Characterization of Effects of Door Materials to Integrated Radio Radiation Patterns in Locker Unit

Markku Jokinen, Markus Berg, Heikki Karvonen, Marko E. Leinonen, Tuomo Hänninen and Ari Pouttu
Centre for Wireless Communications
University of Oulu
Oulu, Finland
{markku.jokinen, markus.berg, heikki.karvonen, marko.e.leinonen, tuomo.hanninen, ari.pouttu}@oulu.fi

***Abstract*—The current trend of delivering goods is to use lockers located close to the customers. The locker needs to communicate with a delivery system, which is most convenient to achieve with wireless technologies. There are mechanical, industrial design and reliability advantages to place a radio unit inside of the locker. However, it is challenging from a radio communication perspective, especially with conducting door material like metal. In this work, RF radiation performance from inside of the metallic locker with two different door materials was studied. The studied RF frequencies cover operational frequencies of LTE NBIoT, Sigfox, LoRa, Wifi, and 5G NR at 3.5 GHz. The simulations and measurements show that the radiation pattern of the metal door locker resemble radiation pattern of array. The main radiation direction with metal doors can be backside of the locker, while with a wood laminate the primary radiation direction is toward front side of the locker.**

***Index Terms*—antenna pattern, backward radiation, metal locker, radiation intensity, wireless last mile**

I. Introduction

During the web-era, e-commerce has been growing very fast globally in many different domains. In addition to technologies that have been enabling the e-commerce, also the megatrends like circular economy, eco-efficiency, and sharing economy have been boosting need of postal services, need for efficient item handling and delivery systems as well as entirely novel solutions for the delivering goods.

In the next generation communication system such as 6G [1], environmental aspects are one of the fundamental starting points of the design. By using a locker system for the last-mile delivery, carbon dioxide emissions can be reduced up to 50% [2]. A new customer attitude towards usage of locker service compared with a home delivery is needed. The willingness of use is related to distance to the closest service [3], so the remote operation and easy installation of the locker in any location will promote this goal.

Currently, part of delivering goods is realised using the automated locker solutions containing lockers that the recipient could access using a specific PIN code to fetch the item [4]. There are two main types of lockers, traditional locker [5] and robotic locker [6], both have their own advantages. Traditional lockers have own door for every item, this makes it simpler and more cost efficient. Robotic lockers, on the other hand, have advantage in resource allocation, because there is no need for a dedicated box for an individual item. Both of the these locker solutions rely on external power source and fixed internet connection.

A battery operation and the wireless connectivity make the locker unit more convenient to install in any location since there is no need for agreeing electricity or internet connection costs with shop or apartment building owners. In this paper, we will focus on measuring radiation characteristics of different radio technologies, i.e., different frequency bands, which can be used for communication purposes of the locker.

Wireless communication from the locker to the back-end network can be established though users' mobile devices, when the communication from the lock is implemented with Bluetooth [7]. Another option is to communicate directly from a lock, or through a dedicated gateway, with the back-end network. In the case of direct communication, the communication method can be some of the wireless internet of things (IoT) technology like Sigfox [8] or LoRa [9]. A system of this kind have quite low data rate demand, and the efficiency of communication is more essential aspect. Efficiency of communication converts to high battery life or self-sufficiency in energy when energy harvesting methods are used.

Usually, locker units have external keypads for customers to operate when opening the door. With current technology, this is not mandatory since the door opening can be made possible with a user's smart device, like a mobile phone application. Keypad-less design makes it easier to design a locker to be resilient against weather conditions, brake-ins and other mechanical misuse. Also, the cost of the locker unit can be reduced by making it as simple as possible, this is important since the amount of locker units will be increasing in the upcoming years.

The communication part of the lock is located inside of the locker unit in a keypad-less design. In this case, the material of the door has a significant impact on the radiation efficiency of the radio. In this work, we investigate two different door materials, wood laminate, and metal. We compare the effect of door material on radiation power, which comes out from the locker unit.

The rest of the paper is organised as follows. First, simulation model and results are presented in Chapter II. In Chapter III, measurement setup is presented, followed by measurement results in Chapter IV. Finally, conclusions are made in Chapter V.

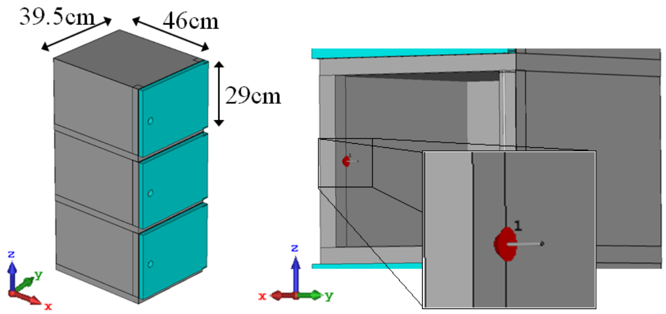


Fig. 1: Simulation model dimensions and antenna location.

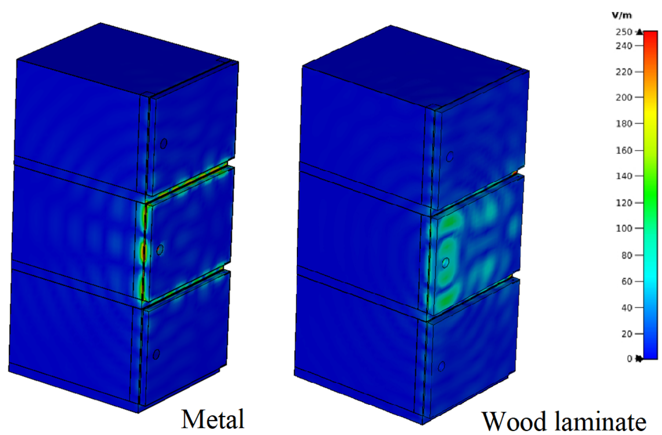


Fig. 2: Simulated electric field distributions at 2.45 GHz.

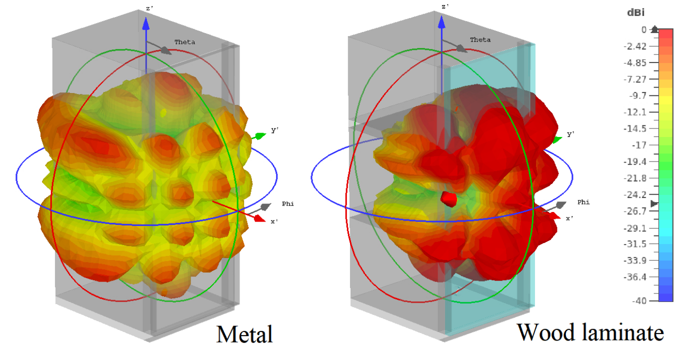
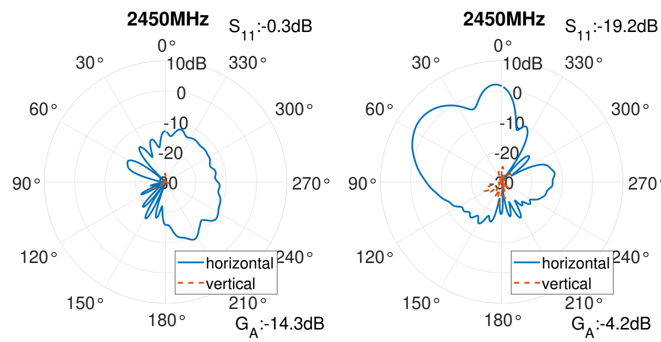


Fig. 3: Simulated 3D radiation pattern of two door materials.



(a) (b)

Fig. 4: Simulated xy-plane cut of the radiation pattern with two door materials: metal (a) and wood laminate (b).

II. Electromagnetic Simulation Model and Simulation Results

An electromagnetic (EM) simulation model was created to better understand radiation mechanisms around the locker. CST Studio Suite, EM field simulation software, was used to create and simulate the model. EM simulations were performed to model electric field distributions and far-field radiation pattern results at 2.45 GHz center frequency. The dimensions of the measured and the modeled locker unit are presented in Fig. 1. The 1/4 wavelength monopole antenna inside of the locker is also shown in Fig. 1, the antenna uses the locker frame as a ground plane. The cap between the door and the frame was measured to be 4 - 5 mm, and in the simulations, a 5 mm gap was used.

Simulated electric field distributions are presented in Fig. 2. In a metal door simulation, fields escape from the cap between door and the locker frame, creating standing waves in the gap, which creates antenna array like radiation outside of the locker unit. Radiation does not penetrate the metallic door, and the surface currents travel along the sidewall of the locker, which creates a radiation pattern to the side and back of the locker. With the wood laminate door, radiation can penetrate the door, and the metallic frame is mostly affecting the radiation pattern of the unit. The laminate door, however, attenuates the radiation intensity.

Simulated far-field radiation patterns are presented in Fig. 3. A strong interference pattern with the metal door is visible in the Fig. 3, where multiple maximums and nulls are observed. Radiation intensity is higher in the direction of the locker door with a laminate door, so the metallic frame directs and shapes the radiation pattern significantly. The xy-plane cut of the radiation pattern is presented in Fig. 4, where the locker door is pointing in the direction of Phi $= 0°$. The maximum radiation is directed towards the backside of the locker with a metal door, which correlates well with the measured radiation patterns. Radiation towards the backside of the locker is considerably lower in the case of the laminate door. Further, the maximum radiation is observed for elevation angles $\pm 30°$ from the horizontal xy-plane and is 4 dB and 7 dB higher than the maximum horizontal value for metal and wood laminate doors, respectively.

III. Locker Measurement Setup

A measurement setup to validate simulation results is presented in Fig. 5, where the measured locker unit is placed on a rotating table and rotated from $-180°$ to $180°$ with $1°$ steps. The radiating test antenna was placed inside of the locker unit, and radiated power was measured 3.5 meters away with a reference antenna Satimo SH800 [10]. The SH800 supports a frequency range from 800 MHz to 12 GHz. The received signal level was measured with Hewlett Packard

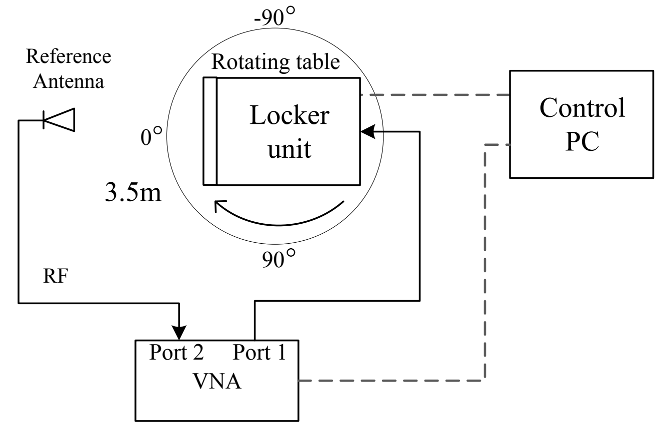


Fig. 5: Radiation pattern measurement setup.

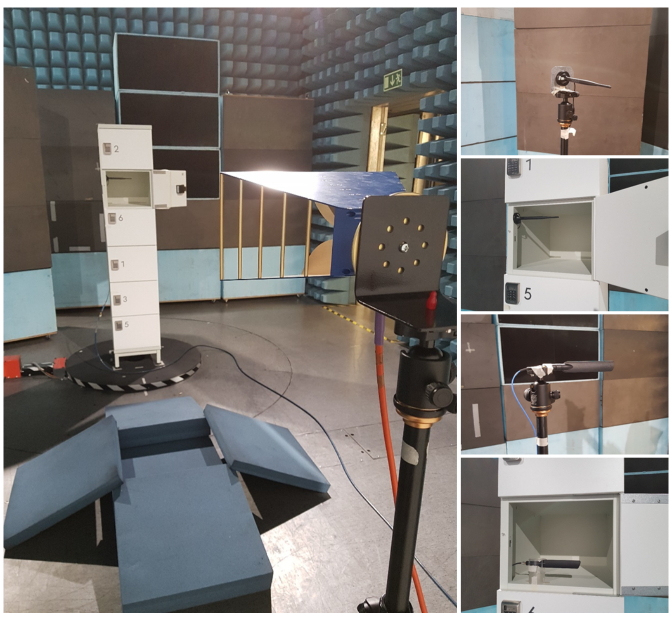


Fig. 6: A photograph of the radiation pattern measurement setup in an anechoic chamber and measured antenna placements.

8720ES network analyzer (VNA) over the frequency range of 800 MHz - 4 GHz (1601 points). This frequency range includes Sigfox [8], LoRa [9], Bluetooth Low Energy (BLE) [7] and 5G NR [11] systems, corresponding to 868 MHz, 2.45 GHz and 3.5 GHz center frequencies, respectively. The whole measurement setup was placed inside the anechoic chamber to reduce other than the direct propagation paths. Measurement cable losses were compensated by calibrating the measurement setup. A photograph of the measurement setup is presented in Fig. 6, where also test antenna placement is presented inside of the locker unit. Antenna placement close to the door was selected since the lock inside of the door will be a feasible place to integrate the radio unit.

Wood laminate and metal door materials were used for measurements. Studied door materials are very different since metal is conducting material, and the radiation does not penetrate easily through it. On the other hand, the wood laminate insulates electrical current, and radiation can penetrate it, but the electromagnetic field is attenuated. The second-highest locker was selected for performing the measurements. Doors above and below the measurement locker door were changed to the same material ones. The effect of a floor reflection was mitigated by selecting the highest possible position were door change was possible. Absorbing blocks were used on the floor to mitigate reflection, and the measurement equipment was behind absorbing blocks so that they do not affect the measurement results.

IV. Radiation Pattern Measurement Results

In radiation pattern measurements Laird Technologies Heptaband (MAF94300) [12] (low frequency antenna) and König CMP-ANT5DBI10 (high frequency antenna) were used. Both measurement antennas performed well on 2.45 GHz frequency, so both antennas were used for measurements on that frequency. First, the reference radiation patterns of both antennas were measured in a free space condition. Then, antennas were placed inside of the locker unit and three different scenarios were measured: the locker door open, the wood laminate door closed, and the metal door closed. Antennas were horizontally placed in all measurements, and antenna positions are shown on the right side of Fig. 6, König on two upper photos and Heptaband on two lower ones.

Radiation pattern measurement results are presented in Table I for the low frequency antenna and in Table II for the high frequency antenna. Horizontal and vertical polarization were measured by rotating the reference measurement antenna 90°. A cross-polarization discrimination of the reference measurement antenna is higher than 45 dB.

The measured horizontal component is stronger due to the antenna orientation, which is clearly visible from results of Tables I and II. The S_{11} reflection coefficient value has been presented on the top corners of the result figures to show potential antenna loading by the metallic locker or by the door material. If metallic object is located nearby the antenna, the antenna matching may be deteriorated and the reflection coefficient is increased. Other parameter presented in the result figures in Tables I and II is a average gain (G_A), which was calculated over two dimensional measurement plane. The G_A can be calculated with following formulas,

$$G_M(f) = 10 \cdot \log_{10}(|S_{21,\phi}|^2 + |S_{21,\theta}|^2) \tag{1}$$

$$G_R(f,\alpha) = G_M(f,\alpha) - G_{sh800}(f) - fsl_{3.5m}(f) \tag{2}$$

$$G_A(f_c) = 10 \cdot \log_{10}\left(\sum_{\alpha=-180^\circ}^{+180^\circ} \frac{10^{\frac{G_R(f_c,\alpha)}{10}}}{N_\alpha}\right) \tag{3}$$

where $S_{21,\phi}$ and $S_{21,\theta}$ are forward gain vectors of two measured polarizations. G_M is total gain measured, G_{sh800} reference antenna gain and fsl is free space loss of 3.5 m distance. Frequency index is presented with f (800 MHz

TABLE I: Radiation pattern measurement results with Laird Technologies Heptaband antenna.

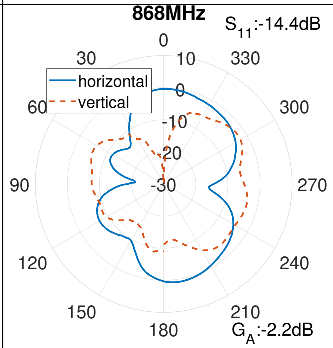
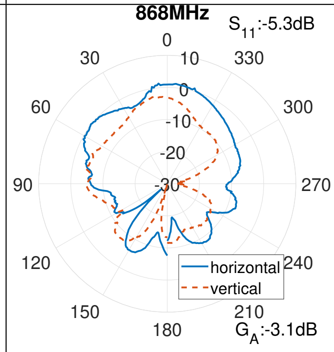
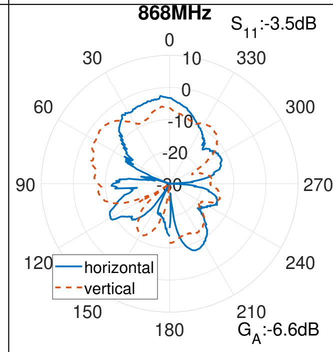
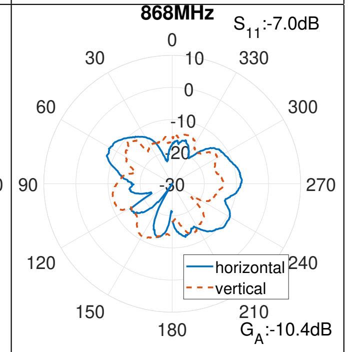
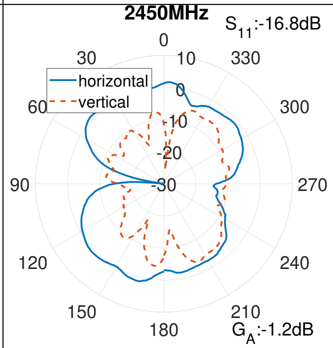
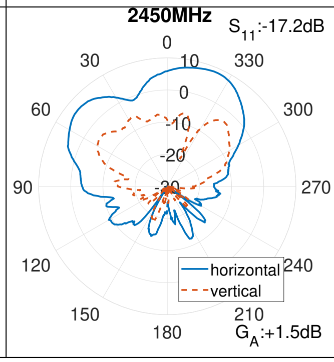
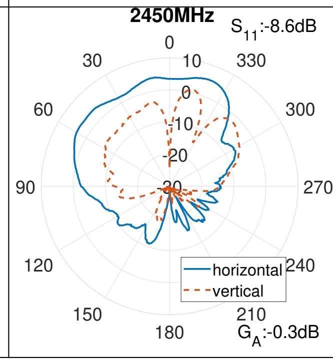
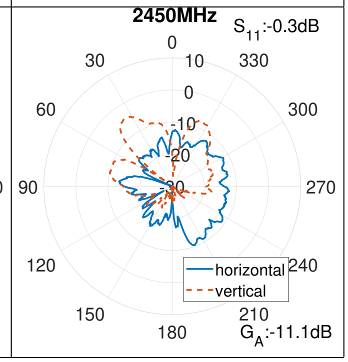
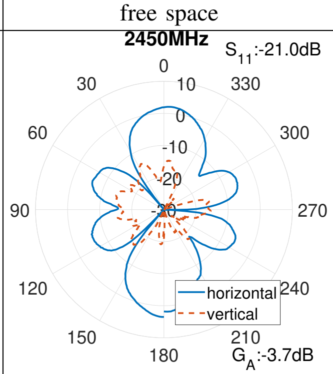
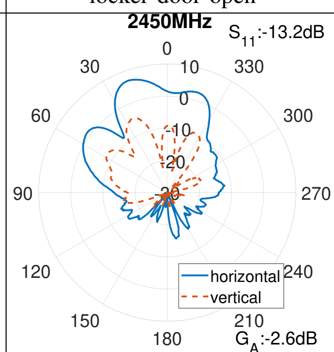
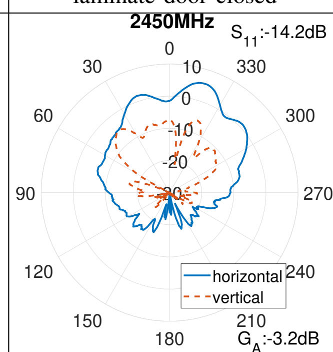
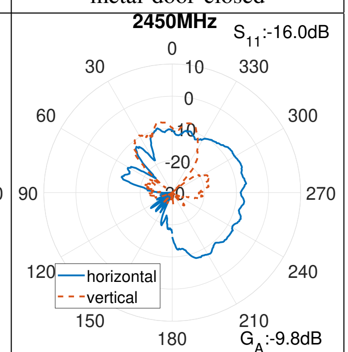
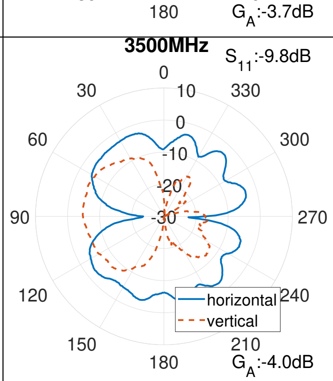
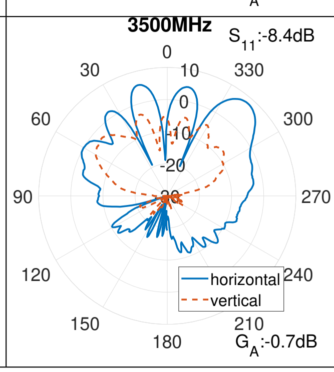
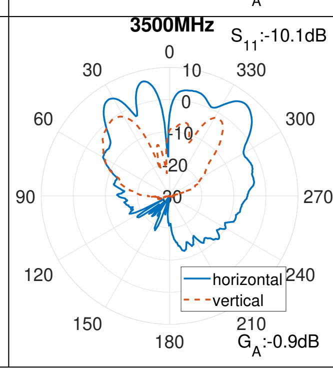
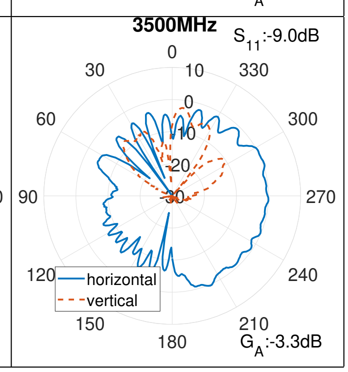
	free space	locker door open	laminate door closed	metal door closed
868MHz				
2450MHz				

TABLE II: Radiation pattern measurement results with König CMP-ANT5DBI10 antenna.

	free space	locker door open	laminate door closed	metal door closed
2450MHz				
3500MHz				

- 4 GHz), measurement angle with α ($-180°$ - $180°$) and number of measured angles $N_\alpha = 361$. Realized gain (G_R), is power radiated in certain direction nearby the locker. Finally, G_A is calculated for the selected frequencies f_c (800 MHz, 2.45 GHz and 3.5 GHz) by calculating average of G_R on linear scale over measured directions α.

The locker door is pointing to $0°$ angle in the measurement results. It can be seen that the metal frame of the locker is directing radiation in the direction of the door when compared with the free space case. In the closed-door measurement case, the wood laminate door is attenuating signal from 0.2 dB to 3.5 dB, but the directivity stays similar like in the open-door measurement case. With the wood laminate door radiation maximum is found on the front side of the locker. The measurement signal does not penetrate the metal door but is radiating out from the locker via gap between the door and the frame. I this case, the signal is attenuated from 2.6 dB to 12.6 dB compared with the open door case. Part of the metal door results show, that the radiation maximum can be found behind of the locker. Back side radiation is almost completely horizontally polarized, which is inline with the simulation result that show surface current on the side wall of the locker. Current along a surface is creating radiation which has polarization perpendicular to the surface, which in this case is horizontally polarized. In the results, higher frequencies can escape from the locker with the metal door better than lower frequencies, since the gap is relatively larger in wavelengths at higher frequencies. The antenna matching of the lower frequency antenna is detuned more when it is placed close to the metal structures, even with the door open. The metal door also has an effect on the antenna tuning and in one case it weakens the signal power significantly. As a summary, the antenna design of the locker unit should be co-designed with a metallic frame of the locker unit to gain the best possible radiation performance.

In the use case where a customer is operating the locker with smart phone, the wood laminate door is a better option, since most of the radiated power is directed towards the door, in which direction usually the user is operating the locker. On the other hand, when a customer is close to the locker lower radiation power is enough to establish communication, hence the metal door is also a feasible option. With metal door radiation is distributed more equally in all directions. This makes wireless communication to IoT or mobile network not so sensitive to the installation direction of the locker.

V. Conclusion

In this paper, the radiation patterns of the antenna inside of the locker were simulated and measured. The wood laminate and metal doors were studied, and it was found out that door material has a significant impact on radiation patterns. The wood laminate attenuates the direct transmitted signal through the door, but it does not change the shape of the radiation pattern. The metal door blocks direct radiation, and thus it directs the surface currents along sidewalls of the locker. The radiation leaks out from the gap between the door and the metal locker frame, which shapes the radiation pattern. At higher frequencies, the radiation level is higher, since the gap is relatively larger with smaller wavelengths. The radiation pattern of locker with the metal door resembles an array radiation pattern, where multiple maxima and minima are visible. A big amount of radiated power with the metal door is directed towards the backside of the locker based on simulations, and it was verified with measurements on 2.45 GHz. This radiation pattern directions should be taken into account when the placement and the direction of the locker is designed to optimize the performance of the wireless connectivity. The achieved results underline the fact that in future cellular system designs, such as 6G, the specific conditions of the use case/vertical need special attention highlighting the need for flexibility in system design as vertical requirements need to be accounted for.

Acknowledgment

This work was supported by Business Finland funded SP400 project and the Academy of Finland 6Genesis Flagship (grant no. 318927).

References

[1] M. Latva-aho and K. Leppänen, *Key drivers and research challenges for 6G ubiquitous wireless intelligence*. Univ. of Oulu, Finland, 2019.

[2] L. Jiang, H. Chang, S. Zhao, J. Dong, and W. Lu, “A travelling salesman problem with carbon emission reduction in the last mile delivery,” *IEEE Access*, vol. 7, pp. 61 620–61 627, 2019.

[3] A. Kedia, D. Kusumastuti, and A. Nicholson, “Acceptability of collection and delivery points from consumers’ perspective: A qualitative case study of Christchurch city,” *Elsevier, Case Studies on Transport Policy*, vol. 5, pp. 587–595, October 2017.

[4] S. Ze-hong and Z. Guang-yuan, “Multi-functional parcel delivery locker system,” in *2015 International Conference on Computer and Computational Sciences (ICCCS)*, Jan 2015, pp. 207–210.

[5] Keba. (2019) Keba logistics solutions. [Online]. Available: https://www.keba.com/en/logistics-solutions/solutions-for/logisticians/logisticians

[6] Cleveron. (2019) Cleveron’s packrobots are one reason behind walmart’s e-commerce success. [Online]. Available: https://cleveron.com/news/cleveron-s-packrobots-are-one-reason-behind-walmart-s-e-commerce-success-forbes

[7] Bluetooth Technology Website. (2019) Core Specifications. [Online]. Available: https://www.bluetooth.com/specifications/bluetooth-core-specification/

[8] Sigfox. (2019) The Global Communications Service Provider for the Internet of Things (IoT). [Online]. Available: http://www.sigfox.com/en/

[9] LoRa. (2019) LoRa Alliance®. [Online]. Available: https://www.lora-alliance.org/

[10] Microwave Vision Group (MVG). (2019) Dual-ridge horns. [Online]. Available: https://www.mvg-world.com/sites/default/files/2019-11/Datasheet_Antennas_Dual-Ridge%20Horns_08_19_BD2.pdf

[11] (2019) 3GPP TS 38.104 - Base Station (BS) radio transmission and reception (Release 16). [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3202

[12] Laird Technologies. (2019) Heptaband external wireless antennas. [Online]. Available: http://assets.lairdtech.com/home/brandworld/files/ANT-DS-Heptaband_100114.pdf