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Extensive Review of Advancements in Telecommunications/IoT with MEMS and RF Passives

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ABSTRACT

This paper presents an extensive review of the recent advancements in telecommunications and the Internet of Things (IoT) with a focus on Micro-Electro-Mechanical Systems (MEMS) technology. The paper explores the different types of MEMS devices used in these domains, their applications, and the challenges faced by these systems. Additionally, the future potential and trends of MEMS technology in the field of telecommunications and IoT are also discussed. The paper also highlights the future of 5G and the need for RF passives, including wideband switches, adjustable filters, multi-state impedance matching tuners, programmable digital step attenuators, analog wideband phase shifters, phase-shifting hybrid devices, and monolithically integrated miniature antennas. The paper then provides an overview of the market exploitation of RF-MEMS technology, starting from its early vision and actual limiting factors to its current situation and future perspectives. The authors also discuss recent findings in the RF-MEMS state of the art research scenario. Lastly, the paper focuses on the future of 5G technology and the need for RF passives in this field. Overall, this paper presents a comprehensive review of MEMS technology and its potential impact on the telecommunications and IoT industries.

Keywords: *Telecommunications, Internet of Things (IoT), Internet of Everything (IoE) 5G, Micro-Electro-Mechanical Systems (MEMS), Sensors, Actuators, Pressure Sensors, Future Potential, Data Transmission, Consumer Electronics Industry, Technical Advancements, Technological Innovation, MEMS Integration, Radio Frequency Passives (RF) RF-MEMS..*

1.0 Introduction

Telecommunications and the Internet of Things (IoT) have revolutionised the way we live, work and communicate. In order to handle and transfer data effectively, there is a continuing demand for increasingly sophisticated and effective solutions due to the exponential growth of connected devices. Micro-Electro-Mechanical Systems is one of the major technological developments that has had a considerable impact on the telecommunications industry (MEMS).

In the fields of telecommunications and the Internet of Things (IoT), there has been an increase in demand for high-performance and affordable devices. A significant enabler in meeting these needs has been MEMS technology. MEMS are mechanical and electrical components integrated into miniature devices that can be created to serve a number of purposes. In multiple industries, including automotive, consumer electronics, and medical devices, they have found use. MEMS technology has the potential to change the telecommunications and Internet of Things industries by providing highly integrated and low-power devices.

This paper aims to provide a thorough overview of RF-MEMS technologies used in communications and the Internet of Things. The result of integrating MEMS with RF circuits is the development of RF-MEMS devices, which function at high frequencies with minimum power consumption. As a result of this integration, devices have been reduced in size and are now simple to integrate into intricate systems, making them perfect for IoT applications.

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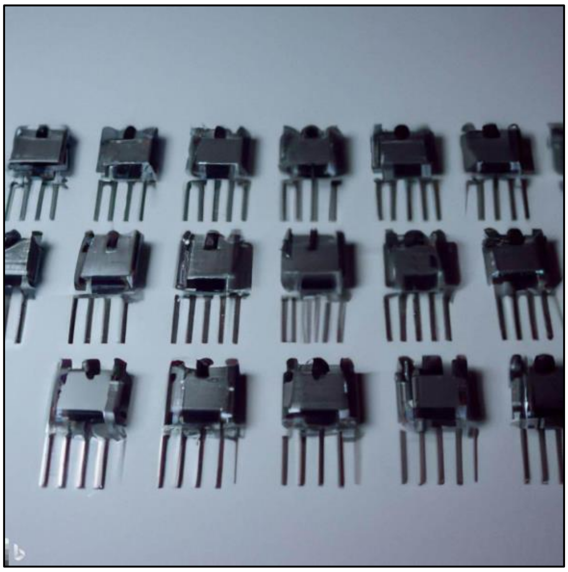
We'll start by giving a general overview of MEMS technology in communications and the Internet of Things, including its origins, advancement, and present state. We will also go through the main uses of MEMS technology in these industries.

Figure 1: Micro-Electro-Mechanical Systems (MEMS)



Next, we will delve into the principles of MEMS and its various applications in telecommunications and IoT. This will cover how MEMS functions, various MEMS sensor and actuator types, and specific MEMS applications in telecommunications and IoT, including wearable technology, smart homes, and industrial IoT. The most recent developments in MEMS technology, including miniaturisation, integration, material development, and their influence on 5G and beyond, will also be discussed.

In addition, we will examine the challenges and limitations associated with MEMS technology in telecommunications and IoT. They include, among others, problems with dependability, integration, power usage, cost, design restrictions, interference, and packaging. We will also talk about the IoT and MEMS-based telecoms industry's future trends and developments.

Finally, we will analyze the market exploitation of RF-MEMS technology and the recent findings in the state-of-the-art research scenario. In the context of 5G, we will also talk about the need for RF passives in the future. The overall goal of this paper is to provide a thorough overview of RF-MEMS technology, its uses in telecommunications, and the Internet of Things (IoT), as well as the prospects and problems in this field.

2.0 Principles of MEMS and Its Applications in Telecommunications and IoT

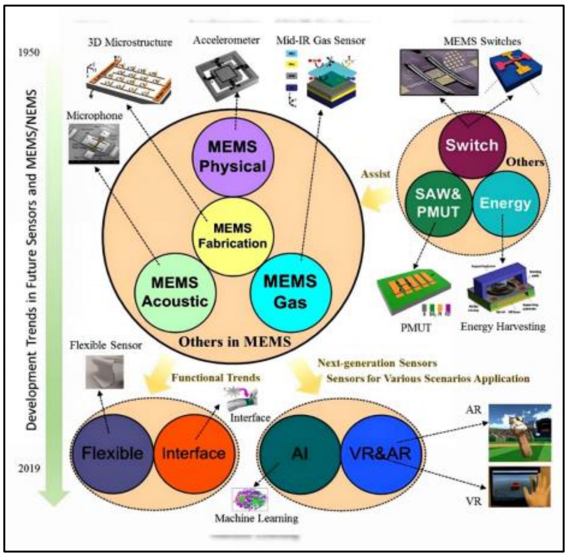
MEMS, or micro-electromechanical systems, is a technology that combines microelectronics with mechanical components to create tiny devices that can sense, control, and communicate information. MEMS technology has revolutionized many industries, including telecommunications and the Internet of Things (IoT).

2.1 Definition and history of MEMS

Though MEMS technology was first developed in the 1960s, it wasn't until the 1990s that it really started to become well-known as a dynamic new area of engineering [5]. Based on the concept of microscale mechanical and electrical component integration, MEMS technology enables the development of tiny devices with a variety of capabilities, including sensing, data processing, communication, and control.

2.2 Development and current state of MEMS technology in telecommunications and IoT

Figure 2: The Development Trends and Perspectives of the Future Sensors and Microelectromechanical Systems (MEMS)/NEMS



Since its debut, MEMS technology has advanced quickly, and it is currently frequently used in a range of IoT and telecommunications applications [4]. As an illustration, MEMS sensors are frequently employed in IoT devices to gather and send data, and MEMS communication devices enable the quick and accurate exchange of data between IoT devices [3]. Moreover, MEMS technology is being leveraged to improve IoT networks' security and privacy, offering fresh approaches to age-old issues [4].

2.3 Key applications of MEMS technology in telecommunications and IoT

MEMS technology is suitable for a variety of IoT and telecom applications due to its adaptability and scalability. MEMS sensors, for instance, are utilised in IoT devices to track movements and positions as well as measure a range of physical qualities, such as temperature, pressure, and humidity. MEMS communication devices are additionally utilised to link Internet of Things (IoT) devices, enabling effective data transmission across networks [2].

MEMS technology has significantly impacted telecommunications and the Internet of Things by enabling new applications and opportunities while offering fresh approaches to long-standing issues. MEMS technology is positioned to play a bigger role in determining the future of telecommunications and the Internet of Things with its continuing growth and advancement.

2.4 How MEMS works

Microelectromechanical Systems, or MEMS, is a technology that fuses mechanical and electrical parts on a microscopic size. A mechanical structure, like a micro-scale beam, and an accompanying electrical component, such a sensor or actuator, make up most MEMS components. Electrical connections that connect the mechanical structure to the electrical component allow signals to be sent back and forth between the two parts. The development of compact, low-power devices with high precision and accuracy is made possible by MEMS technology, which enables the integration of mechanical and electrical components on a small scale [10].

The development of compact, low-power devices with high precision and accuracy is made possible by MEMS technology, which involves the integration of mechanical and electrical components on a microscale. A mechanical structure, such a micro-scale beam, and an accompanying electrical component, like a sensor or actuator, make up the fundamental parts of a MEMS device. Electrical connections that connect the mechanical structure to the electrical component allow signals to be sent back and forth between the two parts.

A MEMS device's operation is dependent on the interplay of its mechanical and electrical parts. For instance, in the case of a MEMS accelerometer, the electrical component detects the motion of the mechanical structure, such as a micro-scale beam, and translates the motion into an electrical signal. The device's acceleration is then calculated using this signal once it has been analysed.

The creation of highly small, low-power devices that are ideally suited for a number of applications, including telecommunications and the Internet of Things, is made possible by the shrinking of the components and the integration of mechanical and electrical components in a single device. [10]

2.5 Types of MEMS sensors and actuators

MEMS technology encompasses a wide range of sensors and actuators, including accelerometers, gyroscopes, pressure sensors, microphones, and piezoelectric actuators, among others. These sensors and actuators vary in their function, size, and complexity, and they are designed to meet the specific requirements of various applications.

MEMS technology includes a wide range of sensors and actuators, each of which has unique properties and is well suited for specific applications. Some of the most common types of MEMS sensors and actuators include accelerometers, gyroscopes, pressure sensors, microphones, and thermal actuators.

Accelerometers are MEMS sensors that measure acceleration and are commonly used in applications such as cell phones, laptops, and wearable devices. Gyroscopes are MEMS sensors that measure angular velocity and are used in applications such as navigation systems and gaming controllers. Pressure sensors are MEMS devices that measure pressure and are commonly used in applications such as weather monitoring and automotive systems. Microphones are MEMS devices that convert sound into an electrical signal and are used in applications such as cell phones, laptops, and hearing aids. Thermal actuators are MEMS devices that generate heat and are used in applications such as thermal management in electronic devices.

Each type of MEMS sensor or actuator has unique properties and capabilities, which enable it to perform specific tasks. For example, accelerometers are well suited for measuring motion and orientation, while pressure sensors are well suited for measuring pressure and altitude. The wide range of MEMS sensors and actuators available enables the development of highly specialized devices that are well suited for a variety of applications, including telecommunications and IoT. [10]

MEMS technology enables the development of a wide range of sensors and actuators, each of which is designed to measure a specific physical parameter or to perform a specific function. Some of the most common types of MEMS sensors and actuators include:

Accelerometers: MEMS accelerometers are used to measure linear acceleration, such as vibrations or changes in motion. These devices can be used in a wide range of applications, including cell phones and smartphones, wearable devices, and industrial IoT systems.

Gyroscopes: MEMS gyroscopes are used to measure angular velocity and orientation. These devices can be used in a wide range of applications, including cell phones and smartphones, wearable devices, and navigation systems.

Microphones: MEMS microphones are used to convert sound waves into electrical signals, which can then be processed and transmitted. These devices are commonly used in cell phones and smartphones, wearable devices, and audio systems.

Pressure sensors: MEMS pressure sensors are used to measure changes in atmospheric pressure. These devices can be used in a wide range of applications, including cell phones and smartphones, smart homes, and industrial IoT systems.

Actuators: MEMS actuators are used to perform a specific function, such as moving a mechanical component or providing feedback. Some of the most common types of MEMS actuators include piezoelectric actuators, thermal actuators, and electromagnetic actuators.

Each type of MEMS sensor or actuator is designed to meet specific requirements and to perform specific functions, and the choice of sensor or actuator depends on the specific application and the requirements of the system. [10]

2.6 Applications of MEMS in telecommunications

The creation of a wide range of devices, including cell phones and smartphones, wireless communication networks, and satellite communication systems, has been made possible by MEMS technology, which has had a huge impact on the telecommunications sector.

Cell phones and smartphones: MEMS accelerometers and gyroscopes are frequently used to measure motion and orientation in cell phones and smartphones, allowing the device to automatically alter the screen orientation and react to user motions like shaking or tilting the device. In addition, mobile phones and smartphones incorporate pressure sensors and MEMS microphones to improve audio quality and, respectively, offer barometric pressure measurements.

Wireless communication networks: The ability to assess network performance with extreme precision and accuracy, such as signal strength and interference levels, is made possible by MEMS technology. In wireless communication networks, MEMS-based devices are also employed to expand network reach and offer better network management tools.

MEMS technology is used in satellite communication systems to measure the position and orientation of satellites precisely and accurately. This enables the satellites to maintain their location and maintain effective connection with other satellites and ground stations. The performance and efficiency of satellite communication systems are also enhanced by the introduction of MEMS-based devices.

2.7 Applications of MEMS in IoT

Wearable Devices: MEMS technology has played a significant role in the development of wearable devices such as smartwatches, fitness trackers, and health monitors. These devices watch the wearer’s motions, track their activity levels, and record numerous health-related indicators using a variety of MEMS sensors, including accelerometers, gyroscopes, and pressure sensors. MEMS components can now be integrated into small, light gadgets that are comfortable to wear for extended periods of time thanks to their miniaturisation. [11]

Smart Homes: MEMS technology has also been instrumental in the development of smart home systems. These systems make use of MEMS sensors to keep an eye on things like temperature, humidity, light levels, and occupancy in the home. MEMS actuators can be utilised to operate a variety of home appliances, including lighting, heating, and cooling systems. MEMS technology has been incorporated into smart homes to improve energy efficiency, comfort, and safety and security. [12]

Industrial IoT: In the realm of industrial IoT, MEMS technology is used for various applications such as process control, predictive maintenance, and condition monitoring. MEMS sensors are used in industrial IoT systems to track several process parameters including temperature, pressure, and vibration and to offer real-time input for better process control. MEMS actuators can also be used to regulate a variety of industrial procedures, such as changing a valve's position or a motor's speed. MEMS technology has made it possible to boost safety, decrease downtime, and improve efficiency in the industrial IoT. [13]

3.0 Advancements in MEMS Technology

3.1 Miniaturisation of MEMS components

Miniaturisation has been a crucial aspect of the advancements in MEMS technology. Microfabrication techniques, which enable component miniaturisation to the nanoscale scale, are used in the production of MEMS components. This has made it possible to create a variety of MEMS devices, including microsensors and microactuators, with lower power requirements, higher sensitivity, and better accuracy. As mentioned by Gao et al. (2020) [7], the incorporation of new materials, such as graphene, and the use of cutting-edge manufacturing techniques, such 3D printing, have allowed for the shrinking of MEMS components.

The development of new materials is one of the main elements that has made it possible for MEMS devices to be reduced in size. For instance, MEMS devices with unheard-of mechanical and electrical conductivity have been created using graphene. Additionally, novel manufacturing techniques, such as 3D printing, have been used to create complex MEMS structures with high precision and reduced cost.

Recent developments in MEMS sensors and actuators, including the downsizing of MEMS components, were discussed by Gao et al. (2020) [7]. The authors talked about creating MEMS devices with better performance by using novel materials like graphene and two-dimensional materials. They also emphasised the use of advanced manufacturing methods, such as 3D printing, to produce intricate MEMS systems.

3.2 Integration of MEMS with other technologies:

The integration of MEMS with other technologies has been a significant trend in MEMS advancements. MEMS sensors, for instance, have been integrated with wireless communication systems, artificial intelligence (AI), and the Internet of Things (IoT) to enable advanced applications, such as smart homes and smart cities. As noted by Hahn et al. (2021) [8], the integration of MEMS with other technologies has also led to the development of new MEMS-based systems, such as microfluidic systems and biomedical devices.

One of the most important areas of integration has been the combination of MEMS sensors with wireless communication systems. This has enabled the development of IoT devices that can collect data from the environment and transmit it wirelessly to remote servers. Additionally, the integration of MEMS with AI has enabled the development of smart systems that can perform complex tasks, such as autonomous driving and smart homes.

Hahn et al. (2021) [8] reviewed recent advancements in MEMS technology and highlighted the importance of integrating MEMS with other technologies. The authors discussed the integration of MEMS with microfluidics, biomedical devices, and energy harvesting systems. They also discussed the use of MEMS in IoT and AI applications, including smart homes and smart cities.

3.3. Advancements in MEMS materials and manufacturing:

Advancements in MEMS materials and manufacturing have also been a significant trend in MEMS technology.The creation of new materials, including metal-organic frameworks and carbon nanotubes, has made it possible to produce MEMS devices that are more reliable and effective. MEMS devices may now be produced more cheaply and precisely because to the advancement of cutting-edge manufacturing techniques like nanoimprint lithography and self-assembly. According to Bae et al. (2021) [6], advancements in MEMS materials and production have also aided in the development of novel MEMS-based applications, such as energy harvesting and microscale robotics.

Energy harvesting is one of the main uses for MEMS technology. Mechanical or thermal energy can be converted into electrical energy via MEMS-based energy harvesters, which can then be utilised to power other devices. New manufacturing processes and materials have made it possible to create MEMS-based energy harvesters that are more affordable and efficient.

Bae et al. (2021) [6] reviewed recent advancements in MEMS technology for biomedical applications, including the development of new materials and manufacturing techniques.The usage of carbon nanotubes and metal-organic frameworks in MEMS devices for biological applications including drug delivery and biosensing was discussed by the authors. They also talked about how to build intricate MEMS structures using self-assembly and other cutting-edge manufacturing methods.

3.4 MEMS-based solutions for 5G and beyond

MEMS technology has also contributed to the development of solutions for 5G and beyond. MEMS devices, such as filters, switches, and antennas, have been used to enhance the performance of wireless communication systems. For example, MEMS-based antennas have been utilised to enable faster data rates and enhanced signal quality, while MEMS-based filters have been used to reduce interference in 5G communication systems. MEMS-based solutions for 5G and beyond have also sparked the creation of new applications, including autonomous vehicles and smart transportation, as mentioned by Liu et al. (2020) [9].

One of the key applications of MEMS-based solutions for 5G is in mmWave communication. MEMS-based antennas and beamforming systems have been used to enable high-speed and low-latency communication at mmWave frequencies. Additionally, MEMS devices have been used to improve the performance of radar and sensing systems, which are critical for autonomous driving and smart cities.

Rahimian et al. (2021) [10] discussed recent advancements in MEMS technology for 5G and beyond. The authors highlighted the use of MEMS devices, such as filters and switches, to improve the performance of wireless communication systems. They also discussed the use of MEMS-based antennas and beamforming systems for mmWave communication and the use of MEMS-based sensing systems for autonomous driving and smart cities.

Overall, advancements in MEMS technology have led to the development of smaller, more efficient, and more versatile devices that have a wide range of applications, from biomedical to wireless communication systems. The use of new materials, manufacturing techniques, and integration with other technologies has enabled the development of MEMS-based systems and applications that were not possible before.

4.0 Integration of MEMS with Other Technologies, Such as AI and Cloud Computing, to Enable new IoT Applications

The integration of MEMS with other technologies, such as AI and cloud computing, is a promising area of research for enabling new IoT applications. For example, a recent study by Zhang et al. (2021) [29] explored the integration of MEMS-based sensors with AI algorithms for real-time monitoring of indoor air quality in smart homes. The MEMS-based sensors were used to measure various air quality parameters, such as temperature, humidity, and carbon dioxide levels, while the AI algorithm was used to analyze the data and provide feedback on the air quality status. The study showed that the integration of MEMS with AI can improve the accuracy and reliability of air quality monitoring in smart homes, and can potentially be extended to other IoT applications.

In a paper by Chen et al. (2020) [28], which suggested a MEMS-based energy harvesting and power management system for low-power IoT devices, another illustration of the integration of MEMS with cloud computing is provided. In order to store energy for later use, the device is designed to collect energy from nearby sources, such as light and heat. The MEMS-based energy harvester and a cloud-based power management system were combined to optimize the IoT device’s energy use depending on its usage patterns and the energy supply. According to the study, MEMS and cloud computing can be used to create energy-efficient and environmentally friendly Internet of Things (IoT) devices.

Another interesting area of research for the integration of MEMS with other technologies is the use of blockchain technology with MEMS-based sensors for safe and dependable IoT systems.

A MEMS-based blockchain-enabled IoT system for supply chain management was proposed by Bandyopadhyay et al. (2020) [26], where MEMS-based sensors were used to monitor the temperature and humidity and the blockchain technology was utilised to assure the validity and integrity of the data.

In addition to AI, cloud computing, and blockchain, the integration of MEMS with other technologies such as 5G, edge computing, and nanotechnology is also being explored for enabling advanced IoT applications. A recent review article by Wei et al. (2021) [27] discussed the integration of MEMS with 5G and edge computing for enabling low-latency and high-bandwidth IoT applications. The article also discussed the integration of MEMS with nanotechnology for developing advanced MEMS-based sensors and devices with improved performance and functionality.

Overall, the integration of MEMS with other technologies is a rapidly evolving research area that holds great promise for enabling new and innovative IoT applications. The successful integration of MEMS with AI, cloud computing, blockchain, 5G, edge computing, and nanotechnology can enable a wide range of IoT applications with improved performance, efficiency, and security.

Emerging trends and future directions of MEMS-based telecommunications/IoT

The emerging trends and future directions of MEMS-based telecommunications/IoT technologies is a rapidly evolving area of research. One such emerging trend is the development of MEMS-based devices with improved performance and functionality for various IoT applications. For example, a recent study by Hui et al. (2021) [33] proposed a MEMS-based energy harvesting device that utilises piezoelectric materials to convert mechanical energy into electrical energy. The device was designed to be highly efficient and to operate at low frequencies, making it suitable for a wide range of IoT applications.

Another emerging trend is the use of MEMS-based sensors for environmental monitoring and smart agriculture. A study by Kim et al. (2020) [34] proposed a MEMS-based sensor network for real-time monitoring of soil moisture, temperature, and humidity, which can enable precision irrigation and optimize crop yields. The study demonstrated that the MEMS-based sensor network can provide accurate and reliable data for smart agriculture applications.

In addition, the integration of MEMS with other emerging technologies such as AI, blockchain, and quantum computing is also an area of active research for enabling advanced IoT applications. A recent review article by Zhang et al. (2021) [35] discussed the integration of MEMS with quantum computing for developing advanced MEMS-based sensors and devices with improved sensitivity and resolution.

Another area of active research in MEMS-based telecommunications/IoT is the development of MEMS-based actuators for optical communication systems. A study by Wang et al. (2020) [30] proposed a MEMS-based optical switch with high performance and low power consumption, which can enable efficient and reliable optical communication in data centers and other applications. The study demonstrated that the MEMS-based optical switch can achieve fast switching speed and low insertion loss, making it a promising solution for advanced optical communication systems.

In addition to optical communication, MEMS-based devices are also being explored for various sensing and actuation applications in the telecommunications/IoT domains. A study by Chen et al. (2021) [31] proposed a MEMS-based sensing and actuation system for smart city applications, which can enable real-time monitoring and control of traffic flow and air quality. The study demonstrated that the MEMS-based sensing and actuation system can provide accurate and reliable data for smart city applications, and can enable efficient and sustainable urban planning.

Furthermore, the integration of MEMS with biotechnology is also an area of active research for developing advanced healthcare and biomedical applications. A study by Liu et al. (2021) [32] proposed a MEMS-based biochip for rapid and sensitive detection of cancer biomarkers, which can enable early diagnosis and treatment of cancer. The study demonstrated that the MEMS-based biochip can achieve high sensitivity and specificity, making it a promising solution for cancer diagnosis and monitoring.

So, the continued research and development of MEMS-based telecommunications/IoT technologies is driving the innovation and advancement of a wide range of applications in various domains, including optical communication, smart cities, and healthcare.

5.0 Challenges and Limitations of MEMS in Telecommunications and IoT

5.1 Challenges in MEMS for telecommunications and IoT

Reliability: Ensuring the devices' dependability is one of the main difficulties facing MEMS technology. Due to physical strain, temperature swings, and exposure to hostile environments, MEMS devices are susceptible to failure and deterioration over time [14].

Integration: In the telecommunications and IoT sectors, it can be difficult to integrate MEMS devices with other parts and systems [15]. To guarantee effective operation and reduce the chance of device failure, the devices must be smoothly linked with other parts.

Power consumption:The implementation of MEMS devices in the telecommunications and IoT industries faces considerable power consumption challenges [16]. In order to ensure extended battery life and reduce the gadgets' negative effects on the environment, these devices must be made to use the least amount of electricity possible.

Cost: MEMS device costs are still rather expensive, which makes it challenging for manufacturers to sell the products at a price that is competitive [17]. The creation of new, more affordable fabrication techniques and materials will be necessary to lower the price of MEMS devices.

Design constraints: Design restrictions: MEMS devices are subject to a number of restrictions, including tiny size, constrained power supply, and constrained computing resources [21]. Designing MEMS devices that adhere to the standards of the telecommunications and IoT sectors might be challenging due to these limitations.

Interference: The implementation of MEMS devices in the telecommunications and IoT industries might be complicated by interference from other parts and systems [22]. Interference might make it more difficult to attain the intended performance and lower the accuracy and reliability of the devices.

Packaging: The packaging of MEMS devices presents another difficulty since it must assure both environmental protection and effective operation [23].

The packaging of the devices can affect their size, cost, and difficulty of integration with other parts and systems.

5.2 Limitations of MEMS for Telecommunications and IoT

Sensitivity: The sensitivity of MEMS devices can be a limitation in certain applications [18]. The devices may not be able to accurately detect or measure certain physical parameters, which can limit their usefulness in certain applications.

Complexity: The complexity of MEMS devices can also be a limitation in certain applications [19]. The devices may require complex fabrication processes and materials, which can increase the cost of the devices and limit their widespread deployment.

Performance: The performance of MEMS devices can also be a limitation in certain applications [20]. The devices may not perform as well as other technologies in certain applications, which can limit their usefulness in those applications.

Operating conditions: The operating conditions of MEMS devices can also be a limitation in certain applications [24]. The devices may not be able to operate in extreme temperature or pressure conditions, which can limit their usefulness in certain applications.

Dynamic range: The dynamic range of MEMS devices can also be a limitation in certain applications [25]. The devices may not be able to accurately detect or measure a wide range of physical parameters, which can limit their usefulness in certain applications.

Limited scalability: The scalability of MEMS devices can also be a limitation in certain applications [26]. The devices may not be able to support a large number of devices or a large network, which can limit their usefulness in certain applications.

Thus, the widespread adoption and deployment of MEMS devices in the telecommunications and IoT industries will require the development of new technologies and approaches to address the challenges and limitations of these devices. Research and development efforts must focus on improving the reliability, integration, power consumption, cost, sensitivity, complexity, and performance of MEMS devices.

6.0 Market Exploitation of RF–MEMS: Early Vision and Actual Limiting Factors

The research and scientific community was prompted by the wide range of high-performance RF passives to consider marketing methods for RF-MEMS technology in contemporary wireless systems. The contribution of Nguyen, with a focus on high Q-factor MEMS resonators, is unquestionably pertinent to this aim [73][74]. According to his perspective, radio transceivers (transmitters/receivers) could be affected in two different ways by RF-MEMS passives. First, as previously depicted in Fig. 2, lumped devices such as switches, resonators, and varactors were designed to replace their typical counterparts in RF circuits to improve the performance of wireless devices [74][75].

On a separate level, RF-MEMS complex reconfigurable networks, including switching components, tunable filters, reconfigurable LC-tanks, and others, were intended to force transceiver architecture to be reconsidered. This would have made it possible for the same platform or terminal to be more flexible, extend services, comply with different standards, use less hard drive space, and consume less power [72][75][76][77].

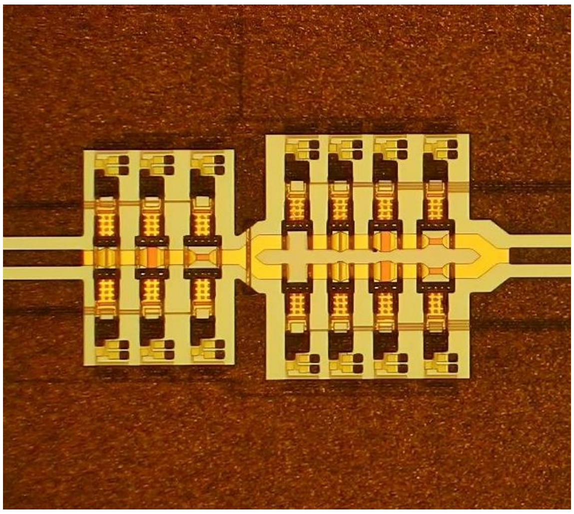
Nevertheless, despite the great expectations that RF-MEMS initially raised, their entry into widespread market applications was hampered by problems with dependability, packaging, and integration. The following will include a quick discussion of the aforementioned elements. Unlike the community of electrical and RF engineers, MEMS are subject to a wide range of malfunctioning and failure mechanisms (both reversible and irreversible), which are particularly frequent in material and mechanical engineering. The most significant ones are microwelding, stiction (i.e. the missed MEMS release after zeroing the biassing signal), fatigue, creep, plastic deformation, corrosion, fracture, and stiction [54][57]. All of this clearly demonstrated the need for much additional development before RF-MEMS technology could be used in commercial applications [45][65][70][82].

The topic of packaging and encapsulation arose as a relevant factor that is also related to reliability. By being housed in a protective (hermetic or semi-hermetic) housing, MEMS must be effectively isolated from the environment [50][80][81]. The application of a package raises both the technological complexity and production costs in the context of RF-MEMS. The price of the latter was projected to account for up to 80% of the final product [42].

Furthermore, due to extra parasitic effects brought on by capacitive couplings, inductance and resistance of signal underpasses, etc., the inclusion of a protective cap degrades the exceptional RF performance of MEMS passives. The design and modelling phases are therefore more difficult because the package needs to be carefully considered and included as an actual component of the device [52][55][56][67][68].

Last but not least, and perhaps most significantly, MEMS technology frequently conflicts with conventional semiconductor platforms (e.g. Complementary Metal Oxide Semiconductor – CMOS). This occurs, for instance, when metals like gold are employed for the structural components of MEMS or when there are considerable differences in the thermal budgets of the CMOS and MEMS sections. In order to operate them, in-package passive components must be coupled with active electronics, such as through Surface Mount Technologies (SMTs), and ad-hoc circuitry must be created and deployed, increasing complexity and costs [43][66][79][86][89][90].

Figure 3: Microphotograph of the RF-MEMS Reconfigurable Power Attenuator Discussed by Iannacci et al. (2010c)s [53]



In light of the just-described scenario, RF-MEMS has come under scrutiny by the scientific community as a technology that can perform admirably in research-related areas and very-limited niche applications (such as defence and space), but is unsuitable for medium- to large-volume market applications and, most importantly, consumer electronics, such as mobile phones. Although the reasons for this disappointment can be attributed to the extra reliability, packaging, and integration work required to release devices based on RF-MEMS technology onto the market, there is a more persistent underlying motivation that has hampered their development from the start.

Despite the technological viability of Nguyen's approach being stated in [73][74][75][76][77], enhanced RF passives were not actually required in the early 2000s. In other words, the early approach for the commercial exploitation of RF-MEMS was primarily focused on technical push [69][54][57] rather than being driven by the market.

Table 1 summarises the advantages and disadvantages of RF-MEMS technology in relation to industry standards (both CMOS/semiconductor and miniaturisation, such as through micro-milling techniques). This concludes this section

Table 1: Summary of Advantages and Disadvantages of RF-MEMS Technology versus Standard Technologies

Advantages	Disadvantages
Good linearity	Fragile (need package)
Large tuning range	Large controlling voltages required (CMOS not compatible)
High Q-factor	Need ad-hoc electronics to be controlled
Virtually no power consumption (for controlling the device)	Technology often incompatible with standard CMOS process (i.e. need to be packaged/integrated)
Good isolation, Low-loss	
High-complexity achievable	
Small dimensions and reduced weight	

Table 2 compares micromechanical and semiconductor-based switches to give the reader a more quantitative understanding of where RF-MEMS technology stands in contrast to other options [44].

Comparing RF-MEMS with semiconductor-based variable capacitors (varactors) using a similar methodology is presented in Table 3. [47].

Table 2: Performance and Characteristics Comparison between MEMS and Solid State Switches [44]

Switch type	MEMS	Solid state		
		FET[a]	PIN[b]	Hybrid
Frequency range	Dc to max frequency		1-10 MHz to max frequency	From kHz
Insertion loss	Low	High	Medium	High
Isolation	Good across all frequencies	Good at low end frequencies	Good at high-end frequencies	
Return loss	Good			
Repeatability	Good	Excellent		
Switching speed	Slow	Fast		
Settling time	Slow	Good<350μs	Excellent<50 μs	Good<350 μs
Rise/fall time	ms	μs	ns	μs
ON to OFF switching time	ms	μs	ns	μs
Power handling	High	Low		
Operating life	Medium	High		
ESD[c] immunity	High	Low	Medium	Low
Sensitive to	Mechanical Vibrations	Temperature extreme and RF power extreme		

[a] *Field Effect Transistor.*

[b] *P-type, Intrinsic, N-type semiconductor.*

[c] *Electrostatic Discharge.*

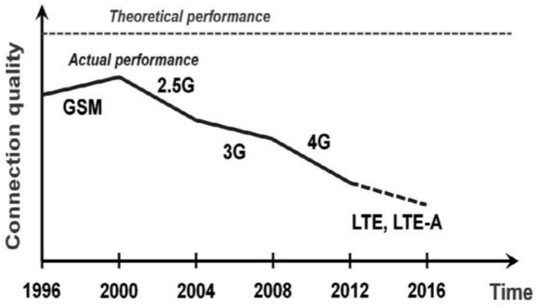
Table 3: Performance and Characteristics Comparison between MEMS and Solid State Variable Capacitors (Varactors) [47]

CMOS varactors	MEMS varactors
Leakage currents	No significant leakages
Typical Q–factor of 30–40, in a few cases up to 50–60	Typical Q–factor of 200–300
Decreasing tuning range (C_{max}/C_{min}) due to continuous downscaling. Maximum ration of about 3 in the millimetre-wave range	Tuning ranges typically spanning between 5 and 50
Rather lossy in the millimetre-wave range	Always low-loss

7.0 Market exploitation of RF–MEMS: current situation and perspectives

In fact, due to the integration of the antenna with many other components, the recent rapid spread of 4th Generation-Long Term Evolution (4G-LTE) smartphones caused an unintended trend in the degradation of speech signal and data transmission quality [36]. (see Figure 4).

Figure 4: Decreasing Trend in Communication Quality Stepping from One Generation to Another, as Hopping from Early Mobile Handsets in Late '90s to Modern Smartphones [36]



It was possible to take advantage of RF-MEMS properties, particularly in terms of tunability, in this previously unheard-of environment. To achieve the best adaptive matching in this regard, analogue impedance tuners are used between the smartphone antennas and the RF Front Ends (RFFEs). As a result, the impedance tuners implemented by RF-MEMS are one of the technology's initial commercial applications [41].

The rapidly developing 5G industry seems to be a field of convergence for many needs and difficult requirements that the research and industrial community has rarely seen before. After all, the trend toward integrating additional wireless services supported by the same device has been unrelenting ever since the widespread adoption of mobile handsets about two years ago. And rather than moving at a linear rate, it has been expanding at an exponential rate. Regarding this, it is anticipated that 5G systems will supply up to 1000 times the capacity of present mobile networks [38].

For instance, broadband wireless applications would demand data rates that could be 10–100 times higher than what 4G wireless networks can provide, such as high-resolution video streaming and Tactile Internet [71].

The Internet of Things (IoT) paradigm depicts an ongoing technological development path in which each environment and object from our daily lives acquires its own identity in the digital sphere by using the Internet at a higher degree of abstraction [46][87]. With the IoT as their frame of reference, 5G mobile systems are anticipated to support a wider range of wireless connections, supporting emerging applications like Machine-To-Machine (M2M), and, consequently, all the more strict requirements they bring in terms of Quality of Service (QoS), concerning reliability, spectral and energy efficiency, and other factors [88][39][40].

In this sense, the use of smart connected vehicles for improving road safety aids in understanding how important delay and dependability issues may be. Given the just-described situation, it is obvious that no one enabling technology will be able to handle all of the difficult and frequently contradictory requirements of next-generation 5G applications [64]. From a broad perspective, network architecture and algorithms will require innovation and re-engineering.

Naturally, this will necessitate the development of unique hardware and software solutions. More specifically, the currently in use Orthogonal Frequency Multiple Access (OFDM) waveform—which is exploited in 4G applications—will need to be replaced by more effective solutions, to name just a few of the current limitations that will need to be overcome at the architectural and implementation level. Additionally, in order to assure gigabit (Gb) communications, network diversification, the use of large-scale Multiple Input Multiple Output (MIMO) units, and the usage of mmW spectrum must be explored [64].

It is anticipated that 5G communication protocols will require higher operation frequencies (e.g., well above 6 GHz) and large reconfigurability to cover different services, while reducing hardware redundancy and power consumption. This is based on the previously discussed market pull scenario that began making RF-MEMS solutions successful (up to this point for impedance matching tuners). It is required to use passives with enhanced properties (low-loss, high-isolation, etc.) to address these difficulties, and RF-MEMS technology is suggested as one of the more attractive choices, both for 5G smartphones (i.e., RFFEs) and base stations [63]. Of course, there will be significant issues with frequency operating that need to be resolved. In this manner, millimetre-wave frequency operation is intended for the backhaul section of the infrastructure that is closer to end users (60–70 GHz). This is the situation with the so-called 5G tiny cells, which will provide solitary users in constrained spaces with very-wide data rate access (up to the Gbps range). As will be covered further in this work, literature has already shown RF-MEMS devices with micro-relays running at frequencies as high as 110 GHz and displaying good features. More work will need to be put into making resonant classes of MEMS devices, which serve as filters with electromechanical transduction mechanisms, operate at higher frequencies.

From a different angle, RF components always need to be packed and integrated into more complicated sub-systems and systems, regardless of the specific technology used for their realisation. On the one hand, the package’s principal job is to shield electronics from potentially damaging (environmental) variables including shocks, contaminations, moisture, dust particles, and so on [49], but on the other hand, it has been realising an increasing number of functionalities [51]. In reality, the rapid expansion of RF systems for mobile communication over the past few years has fueled the development of miniaturisation, high-integration density, and low-cost fabrication techniques.

Today’s RF Systems on Chip (SoCs) only use a few tens of Integrated Circuits (ICs) compared to hundreds of passive components [84]. It is understandable that since these components are frequently produced using different, incompatible, and non-monolithic technologies, their successful integration can only be accomplished using high-performance and high-density Wafer Level Packaging (WLP) methods. It is undoubtedly a difficult challenge to design and implement a package that guarantees excellent reliability [54][57], high density integration, and very little impact on the performance of RF passive (MEMS and non-MEMS) components [62][56]. This is the reason that, as was already indicated, the packaging/integration process sometimes ends up being more expensive than the actual RF components that need to be packaged.

8.0 Recent Findings in the RF–MEMS State of the Art Research Scenario

Since the beginning of 2000, a few research articles reporting high-performance devices and networks operating at frequency ranges as high as W-band have begun to populate the literature on RF-MEMS (i.e. above 75GHz). The development of such components was studied primarily for the purpose of showcasing and communicating the exceptional properties made possible by RF-MEMS technology.

For instance, switch-based phase shifters and high-isolation RF-MEMS switches have both been demonstrated to function well in the frequency range from 70 GHz to 110 GHz [83][85]. According to Baghchehsaraei et al.[37], there is an intriguing way to increase isolation in the switch OFF state and decrease losses in the switch ON state (2012). It is built on a waveguide switch that has laterally movable fingers that can short electric field lines, implementing the OFF state. Fig. 6 reports the switch’s 3D schematic in both the ON and the OFF states.

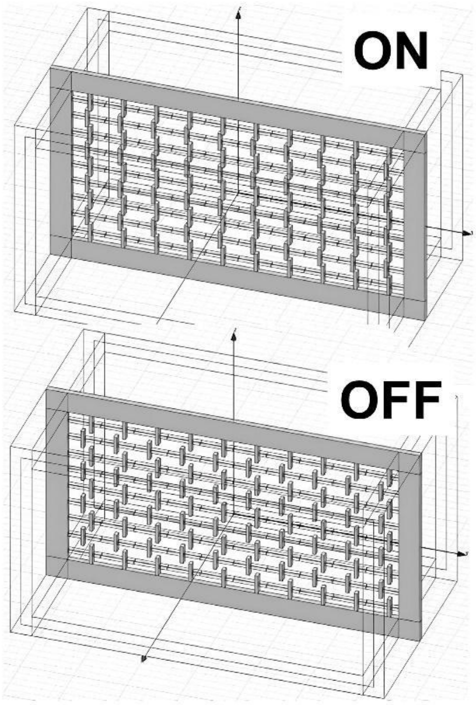
In the frequency range from 62 GHz to 75 GHz, the examined samples showed losses greater than 1 dB and isolation better than 20 dB. More recently, it has been suggested that RF-MEMS would be a major enabling technology for future 5G applications, both for complicated networks and basic elements [58][59][60][61]. This shows that there is increasing consumer interest in high-frequency functioning RF-MEMS devices, in addition to research and niche market activity.

9.0 Future of 5G and Needs for RF Passives

From the first cellular network generation (1G) in the 1970s and 1980s to the current fourth generation Long Term Evolution (4G-LTE), deployed in 2010, there has been a smooth spread and evolution of mobile communication devices and services over the previous four decades [91–97].

In light of this situation, the next 5G mobile communications standard will advance in the imaginative direction of a globally communicative world [8, 9].

Figure 5: 3D Schematic of the Waveguide RF-MEMS Switch Proposed by Baghchehsaraei et al. (2012) [37], in both ON/OFF Configurations



In high-level specifications, such a viewpoint can be incorporated in accordance with the references listed below [100-103]:

1. Up to 1000 times more data volume;
2. 10 to 100 times more connected devices;
3. 10 to 100 times more typical user data rate;
4. 10 times longer battery life; and
5. End-to-End (E2E) latency in the millisecond range.

The realization of a common, linked platform capable of meeting the aforementioned requirements will be a requirement of 5G. Acting at several technological levels, including

A. radio links,
B. multi-node/multi-antenna transmission,
C. network dimension, and
D. spectrum usage will be necessary [104-108].

In order to support and enable the high-level vision of 5G, it is now required to frame how the system-level standards stated above reflect the qualities and specifications that fundamental hardware components and RF passives must meet. To do this, it is appropriate to list the classes of RF passive components and networks that will be required for 5G applications as the first stage. Additionally, it must be stressed that all of the aforementioned devices can be successfully implemented in RF MEMS technology [109]:

- Wideband switches and switching units operating from 2-3 GHz up to 60-70 GHz (and beyond), with low-loss, high-isolation, and very-low neighbouring channels cross-talk;
- Adjustable filters with strong stopband rejection and minimal passed band attenuation;
- Multistate impedance matching tuners for wideband;
- Flat characteristics and programmable digital step attenuators with different settings for frequency ranges between 60 and 70 GHz;
- Analog, wideband, multi-state phase shifters;
- Phase-shifting hybrid devices with configurable attenuation (i.e., instances 4 and 5 as a special device);
- Monolithically integrated miniature antennas and arrays of antennas using one or more of the earlier components.

It is helpful to highlight the most essential tentative parameters that such devices will need to meet in order to be successfully employed inside 5G-related applications now that the primary macro-classes of RF MEMS passives that 5G will demand have been identified. These parameters are succinctly listed below:

Frequency range: 60-70 GHz and above (mm-wave range), starting at sub-6 GHz;

- Isolation: better than 30/40 dB for highest frequencies;
- Loss: Lower than -1 dB over the broadest frequency range;
- Cross-talk: less than 50/60 dB throughout the broadest conceivable frequency range;
- Switching time: less than 1 ms, with a feasible objective of a few fractions of a second (for example, 200-300 s);
- Control voltage: a few volts or less (e.g., 2–3 V).

Given the just-described scenario, RF MEMS technology has already shown that it can meet the stringent demands placed on RF passive components by 5G in terms of wide reconfigurability/tunability, wideband operability, and frequency agility [110, 111, 112].

However, packaging and integration must be handled with extreme care if the economic promise of RF MEMS is to be completely realised.

In actuality, traditional semiconductor technologies and microsystems technology are either incompatible or difficult to monolithically integrate (e.g., CMOS). The use of RF MEMS components in systems and subsystems therefore always relies on integration via surface mount technologies (SMTs), such as flip-chip, ball grid arrays (BGAs), wire-bonding, and so on [113].

MEMS devices must be encased and safeguarded in addition to these factors. Microsystems in particular require a container because of their fragility and exposure to potentially dangerous environmental conditions such mechanical shocks, contamination, the presence of dust particles, moisture, etc. [114].

There are extra factors that must be carefully considered while working with RF MEMS. When a protective cap is applied to RF passives, numerous parasitic effects are also introduced, which can reduce electromagnetic performance and increase loss [115]. Applying protective packaging to RF MEMS specifically entails creating a housing for the device with a physical component (such as a dome) close to the RF passive itself. As a result, such a dome will interact with the electromagnetic field surrounding the object, resulting in extra, undesirable capacitive couplings. Additionally, handling the redistribution of the electrical signals from the RF MEMS device to the outside environment is frequently necessary for the packaging solution.

For example, signal underpasses or through-silicon vertical vias filled with conductive materials can be used to achieve this [116, 117]. The properties of the initial RF MEMS device are jeopardized by extra resistive losses, RF path discontinuities, series inductive contributions, and shunt capacitive contributions, regardless of the particular signal redistribution method. Because of this, it is recommended that the electromagnetic design of the package be optimized with at least the same care as the RF MEMS devices themselves [118, 119].

The thin film capping method is the foundation of the packaging strategy outlined in this work and described in the following pages. This indicates that no new RF signal routes are required. The capping dome's interaction, nevertheless, can still be problematic. The next sections will report on and discuss electromagnetic simulations as a result.

At this time, our investigations only deal with basic CPWs. This is a result of two different driving forces. Behavior is quite similar to that of conventional CPWs, with the exception of switching and reconfigurability functionalities.

10.0 Conclusion

In conclusion, the next generation of mobile communication technology, 5G, promises to revolutionize the way we communicate, with a globally connected platform capable of handling up to 1000 times more data volume, supporting 10 to 100 times more connected devices, 10 times longer battery life, and E2E latency in the millisecond range. To achieve this, 5G will require RF passive components and networks that meet the stringent demands of the new standards. RF MEMS technology has already shown that it can meet these demands, but packaging and integration must be handled with extreme care.

Traditional semiconductor technologies and microsystems technology are either incompatible or difficult to monolithically integrate, requiring the use of SMTs such as flip-chip, BGAs, wire-bonding, and protective packaging to safeguard the fragile MEMS devices from mechanical shocks, contamination, moisture, and other environmental conditions. Careful design optimization of the package is essential to avoid parasitic effects and preserve electromagnetic performance. The successful implementation of RF MEMS components will require a multidisciplinary approach that integrates the knowledge and skills of various fields, including materials science, electronics, and mechanical engineering, to ensure that the promise of 5G is fully realized. The review paper is a valuable resource for researchers, students, and practitioners interested in "Advancements in Telecommunications/IoT with MEMS and RF Passives", and serves as a foundation for further research in this field.

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