Indoor Body-to-Body LoRa Link Characterization

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***Abstract*—This contribution examines the performance of LoRa in an indoor, body-centric IoT context. This was achieved by deploying custom-made wearable LoRa nodes, featuring a textile substrate-integrated-waveguide antenna, on the chests of test persons who walked around in a modern office environment, logging the strength of the link between them. Both the influence of the test person's bodies as well as the challenging environment, which includes large masses of reinforced concrete, are investigated. The measured channel characterization data illustrate the excellent performance achieved by combining the building penetration qualities of signals at sub-GHz frequencies and the high link budget of the LoRa modulation standard.**

***Index Terms*—Body-centric communication, Indoor Propagation, LoRa, Substrate Integrated Waveguide, Textile Antenna**

I. Introduction

As wireless sensor networks (WSNs) are being rolled out all over the world, relentlessly expanding the Internet of Things (IoT), a lot of research and development is being carried out to continuously improve the performance of low-power network technologies. At the heart of this new communication technology revolution are emerging industrial standards such as LoRa [1], SigFox [2] and NB-IoT [3]. They enable distributed sensors to operate autonomously for years on end, often communicating over sub-GHz industrial, scientific and medical (ISM) bands. Furthermore, large distances can be covered owing to the excellent propagation characteristics associated with these sub-GHz bands, enabling ever more widespread WSN deployments.

Yet, the potential applications of these technologies are far more diverse than industrial sensor network deployments. By integrating low-power sub-GHz network systems on wearable antennas, off-body communication ranges can be greatly improved, provided that a lower data rate is acceptable. The superior building penetration offered by radio wave propagation at sub-GHz frequencies is also expected to enable these body-worn systems to operate in far more demanding indoor environments than previously deemed possible.

To assess the performance of such a system, a custom-built LoRa node [4] was integrated on a wearable substrate-integrated-waveguide (SIW) antenna [5]. By transmitting very short packets with a low LoRa spreading factor, a decent repetition rate can be achieved to probe channels and characterize off-body wireless links. This contribution presents the characterization of an indoor body-to-body LoRa link, with the focus on determining building penetration behavior.

In the experiments to determine this behavior, two persons equipped with wearable LoRa nodes perform a set of walks in a modern building featuring different construction materials, including large masses of reinforced concrete. The paper is structured as follows. In Section II, the wearable LoRa system, measurement strategy and indoor environment used for these experiments are discussed. Next, the statistics of the recorded signal levels are analyzed to characterize the performance of the body-to-body LoRa link. Finally, in Section IV, a conclusion to this work is formulated

II. Materials and Methods

A. Wearable LoRa system

To probe the indoor channel, two custom-built wearable LoRa nodes are used. These nodes consist of a compact, low-power LoRa system with extended dynamic range for performing channel measurements [4], integrated on a substrate integrated waveguide textile antenna [5]. Each node is powered using a low-profile LiPo battery, which is also integrated on the antenna. The front and back sides of this wearable LoRa system are shown in Fig. 1. A more detailed description of this system is presented in [6].

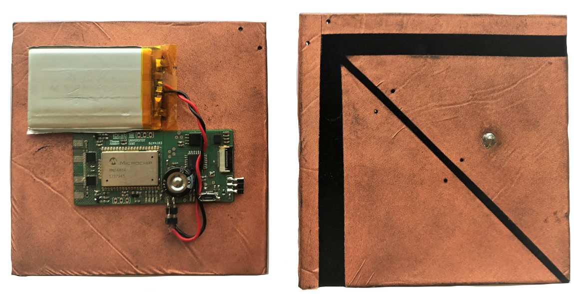

Fig. 1: Front and back sides of the wearable LoRa nodes.

B. Measurement Strategy

To gather an acceptable amount of data points, a high channel probing rate should be used to examine the highly fluctuating indoor channel between two moving nodes. To this end, a LoRa spreading factor (SF) of 7 and a bandwidth of $125\,\mathrm{kHz}$ are used, resulting in a packet transmission rate of 10 packets per second. Unfortunately, relying on a low spreading factor also decreases the overall sensitivity of the system and whilst a LoRa system can receive packets with powers down to $-140\,\mathrm{dBm}$ using a SF of 12, this system rarely receives packets with a power smaller than $-125\,\mathrm{dBm}$. Hence, it should be noted that when a lower data-rate is acceptable, a larger range than what is presented in this work could be achieved by adjusting the LoRa modulation settings.

The dynamic range of the LoRa node is extended by continually probing the channel with different dynamic range settings and combining the data from all datasets. Statistical performance data of the channel under investigation are always based on the measurements gathered when using the most sensitive dynamic range settings. However, to create graphical representations of the received power and calculate average values, packets that saturated the receiver are omitted in favor of those packets that were received with a dynamic range shifted up by using the on-board RF-attenuators, as was thoroughly described in [4]. In all experiments, packets are transmitted with a transmission power of $10\,\mathrm{dBm}$.

C. Indoor environment

The measurements presented in this contribution were gathered in an office environment on the top floors of a large, modern office building in Ghent, Belgium. The floors of this building are very similar and consist of a large concrete core, which is surrounded by a square hallway giving access to a large number of offices, located along the outside of the building. These offices and additionally, two meeting rooms located on the inside of the hallway, are separated by thin, plastered walls, which contrasts with the heavy concrete that makes up the rest of the core of the building. An annotated plan of one of these floors is shown in Fig. 2. Additionally, photo's taken at markers B and D are shown in Fig. 3. As LoRa has already been proven to work fairly well in indoor experiments [7]–[10], this work mainly investigates the influence of the thick floor structures and heavy concrete core of this building, features which are very commonplace in modern high-rise buildings.

In all of the experiments presented in this contribution, two male test persons with an average build each wore one LoRa node on the front of the chest. During most experiments, one of the test persons walked around the concrete core of the building with his LoRa node continually transmitting packets to the receiver which was stationary either in the hallway, at marker A, or in an office, at marker Z, on the bottom right of the building layout on Fig. 2. In a final experiment, the transmitter was stationary on the eleventh floor, inside the stairwell in the center of the building, while the receiver walked down the stairs until the connection was lost. At this point, the receiver turned around and climbed the stairs back up to the eleventh floor.

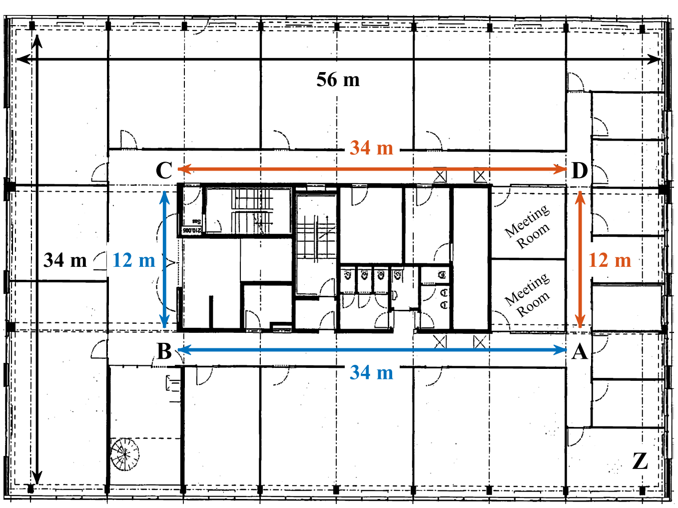

Fig. 2: Annotated layout of the indoor office environment.

Fig. 3: Photo's taken at markers B (top) and D (bottom).

III. Measurement Results and Analysis

A. Nodes on the same office floor

First, a series of walks were performed where both test persons remained on the same floor. As was partly mentioned in the previous section, the transmitter moved through the hallway in different directions while the receiver was either located in the hallway (A), pointing the receiving node towards the transmitter, or located inside the corner office (Z), pointing the receiver away from the hallway. Because of the great similarity between the data gathered in both of these situations, the choice was made to describe those measurements that were gathered in the latter case only by means of their averages, as described in Table I. The sets of measurements corresponding to those situations when the receiver was located in the hallway are shown in Fig. 4. Additionally, these data are represented graphically on the floor plan of the building in Figs. 5 and 6 for those situations when the transmitter walked away from or in the direction of the receiver respectively. To reduce the contribution of small scale fading, averaging is performed by walking all of the the trajectories twice and taking a moving average with a window size corresponding to $4\,\mathrm{m}$.

In the data presented in Fig. 4, the presence of the concrete core of the building is clearly visible. For example, in the CBA data, a sudden increase in signal level is registered around marker B, which is where the link between the nodes is suddenly Line-of-Sight (LoS) as the moving test person turns the corner towards the receiver. A corresponding drop in signal level is not present in the ABC data because these

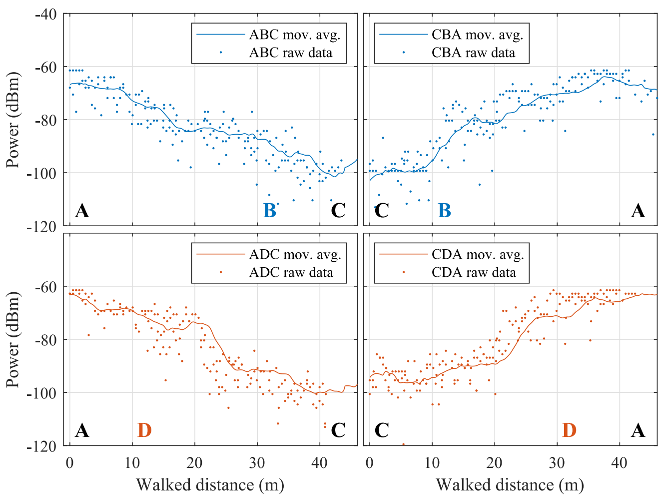

Fig. 4: Power received by the node at marker A when the transmitter walked around the core of the building in different directions. (Mov. avg. = moving average over a window corresponding to 4 m.)

TABLE I: Means of the average power differences (in dB) between the 11th floor trajectories and both receiver locations, expressed as the excess power level of the row element w.r.t. the column element.

		RX @ A			
		ABC	ADC	CBA	CDA
RX @ A	ABC				
	ADC	0.69			
	CBA	3.64	2.95		0.63
	CDA	3.01	2.31		

		RX @ Z			
		ABC	ADC	CBA	CDA
RX @ Z	ABC		5.49		
	ADC				
	CBA	6.38	11.86		3.51
	CDA	2.86	8.35		

		RX @ Z			
		ABC	ADC	CBA	CDA
RX @ A	ABC	8.33	13.82	1.96	5.47
	ADC	9.03	14.51	2.65	6.16
	CBA	11.97	17.46	5.60	9.11
	CDA	11.34	16.83	4.96	8.48

data were gathered when moving away from the transmitter. In this situation, communication is mostly dependent on wave reflections, which are still present after turning the corner towards C. In the ADC and CDA data, similar signal level jumps are present. However, these do not occur around marker D, but at a point 8 meters to the left of this marker. This corresponds to the location where the walls of the building's core are made of concrete instead of the plaster that was used to separate the meeting rooms.

When considering the average signal level differences between the walked trajectories (as given in Table I), it can be seen that on average, the body of the walking test person combined with the radiation pattern of the antenna [6] contribute to the attenuation by 2.98 dB for those trajectories where the receiver was stationed at marker A and 7.36 dB for those situations when the receiver was standing in the corner office (Z). In the latter situations, the differences vary widely between 2.86 dB and 11.86 dB. This illustrates that the added complexity of the propagation paths, caused by the additional walls, doors and furniture between the test persons, contributes strongly to these attenuation values.

When comparing the averaged signal levels received at Z to those received at A, an average additional attenuation of 7.04 dB is observed for those trajectories where the transmitter moved towards the receiver (CBA and CDA). For the opposite trajectories (ABC and ADC), this additional attenuation is equal to 11.42 dB. Naturally, these negative contributions to the link budget are caused by the walls and furniture between markers Z and A, in addition to the body of the test person wearing the receiving node (which, as mentioned before, was turned away from the hallway). Furthermore, not having a LoS component in the data gathered at Z also influences these averages. To assess the reliability of the links discussed in this section, packet reception ratio's (PRRs) were also calculated, all of which exceeded 99 %.

Finally, for the LoS sections of the trajectories, path loss exponents can be calculated using the relation

$$PL(d) = PL(d_0) + 10 \cdot n \cdot log_{10}(\frac{d}{d_0}) \quad (1)$$

in which d denotes the distance between the nodes, n describes the path loss exponent and $d_0 = 1\,\text{m}$. These path

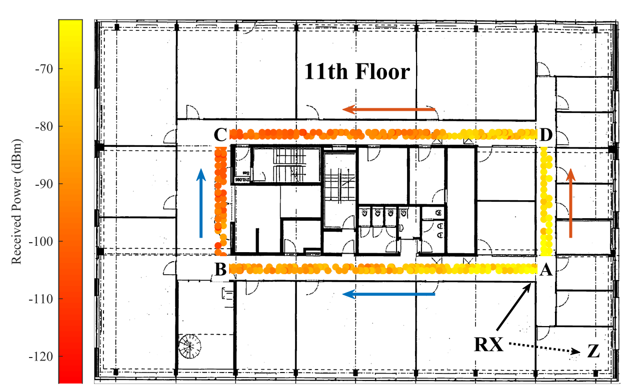

Fig. 5: Power received when moving away from the receiver (A), with both nodes located on the same floor (ABC & ADC).

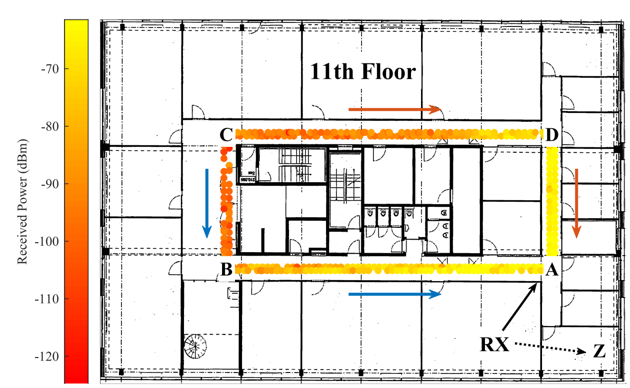

Fig. 6: Power received when moving towards the receiver (A), with both nodes located on the same floor (CBA & CDA).

loss exponents amount to $n = 1.87$ and $n = 0.79$ when approaching the receiver (A) from B and D respectively. The former of these values is more realistic because of the higher number of samples used to obtain it. Nevertheless, both of them are very low, which is testament to the fact that propagation through an empty hallway is subject to a waveguiding effect, which lowers the path loss.

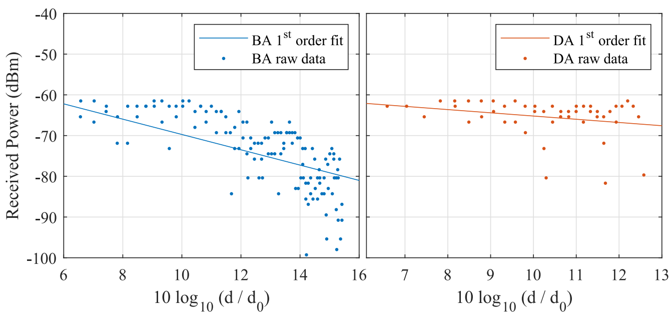

Fig. 7: Path loss data for the LoS trajectories BA and DA.

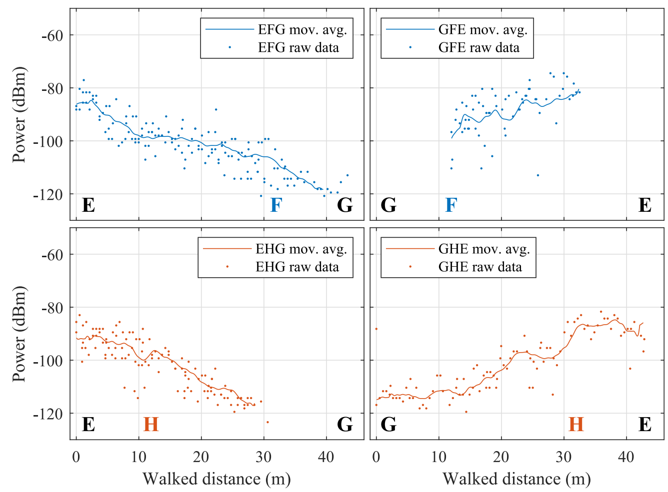

Fig. 9: Power received by the node at marker A when the transmitter walked around the core of the building in different directions, on the floor below. (Mov. avg. = moving average over a window corresponding to $4\,\mathrm{m}$.)

B. Nodes on different office floors

In a second experiment, the walks presented in the previous subsection were performed again, but this time with the transmitter walking on the floor below the one where the receiver was stationed. These data are presented in the same way as those of the previous experiments in Figs. 9, 8 and 10 and Table III.

TABLE II: PRRs for links between nodes on different floors.

	PRR (%)	
	RX = A	RX = Z
EFG	88.8	58.6
EHG	69.4	34.7
GFE	41.3	40.8
GHE	67.2	54.9

In general, it can be seen that the link is lost a lot more frequently now, which is also reflected in the PRRs of these links, presented in Table II. It is also clear that the orientation of the test persons matters more in this experiment, since there is significantly less link budget available to buffer the fluctuations caused by the movement of the test persons. This is most apparent in the average power differences shown in Table III. It should also be mentioned that the influence of the concrete core of the building is less pronounced in these data, as there is no LoS component anymore. In fact, now that all parts of the trajectories are non-line-of-sight (NLoS), the average power level differences between the data gathered when walking towards or away from the receiver are bigger (at $9.48\,\mathrm{dB}$ and $7.90\,\mathrm{dB}$ for receiver locations A and Z respectively). Nevertheless, the difference between having the receiver at A or Z is clearly smaller and this time, having it in the corner office (Z) actually ensures better reception than having it in the hallway (A). This last observation can be explained by considering the radiation patterns of the textile antennas. These roughly radiate in a hemisphere away from the front of the test person's body, thus exhibiting less gain in directions along the coronal plane of the wearer. Consequently, when both test persons are directly below each other, a lower link budget is to be expected.

The average differences between the data gathered when the nodes were on the same floors and those gathered when they

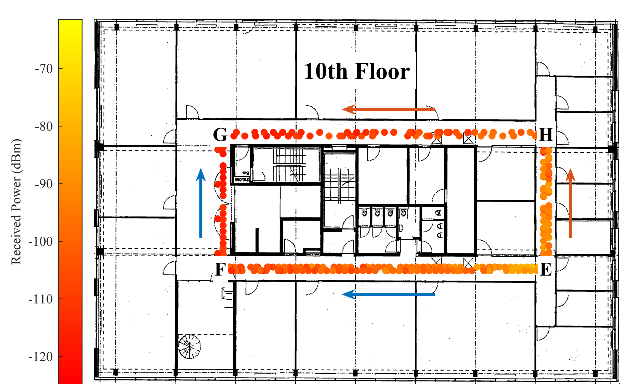

Fig. 8: Power received when moving away from the receiver (A), with both nodes located on different floors (EFG & EHG).

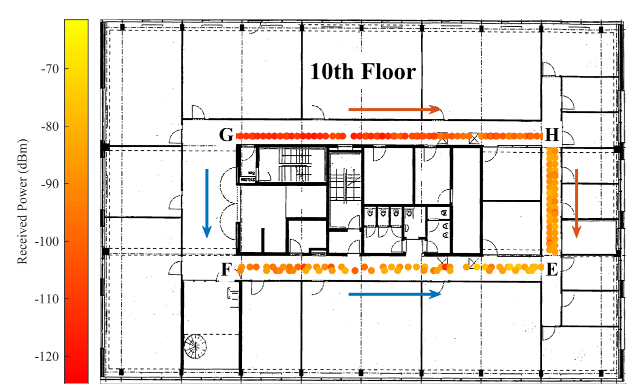

Fig. 10: Power received when moving towards the receiver (A), with both nodes located on different floors (GFE & GHE).

TABLE III: Means of the average power differences (in dB) between the 10th floor trajectories and both receiver locations, expressed as the excess power level of the row element w.r.t. the column element.

		RX @ A			
		EFG	EHG	GFE	GHE
RX @ A	EFG		0.20		
	EHG				
	GFE	10.59	10.90		4.38
	GHE	8.11	8.31		

		RX @ Z			
		EFG	EHG	GFE	GHE
RX @ Z	EFG				
	EHG	0.60			
	GFE	8.04	7.44		
	GHE	8.37	7.76	0.33	

		RX @ Z			
		EFG	EHG	GFE	GHE
RX @ A	EFG	12.65	12.05	4.61	3.13
	EHG	12.34	11.74	4.30	2.93
	GFE	23.24	22.64	15.20	14.87
	GHE	18.86	18.25	10.82	11.24

were on different floors are shown in Table IV. When only considering data gathered using the same walking trajectories, on average, link budget reductions of 16.47 dB and 20.92 dB are observed for receiver locations A and Z respectively. These are directly caused by the structure between both floors. When considering all possible combinations of link trajectories and receiver locations, a more general impact of the floor structure on the performance of the links can be obtained. This yields an average signal level reduction of 18.09 dB when comparing any arbitrary link between nodes on the same floor to one between nodes on different floors.

TABLE IV: Means of the average power differences (in dB) between the 10th and 11th floor trajectories for both receiver locations, expressed as the excess power level of the row element w.r.t. the column element.

		RX @ A			
		EFG	EHG	GFE	GHE
RX @ A	ABC	18.61	18.81	8.77	10.50
	ADC	19.31	19.51	10.24	11.20
	CBA	22.25	22.45	14.24	14.14
	CDA	21.62	21.82	12.09	13.51

		RX @ Z			
		EFG	EHG	GFE	GHE
RX @ Z	ABC	23.51	22.90	15.47	13.41
	ADC	18.28	17.68	10.24	7.93
	CBA	30.72	30.13	22.70	19.79
	CDA	26.44	25.84	18.40	16.28

C. Nodes in stairwell

To evaluate the link between two nodes inside the core of the building, one test person took place in one of the stairwells on the eleventh floor while the other one descended these stairs until the connection was lost. At this point, the second test person turned around and climbed the stairs back up again. The raw and averaged data for these trajectories are presented in Fig. 11. They show an average extra loss of 13.79 dB for each additional floor between the test persons. Note that the average signal level flattens out near the end of the range because packets with a power lower than the sensitivity of the receiving node are not received anymore, skewing the average data at that point. Additionally, some of the direct link power penetrating through the stairs is filtered out by the radiation patterns of the antennas, contributing to link fluctuations in this experiment. Consequently, the estimated average signal loss for each additional floor between the nodes is probably somewhat conservative in this last experiment. However, as both nodes are in the same stairwell, signal reflections definitely increase the average received power as well.

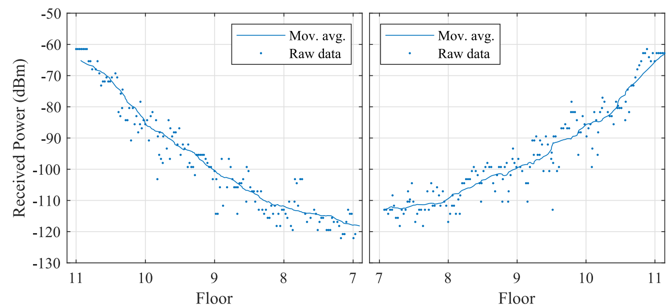

Fig. 11: Power received by the node walking up and down the stairs between the 7th and 11th floors (Mov. avg. = moving average with a window of 30 measurements).

IV. Conclusion

Several LoRa body-to-body link characterization efforts were performed in a modern office environment. They show that even when using a low spreading factor of 7, a near-perfect link can be established when both nodes are moving on the same floor, even when a thick concrete building core separates them. When moving across floors, packet reception ratios start to decline when using this lower spreading factor, because of the lower sensitivity of the node when using these settings. When comparing both cases, it is shown that links across two floors are subject to an additional average loss of 18.06 dB. Additionally, packet reception statistics fluctuate significantly for the different links, which illustrates how indoor propagation is strongly governed by reflections. These may sometimes balance the losses experienced by shadowing of the body of the test persons, which were found to equal 2.98 dB in line-of-sight situations, and 7.36 dB in non-line-of-sight situations. Yet, as can be expected, in other locations, these reflections may just as well degrade the link performance further, resulting in a worst-case average loss of 11.86 dB when compared to a situation without body shadowing. In general, LoRa was found to be an excellent modulation technique for low-power and low data-rate communication in challenging indoor environments, even when using a low spreading factor. Furthermore, its performance could be increased significantly by using higher spreading factors, when a very low data-rate is acceptable.

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