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RESEARCH ARTICLE

A Reliable System-of-Systems Healthcare Monitoring Framework

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ABSTRACT System-of-systems (SoS) have recently been used in several applications and scenarios in the field of safety, defense, and healthcare. In an SoS environment, the entire system is divided into sub-systems, which provides more flexibility and reduces the management cost of the entire system. SoS have been widely used in healthcare monitoring services, where patients are provided with medical sensors that send their medical measurements to a remote unit for further processing and decision-making. These sensors communicate with an access point using the wireless channel, which gives patients flexibility in mobility and makes the monitoring system more convenient and comfortable. However, sending data over the wireless channel presents several challenges, such as contention between the different sensors in accessing the channel and the bit errors associated with the noisy wireless channel. In this paper, an SoS healthcare monitoring framework is proposed, where a wireless communication protocol is proposed that addresses the sensors' node network access contention and mitigates the bit errors of the communication channel by providing forward error correction bits to the transmitted packets. In addition, the protocol takes into consideration the sensors' importance and criticality, such that more important sensors are given more network access time and more error correction bits, which in turn results in a robust transmission process with low transmission delay. The simulation results show the proposed wireless communication protocol's effectiveness in lowering the packet loss, giving higher priority and having higher throughput for the more critical sensors.

INDEX TERMS System-of-systems, e-health, healthcare monitoring, real-time communication, scheduling, reliability, time-triggered Ethernet, wireless communication.

I. INTRODUCTION

There are several reasons why the system-of-systems (SoS) paradigm is gaining increasing attention in the design of large systems. One of them is the continuous development of the Internet and various technologies that make interconnecting autonomous constituent systems (CSs) possible, forming new SoS that promises more efficient, economical, and scalable processes and improved services. SoS has been recently used to manage complex services and applications, where the entire system operation is split into multiple autonomous sub-systems. This structure gives much more management flexibility and reduces system design complexity and infrastructure. SoS has been proposed for several mission-critical complex systems such as healthcare and defense sectors, disaster management and recovery, city and urban planning and management, aviation, and car industries [1], etc. For instance, in the healthcare sector, a medical SoS can be used to provide remote health monitoring for elderly people, where their surrounding environment can be equipped with sensors to capture a variety of medical signals such as heart rate and diabetes level, especially with the proliferation of the Internet of Things (IoT) technology and its wide adoption in many sectors and applications, especially in the medical field [2].

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In the medical field, a set of sensors are used to capture the patient's vital data. The data can be transferred to a cloud infrastructure for further processing and analysis, and based on that, the patient can be alerted for any potential threat or abnormal conditions. Normally, these sensors are connected wirelessly to a gateway that forwards the captured data to the cloud.

One challenge commonly faced in deploying this monitoring system is having a reliable and real-time communication protocol that assures that the captured data are sent to the destination with a high quality and low transmission delay. However, the wireless channel suffers from several impairments such as bit-errors due to interference, fading, multi-path, etc., and collisions caused by sensors' network access contention; these errors affect the transmission quality and cause excessive transmission delay, which affects the strict deadline requirements of these critical applications. Therefore, designing a reliable wireless communication system that considers the medical sensors' low delay and high packet delivery requirements is not easy to achieve, especially with the noisy wireless environment and the network access contention between the various sensors. Another challenge usually faced in medical sensors is that not all sensors have the same importance and priority. For instance, a sensor that monitors the respiratory monitoring sensor used to monitor the patient's breathing is more vital and needs more frequent readings than the sensor used to measure the patient's temperature, which does not change rapidly compared with the breath monitoring sensor. Therefore, there is a need to give more vital sensors higher priority in accessing the communication channel, thus ensuring more frequent updates of the patient's vital data with high reliability.

In fact, designing and implementing such a medical SoS is challenging because the system monitors patients in different ambient assisted living spaces (homes, hospitals, and care centers for the elderly) as well as the development of a distributed embedded system architecture for constantly evolving and dynamic SoS with support for verifiable real-time, reliability, and safety properties. To address the above challenges, researchers proposed to give sensor nodes different access channel times to allow more time for more time-sensitive sensors. Further, to address the noisy behavior and reliability issue with the wireless channel, forward error correction codes (FEC) are normally used, such as Reed Solomon error correction codes [3], where packets are provided with extra channel codes that can detect and correct the bit errors introduced by the wireless channel, without the need for costly re-transmission processes of the errored packets, thus reducing the transmission time and improving the end-to-end delay. In this paper, we proposed using both techniques jointly to provide the sensitive medical sensors with more network access time and error correction codes than other less sensitive sensors.

This paper continues our previous efforts toward building a reliable system-of-systems framework that can be used for various time-critical applications. In [4], a framework for SoS is proposed where SoS is modeled as a set of independent constituent systems. Each constituent system comprises a set of sensors connected wirelessly to a gateway that sends the captured data over wired or wireless networks to a remote node for further processing and decision-making. This paper aims to provide a mechanism to improve the constituent system reliability over the wireless channel while providing priority between the various sensors, such that more sensitive and critical sensors are given more priority regarding channel access time, reducing their access time. Further, sensors are treated unequally by assigning different levels of error correction codes, such that more critical and sensitive sensors are assigned higher error correction bits, which improves their error correction capabilities and reduces packet loss.

The remainder of this paper is structured as follows. Section II reviews related work. In Section III, we describe our proposed framework and approach. Section IV describes the proposed communication protocol for wireless sensors of the Constituent System. Section V depicts performance evaluation results of the proposed protocol. Finally, the paper concludes with a roadmap towards future research in Section VI.

II. RELATED WORK

In literature, recently, Rejeb et al. [2] conducted an extensive review and bibliometric analysis to investigate the potential adoption of IoT-based solutions in the healthcare industry. The resulting concurrency keywords of the surveyed papers revealed that wireless technologies such as WiFi, WSN, RFID, and Blacktooth significantly contribute to renovating the healthcare industry. In [5], the author showed how IoT utilizing the message queuing telemetry transport (MQTT) protocol is widely used for healthcare-related applications and scenarios. The paper summarized several wireless technologies that are used with IoT-based monitoring devices. However, the paper mentioned the reliability challenges associated with wireless technology and its solution from the transport layer perspective, where the transmission control protocol (TCP) can be used to assure transmission reliability instead of the user datagram protocol (UDP). However, utilizing the TCP increases the transmission delay and overhead, which may not be suitable for critical and time-sensitive applications such as health monitoring. Furthermore, TCP cannot prioritize different transmission nodes according to their importance.

The authors in [6] reported a broad literature review for proposed real-time health monitoring solutions, frameworks, and platforms that utilize wireless wearable sensors to monitor patient's medical vital signs. Telemedicare,[1] Mobihealth [7], and the proposed solutions in [8] and [9] are some examples of these platforms. Further, in [10], the authors discussed the potential of utilizing wireless sensor nodes in providing healthcare monitoring solutions. However, several

[1] Telemedicare EU project, "Telematic Support for Patient-Focused Distant Care."

challenges must be tackled to achieve that, such as reliability, power management, time synchronization, and on-chip signal processing. The paper discussed these issues and other implementation challenges and proposed a prototype based on the 802.15.4 protocol, which can be used for health monitoring applications. In [11], the authors highlighted the potential of wireless sensor nodes in providing remote health monitoring and sensing to detect anomalies and alert healthcare personnel and patients accordingly. Finally, the paper surveyed the state-of-the-art solutions for sensor nodes' scalability, security, energy efficiency, etc.

In [12], the authors provided ongoing research challenges and directions for adopting and implementing wireless sensor networks in the healthcare sector. In particular, the authors emphasized some crucial aspects inherent in WSN, such as security, privacy, trustworthiness, reliability, scalability, and resource scarcity, mainly when applied to the healthcare domain, which requires high dependability and security. In [13], the author introduced a methodology for quality-of-service (QoS) at the medium access control (MAC) layer for IEEE 802.11e. This methodology employed a contention-based channel access function called the enhanced distributed coordination dunction (EDCF) and a centrally controlled channel access of the hybrid coordination function (HCF). The control of HCF was built using a polling mechanism with some enhanced QoS-specific mechanisms and frame subtypes to allow QoS data transfers during collision-free periods. The EDCF provided the priority scheme on the wireless medium. In [14], a novel retransmission-combining technique was proposed to enhance the performance of the MAC level of the Forward Error Correction scheme, in which multiple versions of partially corrected frames were combined to reconstruct the complete frame. However, the paper did not prioritize the different nodes' media access levels according to their importance and criticalities.

In fact, despite the abundance of various health monitoring platforms and systems, there are still several critical challenges that must be tackled to leverage the results from these platforms; system robustness, reliability, and real-time capabilities are not well addressed in the state-of-the-art architectures, especially for wireless networks, where data transmission is prone to interference from other wireless devices that may use the same spectrum. Furthermore, media access control between wireless devices is another challenge affecting the reliability and real-time assurance for delivering the patient's critical data to the healthcare monitoring room center. The most closely related work to this paper is presented in [15], where an enhanced time slotted channel hopping (eTSCH) protocol is proposed to address the ability of the TSCH protocol to differentiate between the nodes' traffic according to their criticality. The TSCH protocol does not provide mechanisms for traffic differentiation; thus, all nodes are treated equally regardless of their priorities or importance. Therefore, such a protocol may not be suitable for health monitoring applications, where some critical sensors should have higher priorities than other less critical ones. Accordingly, the authors in [15] proposed an enhanced version of the TSCH protocol, named orchestra-based TSCH (e-TSCH-Orch), where the time slots and the access schedule are adjusted according to the nodes' load importance and criticality, where more important and critical nodes are given higher priority than others by adjusting the nodes' access schedule. However, the proposed protocol addresses the traffic differentiation and nodes' priority from the media access layer perspective, which does not protect the traffic against wireless channel impairment and signal degradation. Therefore, this paper provides an addition to the proposed literature solution by providing unequal network access and unequal error correction codes for the IoT nodes according to their criticality and priorities, such that the critical nodes are given more network access timeslots and higher error correction budget, than the less critical ones, thus reducing the transmission error and reducing the delay of the transmitted packets.

As can be witnessed from the literature review, several mechanisms have been proposed in the literature to alleviate the challenges associated with wireless networks. For example, error correction codes [16], [17], [18] are typically used to detect and correct bit errors caused by the noisy wireless channel. Increasing the error correction code improves the transmission reliability and enhances the error correction capabilities, thus reducing the need for costly re-transmission processes. However, increasing the error correction bits will increase the transmission time and delay, which may affect the delivery time for some critical patients' data. As such, assigning these error correction, bits should be done carefully not to affect the system operation and real-time requirements, as well as the sensitivity of the patient's data.

Regarding media access control, several protocols and mechanisms have been proposed for wireless local area networks (WLAN), such as the 802.11e standard [19] that categorizes data into several categories and schedules their channel access according to their priorities. However, the proposed scheme mitigates potential channel errors caused by other wireless devices within the WLAN contending to access the wireless channel. Still, it does not reduce the bit errors caused by the wireless channel fading due to wave reflection, interference, multi-path propagation, and attenuation. The authors in [20] proposed a mechanism for sensors' nodes polling based on the concept of virtual token, that allows several types of nodes in a disaster monitoring system with different traffic and delay requirements to access the network efficiently. In [21], the authors proposed the concept of having a multi-cast groups for sending the polling signal, where all nodes will receive it and compete for accessing the channel. However, in the proposed scheme, no node has higher priority over the others and nodes' traffic may collide. In [22], the authors proposed an algorithm for WSN that assigns multiple time-slots on each data collection round for each sensor node, according to the node's data collection demand (priority). However, the authors did not propose to protect the packets (either equally or unequally) against the noisy wireless channel using error correction codes. In [23], the authors proposed to improve the transmission quality of the sensor nodes in WSN by reducing the collision between the competing nodes, which can be achieved with proper scheduling and efficient time-slots assignments policy. However, the authors did not propose to use error correction codes to mitigate the wireless noisy channel conditions. Other works that also proposed efficient time-slot assignment for sensor nodes to improve the network access efficiency is presented in [24], [25], and [26]. This paper introduces the system architecture to support reliable open-loop control with stringent real-time requirements for applications such as remote healthcare monitoring. Further, a communication protocol for wireless sensors is proposed that coordinates the wireless network access between different wireless devices and assigns error correction codes differently between the sensors, considering their priorities and delay requirements. This paper focuses on improving the reliability and priority of wireless communication for medical sensors used in real-time health monitoring platforms while providing unequal network access and protection against bit errors for various sensors depending on their importance and priorities. The proposed algorithms make them suitable for integrating with protocols such as 802.11e, TSCH, etc.

III. HEALTHCARE SoS FRAMEWORK ARCHITECTURE

The system-of-systems paradigm enables new healthcare applications, where autonomous constituent systems belonging to different organizations at scattered geographical locations collaborate to establish emergent services that cannot be achieved by any constituent system alone. While a monolithic system is within the control of a single organization, SoS comprise autonomous subsystems under different organizations' control. In contrast to the hierarchical integration of components in monolithic systems, SoS depends on the interoperation of constituting systems in mesh-based structures. In addition, SoS typically have multiple goals and can exhibit unanticipated emergent properties.

An example is personalized care with medical monitoring for patients with different types of diseases. Such an SoS for personalized care encompasses sensors at each patient's home and wearable electronics. Data centers at hospitals will provide medical health records. At the same time, diagnostic knowledge bases establish the foundation to map the sensory data to meaningful patient conditions and actions of personalized care. Patient-specific pattern recognition will infer medical emergencies from the sensor data and trigger emergency treatment by a nearby hospital. Machine learning services will be essential to improve diagnostic knowledge bases and tailor them to individual patients.

This example scenario involves different constituent systems such as hospitals, patient homes, data centers, and cloud computing centers, each providing services and relying upon the services of other constituent systems to establish emergent global services. Hence, an inter-domain communication and coordination protocol is required to orchestrate the computational sequences and to establish the data exchanges. Each constituent system is distributed with local resources such as computing nodes or sensors. An intra-domain communication protocol communicates between the nodes within the constituent system. Wire-bound or wireless communication networks are suitable depending on the type of constituent systems. For example, the sensors for patient monitoring will typically require wireless communication links.

As shown in Figure 1, an inter-domain gateway (IDG) is responsible for connecting the intra-domain services of the constituent system to the inter-domain services of the SoS. The IDG receives requests for services that are required for the SoS level. The IDG must relay these service requests to the nodes within the constituent system and configure the intra-domain communication protocol accordingly.

Each patient will be associated with a constituent system that incorporates monitoring sensors and actuators with processing units (MSPs) exchanging information through wireless communication. Additionally, an analysis and notification unit (ANU) serves for the local pre-processing of the sensor data and relaying it to other constituent systems via the inter-domain gateway.

The following specific boundary conditions need to be considered for the intra-domain communication protocol:

- **Real-time guarantees:** The IDG receives service requests from other constituent systems with deadlines for the export of its services. These exported services must be mapped to the different nodes within the constituent system, and the message exchanges must be planned. Depending on the communication protocol, this involves priority assignments or temporal/spatial resource allocations on the communication links.
- **reliability:** Service requests from the other constituent system will typically involve reliability requirements to achieve the system-level dependability goals of the SoS. Therefore, fault detection, containment, and masking mechanisms need to be configured to meet the reliability requirements. For example, error-correcting codes or redundant message transmission are necessary depending on the reliability goals and the link reliabilities within the constituent system.
- **mixed-criticality:** Services with different reliability goals will have to be provided simultaneously in a constituent system, thus demanding different redundancy configurations for the services. Intra-domain communication needs to improve the communication reliability of wireless communication links to realize safety-relevant healthcare functions. Based on the respective safety integrity level (SIL), different priorities regarding channel access and error correction codes should be assigned to various sensors based on their importance to the patients.

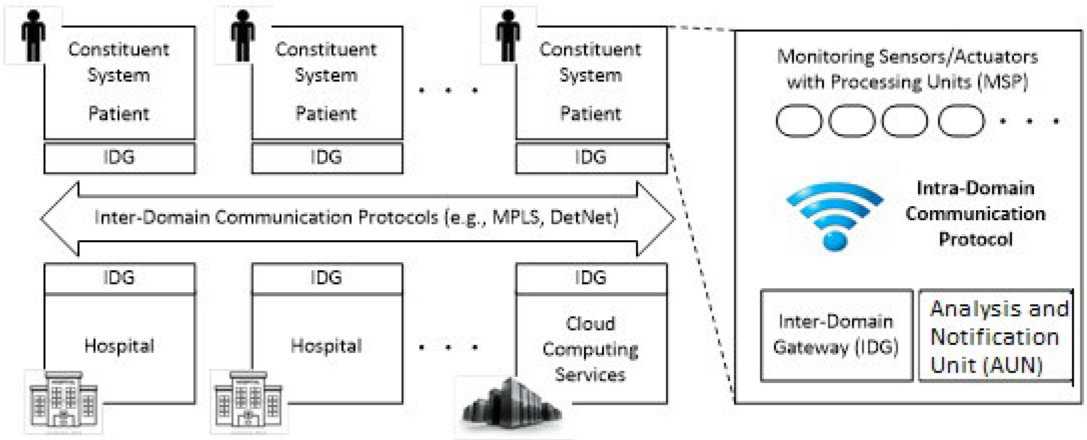

FIGURE 1. Healthcare monitoring SoS.

- **Dynamic system structures:** The nature of an SoS is inherently dynamic, where new services are established at runtime. Therefore, the IDG and the communication protocol within the constituent systems need to cope with the dynamic establishment of service with corresponding reliability and timing requirements.

IV. ROBUST WIRELESS NETWORK COMMUNICATION PROTOCOL

This section proposes an intra-domain wireless communication protocol within the CS. This protocol coordinates the communication between different patients' wireless sensors and actuators. As mentioned earlier, in wireless media, there are two main challenges to having reliable and low-delay data delivery between the sensors and the ANU that can assure a certain level of QoS. The first one is wireless media access and coordination between different wireless nodes. In contrast, the second one is the bit errors due to the open nature of the wireless channel, making it vulnerable to all interferences caused by other wireless devices that may use the same frequency band. The proposed protocol addresses the first challenge by utilizing a polling scheme by the ANU, which acts as an access point (AP) to wireless devices. Polling ensures that only the polled device by the access point can access the wireless channel for a certain pre-determined time slot. As such, other wireless devices will refrain from accessing the channel, thus reducing channel contention and collision if all nodes try to access the channel randomly without coordination. The second challenge is addressed by utilizing Reed Solomon forward error correction codes (RS-FEC) or (FEC) in short [27], where different sensors have different priorities, such that more error correction code is assigned to the more critical and vital sensors, which in turn will improve the probability of correctly receiving the data stream sent by these sensors without the need of having multiple re-transmission rounds, which will cause more delay and reduce the overall network goodput. A detailed description of both mechanisms is provided in what follows, followed by a performance evaluation and analysis of the proposed protocol.

A. POLLING FOR CHANNEL COORDINATION

The ANU will first discover all existing wireless devices within its radio range and collect the sensors' information according to the proposed protocol. It will then determine the best media access scheduling policy based on the sensors' information. Finally, it will calculate the amount of FEC bits for each sensor, taking into account the sensor's priorities and importance. Therefore, it is essential to emphasize that our proposed protocol offers different access times to the communication channel, similar to the standard 802.11e protocol, and provides different error correction capabilities for each sensor based on its priority and importance.

Once all these steps are completed, the ANU will begin polling each sensor and receiving its captured data. The following provides a brief description of each step.

1) Sensors' Exploration

   The exploration phase is achieved by sending a broadcast message to all wireless nodes within its radio coverage. The wireless devices will respond to this message by sending association information; notice that at this stage, the nodes will send their information using the traditional best-effort contention-based mechanisms as polling is still not set up. However, if more than one node responds at the same time, collision may occur. Therefore, we reply on the collision detection/ mitigation mechanism available in the contention-based protocols such as carrier sense multiple access with collision detection (CSMA/CD) protocol that is widely used in wireless networks.

   This information is the node ID (*ID*), which can be the MAC address of the wireless interface card since it uniquely identifies the node among others, the sensor priority level (*P*), where higher values indicate higher priority and vice versa, the sensors' polling frequency (*PF*) defined as the number of polling time slots

(t) within certain polling period (PP). Notice that PF is directly related to the amount of data traffic requirements, defined as the amount of data this sensor needs to send within PP, which depends on the nature of the sensor and the captured data. The PP is defined as the time interval required to poll all the devices at least once, where devices of high priority will be polled more than those of lower priority, as explained later. Further, it is important to mention that during this exploration phase, the ANU will estimate the channel quality by measuring its signal noise ratio (SNR). In the literature, there are different mechanisms for measuring the channel SNR, such as the one mentioned in [17], which utilizes a non-intrusive way of estimating the channel quality. By estimating the channel SNR, the ANU can predict the wireless channel expected bandwidth (BW), which is essential in estimating the transmission delay for the sensors' data packets and determining the amount of FEC bits for each sensor, as will be explained later in this section.

2) Media Access Scheduling
Once the ANU collects the sensors' information, it uses this information to determine the best scheduling policy, which ensures that each sensor will be able to access the wireless channel according to the advertised priorities and polling frequencies within the polling period. The ANU will first determine the time slot duration (t) according to Equation (1)

$$t = PP/(\sum_{i=1}^{n} PF_i), \tag{1}$$

where n is the number of sensors. Notice that each sensor will gain a different access time according to their priorities, that are mainly determined by PF_i. Consequently, the total access time duration (TD) the sensors will receive during one polling period is calculated according to the Equation (2)

$$TD_i = PF_i.t, \tag{2}$$

Notice that PP is a design factor determined by the application under consideration, which is equal to $PP = \sum_{i=1}^{n} TD_i$. Once t is determined, the sensors are accessed in a round robin fashion according to their priorities identified by their polling frequencies. Further, the sensors' priorities levels will be used along with PF later in determining the amount of error correction bits that each sensor will have, which should reflect its importance and priority.

3) Forward error correction assignment: After the ANU identifies the sensors' polling frequencies and the scheduling policy, it should also determine each sensor's forward error correction bit assignments, such that more error correction bits are assigned to higher priorities sensors. To achieve that, the ANU classifies the sensors' priorities into different classes; each class has different error correction bits that are a function of three primary parameters:
   a) The estimated channel SNR (SNR_{est})
   b) The sensors' priorities
   c) The sensors' polling frequencies

The channel SNR is important in determining the error correction bits needed to ensure reliable transmission. Higher values indicate better channel conditions and less errors; thus, less error correction bits are needed, and vice versa. In this paper, we assumed three different SNR levels; low, medium, and high, denoted as SNR_L, SNR_M, and SNR_H. Further, three different FEC bit-assignments are utilized for each SNR level, which depends on the nodes' importance and priority. Algorithm 1 depicts the proposed unequal FEC bits budget (FEC_{bud}) as a function of the SNR levels, node priority, and importance. Notice that the above logical rules can be adjusted according to the application requirements and setup. For example, in our paper, we assumed that we have three classes of sensors with different priorities. Thus, we have three FEC_{class}, where each class corresponds to the amount of error correction bits that can be assigned to each sensor. Furthermore, the amount of $FEC_{symbols}$ represented by the FEC_{class} can be changed according to the channel conditions characterized by the estimated SNR values. In this work, we have assumed three different SNR values; low, medium, and high. Small SNR values indicate noisy channels with a high probability of bit errors, while medium and high SNR values indicate less noisy channels and lower probability of bit errors. As such, in the low SNR values, the three FEC_{class}; ($FEC_{bud}(SNR_L)(1)$, $FEC_{bud}(SNR_L)(2)$, $FEC_{bud}(SNR_L)(3)$), correspond to the three FEC levels will have higher bit budgets when compared to the medium and high SNR values. Notice that the variable $FEC_{bud}(SNR_L)(1)$, refers to the FEC budget of sensor class 1 when the SNR is low. In other words, the FEC_{class} differs from one sensor to the other depending on its priority and from one channel condition to another depending on the SNR values. This gives the best optimization and utilization of the transmission bit budget. Notice that the estimated SNR also determines the expected transmission speed of the wireless channel, which will determine how many bits (B) can be sent within a certain time slot TS using Equation (3):

$$B = TS \cdot BW. \tag{3}$$

According to B, each sensor will determine how many packets (No_{pcks}) it can send when it is polled according to Equation (4):

$$No_{pcks} = \left\lfloor \frac{B}{pck_s} \right\rfloor, \tag{4}$$

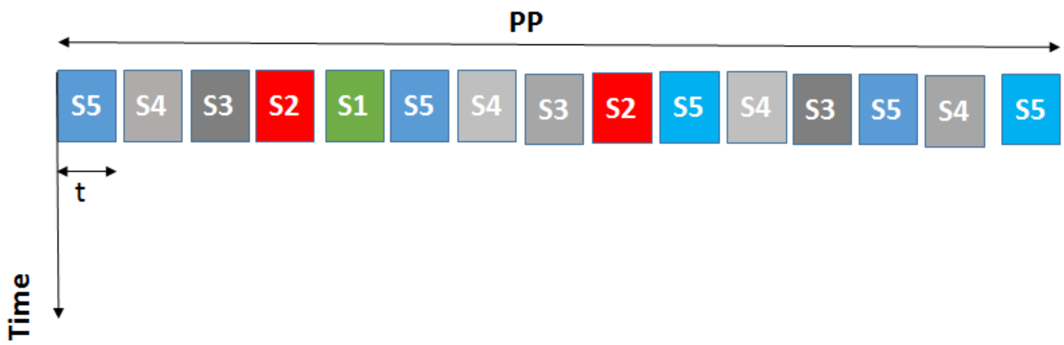

FIGURE 2. Sensors' time-slots scheduling.

where *pcks* is the packet size in bits. In this paper, we propose to use Reed-Solomon error correction codes [3], which work on blocks of bits. The block size (n) is determined using the symbol size (s) measured in bits, such that $n = 2^s - 1$, measured in symbols. Accordingly, if we assume each block is one packet, the packet size in bits equals ns. Notice that since each sensor knows its class, then it can determine how much data (D) measured in symbols will be sent for a given TS using Equation (5):

$$D = pck_{ss} - FEC_{symbols}(i). \tag{5}$$

where pck_{ss} is the packet size in symbols which is equal to $\frac{pck_s}{s}$. Furthermore, the FEC overhead (FEC_{over}) and the goodput G_p for a sensor i can be determined using Equation (6) and Equation (7), respectively.

$$FEC_{over} = \frac{FEC_{symbols}(i)}{pck_{ss}} \cdot 100\% \tag{6}$$

$$G_p = \frac{D}{pck_{ss}} \cdot 100\% \tag{7}$$

where higher FEC results in more reliable transmission but at the expense of more overhead. To clarify the above information, let us consider the following example, suppose the network is composed of 5 sensors with the following information: $PF = [1, 2, 3, 4, 5]$, $P = [1, 1, 2, 3, 4]$, which indicates that sensor 1 needs 1 poll per PP and has a low priority ($P_1 = 1$), while sensor 5 for example, requires 5 polls per PP and has the highest priority ($P_5 = 4$). Accordingly, the scheduling of the sensors will be as follows, which is also depicted in Figure 2:

$scheduling = \{5, 4, 3, 2, 1, 5, 4, 3, 2, 5, 4, 3, 5, 4, 5\}$

According to that, sensor 1 will have the lowest total access time duration with $TD_1 = t$, while sensor 5 will have a higher total access time duration with $TD_5 = 5t$. Furthermore, and according to Figure 2, the FEC classes for the 5 sensors will be as follows:

$FEC_{class} = \{1, 2, 3, 3, 3\}$, which indicates that sensor 1 will have the lowest error correction protection, as it belongs to class 1, sensor 2 has medium error correction protection, while sensors 3, 4, and 5 will have the most protection since they belong to class 3.

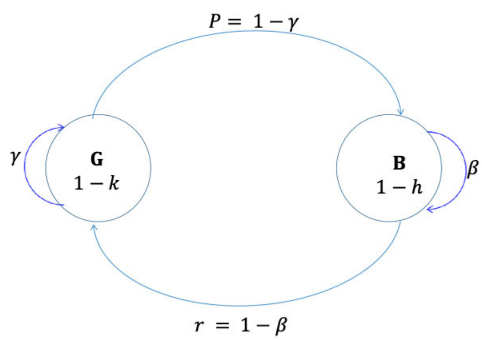

FIGURE 3. Gilbert-Elliot modelling the temporal correlation of the lossy network.

Notice that in this illustration, the number of sensors (5 in this case) is just an example to show the framework validity and to easily compare between the attained priorities per sensor. In case of having more sensors that need to be polled, they either can be added to the polling cycle in case the resulting polling delay per sensor is within the delay bounds for these sensors. However, in case of having time-critical sensors, then the sensors can be divided into clusters, where the cluster size and polling cycle duration will be determined according to the delay constraints of the grouped sensors. As a practical example of these sensors, examples of sensors that may need high priority can be a breath monitoring sensor or heart beat sensor, where it should be given the highest priority in terms of delay and error correcting capabilities. While the body temperature sensor can be an example of less critical sensor, especially that the human body temperature variations is not very fast and its measurement can tolerate some delay.

V. PERFORMANCE EVALUATION

In this section, the performance evaluation of the proposed protocol is studied. Three main metrics have been used to

Algorithm 1 The Unequal Error Correction Bits Assignment for the K Sensors Taking Into Account Their Priorities and the Channel Condition

```
while i ≤ K do
    if SNR_est == SNR_L then
        if PF_i == 1 and P_i == 1 then
            FEC_symbols(i) = FEC_bud(SNR_L)(1)
            FEC_class(i) = 1
        end
        else if PF_i == 2 and (P_i > 1 and P_i ≤ 3) then
            FEC_symbols(i) = FEC_bud(SNR_L)(2)
            FEC_class(i) = 2
        end
        else
            FEC_symbols(i) = FEC_bud(SNR_L)(3)
            FEC_class(i) = 3
        end
    end
    else if SNR_est == SNR_M then
        if PF_i == 1 and P_i == 1 then
            FEC_symbols(i) = FEC_bud(SNR_M)(1)
            FEC_class(i) = 1
        end
        else if PF_i == 2 and (P_i > 1 and P_i ≤ 3) then
            FEC_symbols(i) = FEC_bud(SNR_M)(2)
            FEC_class(i) = 2
        end
        else
            FEC_symbols(i) = FEC_bud(SNR_M)(3)
            FEC_class(i) = 3
        end
    end
    else if SNR_est == SNR_H then
        if PF_i == 1 and P_i == 1 then
            FEC_symbols(i) = FEC_bud(SNR_H)(1)
            FEC_class(i) = 1
        end
        else if PF_i == 2 and (P_i > 1 and P_i ≤ 3) then
            FEC_symbols(i) = FEC_bud(SNR_H)(2)
            FEC_class(i) = 2
        end
        else
            FEC_symbols(i) = FEC_bud(SNR_H)(3)
            FEC_class(i) = 3
        end
    end
end
```

evaluate the effectiveness of the proposed protocol that have a direct effect on QoS of the medical monitoring process. In particular, the packet loss rate, which affects the reception of packets that may carry vital medical information to the inter-domain gateway of the monitoring system. Having a high packet loss rate will affect the system reliability. The second metric is the number of assigned time-slots per node, which will directly affect the network access time for each node thus giving more access time to the nodes with higher priority, which is highly important for sensitive medical sensors such as heart beat/blood pressure sensors, breath and respiration, etc. Finally, the third metric is the sensor nodes throughput, where sensors with higher priorities can achieve higher throughput, thus sending larger amount of data to the monitoring system, which may be needed in some type of sensors that have higher data rates (e.g. vision or ultrasound imaging sensors).

The simulation environment is built using Matlab. Five different sensor nodes with different priorities are used. The IEEE 802.11b protocol is used for the physical layer, given the fact that this is a basic wireless communication protocol that can be used as a base-line for new improvements and development, which utilizes binary phase shift keying (BPSK) or quadrature phase shift keying (QPSK) modulation schemes with an estimated bandwidth of 1, 2, 5.5, 11 Mbps [28], depending on the channel conditions. However, the effective bandwidth (*BWeff*) is a function of the signal to noise ratio (*SNR*) and it depends mainly on the environment nature of the wireless channel. This work used the estimated bandwidth reported by [29] for different *SNR* values. Moreover, to simulate bit errors introduced by the noisy wireless channel. The Gilbert Eliot channel model is used [30]. As shown in Figure 3, in this model, the channel alternates between a good state (G) and a bad state (B), with a probability of P, r, respectively. The channel status has a self-transmission probability of γ, β for the G, and B states, respectively. When the channel state is Good, the probability of bit error equals $1-k$, while when the channel is in a Bad state, the probability of bit error equals $1-h$, where $1-h \ll 1-k$. Further, the overall probability of bit errors ($Perr$) utilizing the GE model is calculated using equations (8, 9, 10) [29]:

$$Perr = (1-k)\pi_G + (1-h)\pi_B. \tag{8}$$

$$\pi_B = \frac{p}{p+r}. \tag{9}$$

$$\pi_G = \frac{r}{p+r}. \tag{10}$$

where π_B, π_G, are the stationary state probabilities in state B and G, respectively, assuming $\pi_G \gg \pi_B$. To analyze the *GE* temporal correlated patterns of bit errors, the Markov chain is used with transitioning probabilities of $\beta = 0.875$, $\gamma = 0.099875$ [30], then p, r, π_G, and π_B are calculated as in Equations (11, 12, 13, 14):

$$p = 1-\gamma = 1-0.099875 = 0.9001, \tag{11}$$

$$r = 1-\beta = 1-0.875 = 0.125, \tag{12}$$

$$\pi_G = \frac{r}{p+r} = \frac{0.125}{0.9001+0.125} = 0.1219, \tag{13}$$

$$\pi_B = \frac{p}{p+r} = \frac{0.00127}{0.00127+0.125} = 0.0101. \tag{14}$$

Then Equations (8, 9, 10) are used to calculate the *GE* parameters corresponding to the bit error rate under investigation.

For example, for $Perr = 0.05 = (1-k)\pi_G + (1-h)\pi_B$ then, if h was set to a specific value (0.5 for example), then $1-k = 0.045$, and $k = 0.95503$. In this paper, the value of h was set close to 0.9999. After calculating the transition probabilities corresponding to the bit error rate under investigation, the *GE* model is used to simulate bit errors on the transmitted bit stream. In wireless transmission, *SNR* is typically used for performance evaluation. As such, for Binary Frequency Shift Keying modulation, *Perr* can be calculated from *SNR* using Equation (15):

$$Perr = 0.5\text{erfc}(\sqrt{\frac{E_b}{N_o}}). \tag{15}$$

$$E_b = \frac{S}{BW}. \tag{16}$$

where S is the total signal power in Watts, BW is the bandwidth measured in bits/seconds, then E_b/N_o is related to S using Equation (17):

$$SNR = \frac{E_b}{N_o} \cdot BW. \tag{17}$$

Consequently, *Perr* can be written as a function of *SNR* using Equation (18):

$$Perr = 0.5 \cdot erfc\left(\sqrt{\frac{SNR}{BW}}\right) \tag{18}$$

In the simulation, for a given *SNR*, we calculate *Perr* using Equation (18), then we estimate the *GE* parameters as discussed above. Moreover, to have a simulation environment that resemble the real-world, we have used the estimated effective bandwidth.

To mitigate the bit errors introduced by the wireless channel, Reed Solomon Forward Error Correction ($RS-FEC$) codes are used [3]. Each packet is coded as one RS coding block with a size n symbols equal to $n = 2^s - 1$, where s is the symbol size in bits. Here we used $s = 10$ bits, corresponding to an RS block size $n = 1023$ symbols. An encoded block contains k data symbols and $C = n - m$ parity symbols. An *RS* channel code RS(n, m) can correct as many symbol errors as $t_c = \lfloor \frac{C}{2} \rfloor$ symbol errors in a block. Symbol errors can occur if one or more bits with the symbol bits have an error. As such, the probability of symbol error (ϵ) is upper bounded by *Perr* calculated in Equation (8). In this paper, each sensor has a different priority, which identifies the channel access time, which is identified by the polling frequency and the amount of *FEC* budget assigned to it, where higher priority sensors have higher polling frequency and higher *FEC* budget. Further, the *FEC* budget allocation is proposed to be a function of *SNR* since if the channel is good, there is no need to assign a high *SNR* budget since the probability of bit errors will be low in this case and vice versa. In the simulation, the sensors' polling frequencies and priorities were set to $PF = [1, 2, 3, 4, 5]$, and $P = [1, 2, 2, 3, 4]$. The polling period was set to

TABLE 1. Simulation main parameters.

No.	Parameter	Value
1	Symbol size (s) in bits	10
2	RS Block size in blocks (n)	1023
3	No. of sensor nodes	5
4	No. of simulation runs	10
5	The polling period in ms	250
6	The sensors' polling priorities	$PF = 1, 2, 3, 4, 5$
7	The sensors' polling frequency	$P = 1, 2, 2, 3, 4$
8	γ in GE error model	0.0099875
9	β in GE error model	0.875
10	h in GE model	0.9999

250 ms, and the simulation time was 10 seconds. Notice that the 250 ms polling cycle/period is a design parameter that can be changed according to the application under consideration. In case of having medical sensors that require lower delay, then this can be addressed in several ways in the proposed framework such that increasing the sensor's polling frequency within the same polling period, thus reducing the network access time. Another way is to reduce the polling period and also to reduce the number of polled sensors within the polling cycle. However, in case there are many sensors that should be polled, then several clusters of sensors can be formulated, where each cluster will have its own polling period using a dedicated wireless channel that will ensure an interference-less communication process. Furthermore, three different *SNR* values have been used which correspond to three different channel conditions low, medium, and high, with *SNR* and estimated effective bandwidth *BWeff* values for an indoor environment [31] equal to: $SNR_L = 32$ dBm, $BWeff_L = 760$ Kbp, $SNR_M = 34$ dBm, $BWeff_M = 770$ Kbps, and $SNR_H = 35$ dBm, $BWeff_H = 775$ Kbps, respectively. We used different error correction bits for each channel condition, where higher bits are used when having low *SNR* values. In particular, the first SNR value (SNR_L) used equals 32 dBm, with three different FEC_{class} for each *SNR* value. At SNR_L, $FEC_class(1)$ equals $FEC_{bud}(SNR_L)(1) = 32 + q * 16$ symbols, where q is varied from 1 to 10, to show the performance for this budget allocation class at 10 different budgets. $FEC_{class}(2)$is equal to $FEC_{bud}(SNR_L)(2) = 64 + q * 16$ symbols, and $FEC_{class}(3)$ is equal to $FEC_{bud}(SNR_L)(3) = 128 + q * 32$ symbols. At SNR_M, $FEC_{class}(1)$ is equal to $FEC_{bud}(SNR_M)(1) = 8 + q * 16$ symbols, $FEC_{class}(2)$ is equal to $FEC_{bud}(SNR_M)(2) = 16 + q * 16$ symbols, and $FEC_{class}(3)$ is equal to $FEC_{bud}(SNR_M)(3) = 32 + q * 16$ symbols. Finally, at SNR_H, $FEC_{class}(1)$ equals to $FEC_{bud}(SNR_H)(1) = 8+q*4$ symbols, $FEC_class(2)$ is equal to $FEC_{bud}(SNR_H)(2) = 16 + q * 4$ symbols, and $FEC_{class}(3)$ is equal to $FEC_{bud}(SNR_H)(3) = 32 + q * 4$ symbols. Table 1 summaries the main simulation parameters used in this paper.

Figures (4,5, 6) depict the simulation results for the five sensors for different channel conditions and FEC budget allocations. The x-axis represents the q variable defined

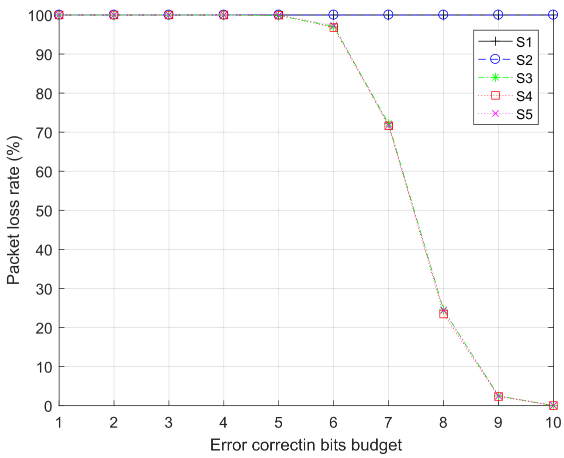

FIGURE 4. The packet loss rate of each sensor as a function of the allocated error correction code budget at low SNR condition with *q* ranges from 1 to 10.

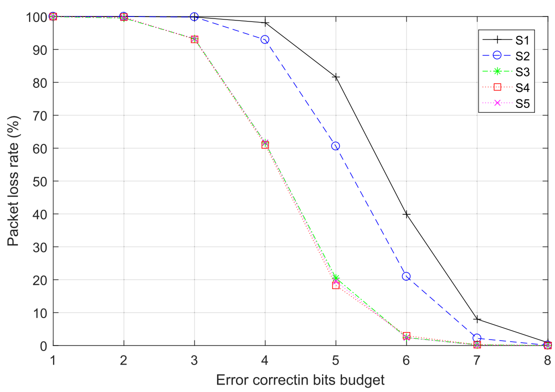

FIGURE 5. The packet loss rate of each sensor as a function of the allocated error correction code budget at medium SNR condition with *q* ranges from 1 to 10.

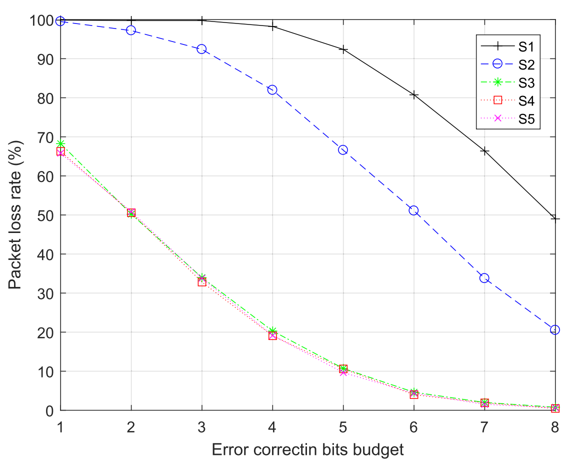

FIGURE 6. The packet loss rate of each sensor as a function of the allocated error correction code budget at high SNR condition with *q* ranges from 1 to 10.

earlier which controls the error correction budget bits FEC_{bud} that are allocated for each class and according to the channel condition. One can notice that at a low SNR value

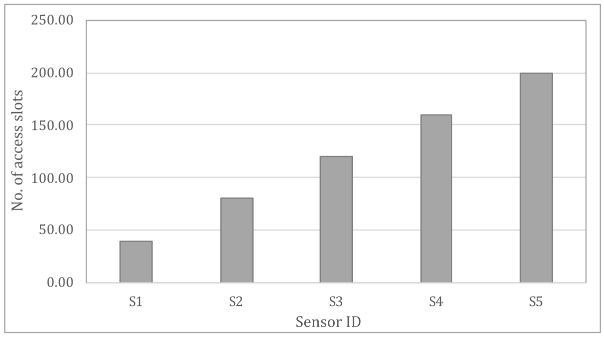

FIGURE 7. No. of assigned access time slots of each sensor according to their priorities.

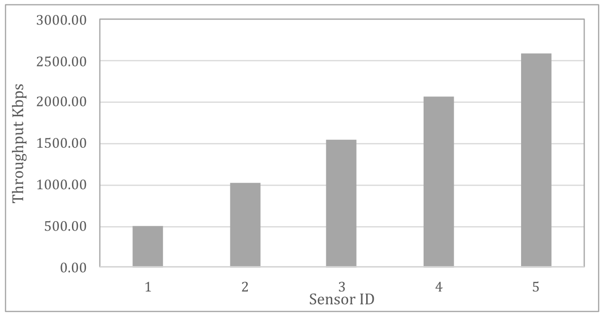

FIGURE 8. The throughput of each senor.

(Figure 4), all the sensors lost all their packets at a low FEC budget. However, when the budget increased, the packet loss dramatically decreased for sensors S3, S4, and S5, while it remained the same for sensors S1 and S2. The justification for that is that since the first two sensors have low priority, they were allocated a low FEC budget to allocate more FEC budget to the higher priority sensors (S3, S4, S5). However, one can notice that the three sensors have relatively similar performance at low channel conditions, although they do not have the same priorities. The reason for that is that the channel is causing a lot of bit errors at low channel conditions, so if the budget allocation differences were not large, then the probability of packet loss would be almost the same. However, when the channel conditions were improved (Figure 5 and Figure 6), one can notice that the packet loss of all the sensors, including the low-priority sensors, decreased as the budget increased. Further, the distinguishing between the high-priority sensors (S3, S4, S5) starts to be more significant compared with the lower-priority sensors (S1, S2) since the channel conditions improve and the effect of adding extra error correction bits becomes more viable.

Figure 7 depicts how the proposed protocol assigns more channel access slots to the sensors with higher priorities, which leads to an increase in the overall throughput of these sensors, as depicted in Figure 8. However, since higher priority sensors are assigned more FEC budget, this will lead to higher channel coding overhead than less priority

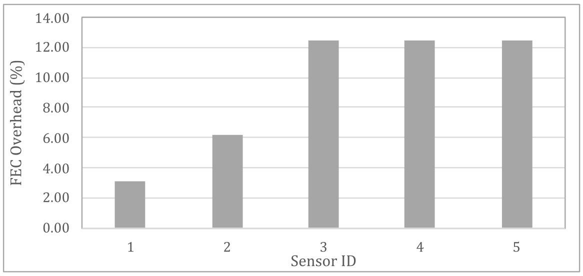

FIGURE 9. The FEC overhead of each sensor.

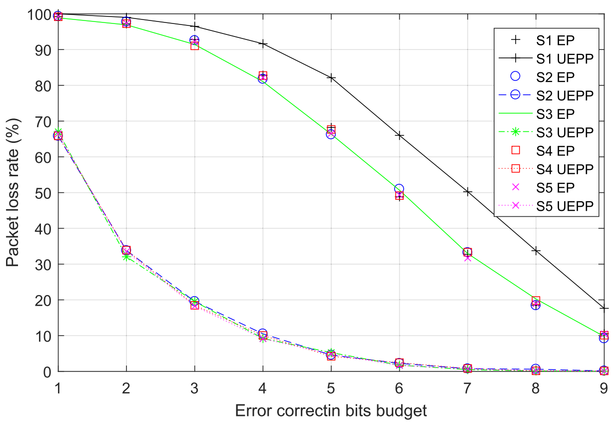

FIGURE 10. A comparison between the proposed unequal error and polling protection (UEPP) protocol and the equal polling and error protection scheme proposed in the literature at high SNR condition.

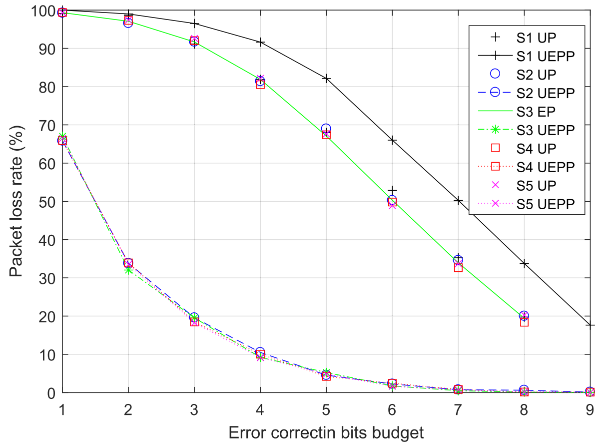

FIGURE 11. A comparison between the proposed unequal error and polling protection (UEPP) protocol and the unequal polling (UP) proposed in the literature at high SNR condition.

sensors, as depicted in Figure 9. Finally, it is important to notice that even though the sensors $S3$, $S4$, and $S5$ have similar FEC budgets, the throughput of $S5$ is higher than $S4$ since this sensor node requires more time slots than the others. In other words, sensor priorities are given regarding a higher FEC budget and more time slots per polling period. Finally, the proposed unequal error and polling protection (UEPP) protocol is compared with some proposed work in the literature. As described in the literature review section, the majority of the research work proposes equal time slot assignment for each sensor node within the polling/data collection cycle like the work presented [21]. However, some authors like [22] proposed to assign more than one-time slot per node within the polling cycle based on the node's delay requirements. Therefore, a comparison has been conducted with both approaches (equal polling (EP)) and unequal polling (UP). Furthermore, to have a fair comparison, we have assigned each node an error correction bit such that the assigned bits are either equal or less than the bits assigned for the nodes that utilized the UEEP protocol. In this simulation setup, the comparisons were made by assigning the nodes that utilized either EP or UP equal error correction bits that are associated with $FEC_{Class} = 2$. As depicted in Figures 10 and 11, the UEEP succeeded in giving the high priority sensors more error correction bits and more network access time than the EP scheme, thus achieving a lower packet loss ratio. Furthermore, although the UP scheme assigns different time slots to the sensor nodes based on their priorities, where the same polling frequency used in the EEP scheme was used in the UP scheme for having a fair comparison, the EEP achieved better results in terms of packet loss ratio, especially for the most important and high priority sensor nodes.

VI. CONCLUSION AND FUTURE WORK

This paper presented a system-of-systems framework for healthcare monitoring services. In this framework, patients are provided with sensors that monitor their healthcare conditions and send the captured data over a wireless communication channel to a remote unit for further processing and actions. To provide patients with a reliable and efficient system, a robust wireless communication protocol is proposed that provides reliability to the sensor nodes while taking into consideration the channel conditions and sensors' priorities and importance, where higher error correction bits and more network access time are allocated to the more important sensors. In future work, we are working to optimize the amount of assigned error correction codes for each sensor, taking into consideration factors other than the channel condition, such as the sensor battery status and wireless network conditions. Furthermore, we are working to build a prototype of the proposed framework and conduct an experimental evaluation of the proposed wireless protocol.

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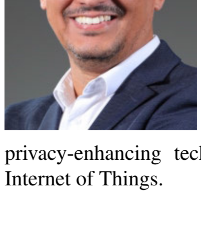

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