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Impact of optical wireless transmission reliability on ECG signal quality

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Abstract— In this article, we study an optical wireless ECG monitoring system for an elderly person, using an infrared link between a transmitter placed on the wrist and receivers on the ceiling of a room. It is assumed that the person walks across the room so that the transmission channel varies, which impacts the quality of the transmission and the ECG signal. Signal quality indices (SQIs) are a common measure used to assess ECG signal quality, regardless of acquisition and transmission conditions. Our main contribution is to evaluate the evolution of the SQIs, focusing on the spectral characteristics of ECG, as a function of the reliability of the optical transmission channel evaluated using low layer metrics such as the signal to noise ratio (SNR) and outage probability. For this purpose, we develop a transmission chain in simulation in order to evaluate the two metrics during the walking of the person using a channel model including mobility. The results show that it is possible to ensure satisfactory ECG quality even if the received optical signal is strongly affected by channel variation due to mobility.

Keywords— *Electrocardiogram (ECG) Outage Probability, Optical Wireless Communications (OWC), Signal Quality Indexes (SQIs)*

I. INTRODUCTION

Among age-related pathologies, heart failure affects about 20% of people over 75 years old, constituting one of the main causes of hospitalization in elderly [1]. Since the symptoms of heart failure are particularly atypical in the elderly, it is important to be able to monitor the electrical activity of the heart. For this aim, the main examination is the realization of an electrocardiogram (ECG) classically performed by a health professional. Moreover, with the evolution of medical monitoring systems, it is also possible today to use wearable ECG systems based on wireless body sensor networks (WBSN) [2-6]. These systems provide reliable, non-invasive and inexpensive monitoring allowing follow-up at home.

WBSN generally uses communication technologies based on radio frequencies (RF) mostly according to IEEE 802.11 standards such as Bluetooth low energy (BLE), Zigbee, Wi-Fi [7][8]. However, due to a set of challenges such as privacy, security, energy efficiency, spectrum congestion and interference issues, the use of RF technologies can be limited in

the transmission of vital signs such as ECG, which is sensitive to noise and disturbances. In addition, long exposure to RF remains an issue discussed for its health effects [9]. Thus, our motivations in this work came from the need to realize an RF-free wireless system for reliable ECG monitoring of elderly people.

Optical wireless communication (OWC) technologies in the visible, ultraviolet and infrared (IR) bands are not hazardous to health and offer several advantages such as robustness, reliability, simplicity and low cost of deployment without license requirement [10-15]. They are today recognized as an excellent alternative to RF for health monitoring applications and for in body applications and implantable medical devices [16-20]. On the other hand, optical beams can be attenuated due to the person wearing the monitoring device. This poses a challenge for signal quality, especially when the person is in motion. Several OWC-based ECG systems have been investigated in the literature [21-26]. In [21] the use of IR communications is studied for biomedical data including ECG. An experimental demonstration is carried out to verify the efficiency of the system in terms of BER, showing good results. The visible light communication (VLC) performance has been also studied to perform short-range ECG transmission in static scenarios [22-25]. More recently, Optical camera communications (OCC) has been considered for health applications as in [26] where a hybrid OCC/BLE system is proposed to ensure the network efficiency for ECG transmission when patients are moving. All the mentioned literature focused on the optical transmission reliability at physical layer linked to signal to noise ratio (SNR). On the other hand, the ECG signal quality is commonly evaluated at upper layer through signal quality indices (SQIs) [27-30], which can be calculated from different signal features: temporal, spectral, morphological and statistical. To our knowledge, there is no published work neither for RF systems nor for OWC ones, based on the two approaches SNR and SQIs. However, it is paramount to assess the impact of transmission reliability on SQIs, in order to discuss the reliability of ECG for detecting symptoms of heart failure, especially for the elderly.

In this article, our main contribution is to highlight the effect of transmission performance in terms of SNR and outage probability on the quality of the ECG signal evaluated by the

SQIs method during the IR transmission of ECG data of an elderly person. The person is equipped with an ECG sensor and an optical transmitter attached to his wrist. In addition, we consider that the person is randomly walking in a confined environment. In such a context, channel is time varying and thus signal quality also. The objective is to determine the conditions required by the transmission system to obtain an acceptable ECG quality index.

The rest of the article is organized as follows. In the section II, we first study the impact of the optical wireless transmission chain on some ECG signal SQIs in a static configuration in order to determine the link between low layer metric (SNR) and higher ones (SQIs). Then in section III, we describe the studied case that is the ECG monitoring of an elderly person walking within a confined environment and the corresponding OWC channel. The analysis of ECG reliability taking into account mobility and channel time variations is discussed in section IV before conclusion.

II. OPTICAL WIRELESS ECG TRANSMISSION

A. ECG and SQIs

An ECG is a non-invasive technique used to record the electrical activity of the heart. Cardiac electrical signals, due to variations in the concentrations of intra- and extracellular ions, cause the myocardium to contract, and pump blood through the body during each beat. Several normalized leads exist for ECG signal acquisition and the most widely used is the first, from which is defined the reference morphology of a normal ECG signal, as shown in Fig.1 that includes five waves: P Q R S T. The atria of the heart produce the first wave "P" followed by a brief period that characterizes the displacement of the electrical signal to the AtrioVentricular node (AV). The depolarization of the ventricles forms the next wave, which is the "QRS" complex. The "T" wave represents the return of the ventricles to their resting state. Measuring the time intervals of the ECG signal allows the physician to determine how long takes the electrical signal to travel from one place to the next in the heart. In addition, the amplitude of the different waves provides information on the state of each part of the heart and its activity.

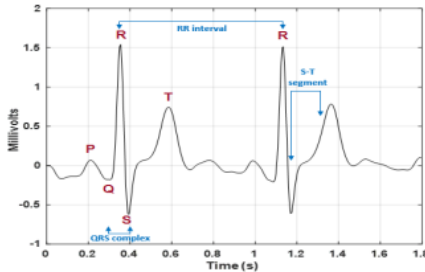


Fig. 1 : Reference morphology of a normal ECG signal

The quality ECG signal is thus important for the diagnosis and can be defined by different SQIs based on different approaches: spectral analysis or statistical/time analysis [27-30]. In this article, in order to illustrate the link between SQI and OWC link quality of service, we simplify the analysis by focusing only on spectral SQIs permitting evaluating two basic characteristics: the QRS wave quality and the low/high frequency noise effects. Thus, we consider two indices: QRS power spectrum distribution (pSQI) and noise relative power in

the ECG spectrum (noiseSQI), defined in the following. QRS wave is concentrated in a wide frequency band of 10 Hz, centered around 10 Hz. Thus, the pSQI is defined as the ratio of the normalized Power Spectral Density (PSD) in QRS band to the PSD in the overall ECG signal, which is approximately between 5 Hz and 40 Hz. It is expressed as:

$$pSQI = \frac{\int_{5Hz}^{15Hz} P(f)df}{\int_{5Hz}^{40Hz} P(f)df} \quad (1)$$

With P is the power of ECG signal.

A low pSQI value means that the ECG signal is contaminated by high-frequency noise such as electromyogram (EMG) interference. However, if the pSQI is very high, contamination by QRS artifacts is probable. Based on published studies [29], the pSQI is defined as:

$$ECG_{analog} \begin{cases} \text{excellent if } pSQI \in [0.5; 0.8] \\ \text{suspicious } pSQI \in [0.4; 0.5] \\ \text{unqualified if } pSQI < 0.4 \text{ or } pSQI > 0.8 \end{cases} \quad (2)$$

To measure the low frequency LF baseline-drift situated within the [0-1Hz] and the high frequency HF perturbations (higher than 40Hz) in respect with the overall ECG spectrum, we compute the noiseSQI defined as:

$$noiseSQI = \frac{1 - \int_{0Hz}^{1Hz} P(f)df}{\int_{0Hz}^{40Hz} P(f)df} \quad (3)$$

A noiseSQI value close to 1 indicates a good quality of the ECG signal and no baseline drift is noted. However, a low value of noiseSQI means an abnormal increase of the power in the [0-1Hz] band compared to the power in the [0-40 Hz] band, which can be caused by an unusual shift in the baseline. In addition, by its definition, a noiseSQI value higher than 1 means that the ECG signal is contaminated by high frequency perturbations (higher than 40Hz). According to [29], the noiseSQI is identified as follows:

$$ECG_{analog} = \begin{cases} \text{excellent if } noiseSQI \in [0.95, 1] \\ \text{noisy if others} \end{cases} \quad (4)$$

B. ECG optical wireless transmission chain

A transmission chain is mainly composed of a transmitting device, a transmission channel and a receiving device. The Fig.2 illustrates the general ECG transmission chain using OWC technology we considered. The signal used for simulation chain is an analog-recorded ECG signal of length N recorded during 6 min with a given sampling frequency $F_s=200Hz$ [31]. It is affected by a 60 Hz power-line frequency noise. We thus used a notch filter to remove this artifact from the ECG signal and we digitalized it with 10 bits. Thus, the minimal required data rate to perform real time transmission and analysis is $R_{bmin} = F_s \times n = 2kbits/s$. For this low data rate, we consider a basic On-Off Keying (OOK) emitter with a given average emitted optical power P_t , and assume that inter-symbol interference can be neglected [19]. Thus, the OWC channel is characterized by the DC gain H_0 defined from impulse response $h(t)$ as:

$$H_0 = \int_{-\infty}^{+\infty} h(t)dt \quad (5)$$

The emitted signal $ECG_{emitted}$ undergoes optical channel attenuation (see Fig.2) and the average received power P_R is given by:

$$P_R = P_t \times H_0 \quad (6)$$

Moreover, it is traditionally assumed that noise is an additive white Gaussian noise (AWGN) of variance σ^2 .

At the reception, the noisy and attenuated $ECG_{received}$ is applied to an adaptive threshold decision system. According to threshold Th , the decided digital signal $ECG_{decided}$ is identified as:

$$ECG_{decided} = \begin{cases} 1 & \text{if } ECG_{received} \geq Th \\ 0 & \text{if } ECG_{received} < Th \end{cases} \quad (7)$$

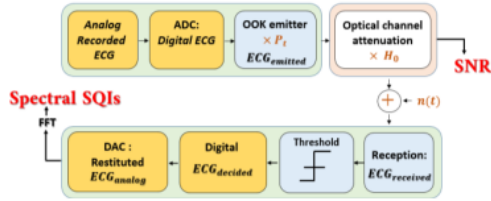


Fig. 2 : General optical wireless ECG transmission chain

Finally, the restituted analog signal ECG_{analog} obtained using Digital-to-Analog Conversion (DAC) is assessed using SQIs method as described previously.

C. Transmission performance and SQIs

For the transmission performance evaluation, we used the classical SNR metric, which is expressed as:

$$SNR = \frac{R^2 P_R^2}{\sigma^2} \quad (8)$$

R represents the optical receiver responsivity set to 1 A/W in the following.

In order to study the link between SQIs and transmission performance, we first consider a configuration where the SNR do not vary during the time of SQI analysis. For this aim, we have varied the emitted power P_t for a given attenuation H_0 and noise variance, considering equiprobable transmission. For each SNR value given by the expression (8), the corresponding SQIs values are computed using expressions (1) and (3). All the results are reported in Fig.3.

We can first observe that when SNR increases, pSQI, resp. noiseSQI tends to a limit value (0.62, resp. 0.95) corresponding to an excellent ECG signal. This floor is reached for a SNR around 9.7dB for both SQIs. In fact, the pSQI is defined as excellent from a value of 0.5, which is reached before, for a SNR value of around 5dB. However, for this SNR value, noiseSQI is not good, so it is important to consider both SQI information to classify the ECG signal as good or not. Therefore, following this observation, we define an adjusted identification criteria as excellent ECG if $pSQI \in [0.62; 0.8]$ and $noiseSQI \in [0.95; 1]$.

Finally, we can conclude from this first analysis that considering a fixed noisy transmission, an SNR of 9.7dB must be ensured in order to obtain excellent SQIs. In the next section,

we extend our analysis to the monitoring of the ECG during the walk of an elderly person. The evaluation of SQIs is generally performed on an entire acquired signal. However, due to walking, the transmission channel varies over time and so does the SQI. Due to the specific signal shape and cardiac frequencies, a minimal window is required to evaluate SQI in order to get several cardiac cycles. In the following, an arbitrary window of 6s is chosen in order to evaluate SQI.

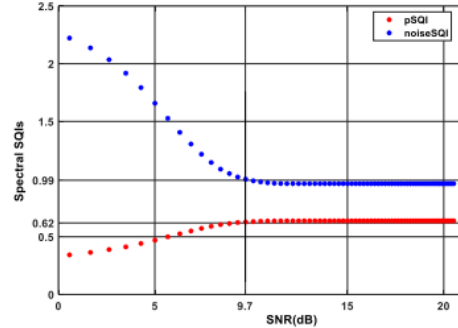


Fig. 3 : SQIs evolution as a function of the SNR for different emitted power

III. CASE STUDY

A. Context and objectives

Fig.4 illustrates the proposed system for the surveillance of the ECG of an elderly person. To model walk monitoring, we exploit the OWC channel model proposed in [32]. We consider that the elderly person is equipped with a wrist-worn device composed of an ECG sensor and its associated electronics formatting data to feed an optical wireless emitter. We consider the same ECG signal as in part II [32], transmitted over the optical channel. At the ceiling, optical receivers collect and decode data. Then, digital-to-analog conversion is applied to obtain a received analog ECG signal from which we compute the high layer metrics, SQIs, to assess the ECG signal quality.

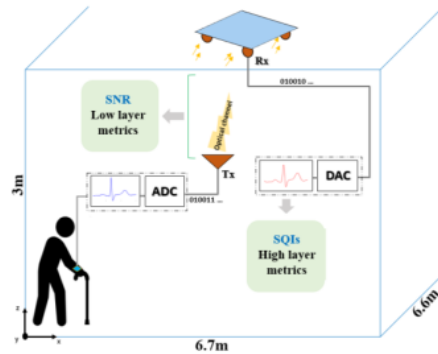


Fig. 4 : Context illustration

B. Environment and channel modeling

The environment considered in [32] is an empty room of dimensions $6.6 \times 6.7 \times 3$ m³ with Lambertian surfaces of reflectivity equal to 0.8. To ensure a good coverage, four receivers are placed at each corner of a central panel with an orientation of 45° from the room ceiling. Each receiver Rx includes a photodiode with a Field Of View (FOV) of 45°, and

a physical surface of 34.5mm^2 . In this configuration, we use a method consisting in processing only the information with the highest SNR (switching combining). During the walk, it is not always possible to ensure a line-of-sight (LOS) link with a receiver. Therefore, Non-LOS (NLOS) contributions due to optical reflections in the environment have to be taken into account for channel modeling. This has been done thanks Monte Carlo ray tracing simulations (MCRT) using dedicated software [33] considering 3 reflections per optical beam. In addition, we use the 3D model of person proposed in [32] as shown in Fig. 5a). It represents an elderly person with the torso leaning forward. The body of the person is considered rather blocking for optical rays with a reflectivity fixed at 0.1. As shown in Fig 5a), the transmitter Tx is placed at the wrist at a position of $(X = 0.22, Y = 0.14, Z = 0.88)$ m and its orientation varies during the walk according to the arm movements. The body mobility model is obtained from the discretization of an elderly person's gait cycle using 3D animation software as in [32]. In addition, it was considered that the elderly person walks at a speed of 0.5m/s with a step length of 20 cm .

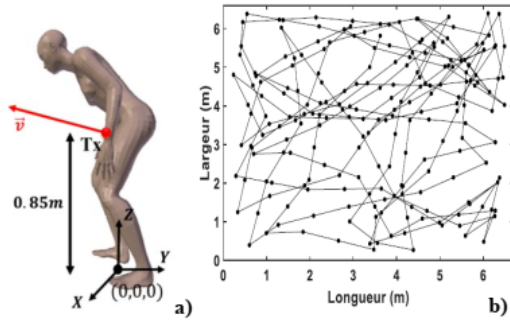


Fig. 5. a) Elderly person body, b) illustration of the person's travel trajectory using the RW mobility model [32]

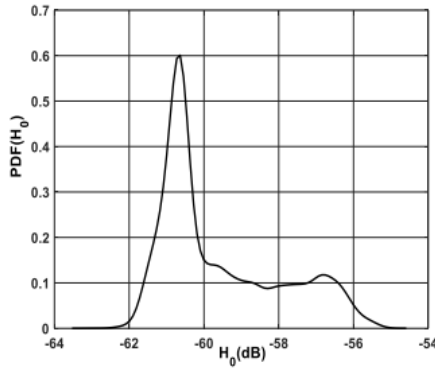


Fig. 6 : H_0 distribution

Moreover, a random walk model is used to describe the walking trajectory, with a constant travel time T_{step} of 0.4s corresponding to the step length and the walking speed of the elderly person. Fig. 5b) illustrates the trajectory described in [32].

Thanks to MCRT simulations, 1000 impulse responses resulting from all movements are obtained, corresponding to the different Tx positions and orientations inside the room during a trajectory of around 6 min . The distribution of H_0 is then obtained, shown in Fig.6 for a Tx half-power angle $\phi_{\frac{1}{2}}$ equal to 45° .

C. Impact of channel behavior on ECG transmission

In order to illustrate clearly the signal, we have plotted in Fig.7. signal evolution over a duration of 12s , which corresponds to $30 H_0$ values considering the walk speed and step length. By using the ECG transmission chain described in II.B, the original analog ECG signal is plotted in Fig.7.a). The received signal $ECG_{received}$ with a P_t of 1mW at a R_b of 5kbits/s , obtained after transmission through the channel is reported in Fig.7.b). Finally, the recovered analog ECG signal ECG_{analog} is plotted in Fig.7.c).

We can observe that according to the H_0 value, the ECG signal is either correctly restored or degraded so that the different ECG waves and time intervals cannot be identified. For example, at the beginning of the transmission and between 9 and 11s the signal is strongly affected. This corresponds to a huge channel attenuation during an interval higher than the cardiac cycle due to slow channel variation in this part of the trajectory. However, the channel can be fast varying depending on the trajectory, so it is possible that a strong attenuation does not last long. In this case, the ECG signal can be recovered, as illustrated around 4.5s as shown in Fig. 7c). This illustrates the fact that taking into account the variations of the channel in the studied context, it is possible to receive a correct ECG signal even if the attenuation is significant, provided that it is over a short duration.

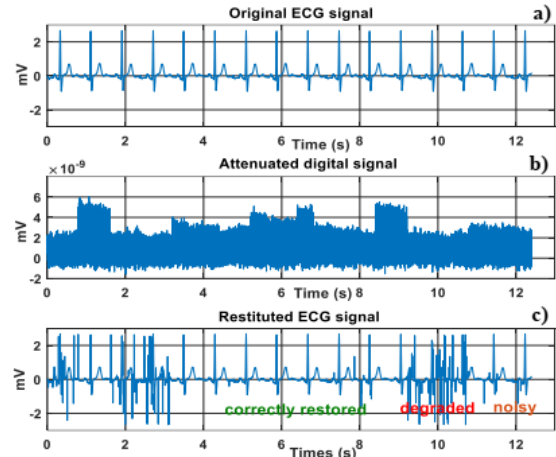


Fig. 7 : ECG transmission: a) Original ECG signal, b) Attenuated ECG signal, c) Restituted ECG signal

Although based on knowledge of the morphology of the ECG signal, these observations can provide a first analysis, but they do not have the precision required for clinical use.

In order to improve the analysis, we compare in the following section the analysis of the SNR and the SQI and observe the evolution of the two metrics during the walking of the elderly person.

IV. ANALYSIS

A. SNR and SQIs statistical distribution

We consider a transmission periodicity of $T_{step} = 0.4s$, i.e. data is sent at each position with a data rate of 2kbits/s. According to expressions (1) and (3), the spectral SQIs are evaluated over a global frequency band of [0Hz - 40Hz] and as described in part II.C. SQIs are computed over 6s duration windows in order to get entire cardiac cycles. In this approach, we considered successive and non-overlapped sliding windows covering a trajectory of around 6 min. Due to transmission periodicity, several H_0 thus several SNR values are experimented over the 6s window used for SQI calculation. This means that we cannot directly use results from Fig.3. Thus, to analyze signal quality as a function of channel variations, we develop a statistical approach. Therefore, we overlaid and reported in Fig.8, SNR and SQIs statistical distributions using the probability density function (PDF) for two P_t values: 1mW and 1.4mW.

Note that $P_t = 1.4mW$ corresponds by using (8) to the target SNR evaluated previously i.e. $SNR_0=9.7dB$.

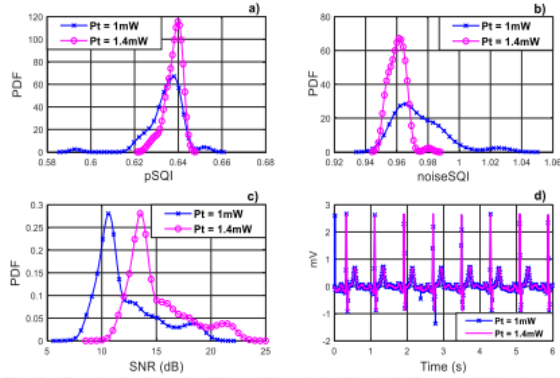


Fig. 8 : Results for $P_t = 1mW$ and $P_t = 1.4mW$: a) SQIp probability density function (PDF), b) SQInoise probability density function (PDF), c) SNR probability density function (PDF), d) Temporal ECG signal evolution

As expected, we can see that, in the case of $P_t = 1.4mW$ pSQI and noiseSQI both entirely satisfy the adjusted criteria as defined in II.C. Visually, a matching good quality of the received signal can be observed in Fig.8.

In the case of $P_t = 1mW$, i.e. a considerable part of SNR lower than SNR_0 (see Fig. 8 c), we can notice that the two SQIs globally respect their thresholds (see Fig. 8 a) and Fig. 8 b). A good morphology of the ECG signal can be observed even if the SNR_0 is not reached (see Fig. 8 d). This can be explained by the rapid variation of the channel due to elderly walking.

To deepen the analysis, we study in the following the conditions required in terms of outage probability i.e. probability that the SNR is lower than SNR_0 , in order to obtain excellent ECG SQIs.

B. SNR and SQIs outage probability P_{out}

To discuss the impact of OWC reliability on ECG signal, we consider the OWC outage probability defined as:

$$P_{out_{SNR}}(SNR_0) = P(SNR < SNR_0) \quad (9)$$

The study focuses on $P_{out_{SNR}}(9.7dB)$ as it corresponds to the target SNR_0 of 9.7dB obtained in II.C to reach SQIs criteria.

We also introduce the probability that obtained SQIs do not respect identification criteria. Therefore, we can define corresponding SQI outage probabilities as:

$$P_{out_{pSQI}} = P(pSQI < 0.62 \text{ or } pSQI > 0.8) \quad (10)$$

$$P_{out_{noiseSQI}} = P(noiseSQI < 0.95 \text{ or } noiseSQI > 1) \quad (11)$$

According to the considered target SNR_0 , we then fix a set of target $P_{out_{SNR}}$ and determine corresponding probabilities $P_{out_{pSQI}}$ and $P_{out_{noiseSQI}}$ using (10) and (11).

All results are reported in Table.I. First, we can observe that the outage probabilities of SQIs gradually increase with respect to the $P_{out_{SNR}}$ reaching 30.3% and 56% for $P_{out_{pSQI}}$ and $P_{out_{noiseSQI}}$ respectively for $P_{out_{SNR}}$ of 50%. At this level, the two SQIs indicate that the ECG signal quality is very bad.

TABLE I. SNR AND SQIS OUTAGE PROBABILITIES

$P_{out_{SNR}}$ (%)	$P_{out_{pSQI}}$ (%)	$P_{out_{noiseSQI}}$ (%)
0.1	0	0
1	0	0
10	3	6
15	3	7.6
20	3	18.2
30	9	31.8
40	22.7	37.9
50	30.3	56

We also can note that $P_{out_{pSQI}}$ reaches lower values faster than the $P_{out_{noiseSQI}}$. This means that the pSQI, which defines the quality of the QRS wave, is less affected by transmission conditions, which is promising for the accurate measurement of the heart rate defined by the RR interval (see Fig.1) and various other cardiac information. Regarding $P_{out_{noiseSQI}}$ evolution, related to low frequency baseline drifting and high frequency transmission attenuation, we can note that even if it is strongly affected for $P_{out_{SNR}}$ higher than 20%, it is null for $P_{out_{SNR}}$ lower than 1%, as $P_{out_{pSQI}}$ is. This means that the ECG signal is properly restored under these conditions. So, we can deduce that, with channel variations due to the studied mobility scenario, a sufficient ECG signal quality can be obtained with a reliability defined by $P_{out_{SNR}}$ of 1%.

In this context, we conclude that the two spectral SQIs give complementary information, which requires conducting a joint analysis to accurately assess the quality of the ECG signal.

However, we have analyzed only spectral features of ECG signal, which can be not sufficient in terms of accuracy for more challenging conditions implying for example other type of noise or interferences due to multiple monitoring or ECG specificities related to the patient such as heart rate variations or particular pathologies.

V. CONCLUSION

In this work, we investigated the quality of optical wireless ECG monitoring of elderly people. The scenario studied consisted of establishing an IR uplink between an ECG sensor worn on the wrist of a moving elderly person and four receivers placed at each corner of a panel in the center of a room.

Taking into account walking and random movements our objective was to study the impact of optical transmission performance on ECG signal quality indices.

For this aim, we have first determined the conditions on the SNR for a static optical wireless channel considering OOK modulation. We have pointed out that for SNR greater than 9.7dB, the two spectral SQIs allowing evaluation of QRS wave quality and baseline drifting reached the criteria of excellence.

Then, by considering the time-varying channel related to walking of elderly people, it was deduced that it is possible to correctly receive the ECG signal even if the channel attenuation induces a lower SNR but under the condition that the channel variations are fast. This conclusion led us to deepen the analysis in terms of reliability by comparing the outage probabilities of SNR and SQIs. We have thus verified that sufficient ECG signal quality is ensured at 1% of $P_{out,SNR}$. These are promising results regarding the mobility challenge.

In future work, these analyses could be improved by considering more ECG features to guarantee an accurate ECG quality assessment and efficient classification in more challenging scenario.

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