Optical wireless connected objects for healthcare

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In this Letter the authors explore the communication capabilities of optical wireless technology for a wearable device dedicated to healthcare application. In an indoor environment sensible to electromagnetic perturbations such as a hospital, the use of optical wireless links can permit reducing the amount of radio frequencies in the patient environment. Moreover, this technology presents the advantage to be secure, low-cost and easy to deploy. On the basis of commercially available components, a custom-made wearable device is presented, which allows optical wireless transmission of accelerometer data in the context of physical activity supervision of post-stroke patients in hospital. Considering patient mobility, the experimental performance is established in terms of packet loss as a function of the number of receivers fixed to the ceiling. The results permit to conclude that optical wireless links can be used to perform such mobile remote monitoring applications. Moreover, based on the measurements obtained with one receiver, it is possible to theoretically determine the performance according to the number of receivers to be deployed.

1. Introduction: Today, remote monitoring is a classical solution to improve healthcare and medical services. In particular, it aids patient safety by a continuous observation of the health status. When patient mobility is essential, one major issue is to develop monitoring systems with mobile and wireless communication capabilities. This involves the use of wearable sensor devices usually interconnected through short-range wireless technologies.

The standards are based on radio-frequency (RF) technologies that present some drawbacks in a sensitive environment such as hospitals because of the electromagnetic interference on medical equipment [1]. As the market for connected health objects is currently experiencing exponential growth, the impact of interference can be a significant problem, inducing limitations on such devices. Besides, the question of the prospective health effects of RF signals in particular from long exposure impact is still open [2]. So, when the electromagnetic interference is critical, an alternative method relies on using optical wireless technology-based systems.

For around 50 years, optical wireless communications have been investigated for different applications including short-range indoor links or outdoor intra-building and inter-satellite uses [3–8]. The potentialities of using optical wireless communications in the infrared range for healthcare monitoring have already been investigated from a theoretical point of view [9–11]. Indeed, using optical wireless links permits reducing the amount of RF effects in the patient vicinity and ensures that there is no interference with existing RF and electronic equipment. In addition, optical wireless-based systems are free of license, compact, low cost and have a great level of security because light cannot pass through walls.

In this Letter, we experimentally study the feasibility of a wearable device designed to transmit healthcare data to base stations fixed in the environment, using non-directed optical wireless links. The main challenge is that the system is worn by a patient moving in an indoor environment.

For this Letter, we consider an accelerometer device that constitutes one simple solution to assess the physical activity (PA) level. Such a device is of major concern for post-stroke patients in hospitals during the rehabilitation phase [12, 13]. Rehabilitation is a system of care involving multidisciplinary staff in hospital; thereby this is generally a complex and costly process. Given the ageing population and hence the expected increase in the number of stroke patients, there is thus a challenge to make the rehabilitation system more efficient in order to control health costs. Moreover, has

been well known for many years that PA can provide benefits for post-stroke patients [14, 15]. Thus, using wearable or body-fixed motion sensors such as accelerometers can contribute to accelerate recovery, thereby reducing hospitalisation time and costs by helping with providing personalised PA programmes in hospital.

In this context, our main contribution consists in evaluating the optical wireless technology reliability for accelerometer data monitoring considering patient mobility within an indoor environment. The study is realised both experimentally and theoretically as a function of the number of optical receivers deployed on the ceiling.

This Letter is organised as follows: in Section 2 we describe the wearable system, the associated optical wireless transceivers and the test environment. Section 3 reports the experimental transmission performance as a function of the number of receivers fixed on the ceiling and the results are discussed. The optical wireless theoretical study is developed in Section 4 to validate the experimental results before concluding in Section 5.

2. System description: The wearable device is composed of a triaxial accelerometer (MMA7631LC) integrated in a unit attached on the patient arm (Fig. 1).

This unit is composed of a microcontroller based on Atmega328, a battery pack (9 V) and an electronic LED driver. The optical

Fig. 1 Accelerometer-based system

Fig. 2 Experimental indoor environment

source is a high-power infrared diode (TSAL5100) emitting around 940 nm, having a half-power angle of 10° and generating a maximal optical intensity of 130 mW/sr.

The patient is moving in a room of dimension (6.6 m $\times$ 6.7 m $\times$ 3 m) as shown in Fig. 2. Black areas in the figure correspond to elements of the furniture.

Four receivers numbered from 1 to 4 in Fig. 2 are fixed on the ceiling. They are all powered by Ethernet modules and connected to a switch transmitting the received data to a remote computer connected to a standard RJ45 which analyses the received data.

Each receiver consists of an infrared module composed of a photodetector and preamplifier (TSOP34338) with a large field of view (FOV) of 45° and a minimal irradiance of 0.1 mW/m². Each of the receivers is fixed on the ceiling and oriented towards the floor.

Moreover, there exists a constraint on the emission due to receiver module features. Actually, as the TSOP34338 is working with a carrier frequency of 38 kHz and detects frames with a minimum of six cycles per burst, this means that data must be emitted with a subcarrier of 38 kHz and a maximal data rate of $38/6 = 6.33$ kbps in order to have at least six cycles per burst.

The emission is thus done using the pulse width modulation (PWM) output of the Atmega328 with a frequency of 38 kHz and data are emitted with the RS232 protocol. The highest data rate available with the RS232 protocol under 6.33 kbps is 4.8 kbps so this is the chosen data rate. Thus, logical operation is realised before optical transmission thanks to the additional electronic circuit. It combines the data at a rate of 4.8 kbps and the PWM 38 kHz output in order to emit on-off keying (OOK) modulated data.

In addition, data are transmitted following a scheme represented in Fig. 3. We have considered a frame delimiter, a patient identifier (four digits: $P_3P_2P_1P_0$), a verification code obtained by summation of information data (nine digits: $V_8V_7V_6V_5V_4V_3V_2V_1V_0$) and a measure increment (three digits: $I_2I_1I_0$) to identify the information once it is received from different receivers. The verification data and the redundant transmission of the patient identifier are two

different ways to check the integrity of the data. The accelerometer raw data from the 10 bit analogue to digital converter are included in $N_d = 6$ bytes.

So, this scheme leads to packet duration T_p of 10 bytes, that is 80 bits at 4.8 kbps that is around 16.7 ms. In addition, data are transmitted every 0.1 s so that the ratio T_p/T is around 16.7%, where T is the transmission periodicity. This value permits determining the maximal forward current through the photodiode (300 mA) from the TSAL5100 datasheet.

3. Experimental results: To evaluate the transmission reliability of the wearable accelerometer, we have measured the percentage of packet lost during mobile transmission within the room presented in Fig. 2. This has been performed considering different configurations at the reception side. Actually, as all the receivers are connected to a switch we have investigated four scenarios:

- In the first scenario, we analyse the data received considering that there is only one receiver in the room that is receiver #1.
- In the second scenario, two receivers are involved: receivers #1 and #3 or receivers #2 and #4.
- The third scenario corresponds to the case where three receivers are active: receivers #1, #2 and #3.
- Finally, the four receivers are considered in the last scenario.

Several measurements have been performed with different persons equipped with the device and different conditions of lighting from solar lights to neon lights at the room's ceiling. Moreover, during the test, persons moved regularly throughout the environment.

The measurements were carried out over a period of 30 min in order to detect at least 20 packet losses which are necessary to have reliable results. A packet can be lost for two reasons: the signal is not received or it is poorly received. The signal is not received if its amplitude is too low to be detected by the photodetector. A packet is poorly received when it contains an error so the receiver rejects it. An error is detected as soon as the redundant patient identifier or the verification code is wrong.

As a result, it is obvious that the percentage of packet lost will diminish as the number of considered receivers in the room increase. Actually, the receiver locations permit room coverage.

The experimental values of packet losses averaged from ten measurements in each scenario are reported in Table 1 considering 1–4 active receivers.

As expected, we can see that the performance in terms of packet loss improves when the number of receivers increases. It is enhanced by one decade by comparing the results obtained from 1 to 2 receivers and also from 2 to 3 or 4.

The best performance corresponds to one packet lost per 1000 sent. As the transmission periodicity T is 0.1 s, this means that the loss of one packet would affect the PA assessment during 1/100 s. As the device is used for post-stroke patients who have generally low levels of activity, this result shows that the proposed system is suitable.

In addition, we can point out that if the transmission periodicity T is increased, it would be possible to either improve the performance

Fig. 3 Accelerometer data packet description

Table 1 Experimental results in terms of packet loss

Number of receivers/scenario	Experimental packet loss, %
1/receiver #1	11
2/receivers #1 and #3 or receivers #2 and #4	1.5
3/receivers #1, #2 and #3	0.4
4/receivers #1, #2 #3 and #4	0.1

because of maximal forward current gain or to extend the lifetime of the system.

4. Theoretical analysis: To validate this result we have theoretically studied the performance.

For this purpose, we have first modelled the optical wireless channel behaviour considering only one receiver in the room that is receiver #1 in Fig. 2.

The optical link configuration in our context is a non-directed line of sight (non-directed LOS). In this case, the received optical power consists of the power from the LOS path and the reflected paths over the surface environment. However, as in the case of health monitoring the data rates are low [16], we neglect the temporal dispersion because of optical beam reflections.

Thus, the channel is characterised by the optical gain defined as in [4] by

$$H(0) = \int_{-\infty}^{\infty} h(t) dt \quad (1)$$

where $h(t)$ represents the channel impulse response.

To obtain the optical wireless channel impulse response, an accurate way is to use ray-launching methods. For this purpose, a ray-based simulator is used [17]. It is based on the classical ray-launching technique associated with the Monte Carlo algorithm. To determine $H(0)$ for the transmission between the mobile transmitter and one receiver, we consider three reflections per optical beam. This simulator allows taking into account the positions and the main characteristics of the transmitter and the receiver such as directivity, FOV and surface area of the photodiode. Moreover, it permits modelling the indoor environment and the spectral reflectance properties of the surfaces.

By considering transmitter mobility, the channel static gain $H(0)$ randomly varies due to the random transmitter position.

Thus, to study the optical gain probability density function (pdf), we have performed several simulations to determine $h(t)$ and also $H(0)$ according to the source position. For this aim, we have defined a uniform distribution of emitter positions over a two-dimensional plane in the room, which can correspond to a device worn on the patient arm. The source is supposed to be at a fixed height of 1.5 m from the floor.

In addition, we also make several assumptions:

- the room is considered to be empty,
- indoor material reflection coefficients ρ are set to 0.8,
- the patient's body is neglected,
- the optical source is assumed to be pointing towards the ceiling.

The simulation parameters are reported in Table 2.

Note that, because of the assumptions, the results would be identical considering any other receiver that is #2, #3 or #4.

From the simulations considering a uniform distribution of (x, y) transmitter coordinates in the room, we have plotted in Fig. 4 the pdf of the static gain $H(0)$ values in dB.

Table 2 Simulation parameters

Features and parameters		Value
room	empty surface reflectivity	0.8
transmitter	coordinates $[x \ y \ z]$, m	$[x \ y \ 1.5]$
	directivity	10°
receiver #1	coordinates $[x \ y \ z]$, m	$[4.3 \ 5 \ 3]$
	surface area of the PIN photodiode	34.5 mm^2
	field of view	45°

Fig. 4 PDF of optical gain

As expected, we can remark that there are few cases where the gain reaches its highest values (around -54 dB) corresponding to LOS paths, whereas many of them are from non-directed configurations.

Besides, from $H(0)$ it is possible to determine the average received optical power P_R given by

$$P_R = H(0)P_t \quad (2)$$

where P_t is the average transmitted optical power.

As explained in Section 2, considering the packet duration T_p and the transmission periodicity of $T = 0.1$ s, the maximal forward current of the photodiode is 300 mA. From the TSAL5100 data-sheet, we can obtain the corresponding instantaneous radiant power which is $P = 90$ mW. This corresponds to the power of an emitted optical pulse provided by the logical operation between a 4.8 kbps bit datum and the 38 kbps PWM output.

Assuming an equiprobable number of PWM pulses, this means that the optical power of a '1' bit datum is $P/2$. Thus, for an equiprobable OOK transmission of symbols $\in \{0; 2P_t\}$, the average transmitted optical power P_t to be taken into account in (2) is $P_t = P/4 = 25$ mW.

Note that the average emitted power considering the temporal occupancy of 16.7% is < 4 mW. Then, the signal-to-noise ratio (SNR) can be written as

$$\text{SNR} = \frac{R^2 P_R^2}{R_b N_0} = \frac{2R^2 H(0)^2 P_t^2}{R_b N_0} \quad (3)$$

R_b is the data rate of the optical pulses. As we have seen, because of the PWM output at 38 kHz, the equivalent optical pulse rate is double: $R_b = 76$ kbps.

R is the photodiode responsivity which is equal to 1 at 940 nm for TSOP34338.

N_0 is the noise power spectral density. Considering that shot noise is the dominant one, it can be expressed as [18]

$$N_0 = 2 \cdot q \cdot I_B \quad (4)$$

where q is the electron quantum charge. The DC current I_B is due to the irradiance produced by ambient light sources. Typical average values on PIN photodiodes are of the order of $200 \mu\text{A}$. This corresponds to $N_0 = 6.4 \times 10^{-23}$ W/Hz.

From (3), we can see that considering mobility and one active receiver, the SNR pdf is obtained from the $H(0)$ one previously determined.

Fig. 5 PDF of SNR in dB for 1–4 receivers in the room

In addition, when considering several active receivers, the SNR value at each receiver is compared for a given position of the emitter. Then, the SNR value used is the highest one.

The results obtained are reported in Fig. 5 as a function of the number of receivers considered. We have set $N_0 = 6.4 \times 10^{-23}$ W/Hz, $R_b = 76$ kbps, $R = 1$ and $P_t = 25$ mW.

We can verify that the performance is improved when the number of receivers is >1 . Besides, we remark that the performance for three and four receivers is close. These findings are consistent with the remarks made for experimental results.

Besides, in order to compare theoretical and experimental results, we introduce the probability p that the SNR is lower than a given value of SNR_0 defining the quality of service

$$p = \text{prob}(\text{SNR} \leq \text{SNR}_0) \quad (5)$$

Actually, from the experimental process, a packet loss occurs when the quality of service is not ensured so that the receiver does not detect correctly.

Fig. 6 shows the evolution of p as a function of SNR_0 varying between 0 and 30 dB for the different number of receivers.

First, we can see that whatever the number of the receivers be, p increases with SNR_0 and so the performance degrades.

In addition, if we search the SNR_0 value corresponding to the experimental result obtained with receiver #1 ($p = 11\%$), we can see from Fig. 6 that it is around 8.2 dB.

For this particular SNR_0 value, we have then extracted from the theoretical curves, p values for the cases with two, three and four

Fig. 6 Probability of having an SNR lower than a given value for 1–4 receivers in the room

Table 3 Theoretical results

Number of receivers	Theoretical probability of having $\text{SNR} \leq 8.2$ dB, %	Experimental packet loss, %
2	1.3	1.5
3	0.2	0.4
4	<0.1	0.1

receivers. The results are reported in Table 3 and compared with the experimental ones.

We can see that the theoretical and experimental results are close and follow the same evolution with the number of active receivers.

From the measurements performed with one receiver, it is thus possible to theoretically determine the optimal number and position of the same receivers needed to attempt a given performance.

Despite the simplifications and assumptions, the theoretical model permits to predict the effectiveness of the optical wireless transmission technology for mobile monitoring devices used in an indoor environment.

5. Conclusion: We have presented in this Letter the development of a connected object for accelerometer data monitoring using indoor optical wireless transmission. The context is physical activity assessment of post-stroke patients at a hospital. A wearable device has been made using commercially available components. Experimental evaluation of the optical wireless transmission reliability in terms of packet loss was conducted and showed good performance especially when several receivers are deployed in the environment. This has been validated by the theoretical analysis performed assuming an ideal scenario. We can therefore conclude that it is possible to design portable devices based on optical wireless technology to perform the monitoring of low-speed data. This result is particularly interesting for the field of healthcare because it can realise remote monitoring without the use of potentially disruptive RF technology.

6. Declaration of interests: none declared

7 References

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