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# Optimization Analysis of Average Message Delivery Time for Healthcare Monitoring Using a Developed NB-IoT Technology in a Smart City

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## Abstract

In contrast to prior research that lacked a comprehensive analysis of a fundamental parameter, namely the average message delivery time (AMDT), this study significantly contributes to the academic community by offering cutting-edge insights into AMDT analysis for wireless healthcare monitoring in smart cities. Employing the innovative Narrowband Internet of Things (NB-IoT) technology, this article thoroughly investigates AMDT within wireless healthcare monitoring. The study focuses on analyzing AMDT during the transmission and reception of messages from base stations (BS) to remote healthcare data aggregators (HDAs) serving remote patients (RPs). Various vital parameters are considered, including modulation rate, average message length (AML), the average number of hops per path (H) required to reach remote patients, patient count, sub-carrier spacing (SS), and the modulation type within the communication range of the BS. This proposed assessment of health network performance offers a brief overview based on essential criteria, facilitating swift and precise evaluations of the efficacy of mobile health applications. The results obtained and the in-depth discussion of the outcomes of AMDT analysis provide valuable insights that can be harnessed to enhance the design and operation of wireless healthcare monitoring systems.

*Keywords:* NB-IoT, Average message delivery time, Modulation rates, Multi-hop wireless networks, Remote patient monitoring, Smart city patients.

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## 1. Introduction

Within the dynamic healthcare realm of smart cities, the convergence of mobile computing and healthcare monitoring has forged a path toward groundbreaking advancements, reshaping the foundations of patient care and medical services. Central to this transformation is a pivotal technical parameter known as AMDT [1], which wields a fundamental influence over the effectiveness, dependability, and real-time functionality of mobile computing in healthcare monitoring systems. Moreover, the AMDT holds particular significance in real-time applications, where the prompt conveyance of information is paramount. In such scenarios, minimizing the AMDT is imperative to ensure seamless and punctual operations. In this context, the AMDT for monitoring remote patients from a BS refers to the average duration for a transmitted message containing essential health-related data or information to travel from a patient's remote location to a central base station. These systems rapidly share medical data, using technologies from wireless networks to advanced spread-spectrum techniques. Multi-user, multi-access methods, and advanced coding quicken data transmission and resource use. Emerging techs like artificial intelligence (AI), machine learning (ML) [2], Internet of Things (IoT), edge computing, and sensors fuel innovation, enabling predictive analytics, personalized treatments, and better patient results. These technologies redefine healthcare monitoring, ensuring unprecedented accuracy and efficiency.

In communication technology and Information Theory, the average AMDT measures the time it takes for a message to be transmitted from a sender to a receiver in a communication system. It is an important metric in evaluating the performance and efficiency of communication systems. In this context, the AMDT [3] is a vital performance metric that measures the time required for a message to be successfully delivered from a BSs to a remote receiver patient within the NB-IoT coverage in a communication network. It is calculated as the average time between message transmission and receipt by the intended recipient.

NB-IoT [4] is a low-power, wide-area network (LPWAN) technology specifically designed for IoT applications. It enables devices to connect to the internet

and communicate over long distances while consuming minimal power. The AMDT in NB-IoT is critical for efficient and reliable communication between IoT devices and the network infrastructure essential for critical NB-IoT applications [5] that support medical patients. The ability to transmit messages quickly and reliably is essential for IoT applications such as remote health monitoring [6]. NB-IoT technology offers reliable and secure connectivity to various medical and industrial applications, enabling remote monitoring and control of devices. The potential of NB-IoT [7] technology to transform several industries, such as smart metering, asset tracking, industrial automation, and environmental monitoring, cannot be overstated. Its low power consumption, long-range communication, and bi-directional communication capabilities make NB-IoT technology [8] a highly promising technology for the future of medical and industrial IoT. The NB-IoT technology is highly promising and can potentially enhance commercial activities in various critical sectors [9]. The most advanced technological standard [10] for short messaging services, such as transmitting medical sensor data [11], has been developed in 3GPP Release 13 and beyond, known as NB-IoT. The foundation for the NB-IoT is the Long Term Evolution (LTE) Advanced Pro design, which can transmit data up to several kilometers from the BS. Furthermore, the NB-IoT has opened up new horizons in healthcare [12] by allowing the diagnosis of a patient's condition through a range of medical sensors and health detection capabilities. The work suggests that while traditional time division multiple access (TDMA) is not directly applied in LTE, its principles are essential for optimizing channel usage and reducing collisions through LTE's Orthogonal frequency-division multiplexing (OFDMA) (downlink) and SC-FDMA (uplink) technologies. These technologies, employing time and frequency domain resource allocation, facilitate efficient data transmission and dynamic time-slot scheduling. This approach is vital for NB-IoT applications within LTE, particularly for ensuring the reliable delivery of healthcare data in smart cities, highlighting the importance of effective time-slot management for patient care and monitoring.

Data aggregation via HDA is the process that collects information from many IoT medical sensors to create interconnected, shared healthcare data. To increase patient safety and maintain their privacy, an HDA is assigned to each patient so that they may compile their data. The proposed method investigates wireless bidirectional point-to-multipoint communication in medical NB-IoT networks by using BS-HDA software. The study's authors [13] discuss how they use a protocol for the IoT to identify the access points of patients and how the patients may get messages from the hospital encouraging

them to take precautions against potential dangers. Delivery time is vital when providing a short performance summary based on these fundamental metrics. The number of patients, the number of packets received, sent, and transferred, the size of the buffer and the packets, channel spacing[14], SS [15], modulation techniques such as QAM (Quadrature Amplitude Modulation) and FSK (Frequency Shift Keying) [16], and the modulation rates are the parameters considered during the work to determine the switch over time. The proposed system architecture uses TDMA technologies as applied in [17] to improve channel usage and reduce the severity of collisions inside the wireless network. According to the research presented in reference [18], a wireless collision detection system has been designed to monitor a physical approach.

It is required that medical sensors and their basic settings be defined for each user to accommodate various laws. Without a doubt, functioning a medical mesh network [19] in polling mode will be the future of communications for patients free to move around. For instance, it enables a wide range of modulation rates [20] to be derived from various restrictions placed on the properties of the broadcast signal. When many patients are connected to a medical network in a smart city, each of whom generates traffic on a low-duty cycle, the polling procedure [21] may become inefficient, consuming a significant amount of bandwidth and occupying the channel with useless polling message size [22] for extended periods. This can cause the network to run slowly. It is becoming more unusual for typical wireless medical networks to include true complements that provide flexibility and patient freedom to roam. However, they are tools patients in the city may use to interact, arrange their benefits, and trade with one another. Several research projects [23] [24] have examined the performance of different strategies for data transmission over wireless communication networks. However, if a network has numerous HDAs producing traffic with a high-duty cycle, the AMDT procedure may become exceedingly efficient. This restriction arises because many HDAs must have a default policy to enter standby, yet only a fraction of those users have data to contribute. Consequently, the delivery time operation uses up a substantial amount of bandwidth and monopolizes the channel by delivering meaningless delivery time messages.

The AMDT is linked to channel capacity and Information Theory concepts. Channel capacity sets a communication system's highest reliable information transmission rate: noise, interference, bandwidth limits, and signal processing impact message delivery time. Coding, modulation, and protocols optimize

the AMDT, aiming to boost the transmission rate while reducing errors and delays. This article has expanded upon the technical parameters of the extended version of NB-IoT technology, as utilized in [15]. Our expansion includes a comprehensive and detailed analysis of AMDT, aiming to provide a deeper understanding of its implications and applications.

The researchers focus on transmitting messages from BSs to remote HDAs to achieve their goal. They take into account various crucial factors that can influence the AMDT, such as the modulation rate used, the AML, the average number of H required to reach remote patients, the number of patients being monitored, the  $SS$  utilized, and the specific modulation type deployed within the communication range of the BSs. This study aims to provide healthcare professionals and network administrators with a concise summary for rapid and accurate evaluation of mobile healthcare applications by conducting a comprehensive healthcare network performance assessment. The findings from the detailed AMDT analysis offer insights to optimize wireless healthcare monitoring system design and operation. This paper makes a valuable contribution to wireless healthcare monitoring by leveraging novel technology proposed for NB-IoT, as demonstrated in the case of the article [15]. The study bolsters effective healthcare solutions for remote patients, supporting technology selection, network design, and resource allocation to elevate performance and patient care standards.

The structure of the remaining sections in this paper is outlined as follows: Section II provides an overview of the study's context and focus. Section III delves into the enhancement of Smart City Healthcare by exploring NB-IoT Patient Networks alongside a comparison with 5G technology. Section IV introduces the system model. Section V offers a comprehensive functional description of the proposed system. Section VI presents the numerical results and their corresponding analysis. Finally, in Section VII, the paper concludes and highlights potential avenues for future research.

## **2. Context, Focus, and motivation**

This section reviews pertinent literature, identifies gaps, and highlights our study's unique contributions, including novel methodologies to address these gaps. Clear research objectives guide our cohesive study, while proactive hurdle anticipation strengthens credibility and facilitates impactful outcomes. We also provide a comprehensive list of abbreviations and symbols.

### *2.1. Related Works*

The literature concerning the analysis and optimization of AMDT remains limited, particularly within the context of Healthcare Monitoring utilizing NB-IoT Technology. Notably, there is a distinct absence of research dedicated explicitly to AMDT, a gap this paper seeks to address. The presented study introduces an innovative analysis approach for AMDT, significantly advancing the current research in this field.

Although prior investigations have explored related aspects of this work, including Healthcare Monitoring with NB-IoT Technology, the complexity of analyzing AMDT for healthcare monitoring in remote patient scenarios necessitates a multidisciplinary approach. This approach encompasses diverse facets such as mobile networks, technology, protocols, and applications. Optimizing AMDT in NB-IoT for healthcare is crucial for quick data transmission critical to timely patient care. Despite NB-IoT's low power use and wide coverage being ideal for healthcare, improving AMDT is key for better system reliability and responsiveness, especially in emergencies and continuous monitoring. The need to minimize AMDT arises from challenges like the urgent nature of healthcare data, resource limitations, network reliability, device scalability, service quality, interference, security, and system integration. Enhancing AMDT tackles critical challenges, optimizing the use of NB-IoT in healthcare. Such advancements demand cross-disciplinary collaboration in telecommunications, computer science, and healthcare to boost patient care and system performance.

Similarly, the authors of [25] analyze the average message delivery time within densely interconnected small-world networks on a plane. Addressing issues like intermittent connectivity and prolonged message duration, [26] evaluates the effectiveness of strategies in mitigating end-to-end message delay. Utilizing instantly decodable network coding (IDNC), [27] delves into methods for reducing delivery time. Meanwhile, [28] proposes a message propagation model tailored for opportunistic networks, incorporating heterogeneous device participation and ensuring real-time network behavior by bounding maximum message transmission delay.

The authors of [29] focus on applying opportunistic non-orthogonal multiple access (NOMA) modes to short-message transmissions, with user power control operating under finite power constraints. Likewise, [30] compares message delivery probability and network overhead through simulations. The results of [31] demonstrate the substantially enhanced vehicle data communication through the proposed scheme, ensuring real-time safety message delivery.

The up-to-date research approaches discussed in [32] outline critical features of real-time communications in wireless sensor networks. Shifting the focus to practical implementation, [33] conducts an intervention study to enhance in-hospital telemetry monitoring within coronary care units to communicate critical patient information effectively. Additionally, [34] details implementing a communication system that optimizes medical personnel productivity within hospital environments, tracking patient and medical equipment locations.

Diving further into specific methodologies, [35] tackles the problem of minimizing delivery time through instantly decodable network coding. At the same time, [36] seeks to develop approximations for mean message delay, message delay variance, and power consumption, providing efficient estimation techniques. Furthermore, [37] presents analytical expressions to calculate the AMDT in small-world networks based on source-target separation.

This study's innovative AMDT analysis technique addresses a critical research gap, substantially advancing field knowledge. Prior works have explored healthcare monitoring, network coding, and communication systems, each uniquely contributing to a broader understanding. This research offers a comprehensive AMDT analysis within NB-IoT-based healthcare monitoring. Its insights promise improved healthcare efficiency, prompt patient attention, and enhanced productivity, safety, and profitability in smart cities. Minimizing AMDT in communication systems, especially NB-IoT, is pivotal for efficient data transmission and real-time applications. Achieving this entails optimizing signal processing, modulation, error correction, and channel access to ensure reliable, timely message delivery.

## *2.2. Motivation*

The motivation of the paper can be summarized as follows:

- This study underscores the pivotal role of AMDT in the efficacy, reliability, and timeliness of wireless healthcare monitoring systems within smart city frameworks. It critiques the lack of depth in existing AMDT analyses and proposes a detailed examination to fill this research void.
- We emphasize the paramount significance of AMDT in real-time healthcare applications. Rapid data transmission transcends mere advantage, becoming crucial to maintaining these systems' operational integrity and reliability.



- The paper acknowledges the pivotal role of wireless communication in healthcare monitoring and delves into how innovations in NB-IoT, AI, ML, edge computing, and sophisticated sensing technologies are revolutionizing this field.
- Focusing on NB-IoT technology, the paper elaborates on its suitability for IoT applications due to its low-power consumption and extended coverage capabilities, underscoring its relevance in enhancing AMDT for reliable remote health monitoring.
- The research delves into the factors affecting AMDT, including but not limited to modulation rate, message length, network topology, patient data volume, and technological parameters, thus offering a holistic view of system performance influencers.
- Through an extensive network performance analysis specifically designed for healthcare settings, this study seeks to furnish healthcare professionals and network administrators with the insights necessary for assessing and enhancing mobile healthcare services.
- The paper extends its focus beyond operational enhancements to outline strategies for advancing wireless healthcare monitoring systems. It aims to raise patient care standards by optimizing the management of essential data types, such as textual messages and images, ensuring a comprehensive approach to healthcare delivery.
- The multidisciplinary approach of our research bridges mobile networking, technological advancements, and healthcare applications, illustrating the interconnectedness of these fields in advancing patient care.
- Identifying a lacuna in the AMDT optimization within the context of NB-IoT-enabled healthcare monitoring, our study introduces novel analytical methodologies to address this challenge.
- By offering an exhaustive analysis of AMDT in NB-IoT-based healthcare monitoring, the paper contributes to the discourse on optimizing healthcare delivery and patient care in the smart city milieu.

Overall, the paper's motivation revolves around the significance of AMDT in wireless healthcare monitoring, the importance of emerging technologies

like NB-IoT, and the need for a comprehensive analysis to enhance healthcare system performance in smart cities.

### *2.3. Abbreviations and Symbols Notation*

To ensure uniformity, eliminate potential ambiguity, and uphold a professional tone, it is imperative to provide a comprehensive summary of abbreviations and symbolic notations employed in this paper. This summary is delineated in Table I as follows.

## **3. Enhancing Smart City Healthcare: NB-IoT Patient Networks and 5G Comparison**

This section elucidates the Interests and Objectives of the Dedicated Patient Network, subsequently presenting the innovative AMDT analysis in wireless healthcare monitoring and culminating with a comparative examination of Healthcare-Centric Networks in Comparison to 5G Technology.

### *3.1. Advancing Healthcare Monitoring through NB-IoT Technology*

Creating and standardizing a dedicated network for patients navigating a smart city involves establishing bilateral communication between patients and their remote healthcare data aggregators facilitated by interconnected base stations. Understanding the significance and objectives of this network in comparison to the existing 5G network is essential. Interest and Objectives of the Dedicated Patient Network:

#### 1. Enhanced Healthcare Focus:

- Prioritizes seamless communication between patients and healthcare data sources.
- Optimizes network resources for healthcare monitoring, ensuring timely and accurate data exchange.
- The dedicated patient network places healthcare at the forefront, prioritizing seamless communication between patients and their healthcare data sources. Unlike the broad scope of 5G, this network optimizes resources specifically for healthcare monitoring, ensuring timely and accurate data exchange.

#### 2. Tailored Connectivity:

- Customizes network architecture for specialized connectivity, optimizing patient data transmission.
- Accommodates unique requirements of healthcare devices for reliable, low-latency communication.

### 3. Prioritized Traffic:

- Designs network to prioritize medical data traffic, ensuring prompt patient information transmission.

### 4. Minimal Latency:

- Aims for ultra-low latency to support real-time healthcare applications and critical conditions.
- Implements robust security measures tailored to patient data, ensuring confidentiality and compliance.

### 5. Efficient Resource Allocation:

- Allocates resources based on healthcare needs, optimizing performance for patient-centric communication.

### 6. Ecosystem Synergy:

- Seamlessly integrates with existing healthcare infrastructure, enhancing patient care.

Our optimization analysis in Healthcare Monitoring with NB-IoT Technology in a Smart City aims to minimize the AMDT of communication systems, with a specific emphasis on NB-IoT technology. By optimizing signal processing techniques, modulation schemes, error correction coding, and channel access protocols, our primary goal is to enhance data transmission efficiency and enable seamless real-time applications. The overarching objective is to ensure messages' prompt and dependable delivery, a crucial aspect for effective healthcare monitoring within a smart city environment. Through these objectives, we aim to contribute to advancing healthcare monitoring capabilities in smart cities, leveraging the potential of NB-IoT technology and improving AMDT in communication systems.

### *3.2. Enhanced Security and Privacy through NB-IoT Technology*

A more comprehensive analysis is needed to address security, particularly focusing on how NB-IoT technology can fortify security and privacy in healthcare monitoring systems.

#### Enhanced Security and Privacy through NB-IoT Technology

##### Implementing Robust Security Measures:

- **Data Encryption:** Detailing the encryption standards and protocols tailored for NB-IoT technology that ensure end-to-end security of patient data during transmission and storage.
- **Access Control:** Discuss the implementation of stringent access control mechanisms to regulate who can access patient data, safeguard privacy, and ensure compliance with healthcare regulations.

##### Tailored Privacy Protections:

- **Anonymization Techniques:** Using data anonymization and pseudonymization techniques to protect patient identities during data analysis and sharing.
- **Compliance and Standards:** Highlighting how NB-IoT systems are designed to comply with global data protection regulations, such as GDPR in Europe and HIPAA in the United States, enhancing patient data privacy.

##### Optimizing Signal Processing and Modulation for Security:

- **Secure Signal Processing:** Explaining how advanced signal processing techniques can mitigate security threats such as eavesdropping and interference, thus maintaining the integrity of transmitted healthcare data.
- **Secure Modulation Schemes:** Delving into the role of secure modulation schemes that improve data transmission efficiency and incorporate security features to prevent unauthorized data access.

Error Correction and Channel Access for Reliable Communication:

- Error Correction Coding: Discuss the application of error correction coding to prevent data corruption and unauthorized modifications, thereby ensuring the accuracy and reliability of patient data.
- Secure Channel Access Protocols: Analyzing secure channel access protocols prioritizing medical data traffic and protecting against cyber-attacks, ensuring reliable and timely delivery of critical patient information.

By providing a detailed examination of these aspects, the paper will offer a comprehensive view of how NB-IoT technology not only advances healthcare monitoring in terms of connectivity and data transmission efficiency but also significantly enhances the security and privacy of patient data. This detailed approach will underscore the multifaceted advantages of adopting NB-IoT technology in healthcare monitoring systems, particularly in smart city environments, where the integrity and confidentiality of patients are paramount. Through this enhanced discussion, the paper aims to contribute meaningfully to advancing secure and privacy-preserving healthcare monitoring capabilities in smart cities, leveraging the full potential of NB-IoT technology.

subsection Comparing Healthcare-Centric Networks with 5G Technology  
Comparison with the 5G Network:

1. Specific Focus vs. Broad Applicability:

- Dedicated network prioritizes healthcare communication, while 5G serves diverse applications.

2. Latency and Reliability:

- Dedicated network targets ultra-low latency for critical healthcare interactions.

3. Data Prioritization:

- Dedicated network prioritizes healthcare traffic over 5G's mixed data types.
- Emphasizing data prioritization for healthcare in the dedicated network, unlike the broader 5G network.

- Highlighting the specific focus of the dedicated network on healthcare communication compared to the broad applicability of 5G.
- Dedicated network customization offers superior healthcare application performance.

#### 4. Privacy and Compliance:

- Dedicated network implements stricter privacy aligned with medical regulations.
- Addressing privacy and compliance concerns by implementing stricter measures aligned with medical regulations.
- While the dedicated network focuses exclusively on healthcare communication, 5G serves a wide range of applications beyond healthcare, potentially leading to diluted resources for medical needs.
- The dedicated network prioritizes ultra-low latency and reliability for critical healthcare interactions, potentially outperforming the generalized low-latency capabilities of 5G.
- Unlike the dedicated network, 5G does not inherently prioritize healthcare traffic, which may delay patient-related data transmission.
- The dedicated network's customization and optimization for patient communication could yield superior performance for healthcare applications compared to the more generalized design of 5G.

The specialized patient network transforms healthcare communication in smart cities, providing precise patient monitoring and care advantages. They aim to establish a patient network that enhances healthcare communication in smart cities. This network boosts healthcare monitoring, ensures timely data transmission, prioritizes patient data, minimizes delays, enhances security, optimizes resource allocation, and integrates seamlessly with current infrastructure. Contrasted with the 5G network, the dedicated network excels in healthcare focus, low latency, data prioritization, customization, optimization, and privacy.

#### 4. System Model Presentation

Consider a model of the system shown in Fig.1. This model consequently includes several moving patients  $P_i, i \in \{1, 2, \dots, n\}$  with their  $HDA_i, i \in$

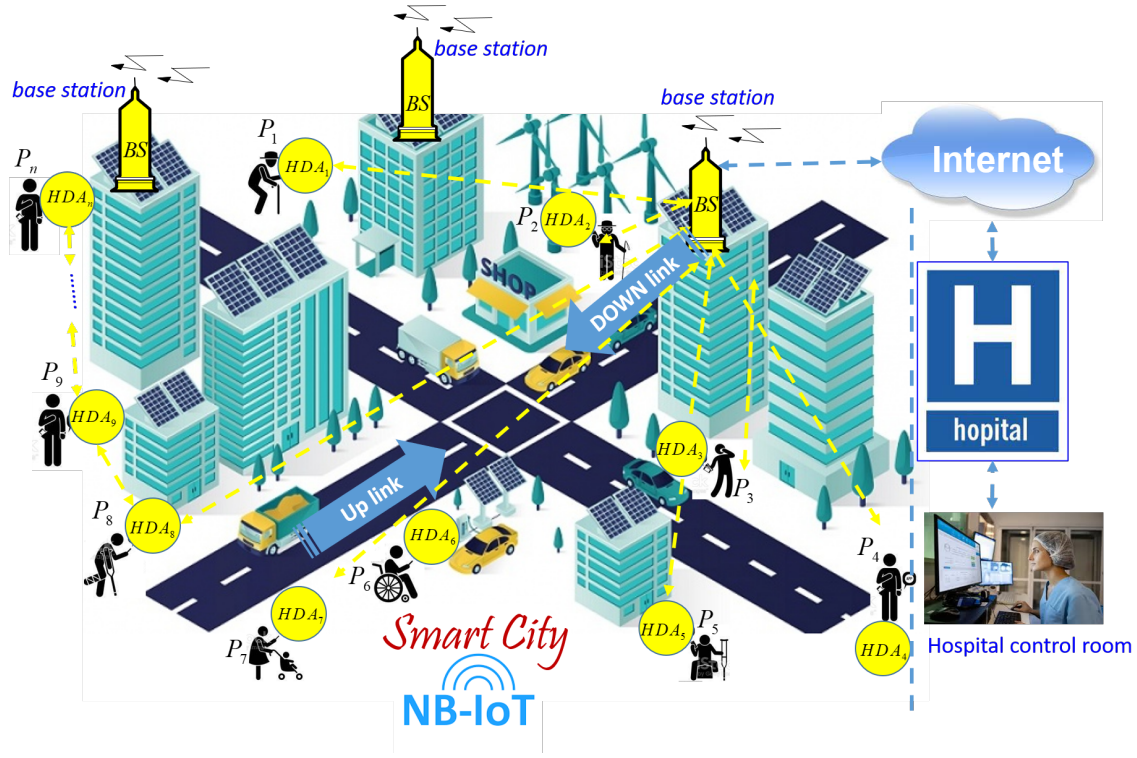


Figure 1: System model for analyzing the AMDT for multiple patients in healthcare using NB-IoT technology within a smart city.

$\{1, 2, \dots, n\}$  denoted by:  $HDA_1, HDA_2, \dots, HDA_n$ . Patients are under the continuous supervision of strategically positioned base stations within carefully selected locations across the smart city, ensuring comprehensive coverage for individuals moving within the urban environment. These base stations establish connectivity with the Internet of Things (IoT), facilitating potential medical collaborations both within the city and beyond its boundaries. Deploying these base stations also serves as a communication channel for critical situations, including emergencies such as ambulance services or other urgent scenarios.

Each patient  $P_i, i \in \mathbb{N}^*$  on the move increasingly use these  $HDA_i$  that connect wirelessly to the hospital and the internet via BS for retrieving and sending healthcare information. In addition, Fig. 1 presents the meta-model of this medical context using NB-IoT for the smart city. The healthcare facility can have a SCADA (Supervisory Control and Data Acquisition)

system [22] to generate requests and receive medical data. This HDA conducts AML of patients' nodes through the internet and BS to the HDA of remote patients. The average time for a message to be successfully delivered within the BS network in report-by-exception mode from the hospital's central control *HDA* must be determined. In Fig. 1, patients share the same channel, and an HDA can serve only one patient at any time. The BS manages the AML of RP nodes by delivering the average message from the BS to the patients.

#### 4.1. A Mathematical Model Considering System Constraints

We designed a mathematical model to minimize AMDT in NB-IoT healthcare applications, incorporating constraints to enhance message delivery efficiency. We denote AMDT by  $T$ , where  $T$  is a function of various parameters such as transmission time  $t_{trans}$ , waiting time in queue  $t_{queue}$ , processing time  $t_{proc}$ , and propagation time  $t_{prop}$ . Thus, the objective function can be represented as:

$$\min T = (t_{trans} + t_{queue} + t_{proc} + t_{prop})$$

#### Constraints

1. **Network Bandwidth (B):** The available bandwidth limits the transmitted rate of data.  $t_{trans} = \frac{\text{DataSize}}{B}$
2. **Power Consumption (P):** Given the power constraints of NB-IoT devices, the power used for transmitting and processing messages should be minimized or kept within a threshold.  $P_{total} = P_{trans} + P_{proc} \leq P_{max}$
3. **Device and Network Capacity (C):** The number of messages that can be processed or transmitted concurrently is limited by device and network capacities.  $N_{messages} \leq C$
4. **Quality of Service (QoS) Requirements (Q):** Certain messages may have priority over others, requiring differentiated handling and timeliness.  $Q(m_i) \geq Q_{min}(m_i), \forall m_i \in M$  where  $M$  is the set of messages and  $Q_{min}(m_i)$  is the minimum quality of service requirement for message  $m_i$ .



5. **Security and Privacy ( $S$ ):** Ensuring data integrity and confidentiality may introduce additional processing time and constraints.  $S_{required} = S_{available}$
6. **Environmental and Operational Constraints ( $E$ ):** Factors such as device mobility, interference, and network conditions may affect message delivery time.  $E_{factors} \leq E_{threshold}$

#### *Variables and Parameters*

- $t_{trans}, t_{queue}, t_{proc}, t_{prop}$ : Variables representing different components of message delivery time.
- **DataSize:** The size of the data being transmitted.
- $B, P_{max}, C, Q_{min}, S_{required}, E_{threshold}$ : Parameters representing network bandwidth, maximum power consumption, device/network capacity, minimum QoS, required security level, and environmental thresholds, respectively.

#### *Solving the Model*

If the objective function and constraints are linear, this optimization problem can be solved using various techniques, such as linear programming. Methods such as simulated annealing or ML-based optimization could be employed for more complex scenarios involving non-linear functions or requiring heuristic approaches. *Implementation Considerations*

- **Data Collection:** Accurate measurement or estimation of parameters like  $t_{trans}, t_{queue}, t_{proc}$ , and  $t_{prop}$  is critical.
- **Model Adaptation:** The model may need to be adapted or extended based on specific application requirements, network characteristics, and the physical environment.
- **Real-Time Optimization:** Dynamic adjustment of parameters and real-time optimization may be required to respond to changing network conditions and device statuses.

This framework provides a starting point for developing a mathematical model to optimize message delivery time in NB-IoT healthcare applications, with the flexibility to be tailored to specific scenarios and constraints.

#### 4.2. AMDT transmission concept

Let's examine the downlink within a mobile radio access network featuring a solitary BS. The task at hand for the BS involves transmitting a designated set of  $m_j, j \in \mathbb{N}^*$  sequentially arranged messages to  $n$  RPs, particularly towards  $HDA_n$ . Every HDA aims to receive all messages indexed as  $m_j$ , where  $j \in \mathbb{N}^*$ , in a sequential manner. Messages decoded out of order are not immediately forwarded to the users' application layer; they are temporarily stored in their respective buffers. Put differently, the  $j$ -th message, successfully received and decoded by the  $i$ -th RP, is marked as delivered to that specific RP only if all preceding messages with indices  $k < j$  have been successfully decoded and delivered. The BS broadcasts a packet containing the source messages to the RPs at each time slot. However, due to independent erasure, the transmission may not be successful at all RPs. The erasure probability assigned to the  $i$ -th RP is represented as  $p_i$ , which is assumed to be accurately recognized by the BS. Moreover, this probability remains unchanging throughout a single transmission episode. Upon the successful receipt of a message, each RP conveys an acknowledgment to the BS. The seamless reception of these acknowledgments is postulated to be flawlessly attainable through the meticulous selection of an appropriate modulation scheme and frequency allocation for the control channel. After each transmission, the messages can be categorized into subsequent sets at every RP. Innovatively, we introduce the AMDT as a pivotal metric that quantifies the deterioration in coding performance when juxtaposed against the pinnacle of optimal coding strategies. This metric serves as a yardstick, elucidating the extent of performance degradation experienced in coding operations.

This metric measures the efficiency and effectiveness of communication between remote patients and the central monitoring station. A lower AMDT indicates quicker and more dependable transmission, facilitating timely updates, interventions, and data collection, which is vital for ensuring responsive and comprehensive healthcare monitoring for remote patients.

To determine this metric, we rely on the following lemma, which characterizes the minimum AMDT the user requires for erasure-free transmissions.

Lemma 1. Given any schedule  $S$ , the minimum AMDT for the  $i$ -th RP is given by the following expression:

$$AMDT_m = \frac{m(m-1)}{2} \quad (1)$$

where  $m$  is the ordered message delivered.

The equation AMDT, in wireless monitoring transmission, can be expressed as follows:

$$AMDT_m = \frac{N_m}{R_T} + \frac{AML}{B} + D \quad (2)$$

where:  $N_m$  represents the total number of messages being transmitted,  $R_T$  denotes the transmission rate of the wireless channel, and AML signifies the average message length.  $B$  stands for the available bandwidth and  $D$  corresponds to the propagation delay.

Any HDA provided by healthcare professionals in hospitals is depicted in the topology network in Fig. 1. In this medical network, any HDA can access any other neighbor HDA randomly and spontaneously. The model system applications can rapidly evaluate AML using a report-via-exception that can be executed over healthcare for smart city networks. The data packets from each patient are sent to the BS and any other distant patients, enabling the linking of multiple HDAs to each distant patient. This diffusion process can be repeated several times, improving the connectivity between the patients and the healthcare facility. A medical hospital center communicates with multiple RPs simultaneously across a delivery time network where the BS exchanges medical data with the currently connected remote patient. The procedure continues until the farthest patient in the polling pattern shown in Fig. 1 establishes a new connection with the system. In the case of an indirect line-of-sight connection, each packet is delayed by the time required to transmit the requested number of bytes before being broadcast through the radio channel. For successful communication and the fair exchange of medical data, IoT patients must be within the communication range of the BS node and must be able to send packets. The chosen modulation rate determines the length of the polling. The repeater and bridge modes are the best choices for Point-to-Multipoint networks with BS-patient applications that interact using a polling-type protocol. Medical devices that operate in repeater and bridge modes use a complex protocol in the radio channel. Despite providing communication reliability and spectrum efficiency, these devices are as user-friendly as virtual transparent devices. It should be emphasized that monitoring medical data from a free patient using NB-IoT models in cities is a novel strategy currently being explored.

### *4.3. Operating Mode of HDA*

In a smart city, signal reception for patients in motion can be hindered by various structures. Tall buildings can result in signal attenuation, reflection, and shadowing among these structures. These factors can lead to inadequate connectivity, potentially isolating patients from communication networks. A viable solution to this challenge involves deploying many BSs across the city. Alongside this, HDAs can be utilized not only for signal reception and transmission but also as repeaters. This strategy effectively expands signal coverage and bolsters communication reliability. The HDA device can receive signals from the base stations and retransmit them to neighbors within its coverage area. This approach successfully extends coverage and overcomes signal obstacles introduced by physical structures. Additionally, the HDA can integrate signal processing algorithms to enhance signal quality, further elevating communication reliability. In addition to providing seamless connectivity for patients in motion, this technology has significant implications for healthcare delivery in smart cities. By enabling reliable communication between patients and healthcare providers, the HDA can support the remote monitoring of chronic diseases, improve emergency response times, and enhance overall healthcare management within the city. Every HDA can function as a repeater (relay) concurrently with its standard mode of operation. In this case, messages received by HDA interfaces from neighboring patients are directly transmitted to the radio channel without undergoing any checks or processing. A wireless repeater, on the other hand, expands the signal coverage within the network by repeating wireless transmissions. The repeaters receive wireless signals, repeating the information they acquire to extend the coverage. Following transmission to or from the radio channel, further transmissions from the same HDA are blocked for a calculated period to avoid colliding with a frame transmitted by a repeater. Before being transmitted on the radio channel, each packet is subject to a delay equivalent to the time required to transmit the set number of bytes. The duration of this delay varies based on the selected modulation rate. The BS is responsible for managing all the traffic on the radio channel. Each HAD employs advanced algorithms to access the radio channel collision-free. The radio channel access protocol combines Carrier-Sense Multiple Access (CSMA) and TDMA techniques and considers the channel available when there is no noise, interference, or transmission from other patients. In such scenarios, the system uses random time slot selection to transmit a frame on the channel. To ensure data delivery and integrity, the system incorporates frame acknowledgment,

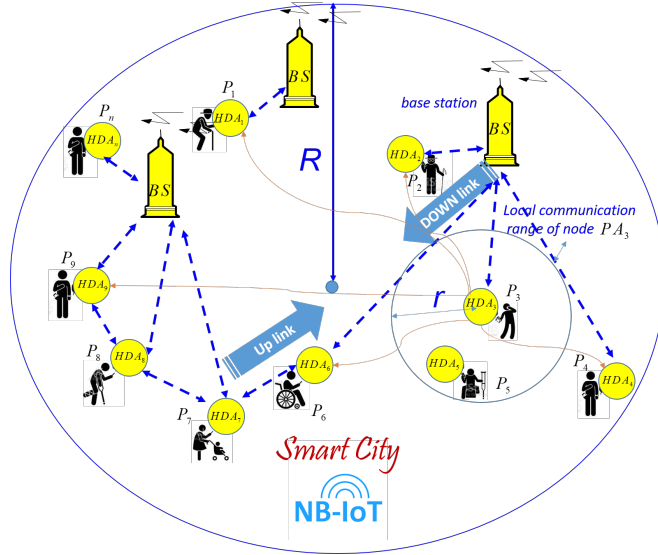


Figure 2: Typical realization of the network for an  $R$  circular network domain.

retransmissions, and cyclic redundancy check (CRC) checks, even in challenging interference conditions on the radio channel.

## 5. Functional Description

Imagine a model system establishing a medical network, illustrated in Fig. 2. The well-being of each patient, denoted as  $P_i, i \in \{1, 2, \dots, n\}$ , is continuously monitored. This system is conceptualized as a cellular medical network situated within a smart city, a concept derived from Fig.1. The network comprises individual patients, specifically  $P_1, P_2, \dots, P_n$ , who are systematically served and evaluated in a cyclical sequence.

### 5.1. Description

We analyze a model system establishing a medical network within a smart city context. This system incorporates a monitoring system dedicated to remotely overseeing each patient's health. The design of this model system resembles that of a cellular medical network, featuring a single BS, with the analysis being grounded in the representation shown in Fig. 2.

We are elucidating the utilization of AMDT for multiple patients within a healthcare network employing NB-IoT technology. Each HDA can directly communicate with other HDAs in this setup, thus establishing multiple communication

pathways. This results in enhanced reliability and robustness in communication compared to conventional networks, as the network can identify alternative routes in case of node failure or unavailability.

NB-IoT offers several advantages, such as low power consumption, extended coverage, and efficient signal propagation. These attributes render it highly suitable for medical devices that transmit small amounts of data over considerable distances. In smart city healthcare, NB-IoT enables remote health monitoring and management. Providing medical professionals with real-time patient health data becomes a critical asset, especially in emergencies.

Nonetheless, the AMDT emerges as a pivotal consideration, given its potential to impact the overall efficiency and effectiveness of the healthcare system. The depiction underscores NB-IoT's role in healthcare and emphasizes the significance of the average message delivery time for multiple patients. This illustration showcases how technological advancements can elevate healthcare and enhance the quality of patient care.

Let's indicate by  $C_c$  the channel capacity (bits/sec),  $C_p$  the channel capacity of the paging channel, and by  $C_d$  the capacity of the data channel. Note  $C = C_p + C_d$  that is constant. We need to find the proper  $C_p, C_d$  pair that minimizes the total downlink message delay  $T$ . We can express  $T$  as a function of  $C_d$  by substituting to (6) the following values for the paging slot duration  $s$  and the maximum message transmission rate  $\mu$ :

$$\mu = AML * C_d \quad (3)$$

$$s = \frac{AML}{C_p} = \frac{AML}{C - C_d} \quad (4)$$

For a simple point-to-point communication system with no retransmissions or errors, the AMDT can be calculated as:

$$AMDT = \frac{AML}{C} \quad (5)$$

The communication channel can transmit the maximum number of bits per second. For a communication system with retransmissions but no errors, the AMDT can be calculated as follows:

$$AMDT = \frac{AML}{C} + 2 * RTT \quad (6)$$

Here, RTT refers to Round Trip Time, signifying the duration required for a message to journey from the sender to the receiver and then return.

For a communication system with retransmissions and errors, the AMDT can be calculated as follows:

$$AMDT = \left(\frac{AML}{C}\right) * (1 + (2 * PER)/(1 - PER)) + 2 * RTT \quad (7)$$

where PER is the Packet Error Rate, it is the percentage of bits transmitted incorrectly, and  $(2*PER)/(1-PER)$  is the average number of retransmissions required to deliver a message successfully.

The general AMDT time formula  $AMDT_k$  is:

$$AMDT_{k+1} = 1 + \sum_{j=1}^k \prod_{i=1}^j \varphi(\beta_i) \quad (8)$$

$AMDT_k = AMDT_d$  for  $((k - 1) \leq d \leq r)$ ,  $r$  is the local communication range of nodes, and  $AMDT_d$  is the AMDT in a healthcare network when the distance between the BS and HDA of the patient  $P$  is  $d$ .  $\varphi(t)$  is the probability-generating function of the number of long-range connections,  $AML$ , per node. It is defined as :

$$\varphi(t) = E[t^{AML}] \quad (9)$$

The parameter  $\beta_i$  is expressed as:

$$\beta_i = \frac{\pi - i \frac{r}{R}}{\pi - \frac{r}{R}} \quad (10)$$

where  $R$  is the network radius for circular network domains and  $R = r \frac{300}{\pi}$ .

## 5.2. Functionality

A standard network setup for remote patient monitoring includes a single BS and multiple remote devices that form a tree-like structure following a specific addressing scheme. Regular checks are conducted to monitor the queue status of patients far from the BS, for whom no queueing information is available. The functionality based on the system model shown in Figure 2 can be described as follows:

The BS broadcasts request packets to all patients ( $P_1, P_2, \dots, P_n$ ) within its average range, which the hospital control center receives via the internet.

Initially, only  $P_1$  responds, while the other  $BS$  coverage patients listen, store the correctly received packet, and wait for their turn to reply.  $P_1$  sends its response packet to the  $BS$  and its neighbors. The  $BS$  receives this packet and automatically transfers it to the hospital control center for medical intervention.

Next,  $P_2$  sends its response packet to the  $BS$  and its neighbors, similar to the previous step. It is suggested that the patients ( $P_1, P_2, \dots, P_n$ ) and the  $BS$  interact directly with each other in turn.

This same procedure continues for the remaining patients ( $P_3, \dots, P_n$ ) until all have responded. Then, the server visits the patients again in a cyclic order ( $P_1, P_2, \dots, P_n$ ), and the medical polling cycle operates continuously.

The medical devices depicted in Fig.3 operate based on the principle of direct line-of-sight (LOS) visibility. However, they can also function in non-line-of-sight (NLOS) scenarios where they can work as repeaters using a fully transparent radio protocol. The diverse simulation configurations and their respective values are delineated in Table II, furnishing a synopsis of the pertinent parameters and their ranges. OFDMA (orthogonal frequency-division multiple access) with a carrier spacing of 15 kHz is used for downlink and uplink transmissions in NB-IoT. Only 12 carriers are utilized in NB-IoT, resulting in a 180 kHz occupied bandwidth. To achieve better results in this work, we request the selection of various parameters in the advanced NB-IoT [9], resulting in a 200 kHz occupied bandwidth. Each modulation type can be distinguished at different SSs for the AMDT. To analyze the performance of the AMDT in the proposed medical network, the following section outlines the simulation results obtained using MATLAB.

The document suggests that appropriate modulation techniques and careful frequency allocation are vital for enhancing channel usage, minimizing collisions, and improving healthcare monitoring applications' overall performance and reliability in smart city environments. We include an Algorithm 1 representation to illustrate the selection process for modulation techniques based on various parameters.

Algorithm 1: Select Modulation for Optimal AMDT

Algorithm SelectModulationForOptimalAMDT

Input: List of modulation schemes, List of SSs, Channel conditions, Required AMDT

Output: Optimal Modulation Scheme, Optimal Sub-carrier Spacing



```

Initialize :
    optimalModulationScheme  $\leftarrow$  NULL
    optimalSubCarrierSpacing  $\leftarrow$  NULL
    minimumAMDT  $\leftarrow$  INFINITY

for each modulationScheme in List of modulation schemes do
    for each subCarrierSpacing in List of sub-carrier
        spacings do
            AMDT  $\leftarrow$  CalculateAMDT(modulationScheme,
                SubCarrierSpacing, Channel conditions)

            if AMDT < Required AMDT and AMDT < minimumAMDT then
                minimumAMDT  $\leftarrow$  AMDT
                optimalModulationScheme  $\leftarrow$ 
                    modulationScheme
                optimalSubCarrierSpacing  $\leftarrow$ 
                    subCarrierSpacing
            end if
        end for
    end for

return optimalModulationScheme, optimalSubCarrierSpacing
End Algorithm

```

## 6. Numerical Results and Analysis

### 6.1. Comparative Analysis of AMDT in IoT-Based Health Control Systems

In this subsection, we delve into the empirical results showcasing the evolution of AMDT analysis within IoT-based healthcare monitoring systems in smart city frameworks. The discussion extends to a detailed comparison of our proposed NB-IoT system against crucial parameters, emphasizing its superior reliability, power efficiency, and extended coverage tailored for healthcare applications. Through graphical representations and comparative tables, we illuminate the system's performance metrics, particularly focusing on AMDT as influenced by the average number of hops per path and the application of various Adaptive Modulation Levels (AMLs). This comparative insight not only underscores the technological advancements of the NB-IoT system but also its practical implications in enhancing healthcare monitoring and disease management in smart urban environments.

Fig.3 displays the variation in AMDT as a function of the average number of hops per path for patients using different AMLs. The results in Fig. 3

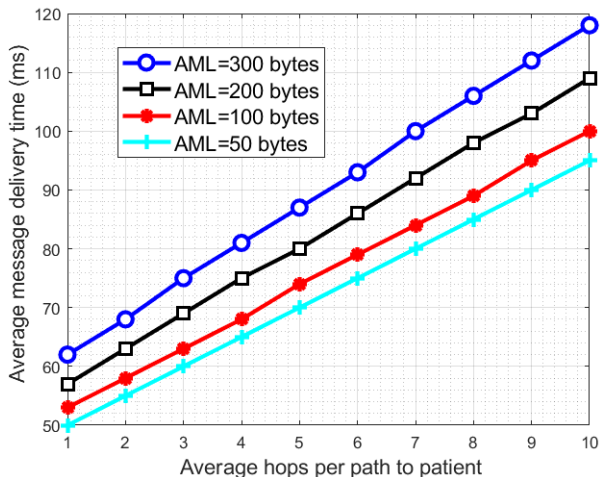


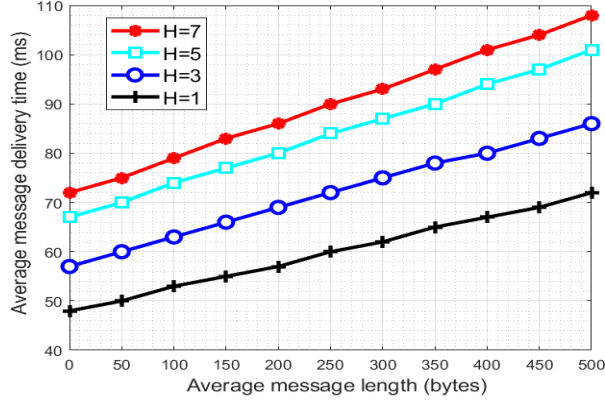
Figure 3: We can compare the average message delivery time and the average number of hops per path by utilizing various AMLs, including those with packet sizes of 300, 200, 100, and 50 bytes.

demonstrate how AML can significantly increase AMDT. Table III provides a comparative overview of the impact of AML on the AMDT for different hops, as shown in Fig. 3.

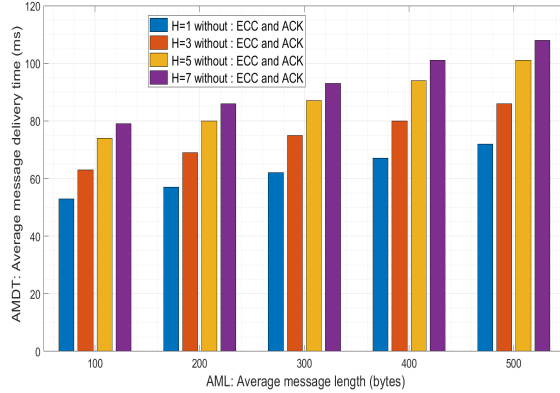
The results presented in Table III suggest a positive correlation between the number of hops and AMDT. The AML experiences a significant increase with each added hop. Furthermore, the analysis indicates that an increase in AML further promotes an increase in AMDT. We also observed that as the number of hops per path increases, there is less overlap between the information exchanges, which results in an increased AMDT for simultaneous transmissions from different remote locations.

Fig. 4 shows how AMDT changes depending on the AML for different hops, including  $H=1, 3, 5,$  and  $7$ . Table IV provides a comparative overview of the impact of AML on the total AMDT for different hops, as presented in Fig.4(a) and(b).

The results depicted in Fig. 4 are supported by the discoveries illustrated in Figs 4(a) and 4(b). The data in Table IV suggests a direct correlation between the number of hops and the AMDT, signifying an escalation in the average time for message delivery. Furthermore, the investigation reveals a positive connection between AML and AMDT, implying that an augmentation in AML corresponds to a proportional increase in AMDT. These findings



(a)



(b)

Figure 4: Variation of AMDT with AML for different Hops ( $H=1, 3, 5,$  and  $7$ ).

underscore the significance of factoring in the number of hops and AML while assessing the efficacy of message delivery systems. In brief, the outcomes outlined in Table IV vividly establish a robust link between the number of hops and AMDT and AML. Additionally, the study accentuates the influence of AML on AMDT, underscoring the necessity to optimize both parameters to achieve proficient message delivery.

Fig. 5 illustrates the change in AMDT over the Interface speed (kbps) for downlink and uplink transmissions with and without ECC.

The comparison results of the present study, presented in Fig. 5, demonstrate a correlation between the interface speed and the AMDT. Specifically, as

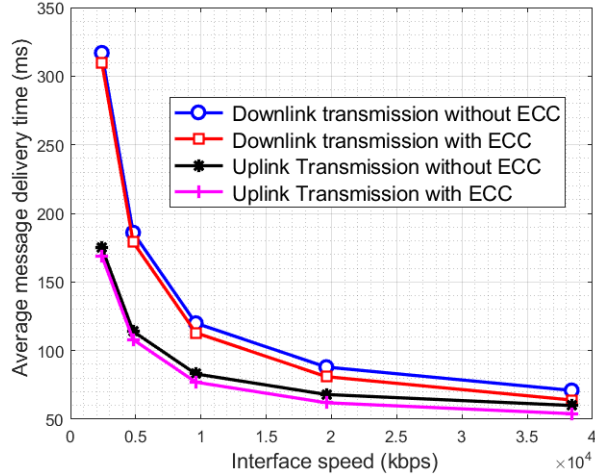


Figure 5: AMDT versus Interface speed (kbps) for downlink and uplink transmission with and without ECC.

the proportion of interface speed increases, there is a decrease in AMDT. These findings provide valuable insights for improving the performance of transmission systems by optimizing the proportion of interface speed. The findings presented in Fig. 5 demonstrate that the downlink and uplink transmission significantly impact the AMDT and interface speed of the entire network. It is clear from these results that a higher interface speed corresponds to a decreased AMDT, as observed in our specific scenario. In other words, it increases the interface speed, resulting in the more efficient transmission of messages across the network. This is a critical consideration when designing and implementing network systems, as the AMDT and interface speed can significantly impact the overall performance and user experience. Therefore, it is essential to carefully evaluate the trade-offs between different transmission modes and interface speeds to determine the optimal configuration for a given network scenario. Other factors, such as network topology, traffic patterns, and link quality, should also be considered when making these decisions.

Fig. 6 illustrates the AMDT versus modulation rates (kbps) for different hops.

Fig.6 is a visual representation that shows the relationship between modulation rates and the number of hops on the AMDT. It highlights how changes in these factors can impact the network's overall performance. By monitoring the AMDT and identifying factors that can affect it, network administrators

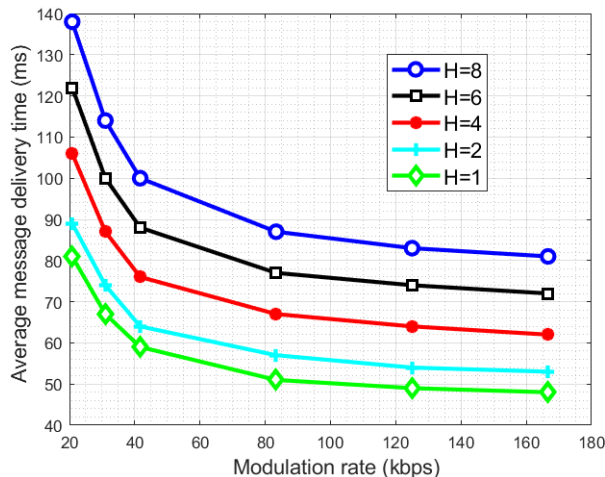


Figure 6: AMDT versus modulation rates (kbps) for different hops.

can optimize the network’s performance and improve its efficiency. Table V provides a comparative overview of the impact of modulation rates on the AMDT for different hops, as presented in Fig.6.

Table IV illustrates that the AMDT decreases as the modulation rates increase. This is because higher modulation rates result in a faster transmission, allowing more data to be transmitted within a shorter period. Consequently, the AMDT is reduced. This is particularly advantageous in medical wireless networks where timely delivery of critical information can be vital for patient care. By utilizing higher modulation rates, medical professionals can ensure that patient information is transmitted quickly and efficiently, enabling them to make informed decisions promptly. This can ultimately improve the quality of patient care and lead to better health outcomes. Therefore, optimizing modulation rates is an essential aspect of enhancing the performance of wireless communication networks, particularly in critical applications such as healthcare.

However, increasing the hops between the sender and the receiver can significantly increase the AMDT. Each hop introduces a delay in the transmission, and as the number of hops increases, the total delay increases proportionally. This is due to the need to route messages through intermediate nodes, which introduces additional delays. Consequently, engineers must design the network with the minimum number of hops possible to reduce the overall AMDT and ensure prompt delivery of messages.

It is essential to note that factors such as signal strength, interference, and network congestion can also impact the AMDT, and these must be carefully considered when evaluating network performance. Regular network maintenance, including monitoring and optimizing network conditions, can help mitigate the impact of these factors and improve the overall efficiency of the medical wireless network. By carefully considering these factors, network engineers can optimize the AMDT and ensure efficient and reliable communication in medical wireless networks. To ensure successful message delivery within a medical wireless network, the AMDT is a crucial factor that several variables can influence. The transmission mode and the distance between the BS and the remote patient in motion are among them. It is particularly important to consider the report-by-exception mode, a critical transmission mode for evaluating AMDT. This mode conserves network resources by sending messages only when specific events occur, or thresholds are exceeded, rather than continuously or at fixed intervals. Consequently, the AMDT for the report-by-exception mode may vary depending on the frequency and type of the monitored events. Therefore, carefully evaluating the AMDT for different transmission modes and network configurations and adjusting the system settings accordingly is critical to achieving optimal network performance. By doing so, network engineers can ensure that messages are delivered efficiently and promptly while minimizing the use of valuable network resources. It is crucial to regularly evaluate and update the network configurations to adapt to changing patient needs and improve the overall performance of the medical wireless network.

Fig. 7, shows the AMDT in milliseconds (ms) for different numbers of hops in a communication path ( $H=1$  to  $H=5$ ), at varying SS (kHz) for remote patient monitoring.

As the number of hops increases, the average message delivery time also increases. This is evident as each subsequent bar (representing more hops) is taller than the last within each SS category. The effect of increased SS on message delivery time is not uniform across different hop counts. For lower hop counts ( $H=1$ ,  $H=2$ ), the increase in SS leads to a slight increase in AMDT. However, for higher hop counts ( $H=4$ ,  $H=5$ ), the AMDT significantly increases with higher SS.

The trend suggests that a higher SS can adversely affect the delivery time, especially when the message has to pass through more nodes (hops). This could be due to the fact that with wider SS, the system may be more prone to errors or delays in processing each hop, accumulating a higher total delay.

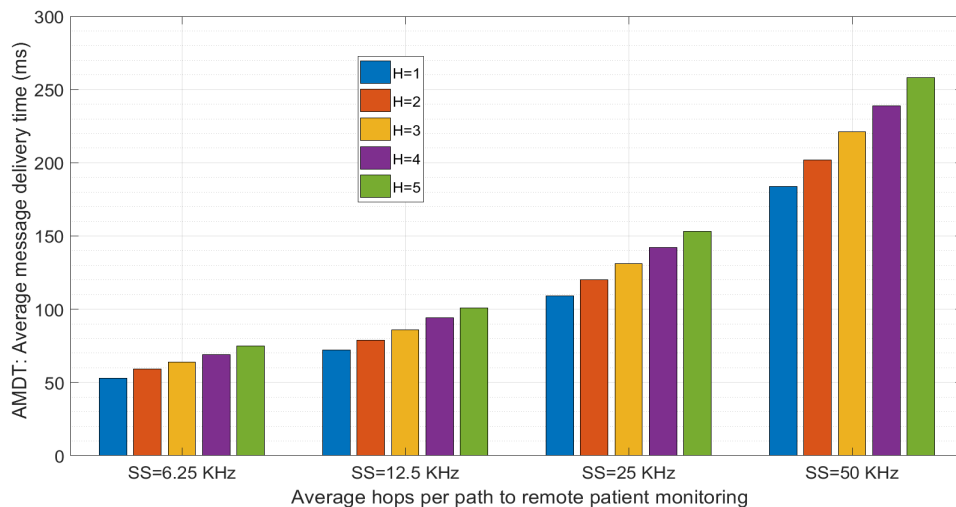


Figure 7: AMDT versus Average hops per path to remote patient monitoring for different SSs (kHz).

For remote patient monitoring, where timely data transmission can be critical, it's important to consider the balance between the number of hops and the SS. Lower hop counts ( $H=1$  or  $H=2$ ) are less sensitive to changes in SS, potentially making them more reliable for time-critical applications. As the hop count increases, it may be beneficial to use a lower SS to mitigate the increase in AMDT, though this could come at the cost of other factors like bandwidth efficiency.

Fig. 7 could be part of a larger study examining the trade-offs in designing a communication system for remote patient monitoring, where both the reliability of data transmission and the efficiency of the network need to be optimized.

Fig. 8 presents data that compares the AMDT (in milliseconds) across different modulation schemes used in communication systems, presumably for remote patient monitoring, as indicated by the context of the previous figure. Each modulation scheme is tested with the same number of hops ( $H=1$ ) but with varying SSs.

Each modulation scheme has four bars representing different subcarrier spacings ( $SS=6.25$  kHz,  $SS=12.5$  kHz,  $SS=25$  kHz,  $SS=50$  kHz). As the SS increases, the AMDT increases for each modulation scheme. This is consistent with the previously analyzed Fig.7, where larger SS spacings resulted

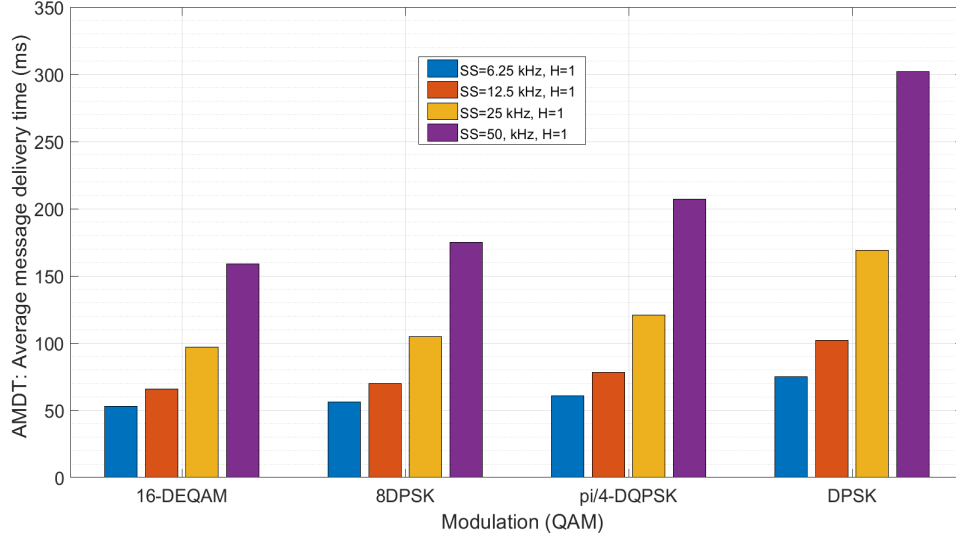


Figure 8: AMDT versus modulation (QAM) for different  $SS$ s (kHz).

in longer delivery times. The 16-DEQAM modulation scheme shows the lowest delivery times across all  $SS$ s, suggesting it is the most efficient among the tested schemes regarding the delivery time at a single hop. The DPSK modulation scheme generally shows the highest delivery times, indicating it is the least efficient delivery time for these settings. The delivery time performance of 8DPSK and pi/4-DQPSK lies between the extremes of 16-DEQAM and DPSK. Fig. 8 can be used to evaluate the trade-offs between modulation schemes and  $SS$  for a given communication system, particularly one with a single hop. 16-DEQAM is the most time-efficient modulation scheme, preferred for applications requiring fast message delivery, such as real-time monitoring. DPSK, while potentially offering other benefits, is less suitable for applications where message delivery time is critical. When designing a communication system for applications like remote patient monitoring, where timely delivery of messages is essential, modulation schemes and subcarrier spacing are crucial factors. A lower subcarrier spacing generally results in faster delivery times, but the choice of modulation scheme can significantly impact performance. The data suggests that using 16-DEQAM with a lower subcarrier spacing could be optimal for minimizing message delivery time in a system with a single hop. However, system designers must also consider other factors, such as signal reliability, complexity, and bandwidth efficiency,



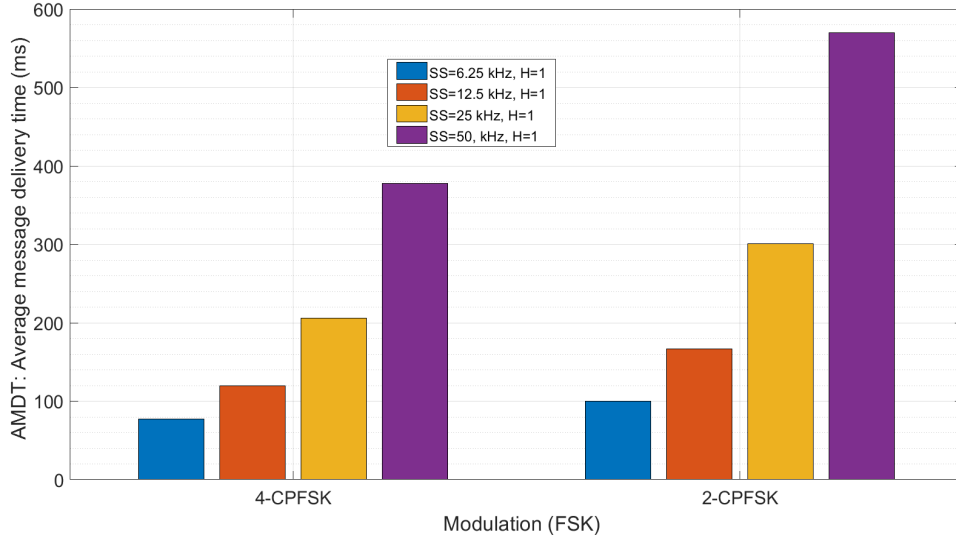


Figure 9: AMDT versus modulation (FSK) for different subcarrier spacing (kHz).

before selecting a modulation scheme.

Fig. 9 is another bar chart that compares the AMDT for different modulation schemes with a fixed hop count ( $H=1$ ) across various subcarrier spacings.

Different bars exist for each subcarrier spacing, just like in Figure 8. The data in Fig.9 may show that some FSK modulation schemes are less efficient as the SS increases, as evidenced by higher message delivery times. This could be due to the inherent characteristics of the FSK modulation schemes and how they interact with the SS. When designing communication systems, especially for critical applications like remote patient monitoring, choosing a modulation scheme that balances speed (low message delivery time) and reliability is important. The data from Fig. 9 may suggest that certain FSK modulation schemes are not as suitable for high subcarrier spacing if low message delivery time is a priority. In both cases, the overall system design must consider the trade-offs between the efficiency of data transmission (affected by modulation scheme and SS) and the requirements of the end application (e.g., latency sensitivity in patient monitoring).

Fig. 10 displays the AMDT in milliseconds (ms) for different modulation schemes, QAM and FSK, at a fixed hop count ( $H=1$ ) across various SS.

Each modulation scheme shows varying sensitivity to changes in SS, with some showing a greater increase in AMDT as SS increases. QAM and FSK

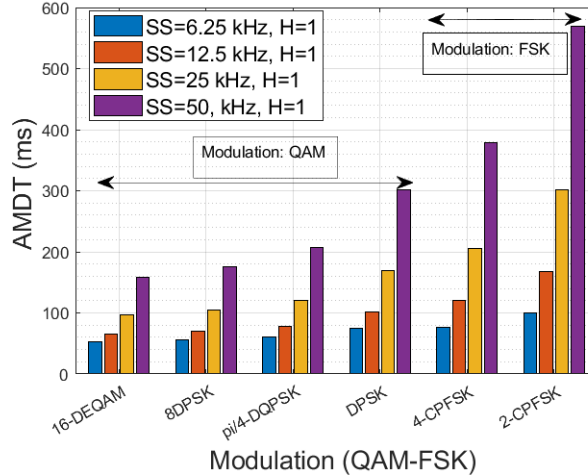


Figure 10: A Comparative Analysis of AMDT using QAM and FSK Modulation with Different  $SS$ s for  $H=1$

modulation schemes seem to have different performance profiles, with each scheme having its unique reaction to the increase in  $SS$ . Modulation schemes with lower AMDT are preferable for applications with critical latency, such as remote patient monitoring or real-time communication. In applications where  $SS$  needs to be higher for other technical reasons (such as spectrum efficiency or channel conditions), the choice of modulation scheme should be carefully considered to manage the trade-off between  $SS$  and AMDT. Network designers would need to balance the requirements of the communication system (e.g., throughput, bandwidth, and latency) with the performance characteristics of the available modulation schemes to ensure optimal system performance. To summarize, selecting a modulation scheme in a communication system design should consider the impact on latency, especially when varying the subcarrier spacing. Understanding the relationship between these factors is crucial for ensuring the reliability and efficiency of communication, particularly in systems that require timely data transfer.

Table VI offers a comprehensive comparative overview of the findings presented in Figure 10.

Table VI, sourced from Figure 10, provides valuable insights into how variations in  $SS$  and modulation rates impact the AMDT within a wireless communication system with a specified number of hops. It is crucial to acknowledge that diverse constraints and limitations affect the characteristics

of the broadcast signal, resulting in a broad spectrum of potential modulation rates. Consequently, strategically selecting an optimal combination of  $SS$  and modulation rates becomes imperative to ensure optimal communication system performance.

Table VI demonstrates that elevating both  $SS$  and modulation rates leads to an increase in the AMDT. This escalation can be attributed to the heightened capacity of the system due to the utilization of more subcarriers for data transmission, which intensifies interference between these subcarriers. Likewise, higher modulation rates enable swifter data transmission but concurrently amplify the system's vulnerability to noise and interference.

Hence, a meticulous selection process for suitable values of  $SS$  and modulation rates is imperative to fine-tune the performance of the wireless communication system. By meticulously analyzing Table VI, one can pinpoint the optimal  $SS$  and modulation rate pairing to attain the desired AMDT for a given number of hops.

In telemedicine, transmitting Health data, encompassing vital signs, electronic health records, medical images, and other sensitive information, is paramount. The *AMDT* system guarantees dependable and secure data transfer over wireless channels. A comparative assessment of the AMDT's performance across various  $SS$  strategies underscores the system's adaptability to diverse channel conditions, optimizing data transmission. Notably, the omission of error correction in this analysis permits a more authentic evaluation of the system's real-world performance, wherein data transmission errors are commonplace.

The experimental outcomes underscore that the transmission of Health data between two BSs and remote patients takes mere seconds when employing QAM, in contrast to the relatively prolonged duration associated with FSK modulation. This observation accentuates the advantages of using QAM modulation for rapid and efficient data transfer in telemedicine scenarios. This reduction in transmission time facilitates real-time delivery of patient data to healthcare providers, expediting diagnosis and treatment and ultimately enhancing patient outcomes.

In summary, the juxtaposition of AMDT performance across distinct modulation types and channel spacing schemes emphasizes the critical nature of selecting an appropriate modulation scheme to optimize data transfer in telemedicine applications. The AMDT is a pivotal metric for evaluating wireless network performance, influenced by topology, signal strength, congestion, and packet loss. A low AMDT ensures reliable message delivery, a crucial

facet for critical NB-IoT medical applications. Conversely, a high AMDT indicates subpar network performance, potentially compromising application functionality. Thus, vigilantly monitoring and optimizing AMDT remains pivotal for robust wireless operations. It gauges the average time required for successful message transmission across the healthcare network in a report-by-exception mode. This scrutiny plays a supervisory role over hospital patients, ensuring the timely conveyance of vital HDA connections. It's important to clarify that " Patient " pertains to individuals undergoing medical procedures.

### *6.2. NB-IoT vs. Existing Technologies in Smart City Healthcare Monitoring*

The NB-IoT-based system markedly outperforms existing technologies, particularly in enhancing the AMDT for healthcare monitoring in urban environments. This improvement is essential for effectively monitoring and managing diseases that can move or spread. When compared to a broad spectrum of existing technologies, such as the Global Positioning System (GPS), satellite tracking, Wireless Sensor Networks (WSN), Radio-Frequency Identification (RFID), drones, Mobile Health (mHealth) technologies, the IoT and cloud computing, along with AI and ML, and Geographic Information Systems (GIS), NB-IoT's unique features become apparent. These features include broader coverage, lower energy use, affordability, real-time data analysis and response capability, better AMDT in healthcare surveillance, and increased capacity for connections. By incorporating NB-IoT into these technologies, the benefits are significantly expanded, resulting in a more thorough monitoring system. This system not only boosts the effectiveness and dependability of health surveillance in smart urban areas but also improves the oversight and regulation of diseases among wildlife and livestock. As a result, it contributes to a healthier living environment for both animals and humans.

## **7. Conclusion**

This paper has presented an in-depth analysis of the AMDT performance based on modulation rates across several hops in a multi-hop wireless network. The primary objective of this paper is to optimize the AMDT by considering various factors that affect it. The simulation results were obtained by varying the number of hops and the number of patients in a smart city scenario, and the resulting AMDT was compared with different modulation rates. These results provide a comprehensive overview of the performance of medical

wireless networks in multi-hop scenarios. This study can be a reference for optimizing medical network performance using various modulations and user scenarios. Additionally, cellular network communication in a cyclical order can effectively achieve a low AMDT under emergency scenarios. Fast algorithms or protocols that can significantly improve AMDT performance are strongly required in the future. Additionally, a priority approach that prioritizes critical messages over non-critical messages can further enhance the efficiency of medical wireless networks. Therefore, future research in this area must focus on developing efficient algorithms and protocols that can address these challenges and enhance the performance of medical wireless networks.

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Table 1: Summary of essential acronyms

Acronym	Definition
AMDT	Average Message Delivery Time
NB-IoT	Narrowband Internet of Things
BS	base stations
HDA	Healthcare data aggregators
H	average hops per path
SS	subcarrier spacing
AML	Average message length
RP	remote patient
AI	artificial intelligence
ML	machine learning
TDMA	time division multiple access
IoT	Internet of Things
CS	channel spacing
SCADA	Supervisory Control and Data Acquisition
QAM	Quadrature Amplitude Modulation
PER	Packet Error Rate
FSK	Frequency Shift Keying
16-DEQAM	16-ary Differentially Encoded Quadrature Amplitude modulation
8-DPSK	Eight-phase differential phase shift keying
$\pi/4$ -DQPSK	$\pi/4$ -differential quadrature phase shift keying
$2/4$ -CPFSK	Continuous-phase frequency-shift keying
RTT	Round Trip Time
OFDMA	orthogonal frequency-division multiple access
MATLAB	Matrix LABORatory
5G	5th generation mobile network
$P_i, i \in \mathbb{N}^*$	the $i$ th patient controlled
$D$	the size of the message in bits
$B$	Channel capacity
$m$	number of the ordered messages delivered
$n$	number of the RP
$N_m$	Total number of messages being transmitted
$R_T$	Transmission rate of the wireless channel
$B$	Available bandwidth
$D$	propagation delay
$R$	circular network domain
$\varphi(t)$	The probability-generating function
$R$	network radius for circular network domains
$s$	Slot duration
$\mu$	and the maximum message transmission rate

Table 2: The designation, notation, and values of important medical network parameters.

The notation and definition of essential network parameters	Values
Total Number of patients (TNPs)	10,20,30,40,50 and 100
Average message size	0 to 500 bytes
ACK (Acknowledgement)	Off/On
FEC=3/4 (Forward error correction)	Off/On
Modulation type	QAM(16-DEQAM, 8DPSK, pi/4-DQPSK, DPSK), FSK ( 2-CPFSK, 4-CPFSK)
Bandwidth	200 kHz
Subcarriers spacing	50,25,12.5,6.25 kHz
Number of Hops	1,2,3,4,...,10

Table 3: Comparative overview of the results presented in Fig.3

Settings	Values			
	Hops=3			
AML in bytes	50	100	200	300
AMDT in ms	60	63	69	75
	Hops= 6			
AML in bytes	50	100	200	300
AMDT in ms	75	79	86	93
	Hops= 9			
AML in bytes	50	100	200	300
AMDT in ms	90	95	103	112

Table 4: comparative overview of the results presented in Fig.4

Settings	Values			
	Hops=1			
AML in bytes	200	300	400	500
AMDT in ms	57	62	67	72
	Hops= 3			
AML in bytes	200	300	400	500
AMDT in ms	69	75	80	86
	Hops= 5			
AML in bytes	200	300	400	500
AMDT in ms	80	87	94	101
	Hops= 7			
AML in bytes	200	300	400	500
AMDT in ms	86	93	101	108

Table 5: Comparative overview of the results analysis of how modulation rates affect the AMDT for various hops presented in Fig.6

Settings	Values			
	Modulation rate= 166.67 kbps			
Hops (H)	2	4	6	8
AMDT in ms	53	54	57	64
	Modulation rate=125 kbps			
Hops (H)	2	4	6	8
AMDT in ms	62	64	67	76
	Modulation rate=83.33 kbps			
Hops (H)	2	4	6	8
AMDT in ms	72	74	77	88
	Modulation rate= 41.67 kbps			
Hops (H)	2	4	6	8
AMDT in ms	81	83	87	100

Table 6: comparative overview of the results presented in Fig.10

Settings	Values			
	Modulation (QAM)			
SS in kHz	50	25	12.5	6.25
AMDT in ms (16-DEQAM)	53	66	97	159
AMDT in ms (8DPSK)	56	70	105	175
AMDT in ms ( $\pi/4$ -DQPSK)	61	78	121	207
AMDT in ms (DPSK)	75	102	169	302
	Modulation (FSK)			
SS in kHz	50	25	12.5	6.25
AMDT in ms (4-CPFSK)	77	120	206	378
AMDT in ms (2-CPFSK)	100	167	301	570