Performance of Wireless ECG Monitoring in City Hospital in the Presence of Interference

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***Abstract*—In this paper we present an experimental campaign which shows the interference levels in the ISM band in a typical City Hospital. This first result leaded us to propose a wireless real-time ECG monitoring system which does not use the ISM band. The performance of the proposed hardware solution has been proven in a real situation by means of experimental trials in the emergency ward of a real city hospital.**

I. INTRODUCTION

Despite the clinical demands for realtime ECG monitoring, there is still little feasibility to put ECG apparatuses on patients for a long period of time in order to constantly monitor and analyze their ECG signals. Part of the difficulties lies in the lack of a technology that can be easily worn by a patient. Recent efforts have been made to develop wearable devices for real-time ECG monitoring [1].

Nowadays the wireless devices which make use of the ISM band are very frequent, in particular the frequency interval $B_s = [2.399, 2.485]$GHz. This increasing number of ISM devices, together with the extremely large spread of Wi-Fi devices, can lead to a high level of interference with ECG wireless systems in a typical hospital. ECG vital signs of hospital patients are extremely important to be monitored, often continuously. The radio signal cannot experience a quality degradation or interruption. For these reasons we firstly investigated the interference levels in the ISM band by means of real experiments in a typical city hospital. The results leaded us to design a wireless ECG monitoring system which does not use ISM band for transmitting the signal. The performance of the proposed system has been proven by means of real experiments in the emergency ward of a typical city hospital.

The wireless ECG system, which is described in the following, is based on a IEEE 802.15.4a standard [2]. A body sensor network, which can real-timely reveal the ECG signal and remotely transmit it to the monitor, was worn by a patient moving around in a hospital. A UWB sub-GHz band ($B_u = [249.6, 749.6]$MHz) is used for the transmission, since it revealed lower interference and better propagation coverage [3][4][5]. The experimental measurements consisted in a person moving around in a hospital emergency ward wearing a body sensor network which measured the ECG signal and a TX module which sends the signal to a remote monitor in a fixed position.

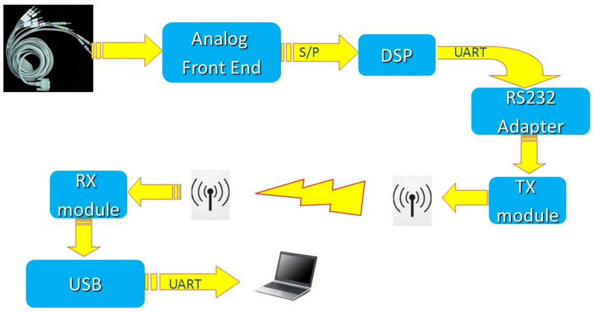

Fig. 1. Scheme of the wireless system which acquires and sends the ECG data.

II. SYSTEM MODEL

The scheme of the wireless ECG system is illustrated in Fig. 1.

The scheme of the analog front end for ECG signal acquisition is shown in Fig. 2, while the DSP for the ECG signal filtering and processing is shown in Fig. 3.

Once the ECG signal is ready to be transmitted, we used the module shown in Fig. 4 for the transmission. This is a transceiver with low cost, low dimension and easy to be integrated. The modulation is a BPM-BPSK, maximum data rate was set to 250 Kbps and the frequency band for the signal transmission is in the interval $[249.6, 749.6]$GHz. The use of this sub-GHz band is motivated by the interference levels measured in the ISM band in the hospital, as shown in the Section III.

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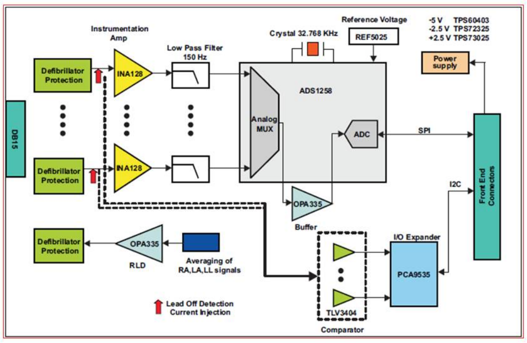


Fig. 2. Scheme of the analog front end.

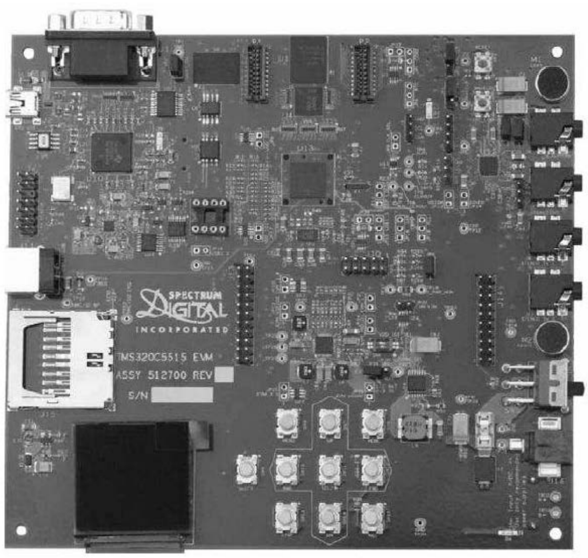


Fig. 3. The DSP TMS320C5515 for the ECG signal filtering and processing.

Fig. 4. Module for the signal transmission.

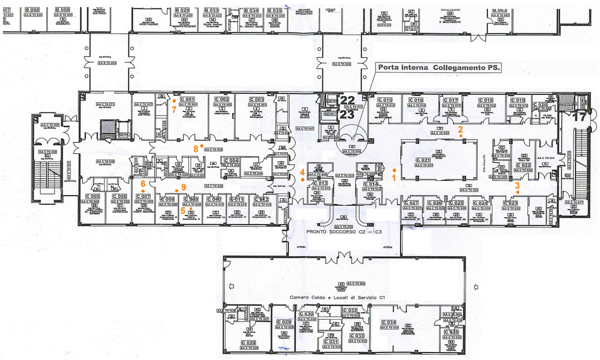


Fig. 5. The planimetry of the emergency ward of the hospital. The numbers show the locations where the interference power is measured.

III. EXPERIMENTAL RESULTS

A. *Experiment no. 1: interference levels in a real city hospital*

The first experiment consist of several measurements of the interference levels sensed in the emergency ward of the Hospital "San Giuseppe" in Empoli, a small town 20 Km west of Florence, Italy. Fig. 5 shows the planimetry of the emergency ward of the hospital where the experiment was conducted. The yellow numbers in the planimetry indicate the locations where the interference power level have been measured. The scanned frequency interval B_s was $2.399 \longmapsto 2.485$ GHz. The frequency band B_s was scanned with a step of 0.5 MHz. The scan time interval was 5 minutes per each location. Each single channel in the B_s band was scanned 1200 times in each location. The power of the interference (IP) sources in each single channel scanned is measured in terms of dBm, collecting 173 samples every 0.5 MHz in each location. For each location of the emergency ward, we report the transmitting interfering sources and the mean and the standard deviation of the samples of the measured interference power for all the channels in the B_s band. We report the measurements of only three significative locations: 2, 7 and 9, from the lowest to highest interference. As it is easy to see, although the mean values of location with less interference such as the no. 2 is almost equal to those with higher interface (no. 7 and 9), the variance can give a measure of the amount of higher level of interface in each location. The hospital has several medical devices which use the B_s band, including a Wi-Fi connection for the patients. In addition, in many locations even the domestic Wi-Fi of the surrounding houses were present.

1) *Location 2:* In Figs. 6 and 7 the mean and the variance of the interference power level measured at location no. 2 are reported, respectively. In Fig. 8 the list of the interfering sources in the B_s band is shown.

2) *Location 7:* In Figs. 9 and 10 the mean and the variance of the interference power level measured at location no. 7 are reported, respectively. In Fig. 11 the list of the interfering sources in the B_s band is shown.

3) *Location 9:* In Figs. 12 and 13 the mean and the variance of the interference power level measured at location no. 9

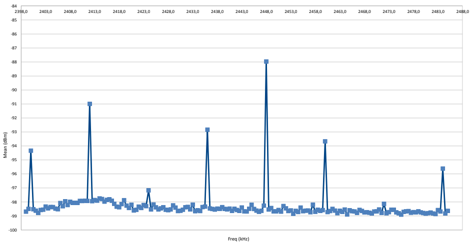


Fig. 6. Mean of the samples of the interference power level (dBm) measured @ location no. 2 in the emergency ward of the hospital for each channel in the $B_s = [2.399, 2.485]$ GHz band with step 0.5 MHz.

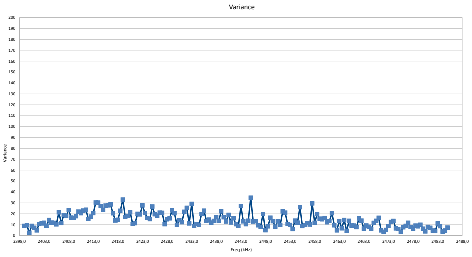
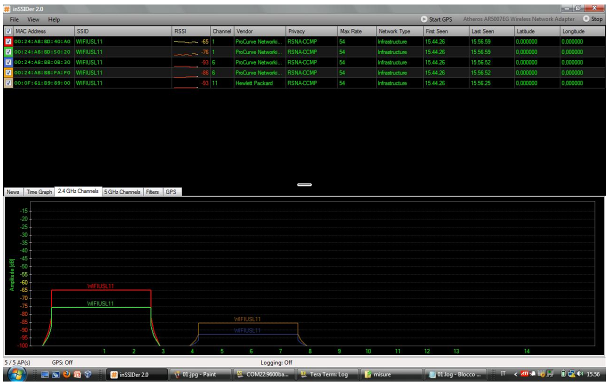


Fig. 7. Variance of the samples of the interference power level (dBm^2) measured @ location no. 2 in the emergency ward of the hospital for each channel in the $B_s = [2.399, 2.485]$GHz band with step 0.5 MHz.



☑	MAC Address	SSID	RSSI	Channel	Vendor	Privacy	Max Rate	Network Type	First Seen	Last Seen	Latitude	Longitude
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☑	00:24:A8:BB:0B:30	WIFIUSL11	-93	6	ProCurve Networki...	RSNA-CCMP	54	Infrastructure	15.44.26	15.56.52	0,000000	0,000000
☑	00:24:A8:BB:FA:F0	WIFIUSL11	-86	6	ProCurve Networki...	RSNA-CCMP	54	Infrastructure	15.44.26	15.56.52	0,000000	0,000000
☑	00:0F:61:B9:89:00	WIFIUSL11	-93	11	Hewlett Packard	RSNA-CCMP	54	Infrastructure	15.44.26	15.56.25	0,000000	0,000000

Fig. 8. Interference sources measured @ location no. 2 in the emergency ward of the hospital for each channel in the $B_s = [2.399, 2.485]$GHz band.

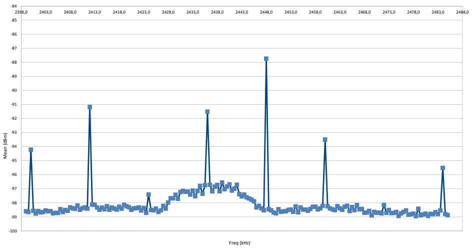


Fig. 9. Mean of the samples of the interference power level (dBm) measured @ location no. 7 in the emergency ward of the hospital for each channel in the $B_s = [2.399, 2.485]$ GHz band with step 0.5 MHz.

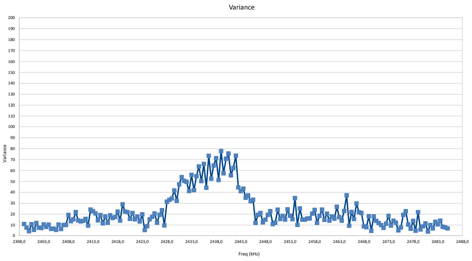
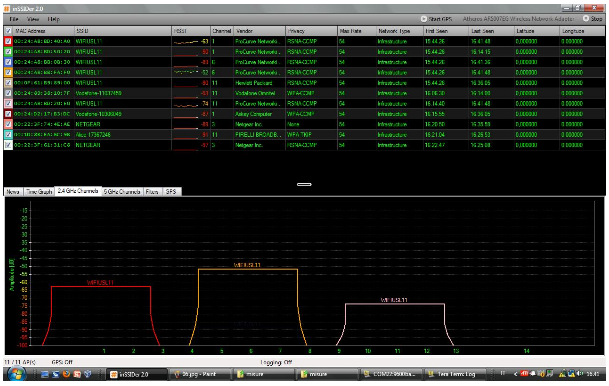


Fig. 10. Variance of the samples of the interference power level (dBm^2) measured @ location no. 7 in the emergency ward of the hospital for each channel in the $B_s = [2.399, 2.485]$GHz band with step 0.5 MHz.



☑	MAC Address	SSID	RSSI	Channel	Vendor	Privacy	Max Rate	Network Type	First Seen	Last Seen	Latitude	Longitude
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☑	00:24:A8:BD:50:20	WIFIUSL11	-90	1	ProCurve Networki...	RSNA-CCMP	54	Infrastructure	15.44.26	16.14.15	0,000000	0,000000
☑	00:24:A8:BB:0B:30	WIFIUSL11	-89	6	ProCurve Networki...	RSNA-CCMP	54	Infrastructure	15.44.26	16.41.36	0,000000	0,000000
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☑	00:0F:61:B9:89:00	WIFIUSL11	-90	11	Hewlett Packard	RSNA-CCMP	54	Infrastructure	15.44.26	16.36.05	0,000000	0,000000
☑	00:24:89:38:10:7F	Vodafone-11037459	-93	11	Vodafone Omnitel ...	WPA-CCMP	54	Infrastructure	16.06.30	16.14.00	0,000000	0,000000
☑	00:24:A8:BD:20:E0	WIFIUSL11	-74	11	ProCurve Networki...	RSNA-CCMP	54	Infrastructure	16.14.40	16.41.48	0,000000	0,000000
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☑	00:22:3F:74:4E:AE	NETGEAR	-89	3	Netgear Inc.	None	54	Infrastructure	16.20.50	16.35.59	0,000000	0,000000
☑	00:1D:8B:EA:6C:9B	Alice-17367246	-91	11	PIRELLI BROADB...	WPA-TKIP	54	Infrastructure	16.21.04	16.26.53	0,000000	0,000000
☑	00:22:3F:61:31:C8	NETGEAR	-97	3	Netgear Inc.	RSNA-CCMP	54	Infrastructure	16.22.47	16.25.08	0,000000	0,000000

Fig. 11. Interference sources measured @ location no. 7 in the emergency ward of the hospital for each channel in the $B_s = [2.399, 2.485]$GHz band.

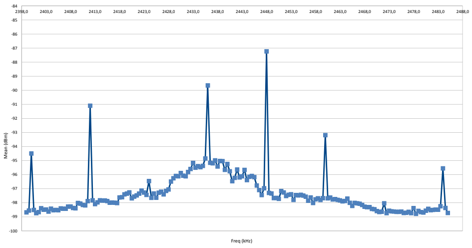


Fig. 12. Mean of the samples of the interference power level (dBm) measured @ location no. 9 in the emergency ward of the hospital for each channel in the $B_s = [2.399, 2.485]$ GHz band with step 0.5 MHz.

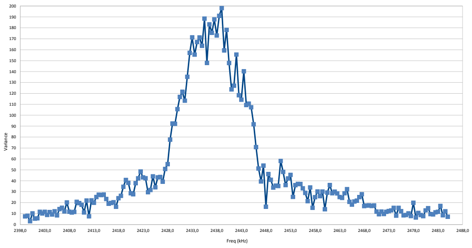
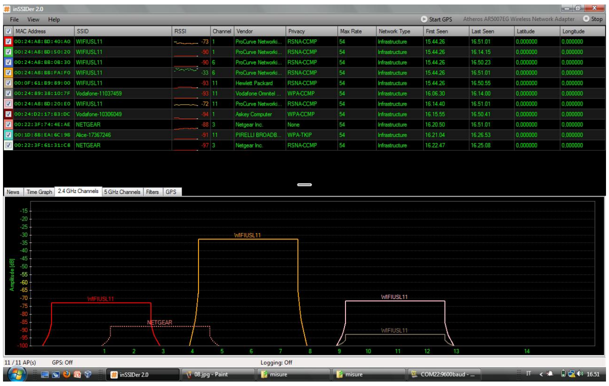


Fig. 13. Variance of the samples of the interference power level (dBm^2) measured @ location no. 9 in the emergency ward of the hospital for each channel in the $B_s = [2.399, 2.485]$GHz band with step 0.5 MHz.



MAC Address	SSID	RSSI	Channel	Vendor	Privacy	Max Rate	Network Type	First Seen	Last Seen	Latitude	Longitude
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00:24:A8:BD:50:20	WIFIUSL11	-90	1	ProCurve Networki...	RSNA-CCMP	54	Infrastructure	15.44.26	16.14.15	0,000000	0,000000
00:24:A8:BB:0B:30	WIFIUSL11	-90	6	ProCurve Networki...	RSNA-CCMP	54	Infrastructure	15.44.26	16.50.23	0,000000	0,000000
00:24:A8:BB:FA:F0	WIFIUSL11	-33	6	ProCurve Networki...	RSNA-CCMP	54	Infrastructure	15.44.26	16.51.01	0,000000	0,000000
00:0F:61:B9:89:00	WIFIUSL11	-93	11	Hewlett Packard	RSNA-CCMP	54	Infrastructure	15.44.26	16.50.55	0,000000	0,000000
00:24:89:38:10:7F	Vodafone-11037459	-93	11	Vodafone Omnitel ...	WPA-CCMP	54	Infrastructure	16.06.30	16.14.00	0,000000	0,000000
00:24:A8:BD:20:E0	WIFIUSL11	-72	11	ProCurve Networki...	RSNA-CCMP	54	Infrastructure	16.14.40	16.51.01	0,000000	0,000000
00:24:D2:17:B3:DC	Vodafone-10306049	-94	1	Askey Computer	WPA-CCMP	54	Infrastructure	16.15.55	16.50.41	0,000000	0,000000
00:22:3F:74:4E:AE	NETGEAR	-88	3	Netgear Inc.	None	54	Infrastructure	16.20.50	16.51.01	0,000000	0,000000
00:1D:8B:EA:6C:9B	Alice-17367246	-91	11	PIRELLI BROADB...	WPA-TKIP	54	Infrastructure	16.21.04	16.26.53	0,000000	0,000000
00:22:3F:61:31:C8	NETGEAR	-97	3	Netgear Inc.	RSNA-CCMP	54	Infrastructure	16.22.47	16.25.08	0,000000	0,000000

Fig. 14. Interference sources measured @ location no. 9 in the emergency ward of the hospital for each channel in the $B_s = [2.399, 2.485]$GHz band.

Fig. 15. ECG received signal.

are reported, respectively. In Fig. 14 the list of the interfering sources in the B_s band is shown.

B. Experiment no. 2: performance of the proposed wireless ECG monitoring system

The second experiment was thought to verify the effectiveness of IEEE802.15.4a transmission of high important data such as ECG. A body sensor network was worn by a person while he was moving around the emergency ward in a hospital. The ECG signal is measured by the body sensors and sent to the receiver (a PC) by a sub-GHz wireless link. An example of received waveform is shown in Fig. 15. The transmission power is set at the maximum admitted by the IEEE802.15.4a standard [6]. Fig. 16 shows the planimetry of the emergency ward of the hospital where the experiment was conducted. The location of the receiver and the locations of the patient are highlighted. In each of the 12 locations (the green points in Fig. 16) the ECG signal was sent for 1 minute to the receiver. Fig. 17 summarizes the results of the 12 tests. Fig. 18 shows the graph of attenuation of the signal versus the distance in the ward. The path loss model which has been used to interpolate the measured data is the following

$$A(d) = \frac{P(d_0)}{P(d)} = 10 \cdot n \cdot \log(d) \tag{1}$$

where $n = 1.6$, $d_0 = 1$m and d is the distance between the receiver and the transmitter.

The behavior of the attenuation reported on the planimetry of the hospital ward is shown in Fig. 19.

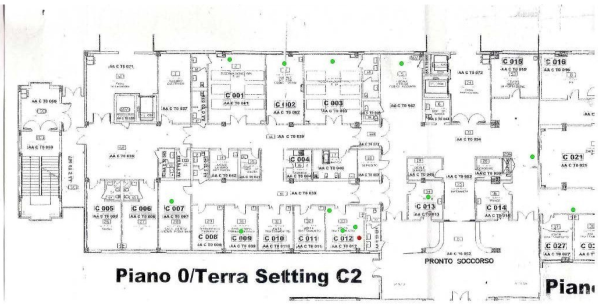
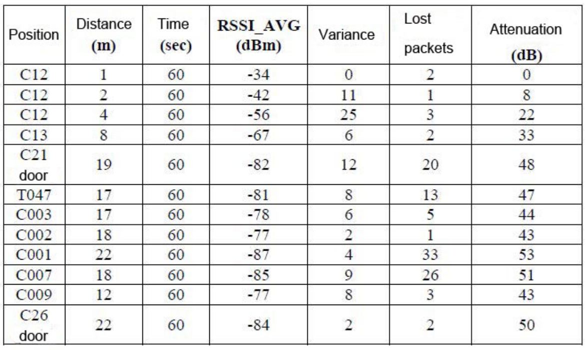


Fig. 16. The planimetry of the emergency ward of the hospital. The red point is where the receiver was located. The green points are where the ECG signal was sent.



Position	Distance (m)	Time (sec)	RSSI_AVG (dBm)	Variance	Lost packets	Attenuation (dB)
C12	1	60	-34	0	2	0
C12	2	60	-42	11	1	8
C12	4	60	-56	25	3	22
C13	8	60	-67	6	2	33
C21 door	19	60	-82	12	20	48
T047	17	60	-81	8	13	47
C003	17	60	-78	6	5	44
C002	18	60	-77	2	1	43
C001	22	60	-87	4	33	53
C007	18	60	-85	9	26	51
C009	12	60	-77	8	3	43
C26 door	22	60	-84	2	2	50

Fig. 17. Summary of the results for the 12 tested locations.

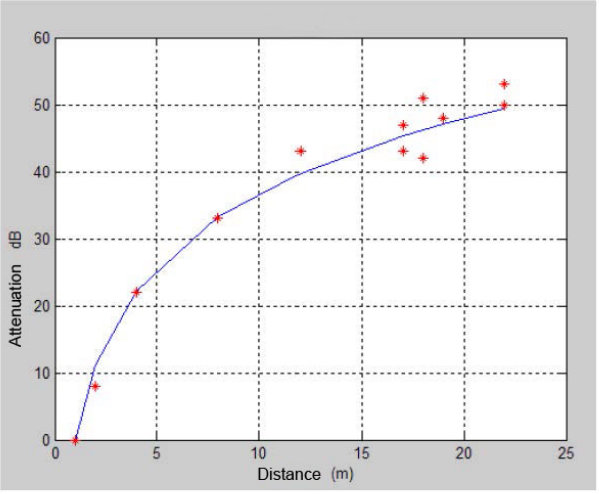


Fig. 18. Path loss model (blue line) and measured path loss (red stars).

The signal quality for the transmission of an important data such as ECG can be maintained only in a range of 18-20 m. An attenuation higher of 47dB makes the received signal quality too low to reconstruct the ECG. In a free-space environment the Rx node is able to receive a power (RSSI) of -83dBm (measured over a time interval of 60 sec) over a distance of 250 m. This comparison (see table 17) can easily prove the amount of attenuation due to multipath and other interference phenomena in a typical hospital ward.

IV. CONCLUSION

The main contribution of the paper is the description of two experimental campaigns: one collecting the typical interference levels in the band $B_s = [2.399, 2.485]$ GHz in a real city hospital, the second collecting the performance of the proposed wireless ECG monitoring wearable system which uses a IEEE802.15.4a sub-GHz transmission. The proposed scheme allows higher penetration and does not experience the high (aggregate) interference level which is indeed present at B_s band in a typical city hospital.

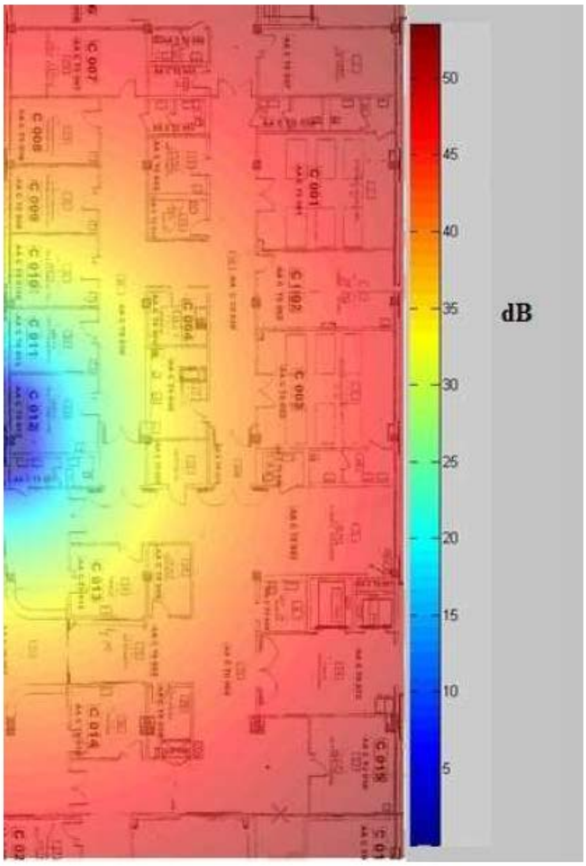


Fig. 19. Attenuation of the received signal in the hospital ward.

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