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Next-Gen Emergency Communication Using Low-Power Wide-Area and Software-Defined WANS

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Abstract: *Among the Internet of Things' (IoT) fastest-growing networks is the low-power wide-area network (LPWAN). Long-range communication and low power consumption are just two of the many exceptional attributes that have made LPWANs the most extensively used networking protocols in the IoT space. But this intriguing network faces a number of privacy and security risks. This paper reviews the integration of LPWAN with Software-Defined Wide-Area Networks (SD-WAN) to develop a robust, scalable, and intelligent communication framework specifically designed for emergency scenarios. Long-range, low-power connection provided by LPWAN technologies makes them perfect for environmental monitoring, remote sensing, and medical applications in disaster areas. However, LPWAN lacks the dynamic routing, quality of service (QoS), and real-time adaptability required for mission-critical communication. SD-WAN addresses these limitations through centralized orchestration, programmable policies, and network-wide optimization. By combining LPWAN's energy-efficient sensing with SD-WAN's programmable, centralized control, the proposed architecture supports low-latency, context-aware communication in infrastructure-limited environments. This work reviews the technical foundations, applications, and security challenges of both technologies and surveys recent advances in AI-driven routing, energy harvesting, and cognitive LPWAN. Despite progress, a unified LPWAN–SD-WAN framework for real-time, large-scale emergency response remains underexplored.*

Keywords: Communication Systems, LPWAN, Software-Defined Networking (SDN), Network Resilience, IoT Security

I. INTRODUCTION

In an increasingly connected world, the demand for resilient and intelligent emergency communication systems has become increasingly pressing as a result of big catastrophes, public safety events, and natural disasters occurring more frequently and with greater intensity. Traditional communication infrastructures often fall short during such critical events, primarily due to their rigidity, limited scalability, and high dependency on centralized resources. To address these limitations, the integration of the new paradigms of Software-Defined Wide-Area Networks (SD-WAN) and Low-Power Wide-Area Networks (LPWAN). LPWAN ensures energy-efficient long-range connectivity for remote sensing and alert systems, while SD-WAN offers centralized control, traffic optimization, and seamless management across distributed network environments [1]. Together, these technologies provide a foundation for building agile and dependable emergency communication infrastructures that can function efficiently even in challenging and infrastructure-deficient scenarios.

Low-power, long-range communication is made possible by LPWAN technologies, including LoRaWAN, Sigfox, and NB-IoT, making them ideal for deploying battery-operated sensors, alarms, and monitoring devices in remote or disaster-struck regions [2][3]. These devices often need to operate for several years without human intervention, and LPWAN's energy-efficient protocols make this possible. However, while LPWAN provides the physical layer and transmission capabilities for such systems, it lacks the intelligent routing, real-time decision-making, and network-wide coordination required for managing large-scale emergency communication frameworks [4]. This is where SD-WAN complements LPWAN, offering dynamic route selection, centralized policy enforcement, and enhanced quality of service (QoS) to guarantee that vital information arrives at its intended location with the least amount of delay and the

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highest level of dependability [5].

By interlinking the lightweight, low-power capabilities of LPWAN with the intelligence and flexibility of SD-WAN, emergency communication networks may attain hitherto unheard-of levels of robustness and efficiency. SD-WAN enables centralized orchestration of multiple LPWAN nodes and integrates them seamlessly with other network segments such as LTE, 5G, or satellite links, creating a unified, software-defined communication layer. This combined architecture supports real-time analytics, automated failover, and secure data transmission, all of which are critical in time-sensitive emergency scenarios. As future emergency communication systems evolve to support more IoT-enabled devices and machine-oriented interactions, Context-awareness is made possible by the convergence of SD-WAN and LPWAN. SD-WAN and LPWAN integration is necessary to provide context-aware, scalable, and robust communication frameworks aligned with next-generation wireless network demands.

A. Paper Organization

The paper is structured as follows: Section II outlines existing emergency communication systems and their security challenges. Section III explains the architecture and applications of LPWAN. Section IV describes SD-WAN components and benefits. Section V presents a literature survey and comparative analysis of recent advancements in communication technologies for emergency scenarios.

II. OVERVIEW OF RELIABLE EMERGENCY COMMUNICATION

A vital component of the entire emergency response system, emergency communication networks offer prompt and efficient communication assistance for all types of situations. A key element of disaster assistance for every nation is the establishment of an efficient emergency communication infrastructure built on a disaster communication backbone. There are several standards for emergency communication networks. The following are the most often used categorization criteria:

A. Wired Communication Networks

In order to communicate, wired transmission medium are used in wired communication networks. The three most popular methods of communication are optical fiber, fixed telephone, and telephone line/network cable connection to the Internet. Wireless transmission medium are used in wireless communication networks. Satellite, mobile, and microwave communication are examples of common communication methods.

B. Public Network

A public network connects each user terminal and private network via a public user network interface, and is run and maintained by operators. A network inside a department or unit is called a private network. Nowadays, Asynchronous Transfer Mode (ATM), Ethernet, and other wireless technologies are the primary tools used in private networks.

C. Local Area Network (LAN)

A communication system that spans hundreds of meters to several kilometers is called a local area network (LAN). With a distribution region that spans hundreds to dozens of kilometers, a MAN's gearbox coverage area is primarily inside cities. A WAN's transmission coverage area spans hundreds to tens of thousands of kilometers and encompasses provinces, nations, and even the whole planet.

D. Security Challenges for Emergency Response Communications

Access control, privacy or secrecy, data integrity, and key management, and authentication are some potential security issues for emergency response communications [6]. These problems are briefly described in the following subsections.

- **Privacy:** Through the use of cryptographic procedures, Confidentiality or privacy ensures that only authorized individuals may access the information. Encrypting the data is necessary to ensure that the appropriate information reaches the proper person.

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- **Data Integrity:** Data integrity verifies that information has not been tampered with during transmission and guarantees its correctness and completeness. Sensitive information, like a patient's medical history, that is obtained at the emergency scene from a distant hospital database may be altered purposefully or unintentionally, which might increase anxiety.
- **Authentication:** User authentication is necessary while transferring medical histories via the emergency network in order to ensure that the information is sent to the rightful owner. In order to authenticate medical personnel when they access patient history from the hospital database, a flexible security architecture is necessary. Additionally, the medical teams ought to be able to transfer access permissions to other colleagues as needed.
- **Key Management:** The assumption that all rescue organizations have shared security credentials prior to joining the emergency response network is not feasible in a large-scale disaster response scenario. For such circumstances, an effective key distribution and management plan must be developed.
- **Access Control:** Access control rules grant access to vital information, including medical records, in a variety of settings and limitations. In most cases, access is granted based on identity, time, and place restrictions.

III. LOW-POWER WIDE-AREA NETWORKS (LPWAN) ARCHITECTURE

An advanced and well-known WAN technology, LPWAN satisfies the IoT goals by using bandwidth effectively, requiring little network infrastructure cost, offering broad-area coverage, and consuming less power. Several wireless communication technologies' energy efficiency and implementation costs are contrasted. LPWAN appears to be the best option since it offers the highest energy efficiency and the lowest implementation costs. IoT devices can observe and engage with their surroundings from any location at any time thanks to M2M communication based on LPWAN. LPWAN typically provides coverage up to 40 km in rural regions (good Line of Sight, or LoS) and 10 km in urban areas (poor LoS), with a minimum battery life of ten years. Layer-wise, the functional design for LPWANs is similar. The difficulties in achieving interoperability stem from the fact that the different names (terminologies) of the MAC and PHY layers, as well as the components that make up the architecture, are usually at fault. The tasks carried out by each component of the architecture are explained in this section. In Figure 1, a basic LPWAN design is displayed.

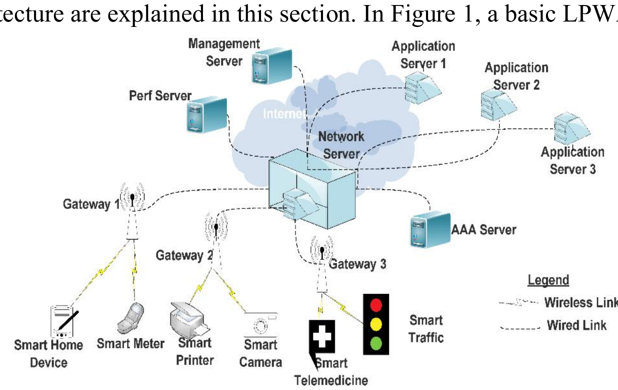

Fig. 1.A Simple LPWAN Architecture

The GW would be connected to all IoT devices, including wireless sensor network (WSN) devices, via LPWAN access protocols in this basic arrangement. These access technologies can be deployed by specific providers, such as Sigfox, Wi-SUN, LoRaWAN, or NB-IoT access providers [7]. The GWs collect data from various IoT devices and transmit it to the NS, which can be reached using wired or wireless internet connections or other IP technologies. To prepare data messages for transmission to an application server, the NS compiles them from the various GWs. The AAA server provides authentication services at the NS, while the Perf server evaluates performance, and the management server handles administrative tasks.

A. Applications of LPWAN Technologies

The transportation, logistics, smart metering, environmental monitoring, agricultural, healthcare, etc. sectors are among those that stand to benefit from the new LPWAN technology (see Figure 2). Since LPWAN technologies have a large communication range and a low consumption rate, they are being used in a lot of IoT applications. Some IoT applications, such as real-time monitoring or emergency warnings, are unable to use LPWAN technology due to issues like poor data rate, low message throughput, and excessive latency.

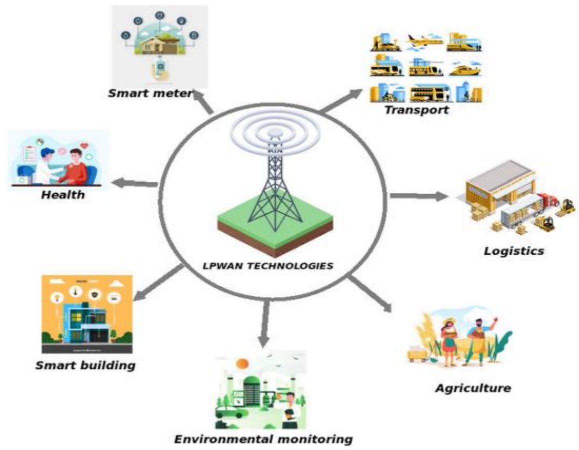

Fig. 2. LPWAN Technologies Application Areas

Nevertheless, LPWAN technologies are needed in a wide range of industries. This section provides an outline of how LPWAN-based IoT projects have been implemented in various sectors. LoRa has a substantial market share in IoT projects based on LPWAN technology, the healthcare industry frequently employs NB-IoT, and cloud is used in IoT projects that offer a public service for treatment.

Transport

LPWAN technology can be applied to intelligent parking and traffic control in transportation. It is true that traffic congestion and bottlenecks are issues in the majority of big cities. This issue is addressed by LPWAN technology, which use sensors to count automobiles at traffic signals or intersections and track occupied parking spots to direct drivers to open spots.

Logistics

The location and condition of their items must be ascertained by logistics organizations or those that use logistics in their production operations. The choice of a supply chain tracking system should take into account two crucial logistical criteria. These are the gadgets' prices and battery life [8]. These specifications encourage the use of LPWAN technology.

Agriculture

Modernization is necessary in the agriculture industry to keep up with the world's population increase. Precision farming, also referred to as "smart farming," is a collection of methods that use technology to cut down on environmental impact and increase agricultural yields. Low-rate data on soil moisture, plant health, and other factors are gathered and sent for long-distance analysis in order to execute smart farming. Other than cellular networks, rural areas where agricultural occurs are frequently supplied by other networks. Consequently, LPWAN technologies are suitable for a number of uses in this sector as they can link equipment that is spread out across large distances [9].

Environmental Monitoring

To protect the environment, environmental monitoring is essential. It's described in [10]. Air quality, water quality, noise, and other environmental elements may all be monitored, as can markers of ecosystem health in soil, water, and air. Large geographic areas are typically covered by monitoring areas. The need for long-distance transmissions and sufficient coverage of the region sparked the creation of LPWA network-based environmental monitoring programs.

Smart Building

Building management automation is becoming more and more common these days, with creative ideas that are aided by sensors and actuators. High levels of comfort and minimal environmental impact are the goals of intelligent buildings.

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Information is gathered for analysis and decision-making, including temperature, CO2 levels, details on the heating system, the amount of energy used in the building's rooms, etc.

Health

The medical industry has seen the emergence of IoT applications built on LPWA technology [11][12]. Vital sign monitoring is the most common use. Data from this monitoring must be sent either promptly or on a regular basis. If the latter is true, LPWANs can offer reasonably priced long-distance communication.

Smart Meter

Businesses with large gas, electricity and Smart meters are necessary for water distribution networks to maximize human resources by eliminating the requirement for manual reading and network monitoring to foresee any problems. Smart meters are often dispersed across a wide region and send data at regular intervals.

IV. SOFTWARE-DEFINED WIDE-AREA NETWORKS (SD-WAN)

The development of SD-WAN (Software-defined Wide Area Network) technology was prompted by the need for WANs to be more scalable, agile, and adaptable. Software-SDN is where SD-WAN originates, a methodology based on software drivers and API, allowing its communication with the physical hardware infrastructure, and facilitating administration and device setup. SDN offers an API for configuration and decouples software logic from the hardware [13]. Optimizing virtualizing network services, this Internet-based technology enables flexible management, usual configuration complexity, and scalability. In Figure 3, the three layers of SDWAN architecture are visible.

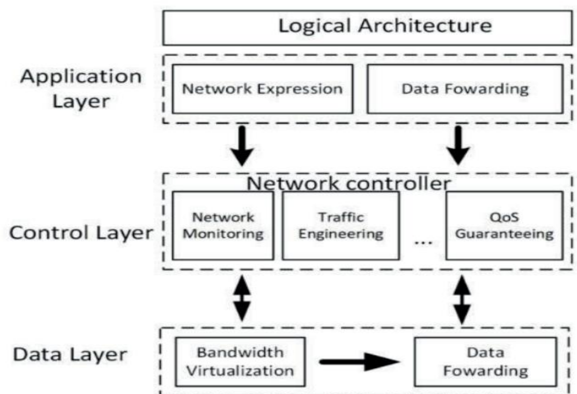

Fig. 3. Basic SD-WAN Architecture

The control layer operates autonomously to execute and oversee network activities. The data layer, on the other hand, is responsible for managing bandwidth and virtualizing data forwarding. The application layer offers services, and developers and Internet service providers can specify the network requirements for those services [14]. There are two interfaces available for layer-to-layer communication: the North Bound Interfaces (NBI), which connect applications to the SD-WAN controller, and the South Bound Interfaces (SBI), which connect the controller to network devices.

It is possible to use private Multiprotocol Label Switching (MPLS) technology to transfer traffic from branches to business data centres over traditional WAN technologies. Apps are moved from data centres to public clouds such as Microsoft Azure and Amazon Web Services (AWS) [15]. An SD-WAN streamlines issues and boosts efficiency by separating control from the underlying hardware and moving it to a centralized software-based controller. These days, businesses use SD-WAN as a crucial tool to lower installation costs, free up human resources, and provide safe, dependable, and quick communication channels. It was developed to meet the demands of new commercial applications as well as the quickly increasing security requirements. An illustration of a paradigm SD-WAN design is provided in Figure 4.

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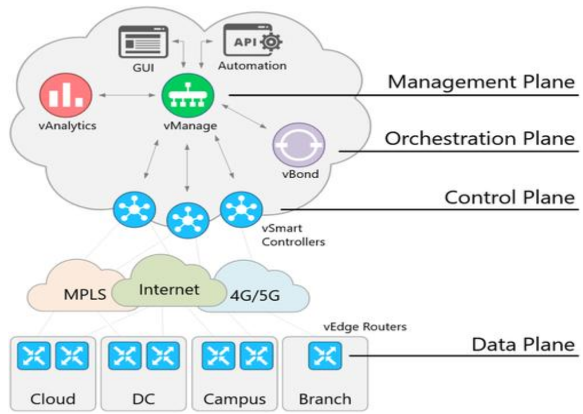

Fig. 4. Software-Defined-Wide Area Network (SD-WAN) Components

The SD-WAN system is composed of four distinct planes: the Data Plane, Orchestration, Management, and Control. As opposed to a standard wide area network (WAN), which shares all devices in the administration plane, data plane (packet forwarding), and control plane, each plane has its own tasks and duties and is separated from the others.

A. Challenges in Implementing SD-WAN

The following are some of the challenges that come with SD-WAN implementation:

- Implementation complexity increases with network size and heterogeneity due to the wide variety of tools, services, and suppliers that are involved.
- Network elements may go inactive for a period of time due to human-caused disruptions. This period of idleness may have an impact on the network's effectiveness and performance [16].
- SD-WAN solutions must integrate and work in tandem with current protocols and infrastructure. This necessitates making sure that legacy network devices integrate seamlessly and that it is compatible with conventional networks and protocols.
- Distributed protocols struggle to adapt to varying user demands, especially in legacy systems lacking programmability and flexibility for seamless updates.
- Network automation in SD-WAN is challenging due to the complexity of translating high-level intents into precise configurations across diverse and dynamic network environments.
- SD-WAN relies on best-effort public Internet, making it difficult to match the QoS and performance levels of traditional dedicated lines, especially in terms of latency and throughput.

Since SD-WAN avoids the use of private lines and instead relies on telco operators' connectivity, monitoring tasks become challenging. To get around this difficulty, new monitoring mechanisms must be developed and implemented. This allow for accurate and real-time monitoring in SD-WAN. While "Active Tomography," which involves injecting probe packets into the network to infer its internal characteristics, is one suggested technique, "Active Monitoring," which involves transmitting probe packets over alternate overlays connecting two edge routers to estimate their delay, is another.

V. LITERATURE REVIEW

There are still issues with the SDN technique's deployment over large geographic areas, despite the fact that it is employed in numerous research investigations, academic studies, and industrial applications. Table I presents a comparative analysis of advanced communication technologies enhancing emergency services through optimized, scalable, and resilient network solutions.

Asif and Ghanem (2021) showed how to develop and deploy AI-secured SD-WAN technology at system-level, assisting service providers in connecting to and integrating with all of the many IoT compute edges needed to maximize 5G cell administration and traffic. This design allows the energy industry to smoothly move to full 5G connections by

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managing any data accessible over the edge and using 5G transport for those critical applications that need higher bandwidths and ultra-low latency. In order to offer the energy industry smooth integration, scalability, and flexibility, also evaluate the benefits and drawbacks of integrating SD-WAN with hybrid Multi-protocol Label Switching (MPLS) [17].

Santos et al. (2021) the IoT service allocation issue is formulated using Mixed Integer Linear Programming (MILP), which considers SFC ideas, various LPWAN technologies, and several optimization targets. A detailed analysis of the suggested MILP formulation for Smart City use cases has been conducted. Trade-offs between the various provisioning options are evident in the statistics. Because the model method is general and appropriate for a variety of IoT use cases, research on resource provisioning in fog-cloud settings may utilize it as a benchmark [18].

Tran, Hoang and Nguyen (2021) demonstrate how cooperative communications and energy harvesting (EH) at the wireless sensor for low-power wide-area (LPWA) systems may be coupled. It is possible to see formulations as the initial outcomes of applying EH to mathematically analyzed LPWA systems. Utilizing half of the gearbox blocks for EH, in particular, can optimize system performance. Furthermore, the system performance may be greatly enhanced if the number of transmit antennas at the power beacon is equivalent to the number of receive antennas at the gateways. Monte-Carlo simulations are performed to demonstrate that the generated expressions are accurate [19].

Mo and Sansavini (2021) present a new Smith predictor (SP) that has the ability to forecast input time delays with accuracy and, as a result, reduce the loss of LFC performance brought on by erratic communication. After then, the SP receives the anticipated delays. After that, a discrete observational space is mapped onto the time delays. The findings show that compared to current delay-margin-based controllers, the SP has more success eliminating load disruptions and enhancing time delay resilience. Utilizing the small gain theorem it is examined if the LFC system is stable with time-varying latency using a Lyapunov–Krasovskii-based delay-dependent criteria [20].

Das et al. (2021) focus on the long-range communication channel design for an optical wireless communication (OWC) link operating at 10 GHz with a laser source at 1550 nm. When optical fibers cannot be cut, OWC is quite helpful. A three-kilometer long-distance communication link with a bit-error-rate (BER) of up to 10−9 has been investigated. This system's architecture allows it to tolerate significant air attenuation of up to 11.67 dB/km without compromising link range or BER. Along with the system's essential design characteristics, Additionally described are an automated laser power control method and an auto alignment approach [21].

Nayyer, Sharma, and Awasthi (2021) model scalability-aware routing inside a controller's domain, and learning is used to deliver the best possible solution. The link load is utilized as effectively as possible, and flow installation is done using both proactive and reactive techniques. When a failure occurs, the Q-learning model assists in selecting the optimal course of action. The model works when learning is complete. Comparing the quantity of messages generated with other existing routing systems in Software Defined Networks, a preliminary study shows improvements of 78%, 58%, and 47% [22].

Onumanyi, Abu-Mahfouz and Hancke (2020) discuss a physical layer front-end paradigm and a generic network architecture that operates well with CR-LPWAN systems. Next, a few noteworthy cutting-edge strategies for CR-LPWAN systems are examined. The study concludes with several research problems and future initiatives in this area. Additionally discussed are CR-LPWAN systems' possible advantages for IoT applications. For the vast majority of prospective researchers interested in developing successful and efficient CR-LPWAN solutions to improve a variety of IoT applications [23].

Gu et al. (2020) evaluate the LPWA technologies' performance based on a number of factors, such as coverage, bandwidth, cost, and so on, and analyze the most recent wireless communication techniques in the IoT. Next, conduct a thorough comparison of several LPWA technologies in order to assess their characteristics. In order to effectively address long-range communication issues between IoT devices, which have grown dramatically in tandem with people's increasing demand for network applications, this article examines the features of these LPWA technologies in a range of application areas [24].

Despite extensive research on LPWAN and SD-WAN technologies for emergency communication, several critical gaps remain. Many frameworks lack adaptability to dynamic and infrastructure-deficient environments, where rapid deployment, interoperability between heterogeneous networks, and context-aware data prioritization are vital.

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Moreover, the combined implementation of AI-driven SD-WAN with LPWAN technologies across diverse IoT ecosystems is still in its infancy. There is limited research on creating unified, intelligent frameworks that seamlessly coordinate LPWAN's energy-efficient sensing with SD-WAN's centralized control for mission-critical, latency-sensitive communication during disasters

TABLE 1: COMPARATIVE STUDY OF RECENT RESEARCH ON ADVANCED COMMUNICATION TECHNOLOGIES FOR NEXT-GENERATION

Author	Focus Area	Technology	Contributions	Communication	Future Study
Asif and Ghanem (2021)	AI-Secured SD-WAN for 5G and IoT	SD-WAN, AI, Hybrid MPLS, 5G	Designed system-level SD-WAN architecture to optimize IoT/5G traffic in energy sector	Supports ultra-low latency and high-bandwidth communication for critical/emergency services	Expand to multi-sector 5G SD-WAN integration with dynamic QoS provisioning
Santos et al. (2021)	IoT Service Allocation in Smart Cities	LPWAN, Fog-Cloud, MILP, SFC	Developed MILP formulation for E2E IoT resource provisioning across Fog-Cloud	Optimizes IoT infrastructure for resilient and scalable emergency communication	Test on real-time emergency response simulations using diverse IoT traffic
Tran, Hoang and Nguyen (2021)	Energy Harvesting for LPWAN	RF Energy Harvesting, MIMO, Cooperative Communication	Derived mathematical models for throughput, outage, and SEP in EH-LPWA	Enables self-sustaining low-power emergency sensor networks in remote areas	Apply EH models to mobile or drone-based emergency LPWAN nodes
Mo and Sansavini (2021)	Delay Compensation in Control Systems	Smith Predictor, DHMM, EWMA, Truetime	Proposed SP for delay mitigation in load-frequency control over unreliable networks	Improves timing accuracy and reliability in emergency control systems	Extend SP models to multi-area wide-area protection systems
Das et al. (2021)	Long-Range Optical Wireless Communication	Optical Wireless, 1550 nm Laser, Auto-alignment	Designed 10 GHz OWC link for 3 km range with BER under 10^{-9}	Alternative to fiber in disaster areas; maintains communication in high-attenuation zones	Integrate adaptive optics and atmospheric channel compensation for reliability
Nayyer, Sharma and Awasthi (2021)	Scalable SDN Routing	SDN, Q-learning, Proactive/Reactive Flow	Presented efficient routing with load balancing and failure recovery using RL	Supports adaptive routing during dynamic emergencies with reduced message overhead	Apply Q-learning to inter-controller coordination and real-time disaster routing
Onumanyi, Abu-Mahfouz and Hancke (2020)	Cognitive LPWAN Architectures	CR-LPWAN, Physical Layer Front-end	Reviewed CR-LPWAN systems and design guidelines for IoT	Enhances spectrum efficiency and reliability in dense emergency environments	Prototype CR-LPWANs for emergency IoT deployments in smart grids
Gu et al. (2020)	LPWAN Evaluation for IoT	LoRa, Sigfox, NB-IoT, LPWA	Compared LPWA technologies across key metrics like	Provides baseline for selecting LPWANs in various emergency	Develop hybrid LPWA frameworks combining best

			cost, range, bandwidth	deployment scenarios	features for disaster resilience

V. CONCLUSION AND FUTURE WORK

The primary driver behind the increasing interest in low-power wide area (LPWA) networks is their ability to provide affordable access to low-power devices spread across huge geographic areas. In a number of innovative smart city and M2M applications, the IoT objective is aided by LPWA technologies, which complement and sometimes outperform conventional cellular and short-range wireless technologies in terms of performance. This research looked at how emergency communication systems have changed over time using LPWAN and SD-WAN technology. The deployment of sensors and IoT devices in rural or disaster-affected areas is made possible by LPWAN, which offers an effective method for long-range, low-power data transmission. SD-WAN, meanwhile, introduces programmability, centralized control, and dynamic traffic management, key features that address LPWAN's inherent limitations, particularly in handling real-time, critical communication. The literature highlights advances such as energy harvesting in LPWAN, AI-based SD-WAN routing, and hybrid models for delay management. However, integrated LPWAN–SD-WAN frameworks for emergency communication remain limited, with most studies addressing isolated challenges. To advance the field, Future research should concentrate on creating intelligent, unified architectures that combine the strengths of both technologies. Real-world validation through simulations and testbeds is essential to translate theoretical models into practical, resilient solutions for next-generation emergency communication systems

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