

Mapping Critical Illness Early Signs to Priority Alert Transmission on Wireless Networks

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Abstract—The prediction of adverse events in patient health has attracted researchers' attention for many years. Sensors in or on the body allow the continuous monitoring of patient's vital signs and their accurate analysis, supporting the generation of medical alerts. Exploring adverse event prediction only makes sense if medical alerts can be promptly transmitted to a hospital emergency response team. However, promptly transmitting them through heterogeneous wireless networks is still a challenge because of wireless communication features, i.e., interferences and collisions, and the current medium access control (MAC) protocol design, that still produces competition between medical alerts, and video, voice and other types of data. Differently from current mechanisms that either are separately concerned to the prediction of adverse events or to give priority to different type of data transmission, this work presents SANTE, a System for Anticipated identificatiON and Transmission of mEdical alerts on wireless networks. Based on trends about the imminence of adverse events on patient health, the system generates medical alerts and promptly transmit them. It presents a novel proposal to medium access control for medical alerts, reducing contention window and Arbitration Inter-Frame Spacing (AIFS) time for them. Simulation results show a reduction of 39% in the average latency for alert transmissions and 8% in losses.

I. INTRODUCTION

Fast advances on wireless communication and nanotechnology have contributed to the development of implantable or wearable sensors. These sensors form Wireless Body Area Networks (WBANs) able to communicate among themselves and to other sensors or devices. WBANs allow the sensing and monitoring of vital signs in human bodies [1], [2]. In general, they are applied in medical contexts where applications receive collected data, analyze them and send information to healthcare professionals. A benefit from this is the possible identification of risks and health issues in their early stages [3].

However, the current medium access control protocols for wireless networks (e.g., WBAN and WLAN) are not yet designed to give exclusive priority to the transmission of medical alerts [4]. Because of their urgent nature, medical alerts require the immediate transmission, accepting maximum 125 ms of latency [5]. Although expecting dedicated WBANs to medical applications, the network infrastructure may carry several data flows like voice and video. Hence, the competition for the medium access causes delays [1] with possible disastrous consequences to patient's health. Further, data delivery in this context passes through heterogeneous

networks and technologies, being a challenge to reach the medical alert transmission requirements. Thereby, besides the urgent transmission of medical alerts, it is necessary to identify as soon as possible adverse events in the patients to support professional decisions and, in some cases, save lives.

For many years, studies have proposed ways to predict adverse events (e.g., respiratory or cardiac arrest) and generate medical alerts [6], [7], [8]. Nonetheless, these works ignore the prompt transmission of medical alerts to hospital emergency response team. Few studies have separately proposed mechanisms for the immediate medical alert transmission [9], [10]. But, despite their efforts, they do not jointly address medical alerts and other data flows (e.g., voice or video). For the best of our knowledge, there is no study that jointly addresses the prediction and the prompt transmission of alerts in heterogeneous wireless network context.

This work presents SANTE, a System for Anticipated identificatiON and Transmission of mEdical alerts on wireless networks. Based on the prediction of trends about imminent adverse events, the system generates medical alerts and assigns to them the highest priority level. A new medium access category is created exclusively for medical alerts, offering to them a special treatment by a novel control of the contention window and Arbitration Inter-Frame Spacing (AIFS) time allowing healthcare professionals to respond in time.

We evaluate the system performance in two phases. First, on the R tool, we analyze the generation of medical alerts, predicting trends of adverse events. For this, we apply a set of indicators over a respiratory frequency dataset collected from real patients with pulmonary edema [11]. Second, we integrate the medical alert generation module to the Network Simulator (NS-3) in order to analyze the system performance on transmitting medical alerts. Based on the identification of adverse event trends, the results show that SANTE can reduce in 39% the transmission delay and in 8% packet losses.

This paper proceeds as follows. Section II introduces the SANTE system. Section III describes the performance evaluation and the results. Section IV presents related work. Section V concludes the paper and presents future directions.

II. THE SANTE SYSTEM

This section details the SANTE system. As stated before, SANTE provides the prompt transmission of medical alerts generated based on the early identification of trends about

adverse events on human health. In this work, *adverse events* include situations that may result in severe consequences for patients' lives, such as a cardiac or respiratory arrest. These events demand immediate action because delays may produce disastrous consequences for patients. Hence, predicting the imminence of such events and transmitting alerts to healthcare professionals benefit health monitoring.

The SANTE architecture comprises of three steps: *data collection, the prediction of adverse event trends and medical alert transmission* (Fig. 1). In the first step, sensors collect vital signs in the human body and transmit them to the WBAN coordinator (i.e., patient's mobile device). In the second step, SANTE predicts trends of adverse events based on a set of well-known statistical indicators. When the indicators show the imminence of a critical event, the system generates a medical alert. In the third step, the WBAN coordinator assigns the highest priority to medical alerts and transmits them. Next, we detail these three steps.

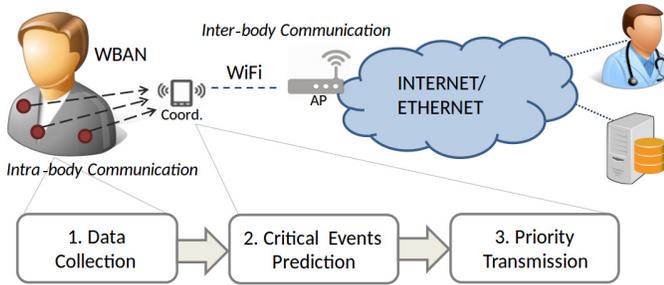


Fig. 1: An Overview of the SANTE Architecture

A. Data Collection

Body sensors collect patient's vital signs and send them to the WBAN coordinator. It is necessary to have a coordinator due to sensors resources limitations, i.e., low energy and transmission range. Because of this, the communication between the sensors and the WBAN coordinator occurs by a low-range communication technology, called in literature as intra-body communication [3]. The coordinator processes the data and transmits them to a healthcare center, in general, through a WLAN and then the Internet [1]. This work focuses on the **inter-body communication**, i.e., the communication between the WBAN coordinator and the access point (AP).

There are different types of body sensors. Each one monitors a certain kind of vital sign [1] (e.g., electrocardiogram sensors, that collect data about heartbeats; and temperature sensors, that monitor the body temperature). Depending on the type of collected data, transmission must achieve specific requirements. For example, some data present a higher urgency to be delivered to healthcare professionals (e.g., ECG) than others, such as medical routine data, that are not time-sensitive [4].

B. Critical Event Prediction

SANTE is founded on the identification of trends about adverse events on the patient's health. Based on the trends, SANTE generates medical alerts (special packets) that must be promptly transmitted to healthcare professionals. In this

work, SANTE employs return rate, autocorrelation, variance, asymmetry and kurtosis as the set of generic statistical indicators. Their joint behavioral analysis can assist the prediction of adverse events [11]. The WBAN coordinator receives data collected from sensors and organizes them in **time series**. Over the time series, the WBAN coordinator calculates the statistical indicators and analyzes their behavior across time. Next, we briefly describe each indicator and the expected behavior for early predicting adverse events in patient's health.

The **return rate** shows how fast a patient recovers from a disturbance (variations in her/his vital signs). This recovery time increases when a critical situation (e.g., a respiratory arrest) approaches in the patient's health condition [11]. Hence, a low return rate may indicate a possible adverse event. However, from the literature, the individual return rate analysis is not enough to predict an adverse event, requiring the joint analysis with the other statistical indicators.

Autocorrelation estimates the correlation degree between a time series and itself delayed over time. Autocorrelation tends to increase when patient's condition become similar between consecutive observations. Therefore, an increase in the autocorrelation indicator, with short discrepancy in time, is expected on the proximity of an adverse event [11], showing similarities between observations across time.

Variance estimates the time series variability, being considered normal when the observations are around stability. Disturbances force patient's conditions (i.e., the heartbeat values) to widely change, increasing variability. Hence, an increase in the variance indicates a possible critical situation approaching a patient's condition [11].

Asymmetry compares time series distribution in relation to a symmetric distribution (i.e., normal distribution). Symmetry indicates stability on patient's condition, whereas asymmetry reveals critical values on the patient's condition. Hence, it is expected an increase in the asymmetry of patient's condition distribution in the imminence of an adverse event [11].

Kurtosis quantifies the dispersion of patient's condition from stability. Strong disturbances drive the patient's condition to reach extreme values, such as high heart beat rates, which are rare to appear. The presence of rare values in the health destabilizes patient's condition, causing an increase in kurtosis. This behavior indicates the presence of a high dispersion on observations, signaling a possible adverse event [11].

From the literature [11], the behavioral analysis of these five statistical indicators can together show trends about a critical condition. In general, to characterize a critical condition, we expect an increase in autocorrelation, variance, asymmetry, and kurtosis values combined with a decrease in return rate. The increasing or decreasing trends of these indicators is measured by a metric called *Kendall tau*. Based these scientific results, SANTE employs the set of *Kendall tau* from the five indicators to decide about the generation of the medical alerts.

C. Priority in the Transmission of Medical Alerts

In this work, when the WBAN coordinator predicts an adverse event based on the behavioral analysis of these five

statistical indicators, it produces a time- and loss-sensitive medical alert that must be immediately transmitted to, for instance, a hospital emergency response team. This transmission requires priority medium access in the WLAN. Hence, this work presents a new medium access control approach in order to give high priority to medical alert transmission. Since most of the WLANs rely on IEEE 802.11, our solution is based on this standard. Particularly, we take as reference the traffic categories presented on IEEE 802.11e amendment [12]. However, in the IEEE 802.11e, medical alerts must follow the same priority level employed for voice traffic, creating an undesirable competition in the medium access between medical alerts and voice traffic.

SANTE provides to medical alerts a new category for exclusive medium access inspired by [13]. SANTE assigns to this new category the highest priority level. Medical alerts have then a reduction in the interval between frames (AIFS) and a reduction in contention window to a single slot. AIFS and contention window are mechanisms to avoid collisions in 802.11 networks. However, they also include delays for data transmission. Hence, following SANTE, medical alerts wait for a lower AIFS and contention window (cw) compared to other data traffic, as voice and video. Furthermore, SANTE keeps the compatibility with the legacy standard.

Fig. 2 compares the AIFS and CW duration for the different traffic in the WLAN in terms of Short-Interframe Space (SIFS) and time slot duration. Depending on the 802.11 amendment, SIFS and time slot duration can vary, e.g., for 802.11b, SIFS is of $10\mu s$ and time slot of $20\mu s$. The medical alerts follow an AIFS equals to a SIFS plus one time slot, and CW of 1 time slot. Differently from the medical alerts, background traffic, such as file sharing, AIFS is of SIFS plus 7 time slots, and CW of 0 to 15 time slots; best effort traffic follows an AIFS of SIFS plus 3 time slots, and CW of 0 to 15 time slots; video traffic follows an AIFS of SIFS plus 2 time slots, and CW of 0 to 7 time slots; and, finally, voice traffic follows an AIFS of SIFS plus 2 time slots, and CW of 0 to 3 time slots.

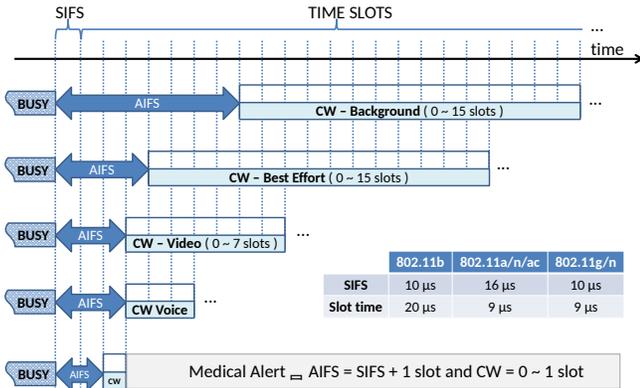


Fig. 2: New Medium Access Category: SIFS and CW

The use of the smallest AIFS interval gives priority to medium access for medical alerts. However, the presence of a large number of medical alerts using this small AIFS may overload WLAN, causing collisions and losses of alerts. To

avoid this, we have limited medical alerts frame size to 50 bytes. As smaller frames occupy medium for a very short interval, SANTE may reduce collisions, losses and channel overload. Moreover, when the WBAN coordinator receives an acknowledgment from the AP, SANTE interrupts medical alert transmissions to decrease the amount of alerts on the wireless medium, and so the transmission competition.

III. PERFORMANCE EVALUATION

We have evaluated SANTE through an integration between results from an analysis using R^1 and the network simulator (NS-3)². In R, we evaluate the potential of the five statistical indicators to early predict signs of adverse events. When identified an adverse event, SANTE generates medical alerts on NS-3. Through NS-3, we evaluate the performance of SANTE to transmit medical alerts under hybrid scenarios WBAN/WLAN. We detail the evaluation methodology.

The prediction of adverse events on patient’s health employs the results from the joint behavioral analysis of the five indicators. As inputs for the five indicators, we use the real labeled dataset MIMIC II from PhysioNet Bank³ containing time series (e.g., Fig. 3a) about the respiratory frequency collected from a 70-years old male patient with pulmonary edema. Time series have respiratory frequency per minute. The patient was monitored during 11 hours and 11 minutes. About 15 minutes after the monitoring begins, the patient suffered a respiratory arrest which lasted about 14 minutes (red box on Figure 3a). The patient was properly assisted and his vital signals were stabilized [14]. We analyze the dataset in small time series, sized to encompass the target adverse event which had approximately 14 minutes duration (Fig. 3b).

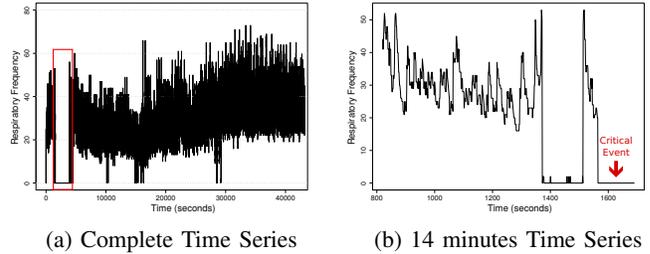


Fig. 3: Real Patient’s Respiratory Frequency

When trends of the adverse event (in this case, a respiratory arrest) are identified in R, a medical alert is generated in the NS-3 simulation. In NS-3, we evaluate the medium access through two metrics: *transmission delay* and *packet loss rate*. We have compared the results of a system using SANTE to a traditional system (i.e., without any critical event identification or priority in medical alert transmission).

We setup a simulation scenario that follows a domestic environment, since one of the environments where patients are monitored is at home. The scenario has a single access point (AP), and users with their mobile devices and body

¹R, <https://www.r-project.org/>. Last access on June/2017.

²NS-3, <https://www.nsnam.org/>. Last access on June/2017.

³PhysioBank, <https://physionet.org/physiobank/>. Last access on June/2017.

sensors. Body sensors send collected data to user’s mobile devices, that analyze the data and send medical alerts to the AP. Further, mobile devices can have other applications that generate and send other traffics, including voice and video, to the AP. The AP presents two network interfaces, one WiFi (following 802.11n) and another to connect to Ethernet.

In a realistic WBAN scenario, the medical alerts are transmitted when an adverse event is identified. In our R analyses, the dataset used contains just one adverse event: a respiratory arrest. Hence, SANTE has only one medical alert to transmit. However, in order to analyze the overload on the WLAN scenario related to the medical alerts transmission, the WBAN coordinator sends several medical alerts informing the same adverse event. These alerts are sent each 1.5 seconds. Besides medical alerts, mobile devices transmit other types of traffic. Table I presents overall traffic settings we consider in our simulations. Voice and video data flows present constant bit rate pattern, as we would expect from a video conference application. Regular data flows have been generate in bursts, following a Pareto distribution, as it occurs to the prevailing web traffic in public hotspots [15].

We have conducted a number of simulations, where we deploy ten mobile devices running medical applications and varied the number of mobile devices running general applications from 5 to 35. Unless we tell otherwise, results we present are an average of 35 repetitions with confidence interval of 95%. For each setup, we compare results from a traditional system and a system using SANTE, under the same conditions.

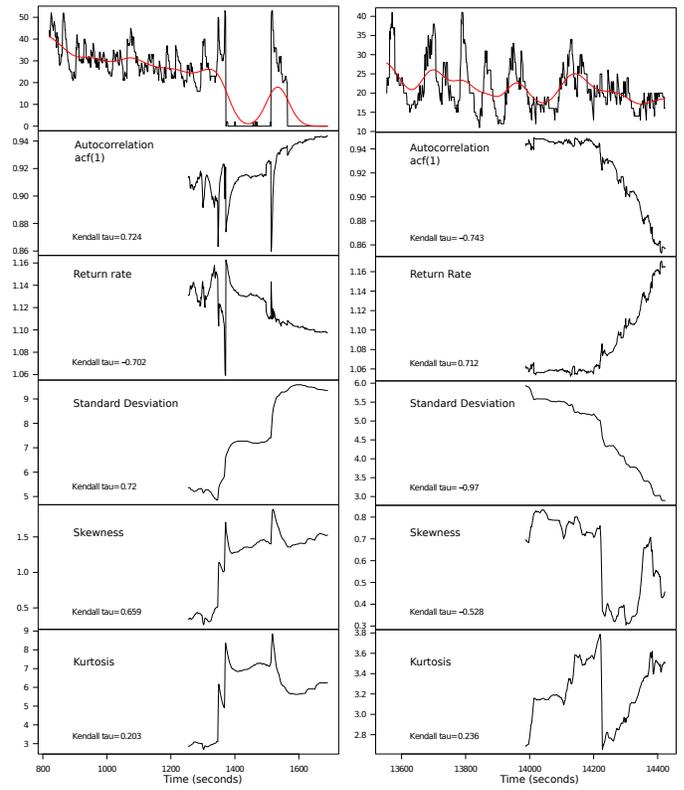
TABLE I: Simulation parameters

Traffic	Priority	Packet Size	Data Rates
Regular network	AC_BE	1450 bytes	100 Mbps
Video	AC_VI	1316 bytes	384 Kbps
Voice	AC_VO	64 bytes	64 Kbps
Medical Alert	AC_MA	50 bytes	50 Kbps

Simulation Results

Fig. 4 shows the results of statistical indicators at the early identification of adverse events on the patients’ health regarding respiratory frequency. The illustrated data on the first plot of Fig. 4a shows a critical transition towards the respiratory failure event. There is a change of the condition during the transition, where values changed abruptly from 50 to 0 at the respiratory frequency. The last two minutes of the time series encompass the initial stages of an adverse event which are necessary to the indicator estimation. While the illustrated data at the second plot of Fig. 4b consists of regular respiratory signs which do not show critical changes. We estimate the indicators in both time series in order to compare their behaviors in regular and critical situations.

Indicator results on plots of Fig. 4b do not show the expected behavior to identify an adverse event. This occurs because respiratory data from this time window do not have abrupt changes, in other words, that vital signs remain around stable values. On the other hand, the time series illustrated in Fig. 4a, the results show an expected generic behavior for the identification of adverse events. The autocorrelation increases



(a) Critical Transition

(b) After the Adverse Event

Fig. 4: Generic Statistical Indicators

considerably showing a strong relation between the respiratory samples with the tendency of remaining with values around 0 and the adverse event still may occur. The decrease in return rate confirms that the patient suffered disturbances close to the respiratory arrest event. Moreover, the variation between 50 and 0 from the respiratory samples caused an increase in the data variance measured by the standard deviation, what may show instability at the patient’s health condition.

In Fig. 4a, the decrease in samples justifies the increase of positive asymmetry (skewness) on data distribution. It indicates that there is a high respiratory signs concentration around the low values, showing this way, there is a tendency on the illness condition to remain in a critical condition in next observations. Also, the high variation and existence of extreme values at the observed data (like value 0) causes an increase on kurtosis, indicating the illness condition is not stable. This indicator behavior set shows an increase at the autocorrelation, variance, asymmetry and kurtosis associated with a decrease in return rate which points out the possibility of occurring an emergency event on the patient’s health. We show that the indicators may point out the adverse event imminence in real vital signs, as we know the occurrence of the respiratory arrest at the time window subsequent to the used window to obtain the indicators of Fig. 4a and the results show the same behavior presented in the literature. In our results, it was possible to identify the respiratory arrest 12 minutes before it happened. Furthermore, the indicator employed does not need specific

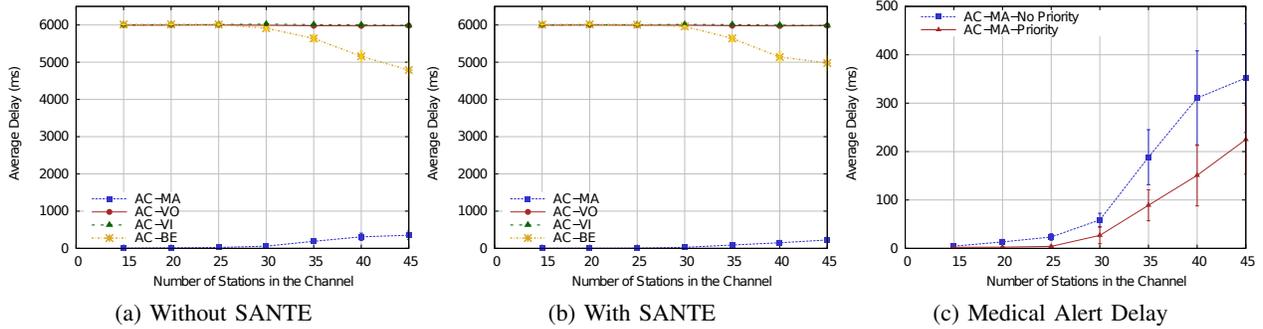


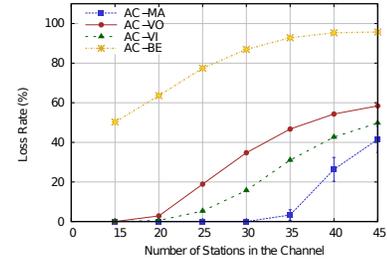
Fig. 5: Average Delay vs. Network Density

parameters of vital signs, allowing its generic use.

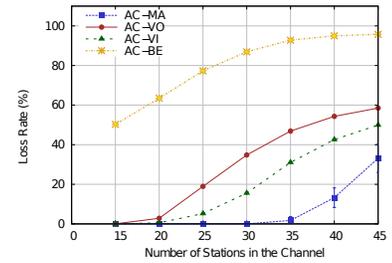
Figs. 5a and 5b show the average delay for all traffics – best effort (AC_BE), video (AC_VI), voice (AC_VO) and medical alerts (AC_MA) – in the network while we vary the total number of wireless devices in the environment. For both scenarios (i.e., a network using SANTE and a traditional network) under a low number of devices, medical alerts (AC_MA) present low average delays. However, when the number of wireless devices increases, we clearly note a difference between both networks. In fact, as we present in detail in Fig. 5c, SANTE presents a better performance for a larger number of devices. For example, under the presence of 30 mobile devices, a network using SANTE results in only 26 ms average delay, while a traditional network presents up to 58 ms average delay. This difference is more significant in a denser network. In special, under the presence of more than 40 devices, traditional system is not able to achieve the maximum allowed latency for medical applications (i.e., 125 ms). Note that, a traditional network practically presents a delay 3 times higher than the allowed (around 350 ms), while SANTE presents a maximum average delay around 244 ms.

Figs. 6a and 6b show the percentage of packet loss rate for both scenarios, while we vary the number of wireless devices. Again, under a small number of devices, both scenarios present similar performance. Intuitively, under a small number of devices we have a small collision probability and, as result, a negligible packet loss rate. Nevertheless, while we increase the number of mobile devices, the packet loss rate increases up to the wireless channel saturation. Even though, packet loss rate for medical alerts is much more notable when using SANTE. For example, in a dense network, under the presence of 40 mobile devices, a traditional system presents up to 26% of packet loss, while SANTE presents less than 13% of packet loss. In a denser scenario and without the SANTE usage it shows around 41% loss. When we use the SANTE at the same conditions, the losses reduce to 33%. Medical applications do not support the traditional systems due to the high loss of alerts. SANTE has been able to reduce the losses and delays, but it is necessary to reduce even more the loss of medical alerts for not cause consequences in patient’s lives.

Finally, it is also important to note that SANTE does not present impact on the remaining traffic (voice, video and regular network). As shown in Figs. 5a and 5b, overall traffic delay does not present significant differences between



(a) Without SANTE



(b) With SANTE

Fig. 6: Packet Loss Rate vs. Network Density

both scenarios. We observe the same for packet losses, when comparing Figs. 6a and 6b. For example, under the presence of 25 mobile devices, both systems presents the percentage of packet loss rate around 18% for voice, 5% for video and 77% for regular network traffic. In a denser scenario, the traditional and SANTE system present up to 54% of packet loss for voice, 42% of loss for video and 94% of loss for regular network traffic. The regular network traffic presents the highest losses on both systems because it has the lowest priority level in 802.11 standards. Hence, we believe that SANTE is able to enhance medical alerts, under a negligible overhead for other types of traffic.

IV. RELATED WORK

A number of works has addressed the prediction of adverse events in patient’s health and the classification of data transmitted to alert healthcare professionals [6], [7], [8]. For example, Misra and Sarkar [6] classify data packets according to their index of priority based on patient’s features, such as age, gender and illness. H. Kim and G. Kim [7] define priority levels of medical data associating them to each type of sensor. In their work, for instance, they define three priority levels, considering only three different sensors: ECG (cardiac

frequency), EEG (brain activity) and EMG (muscle activity). Kathuria and Gambhir [8] also classified medical data packets employing machine learning techniques based on attributes of their packet header like traffic type. In general, these solutions take as basis specific thresholds for vital signs, that require particular knowledge about each monitored vital sign. However, the vital signs can change depending on different features of the patient, such as age, lifestyle, and other, which would require changes in the thresholds. Also, these solutions focus on detecting critical events when they are already in progress, what may be too late for some critical situations (e.g., respiratory or cardiac arrest).

Aiming at transmitting data about patients' health, few works proposed mechanisms for priority transmission [9], [10]. Gundondu and Çalhan [9] proposed the use of non-preemptive queues at the WBAN coordinator to the transmission using three priority levels: emergency traffic (vital signals, as ECG), on demand (patient's geographical position) and normal (non-periodic vital signals, as oxygen saturation). Bhandari and Moh [10] split the WBAN channel allocation phase in exclusive sub-channels to each traffic: emergency traffic (emergency signals, as medical alerts), on-demand (continuous medical signal, as EMG), normal (discontinuous medical signal, as temperature) and non-medical (audio/video/data). Only urgent traffic can use all the sub-channels during the transmission. Despite both works provided low latencies to urgent traffic transmission, the trend prediction about a critical event occurs based on specific thresholds for vital signals. These works also do not consider the integration of different wireless networks and the competition for medium access considering the different types of data transmitted.

There is also a huge challenge in mapping the priority levels defined on the WBAN to the WLAN medium access categories. The works [16], [17] proposed mechanisms to map medical data, including the medical alerts, in the four access categories of the IEEE 802.11 standard. Rashwand and Mistic [16] mapped the two highest WBAN priority levels, which encompass the medical alerts and the network controlling data, in the highest level of WLAN access category (i.e. voice access category). Bradai *et al.* [17] defined three priority categories for WBAN traffic: emergency (medical alerts), on demand (continuous medical signal) and normal (discontinuous medical signal). Next, the authors associated the WBAN emergency category to the highest priority level in WLAN (i.e., voice access category). Both works show latencies less than a second, however medical alerts have the same priority of WLAN voice traffic. Hence, an urgent medical alert must compete with voice data for the medium access, which does not guarantee the special treatment necessary for the medical alerts.

V. CONCLUSION

This paper presented SANTE, a System for Anticipated identification and Transmission of mEdical alerts on the WBAN/WLAN heterogeneous context. Based on the early prediction of trends about adverse events in patient' health,

SANTE generates medical alerts. SANTE attributes to the medical alerts the highest level of priority, then for the medical alert category it reduces the contention window and AIFS of the 802.11 providing an urgent transmission of medical alerts. Simulation results showed the viability in predicting trends of adverse events over a respiratory dataset. Also, SANTE presents a reduction of 39% in the medical alert transmission delay and of 8% in packet losses. SANTE causes no impact on other traffic, such as voice and video. As future works, we will explore even more the reduction in medium access delay for medical alerts. Summing up, applying the indicators in other types of vital signs in order to adjust them and even reducing the window of critical data used in estimation of themselves.

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