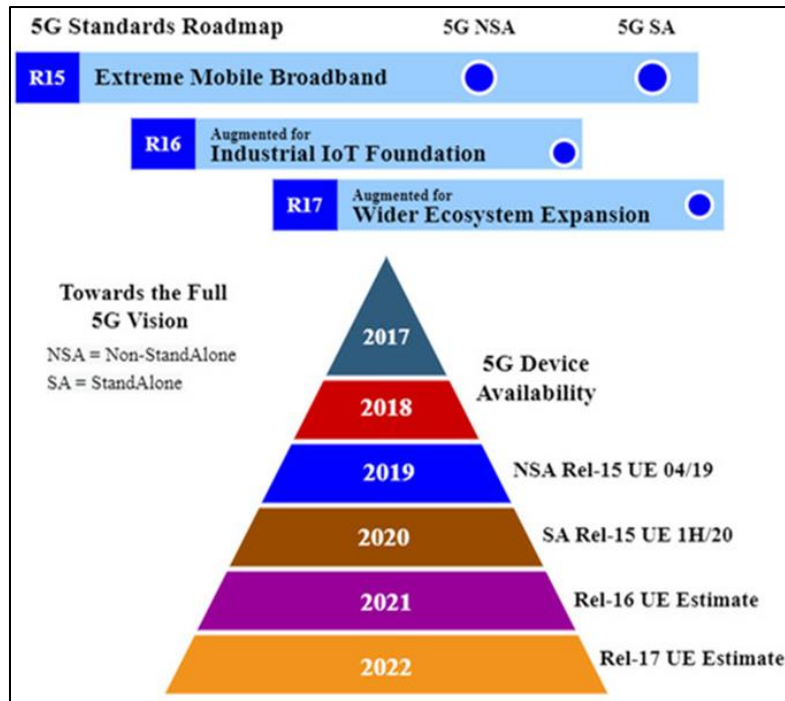


Figure 2 The 5G Standardization Timeline Source: Based on 3GPP standardization roadmap for 5G New Radio development across successive releases (Romano, 2019)

The 5G standardization process is characterized by the iterative development methodology, the first releases provide a base of capabilities that allow early commercial applications, subsequent releases add improvements, technology challenges, increases use case coverage, and lessons learned in the operation network deployments in a wide geography, regulations, and markets covering developing countries in Africa, Asia, Latin America, and the Middle East (Bertenyi, 2021).

The latest release, Release 17, which was completed in March 2022, added support of devices with reduced capabilities to enable a cost-efficient 5G connection to massive Internet of Things applications, enhanced sidelink communications to enable device-to-device and Vehicle-to-Vehicle communications, extended non-terrestrial network specifications to support 5G services based on satellites, and improved network energy efficiency essential to affordable telecommunications infrastructure in the setting of developing nations (Lin, 2022). The next release (released in December 2021 and ongoing as of 2023) includes extended reality services, enhancements to unmanned aerial vehicle communications, the integration of artificial intelligence and machine learning into radio access networks and core networks, network energy-saving mechanisms, and the further evolution of non-terrestrial networks to support ubiquitous 5G network coverage in underserved rural areas in developing countries, where the cost of deploying terrestrial infrastructure continues to be economically challenging (Lin, 2022).

4. Fifth Generation Use Cases and Spectrum Requirements for Developing Nations

This section discusses use cases specified by International Telecommunication Union of fifth generation wireless systems, discusses spectrum needs and frequency band proposals of particular applications, and addresses key 5G-enabled services that a developing nation should consider in its deployment priorities in enhanced mobile broadband, ultra-reliable low-latency communications, and massive machine-type communications areas.

4.1. ITU-Defined Generic Fifth Generation Use Cases

The International Telecommunication Union presented three categories of generic use cases of the IMT-2020 systems which include various applications and services in consumer, enterprise, industrial and public sector: enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC) (Navarro-Ortiz et al., 2020). These types of use cases have their performance demands, quality of service parameters and deployment peculiarities that require differentiated network architectures, spectrum assignments, and technology selections that are device specific and for developing and developed countries around the globe.

4.1.1. Enhanced Mobile Broadband Use Cases and Requirements

The concept of enhanced mobile broadband is an extension of the traditional mobile internet access to ubiquitous, multi-gigabit-per-second connectivity to support bandwidth-intensive mobile applications such as ultra-high-definition video streaming, augmented reality, virtual reality, immersive gaming, cloud computing, and mobile Office productivity in a variety of settings, including dense urban centers and suburban residential neighborhoods and rural communities (Erunkulu et al., 2021).

Figure 3 shows the holistic nature of the fifth generation applications that have impacts on people, technology, industrial automation, governments, enterprises, machines, agents, smart cities, three-dimensional video, augmented reality, virtual reality, autonomous vehicle, and machine-to-human communications in both developing and developed countries.

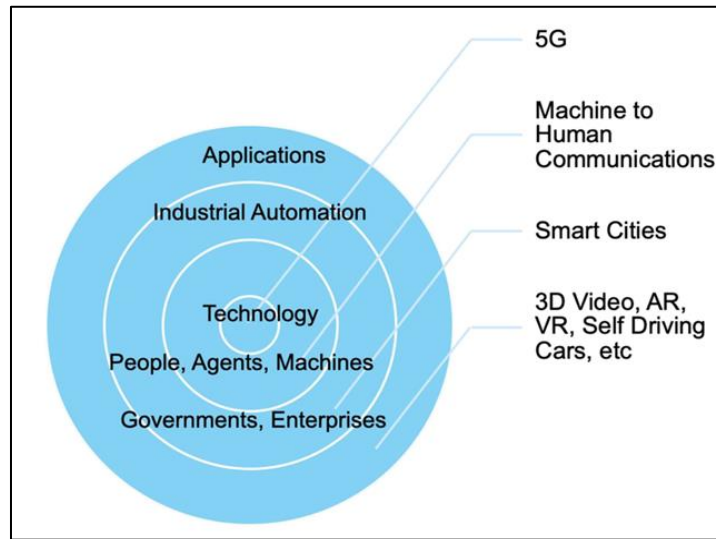


Figure 3 Everything that is affected by fifth generation telecommunication systems Source: Analysis of 5G application domains spanning consumer services, enterprise applications, industrial automation, and smart city infrastructure (Navarro-Ortiz et al., 2020)

4.1.2. Ultra-Reliable Low-Latency Communications Use Cases and Requirements

Ultra-reliable low-latency communications are an approach to mission-critical applications with extremely low end-to-end latency, less than 1millisecons, and very high reliability of 99.999percent to support industrial automation, autonomous vehicles, remote surgery, tactile internet, and emergency services where communication delays or failures may cause damage to equipment, loss of production, face risks, or loss of human life (Siddique et al., 2019).

In the case of developing countries, ultra-reliable low-latency communications can transform industry in developing countries such as South Africa, Egypt, Morocco, India, Thailand, Vietnam, Mexico and Brazil that are implementing industrialization plans by automating factories with robotics, enhancing quality control systems, and boosting their manufacturing productivity and competitiveness (Siddiqui et al., 2019). Self-driving cars, trucks, buses, and agricultural equipment are all applications of autonomous vehicles that need ultra-reliable additive latency vehicle-to-vehicle and vehicle-to-infrastructure communications to avoid collisions, manage traffic flow, and coordinated maneuvers applicable in developing countries investing in smart transportation systems in Kenya, Rwanda, India, Singapore, China, Malaysia, and United Arab Emirates (Siddique et al., 2019).

4.2. Fifth Generation Applications and Recommended Frequency Bands

Table 4 proposes frequency bands that are recommended in particular 5G application according to key performance indicator requirements, deployment scenarios, coverage properties, and capacity requirements in three categories of enhanced mobile broadband, ultra-reliable low-latency communications, and massive machine-like communications use cases. The frequency bands suggestions are balancing propagation features, spectrum availability, equipment ecosystems and regulatory allocations to telecommunications operators as well as spectrum regulators in developing countries planning to deploy 5G.

Table 4 Recommended Frequency Bands for Fifth Generation Applications Based on Key Performance Indicator Requirements Including Data Rate, Latency, Reliability, Coverage, and Connection Density Across Enhanced Mobile Broadband, Ultra-Reliable Low-Latency Communications, and Massive Machine-Type Communications Use Cases

ITU Usage Scenario	Main Service Category	Scenario-Specific Key Performance Indicators	Representative Applications	Proposed Frequency Band	Technical Rationale and Propagation Considerations
Enhanced Mobile Broadband	Higher Peak Data Rates	Downlink bandwidth ≥ 20 Gbps, Uplink bandwidth ≥ 10 Gbps, Spectral efficiency ≥ 30 bit/s/Hz downlink	High-speed train broadband	FR1 mid-band (3.5 GHz)	Balance between coverage and capacity for mobile scenarios
Enhanced Mobile Broadband	User Experienced Data Rates	User plane latency ≤ 4 ms, Cell edge throughput ≥ 100 Mbps	Broadcasting services	FR1 low-band (700 MHz) and mid-band	Wide area coverage with consistent quality of experience
Enhanced Mobile Broadband	Increased Traffic Density	Area traffic capacity ≥ 10 Mbps/m ²	Blind spot coverage	FR1 low-band (700 MHz, 800 MHz)	Superior propagation characteristics for rural areas
Enhanced Mobile Broadband	High-speed Mobility	Service continuity at 500km/h	Ultra-low-cost networks	FR1 low-band and mid-band	Reduced handover frequency with larger cell sizes
Enhanced Mobile Broadband	Broadband Everywhere	Consistent ≥ 50 Mbps experienced data rate	Future smart offices	FR2 mmWave (28 GHz, 40 GHz)	Ultra-high capacity for confined indoor environments

Data Sources: ITU-R recommendations for IMT-2020, 3GPP technical specifications, spectrum allocation studies for developing nations' 5G deployments (Romano, 2019; Ancans et al., 2017; Lee et al., 2018)

The frequency band recommendations understand that lower frequencies in FR1 band below 1GHz such as 600MHz, 700MHz and 800MHz have better propagation characteristics than higher frequencies, better penetration in buildings, and wider coverage areas, and the telecommunications operators of developing countries have limited economic capability to mount infrastructure density (Ancans et al., 2017).

Multi-gigabit per second throughput like that of high-band frequencies such as those of FR2 millimeter wave bands above 24GHz such as 24.25 to 29.5GHz, 37to 43.5GHz, and 45.5 to 47GHz allow very high capacity with thousands of users simultaneous demand of high-bandwidth services within constrained geographic regions (Ancans et al., 2017). Nevertheless, the propagation characteristics of millimeter waves such as heavy path loss, low range, low building penetration, and attenuation by rain cause the requirement of very dense small cell deployments with cell radius less than 100meter creating deployment complexity and cost issues to telecommunications operators in developing countries with limited resources allocation capability of capital and deployment personnel (Lee et al., 2018).

4.3. Key Fifth Generation Applications for Developing Nations

The Fifth generation wireless networks support transformative applications in consumer, enterprise, government, and industrial segments that support development priorities and socioeconomic issues in the emerging market countries across the world. The ten major categories of applications are explored in this subsection, which are especially relevant to developing countries that strive to achieve the goals of digital transformation, economic diversification, and inclusive development in strategic investments in the deployment of 5G.

Multimedia and Entertainment: Multimedia and entertainment use can include ultra-high-definition video streaming, augmented reality, virtual reality content, and immersion gaming, live events streaming at quality levels equal and higher than those of a fixed broadband wireline connection, offering entertainment and information access to people in the developing world where fixed networks are still restricted to urban areas (Dangi et al., 2021). Video traffic already constitutes more than 60percent of mobile-based data flows and is growing exponentially due to the influence of social media platforms, streaming services, user-generated content, and video-based communications, which require 5G capacity to grow to sustain the demands of mobile video consumption rates of over 40percent per annum (Erunkulu et al., 2021).

Satellite Services: When terrestrial fifth generation networks are combined with non-terrestrial satellite systems, this will allow ubiquitous connectivity across geographically separated populations of developing nations where deployment of terrestrial infrastructure is currently economically infeasible due to rugged topography, sparse population density, or nomadic peoples (Lin et al., 2021). 5G services offered by satellites serve emergency services, maritime networks, aviation passenger services, as well as rural broadband connections to populations lacking terrestrial mobile services in countries such as Ethiopia, Kenya, Tanzania, Mongolia, Peru, Bolivia, and Paraguay where large parts of the landmasses do not have terrestrial mobile connectivity (Rinaldi et al., 2020).

Artificial Intelligence Support: Fifth generation networks support distributed artificial intelligence and machine learning applications built upon mobile edge computing infrastructure computing data at the edges of networks, instead of at remote data centres, reducing latency, bandwidth usage, and privacy concerns to applications such as facial recognition, natural language processing, computer vision, predictive analytics and autonomous systems deployed through smart city projects in developing countries, industrial automation projects, and financial inclusion initiatives (Li et al., 2018).

5. Overview of Fifth Generation Enabling Technologies

The fifth generation wireless networks combine a variety of enabling technologies across radio access, transport, core network, management, and operational domains that all provide higher performance capabilities such as a peak data rate of 10to 20gigabits per second, sub-milliseconds latency, connection density of a million devices per square kilometer, and a hundred times the energy efficiency of fourth generation Long-Term Evolution Advanced systems (Dangi et al., 2021). This section offers exhaustive analysis of more than twenty major enabling technologies that are critical in the implementation of the 5G network in both developing and developed countries in the world. Figure 4 represents the 5G network architecture that integrates unified control over macrocells, microcells, picocells, femtocells, device-to-device communications, and the Internet of Things connectivity into the mobile core functions, centralized virtualization network processing, software-defined networking control, and distributed multi-access edge computing platforms to serve a variety of user equipment and applications in the diverse environment of heterogeneous deployment in developing countries.

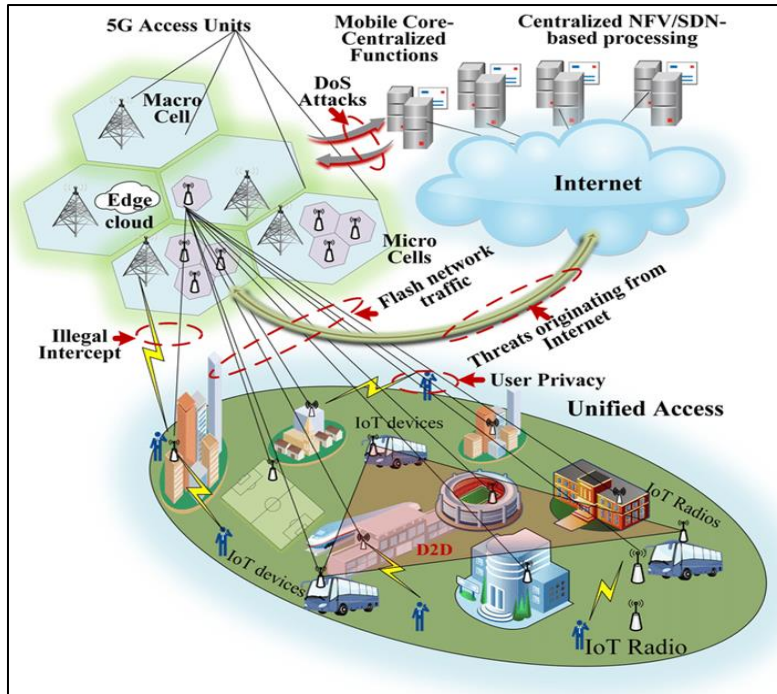


Figure 4 Comprehensive Fifth Generation Network Architecture Illustrating Unified Access Across Macrocells, Microcells, Picocells, Femtocells, Device-to-Device Communications, and Internet of Things Radio Integrated with Mobile Core Centralized Functions, Network Function Virtualization Processing, Software-Defined Networking Control, and Multi-Access Edge Computing Platforms Supporting Enhanced Mobile Broadband, Ultra-Reliable Low-Latency Communications, and Massive Machine-Type Communications Use Cases in Developing and Developed Nations (CISA, 2020; NIST, 2021)

5.1. Key Fifth Generation Enabling Technologies

Subsections that follow discuss twenty two key technologies which make possible fifth generation wireless network accessibility such as millimeter wave communications, massive multiple input multiple output, device-to-device communications, machine-to-machine connectivity, vehicle-to-everything services, network function virtualization, integrated access backhaul, heterogeneous networks, beamforming, non-orthogonal multiple access, radio access technology innovations, green communications, mobile femtocells, spatial modulation, local offloading, machine learning integration, Internet of Things connectivity, fog computing, self-organizing networks, multi-access edge computing.

5.1.1. Millimeter Wave Communications for High-Capacity Fifth Generation Networks

Millimeter wave communications in frequencies of more than 24GHz such as 24.25to 29.5GHz, 45.5to 52.6GHz, and 37to 43.5GHz with very high channel bandwidth of 50MHz-400MHz, offer multi-gigabit-per-second throughput when the capacity spectrum of lower frequency spectrum below 6GHz can no longer sustain the growing data traffic demands exponentially with frequency (Wei et al., 2014). The millimeter wave spectrum has vast available bandwidth in excess of 10GHz throughout the world in comparison with extremely congested frequencies less than 6GHz where mobile, broadcasting, satellite, and military applications demand limited spectrum resources (Rappaport et al., 2017).

Nevertheless, millimeter waves have much greater path loss, low non-line-of-sight range, heavy rain attenuation, and inadequate building penetration than sub-6 GHz frequencies and require very dense small cell designs with inter-site separations of 50to 200meters coupled with large-array multiple input multiple output antennas that achieve high-gain beamforming to address propagation losses (Xiao et al., 2017). The propagation in the free-space is proportional to the square of the frequency of the wave and correspondingly, the path loss at millimeter wave frequencies is proportional to the square of frequency, which means that path loss of 28GHz signals is about 100 times or 20dB greater than that of 2.8GHz signals at the same distance as given in equation:

$$FSPL(d, f) = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right)$$

where d represents transmitter-receiver separation distance in meters, f denotes carrier frequency in hertz, c equals speed of light 3×10^8 meters per second, and resulting free-space path loss FSPL is expressed in decibels (Rappaport et al., 2017).

In the case of developing countries implementing 5G millimeter wave systems, the propagation of small cells is done very densely where it costs a lot of site acquisition, backhaul, and electrical power infrastructure that may not be financially and operationally feasible of the telecommunications operator to implement in resource-limited emerging market environments (Qiao et al., 2015). Besides, the cost of millimeter waves equipment such as base stations, antennas, and user equipment are more expensive than sub-6 GHz versions because of the complex radio frequency devices, advanced semiconductor technologies, and immature equipment ecosystems with few vendor alternatives that pose affordability challenges to telecommunications operators and subscribers in developing countries (Hong et al., 2017).

5.1.2. Massive Multiple Input Multiple Output for Spectral Efficiency

Massive multiple input multiple output antenna, which uses 64, 128, or 256 antenna elements in base stations to support multiple users concurrently by spectral multiplexing and beamforming, are a basic technology of the fifth generation that allows improving spectral efficiency three to five times over fourth generation Long-Term Evolution systems with 2, 4, or 8 antenna systems (Chataut & Akl, 2020). The huge MIMO systems utilize the spatial separation in the wireless channels in order to transmit independent data streams on the same time-frequency resources to several users in the same time-frequency resources, and these systems grow capacity by the minimum of transmit and receive antenna counts in accordance with Shannon-Hartley law generalized to multiple-input multiple-output channels (Lu et al., 2014).

Figure 5 represents the main capabilities made possible by the fifth generation networks such as high speed and throughput of 10 gigabits per second peak data rate, mobile data of 10 terabytes per second per square kilometer, connected device density of 1 million devices per square kilometer, low latency and high reliability under 5 milliseconds with 99.999 percent availability, deployment of service within 90 minutes, 500 kilometers of mobility and 90 percent improvement of energy efficiency compared to the fourth generation systems through the integrated deployment of massive.

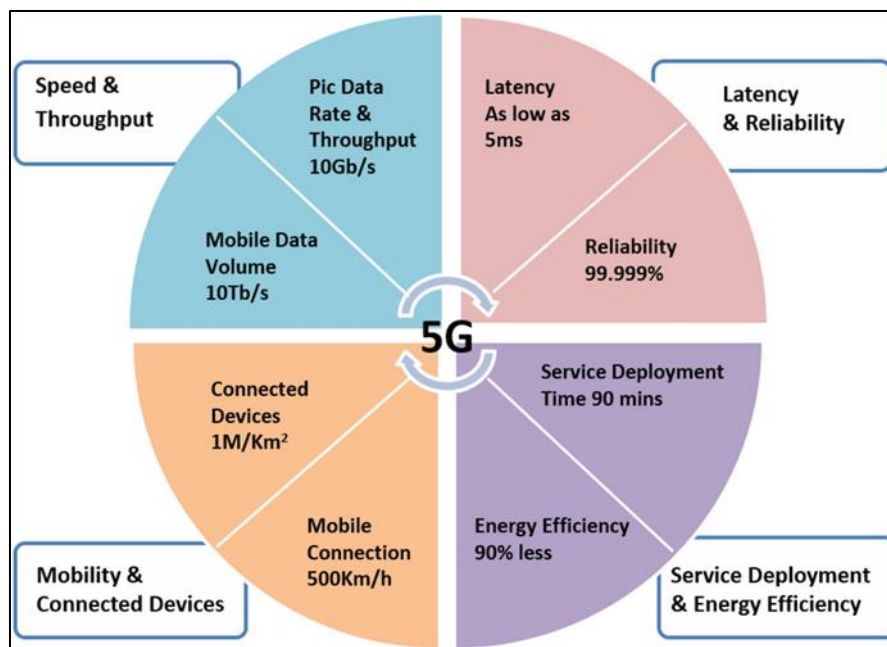


Figure 5 Key Capabilities of Fifth Generation Networks Including Enhanced Speed and Throughput, Mobile Data Volume, Connected Device Density, Low Latency and High Reliability, Service Deployment Time, Mobility Support, and Energy Efficiency Enabled by Massive Multiple Input Multiple Output, Millimeter Wave, Network Function Virtualization, Software-Defined Networking, and Edge Computing Technologies in Developing and Developed Nations (Dangi et al., 2021; Hassan et al., 2020)

for massive MIMO systems serving K single-antenna users from base station with M antennas where $M \gg K$ is given by:

$$C_{DL} = \sum_{k=1}^K \log_2 \left(1 + \frac{P_k |h_k|^2}{\sigma^2 + \sum_{j \neq k} P_j |h_j|^2} \right)$$

where P_k represents transmit power allocated to user k , h_k denotes channel vector between base station and user k , σ^2 equals noise power, and interference from simultaneous transmissions to other users appears in denominator (Chataut & Akl, 2020). For massive MIMO configurations where antenna count M substantially exceeds user count K , channel vectors become asymptotically orthogonal enabling near-interference-free transmission with capacity scaling linearly with K rather than logarithmically as in conventional single-user systems (Hassan et al., 2020).

The adoption of massive MIMO in developing countries is associated with such challenges as increased base station complexity, high power consumption due to the large size of antenna arrays, high channel state information acquisition needs, and complex signal processing algorithms that may surpass the processing capabilities of cost-optimized infrastructure devices (Obakhena et al., 2021). Massive MIMO however is more critical in spectral efficiency gains that can allow telecommunications operators of developing countries with limited spectrum access to allocate their finite frequency space capacity maximally, and extend beamforming gain beyond cell edges to enhance coverage and reduce required base station density relative to traditional antenna designs (Imoize et al., 2022).

5.1.3. Device-to-Device Communications for Offloading and Coverage Extension

D2D communications allow direct transmissions between user equipment and avoids routing traffic through the base stations to achieve spectrum reuse benefits, lower latency, and cell-edge users by providing extended coverage as well as offloading benefits to the telecommunications operator to reduce traffic loads on its core network when serving markets with growing mobile data demand in developing countries with exponentially growing rates (Tehrani et al., 2014). The D2D technology enables proximate devices to find nearby equipment and form direct communication connections based on reusing network-controlled uplink or downlink cellular spectrum resources to create more transmission opportunities and spatial reuse benefits without dedicated spectrum allocation (Fodor et al., 2012).

Figure 6 shows device-to-device communication case scenarios where there is direct D2D between user equipment UE5 and UE6, relay-assisted D2D with UE7 to provide coverage up to UE8, cellular communication between base station and user equipment UE1 to UE4, and indoor users coverage by a femtocell, which will be useful in developing countries where the density of the base stations and the reliability of their coverage differ considerably in geographic scope.

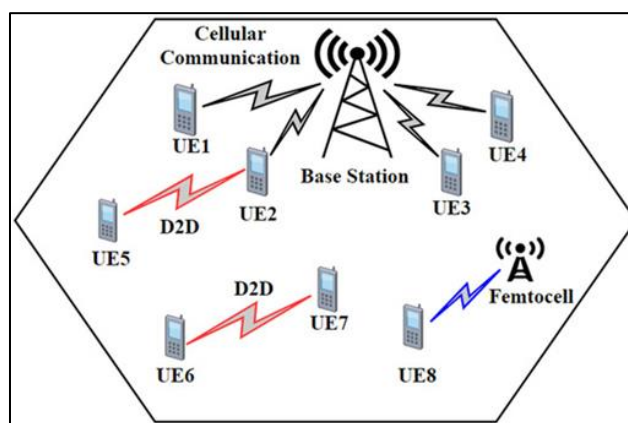


Figure 6 Device-to-Device Communication Scenarios Including Direct Device-to-Device Between Proximate User Equipment, Relay-Assisted Device-to-Device Extending Coverage Through Intermediate Devices, Conventional Cellular Communication Through Base Stations, and Femtocell Coverage for Indoor Users Enabling Spectrum Reuse, Offloading, and Coverage Extension in Developing Nations' Heterogeneous Network Environments (Tehrani et al., 2014; Fodor et al., 2012)

In developing countries, device-to-device communications can be used to cover coverage holes in rural and peri-urban locations where there is sparse base station deployment to create service discontinuities, allowing multi-hop relay environments where the cellular-connected devices can relay the out-of-range equipment to other devices (Tehrani et al., 2014). Moreover, D2D offloading decreases the bandwidth needs of telecommunications operators in developing countries where fiber or microwave transport capacity to the cell sites is limited by little terrestrial infrastructure or the high lease prices of third-party transmission facilities (Fodor et al., 2012).

5.1.4. Vehicle-to-Everything Communications for Intelligent Transportation

Vehicle-to-everything communications that include vehicle-to-vehicle, vehicle-to-infrastructure, vehicle-to-pedestrian, and vehicle-to-network connectivity allow the creation of cooperative intelligent transportation systems to facilitate collision avoidance and traffic management, infotainment services, and autonomous driving features applicable in developing countries with high rates of rapid motorization, intense traffic congestion, and high fatality rates (3 to 5x greater per vehicle-kilometer traveled) on the road (Boban et al., 2017). Figure 7 shows a holistic vehicle-to-everything communication ecosystem involving vehicle-to-infrastructure involving vehicles and road side units, vehicle-to-vehicle involving automobiles, vehicle-to-network involving vehicles through base stations to application servers and cloud platform, vehicle-to-pedestrian to alert susceptible road users, and vehicle-to-home integration to support various intelligent transportation and mobility services in urban and highway settings.

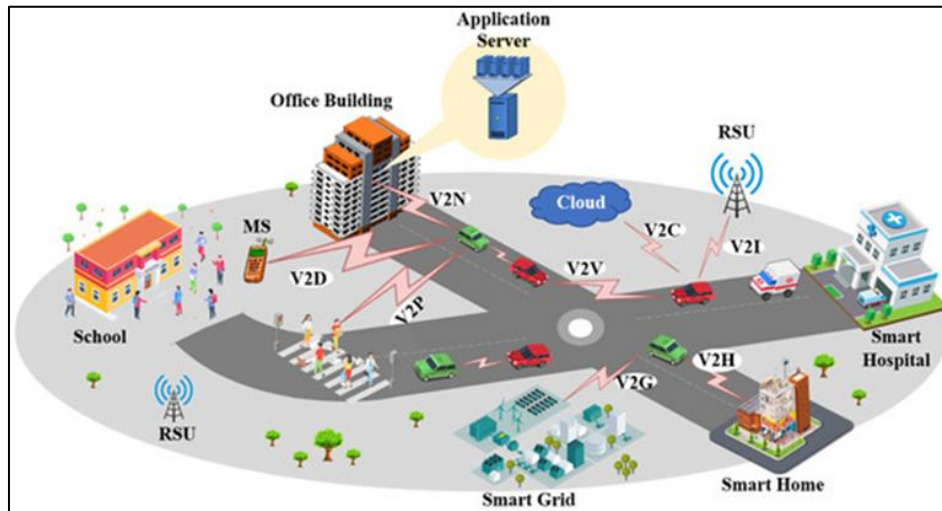


Figure 7 Vehicle-to-Everything Communication Ecosystem Including Vehicle-to-Infrastructure, Vehicle-to-Vehicle, Vehicle-to-Network, Vehicle-to-Pedestrian, and Vehicle-to-Home Connectivity Supporting Cooperative Intelligent Transportation Systems for Collision Avoidance, Traffic Management, Infotainment, and Autonomous Driving in Developing and Developed Nations' Urban and Highway Environments (Boban et al., 2017; Kim et al., 2020)

The V2X communications must have ultra-reliable low-latency features that support safety-critical applications such as forward collision warning, emergency electronic brake light, intersection movement assist, and blind spot warning where message delivery delays of more than 100 milliseconds or packet loss rates of over 0.1 percent may lead to collision incidents with the potential of fatalities or severe injuries (Kim et al., 2020). The V2X safety applications would need communication requirements that are measured using reliability function:

$$R(t) = P(\text{successful delivery within time } t) \geq 0.999$$

for latency constraint $t \leq 100$ milliseconds, ensuring that 99.9 percent of safety messages reach intended recipients within specified time window enabling appropriate driver or autonomous system responses preventing collisions (Boban et al., 2017).

For developing countries that are looking to intelligently transport their citizens, vehicle-to-everything communications can allow them to jump directly to what they might otherwise consider investing in building an extensive fixed infrastructure by having vehicle-mounted sensors, cameras and communication equipment form an ad hoc infrastructure of monitoring and information infrastructure without necessarily installing a lot of infrastructure along the road (Kim et al., 2020). The presence of V2X pilot programs in large metropolitan regions of countries such as India, Indonesia, Brazil, Mexico, and South Africa indicates that intelligent transportation systems can be implemented in the context of developing nations and is able to adapt to the dynamics of mixed traffic environments involving motorized vehicles, non-motorized transportation, informal transit, and vulnerable road users at densities and interaction patterns that may be substantial relative to the transportation systems used in developed countries (Boban et al., 2017).

5.1.5. Radio Access Technology Innovations for Fifth Generation

Fifth generation New Radio brings many radio access technology innovations such as flexible numerology to support the needs of various services, scalable orthogonal frequency division multiplexing with subcarrier spacings of 15kHz to 240kHz, advanced channel coding based on low density parity check codes and polar codes, grant-free uplink access to intermittent transmissions, and ultra-reliable low-latency optimizations with sub-milliseconds transmission interval (Shafi et al., 2017). Flexible numerology enables the 5G to adjust the structure of time-frequency resources to match the needs of particular use cases, with narrow 15kHz subcarrier spacing in the case of coverage-limited use cases where the goal is to maximize energy per symbol, wide 120kHz or 240kHz spacing in the case of ultra-reliable low-latency use cases where the goal is to minimize transmission time, and intermediate spacings in the case of mobile broadband when a balance between throughput and overhead is required (Shafi et al.,

The grant-free uplink frequency allows intermittent machine-type communications of enormous numbers of Internet of Things devices transmitting data packets of small size with infrequent frequency, eliminating the overhead scheduling request signaling and reducing the latency relative to the conventional grant-based access that requires devices to request resources, await grants, and then send data over multi-round trip times in the dozens of milliseconds impractical to run time-sensitive applications (Shafi et al., 2017). In the case of developing countries that implement the enormous machine-type communications that support millions of sensors, meters, and actuators of smart city infrastructure, precision agriculture systems, and industrial monitoring applications, grant-free access offers much-needed features that minimize signaling overhead and battery usage that allow long device life and primary battery power can be of small size (Popoola et al., 2017).

5.1.6. Local Offloading for Network Efficiency

Local offloading aims to avoid sending traffic over long distances by core network data centers to distant cores, instead sending it to local edge computing devices or directly device-to-device links, lowering the consumption of backhaul bandwidth, core network processing capacity, and end-to-end latency especially in applications such as content delivery, mobile gaming, augmented reality and real-time video analytics (Beck et al., 2015). The local offloading strategies focus on the advantage of proximity between source of content, computer resources, and end users to enhance quality of experience at low cost of network and minimal network energy usage with centralized architectures where all the traffic is transported to remote data centres (Beck et al., 2015).

In developing countries where fiber backhaul capacity is limited and core network infrastructure is constrained, local offloading offers the needed capacity that mitigates the transport bandwidth requirement as well as reducing the load of central processing units with better performance when using the existing infrastructure and delaying or preventing the need to expand the backhaul and core network capacity (Beck et al., 2015). Content delivery networks that deploy cache servers at the edges of the network in developing countries such as Kenya, Nigeria, South Africa, India, Indonesia, Brazil, and Mexico show significant performance improvement and bandwidth reduction due to localized content delivery without the need to access long-distance backhaul in the network in order to access commonly delivered content (Beck et al., 2015).

5.1.7. Internet of Things Integration

The Internet of Things integration into the fifth generation networks will provide massive connectivity that supports smart cities, precision agriculture, industrial automation, environmental monitoring, and healthcare applications changing economic and social development in the countries around the globe (Li et al., 2018). The 5G network slicing, massive machine-type communications optimization, and non-orthogonal multiple access facilitate the critical infrastructure to various Internet of Things needs such as ultra-low-power sensors transmitting a few bytes monthly to real-time industrial controllers with milliseconds of latency and 99.999percent availability (Shafique et al., 2020).

In the case of developing countries, Internet of Things applications can be used to solve key development challenges such as agricultural productivity via precision farming, infrastructure efficiency via smart utilities, healthcare accessibility via remote monitoring, and environmental protection via pollution sensing across countries, such as Kenya, Rwanda, Ethiopia, India, Bangladesh, Indonesia, Thailand, Vietnam, Brazil, Mexico, and Colombia (Goudos et al., 2017). Nonetheless, the Internet of Things implementation is fraught with such issues as the affordability of devices, their longevity, coverage in rural locations, security threats, and privacy that requires multi-faceted strategies involving technology, policy, and business model that have to be adjusted to the setting of developing nations (Khuntia et al., 2017).

5.2. Spectrum Sharing for Efficient Utilization

Spectrum sharing is a method of allowing different operators, technologies, or services to share same frequency bands by coordination strategies such as TV white space access, licensed shared access, and spectrum access schemes to solve spectrum scarcity issues that are especially high in developing countries where limited frequency assignments have to support legacy 2G, 3G, 4G systems with new 5G services (Ahmad et al., 2020). These spectrum sharing strategies offer interim solutions which use unused frequencies until long term spectrum refarming and reallocation procedures.

5.3. Fifth Generation Research Groups

International research organizations including Mobile and wireless communications Enablers for the Twenty-twenty (2020) Information Society (METIS), 5G Infrastructure Public-Private Partnership (5G PPP), 5th Generation Non-Orthogonal Waveforms (5G NOW), Enhanced Multicarrier Technology for Professional Ad Hoc and Cell-Based Communications (EMPhAtiC), Network of Excellence in Wireless Communications (NEWCOM), New York University Wireless (NYU Wireless), 5G Innovation Centre (5GIC), and Electronics and Telecommunication Research Institute (ETRI) contributed fundamental research enabling fifth generation standardization and commercial deployment addressing radio access network design, air interface development, spectrum utilization, network architecture, and use case validation (Dangi et al., 2021).

6. Fifth Generation Radio Propagation Mechanisms and Channel Modeling

6.1. Propagation Fundamentals for Fifth Generation

Signal attenuation, delay spread, Doppler shift, and angular dispersion are all determined by radio propagation mechanisms in which electromagnetic waves interact with terrain, vegetation, buildings, and atmospheric conditions in the refractive, diffractive, scattering, and absorbing modes of interaction (Shafi et al., 2017). The knowledge of propagation characteristics allows proper network planning, coverage modelling, interference evaluation, and capacity estimation that are necessary in telecommunications operators to design and deploy fifth generation infrastructure in a wide range of geographic locations and across the diverse geographical areas of urban center, suburban regions, rural villages, and remote areas of developing countries (Imoize et al., 2022).

Path loss quantifies signal attenuation with distance following propagation models incorporating free space loss plus additional attenuation from obstructions and environmental factors, typically modeled as:

$$PL(d) = PL(d_0) + 10n \log_{10} \left(\frac{d}{d_0} \right) + X_\sigma$$

where $PL(d_0)$ represents path loss at reference distance d_0 , n denotes path loss exponent characterizing environment-specific attenuation rate, d is transmitter-receiver separation distance, and X_σ represents log-normal shadow fading with standard deviation σ modeling variations from obstacles and terrain (Shafi et al., 2017). Path loss exponent n varies from approximately 2.0 for free space to 4.0 or higher in dense urban environments with significant obstruction (Imoize et al., 2022).

In the case of developing countries that roll out the fifth generation networks in diverse environments, precise propagation models allow network planning at minimal infrastructure investment to optimise the base stations placement, transmit powers, and antenna configurations to meet the coverage and capacity requirements (Imoize et al., 2022). Nonetheless, propagation behavior is significantly different at frequency bands whereby low-band sub-1 GHz signals propag much further and penetrate buildings much more effectively than 3.5 GHz mid-band or millimeter wave 28 GHz signals that exhibit high free space loss, reflection, and atmospheric absorption (Shafi et al., 2017).

6.2. Indoor Propagation Characteristics

The propagation in an indoor environment also experiences extra attenuation due to the loss of building penetration and internal obstruction that decreases signal levels 10 to 30 dB or more than at outdoor locations at the same distance between base stations, posing coverage challenges to telecommunications companies serving indoor users who make up majority of voice and data traffic (Imoize et al., 2022). Figure 8, below, gives graphs of average penetration loss and average attenuation of ceiling, clear glass, drywall, plywood material at 28GHz, 39GHz, 120GHz and 144GHz millimeter wave frequencies illustrating significant frequency-dependent building penetration losses affecting indoor fifth generation coverage planning of the telecommunications infrastructure of developing and developed countries.

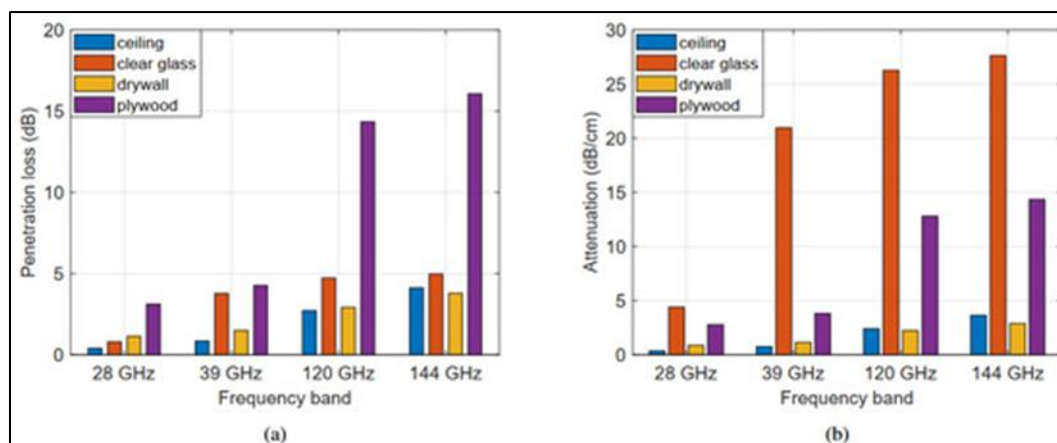


Figure 8 Graphs Showing Average Penetration Loss and Average Attenuation for Ceiling, Clear Glass, Drywall, and Plywood Materials at Twenty-Eight Gigahertz, Thirty-Nine Gigahertz, One Hundred Twenty Gigahertz, and One Hundred Forty-Four Gigahertz Millimeter Wave Frequencies Demonstrating Substantial Frequency-Dependent Building Penetration Losses Impacting Indoor Fifth Generation Coverage in Developing and Developed Nations.

The construction materials used in the developing countries such as concrete, brick, metal roofing, adobe construction have varied penetration losses to those of building materials in the developed countries and therefore local measurements and adaptations of models are required to be able to predict the coverage (Imoize et al., 2022). Solutions to outdoor macro cells with adequate transmit power and low-frequency spectrum that penetrate buildings, distributed antenna system that redirects signals across building interiors, small cells that are placed inside buildings, and femtocells that provide support to residential and small enterprise connections are all part of indoor coverage (Imoize et al., 2022).

7. Conclusions

In conclusion, the findings of this extensive research on security risk propagation across dependencies in the telecommunications infrastructure of developing countries investigated complex interdependencies along the technology architecture, vendor ecosystems, standardization processes, spectrum assignments, propagation, and operational practices that characterize the contemporary mobile networks. The discussion found many avenues by which security vulnerabilities extend across the fifth generation infrastructure such as supply chain relationships, software dependencies, configuration relationship, operation integration, and service interdependencies that form cascading failure risk where localized loss propagate across telecommunications systems.

An effective implementation of secure fifth generation infrastructure in developing countries is a fundamental basis of digital economic change, societal growth, and better quality of life of billions of people who are currently under or underprovided with modern telecommunications connectivity. It is possible to address the security risk propagation issues based on the complex technical, operational, and policy solutions designed to work in the conditions of developing countries, allowing the developing countries to seize the advantages of fifth generation technologies and to control the issue of cybersecurity threats to telecommunications infrastructure, privacy of its subscribers, and the reliance on critical infrastructure.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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