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Simulation framework for data transmission by FM radio broadcasting on a two-ray propagation channel

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Abstract—This paper presents a simulation framework intended to perform realistic simulations of point-to-point transmissions in the FM (Frequency Modulation) band. The considered application is the broadcasting of drivers’ warning notifications by the means of low-resolution images (pictograms) embedded into the FM signal. The proposed simulation framework gives the possibility of obtaining an estimation of the communication range. More in details, it is capable of extracting BER (Bit Error Rate) with respect to different communication scenarios while being able to bring realism in the model of different parts of the transmission chain (e.g., down to circuit level). The proposed tool was validated by simulating transmissions with two digital modulation schemes i. e., QPSK (Quadrature Phase Shift Keying) and 8-PSK respectively, and by modelling a LOS (line-of-sight) two-ray propagation channel.

I. INTRODUCTION

The expansion of the number of motor vehicles led to a dramatic increase in the number of deaths due to road accidents. Indeed, the statistics of the European Union (EU) and of the World Health Organization (WHO) are giving that approximately 20.000 people lost their lives and more than 0.9 million were injured in 2021 because of road accidents [1]. The situation is even worrying in African countries where, in 2018, the WHO reported 26.6 deaths in traffic accidents per 100000 inhabitants, a number that is almost three times higher compared to the one corresponding to the average of the European countries [2].

In this context, the European Commission has officially launched the United Nations’ Global Plan, which sets out how to achieve the target of reducing road traffic deaths and injuries by 50% by 2030 [3]. To meet this goal, a warning system based on visual notifications sent by the means of the existing FM infrastructure was proposed and studied in [4], [5]. Compared to other types of radio access technologies such as cellular vehicle-to-everything C-V2X [6] and dedicated short range communications (DSRC) which are planned to improve the traffic safety, this solution is versatile, and can be implemented relatively rapidly and with lower cost since it is based on the SDR (Software Defined Radio) paradigm.

This warning system is based on the use of the existing FM infrastructure to send low resolution images to be displayed on board of the vehicles to warn drivers from potentially dangerous situations in traffic. This solution is particularly

useful in regions in which Internet coverage is absent or of poor quality. The information may be sent either on the higher part of the FM mono audio spectrum (up to 15 kHz) or by using the subsidiary bands of commercial FM radio systems, defined around the 76 kHz subcarrier. As stated, the transmission is based on the use of the SDR technology which makes its implementation cheaper, more flexible, and, most importantly, compatible with the existing infrastructure.

In [4], the authors demonstrated by simulation and partially through experiments the feasibility of using simple digital modulation schemes, i.e., QPSK (Quadrature Phase Shift Keying), 8-PSK or 16-PSK, in order to transmit low-resolution images embedded in the FM signal. In [5], the use of the DSSS-CDMA (Direct Sequence Spread-Spectrum Code Division Multiple Access) modulation technique to simultaneously transmit 15 low resolution images was also shown.

To have a realistic estimation of the data transmission performance, given as the maximum communication range for which the BER (Bit Error Rate) is smaller than a threshold value, measurement campaigns need to be performed. These measurement campaigns are relatively difficult to be done since the FM band is a licensed one. The use of simulation tools able to implement realistic propagation channel models is a feasible alternative.

In this context, this paper presents a simulation tool able to implement realistic propagation channel models and to calculate the BER variation for different transmission scenarios. The proposed tool is based on Keysight’s ADS and Mathworks’ Matlab - Simulink co-simulations and is fully compatible with the previously developed simulation framework for image transmissions in the FM band, illustrated in [4] and [5]. Moreover, because of its flexibility, this tool may be adapted to other communication scenarios.

To validate the proposed tool, a simple propagation channel model was implemented. However, several other realistic models may be found in the literature and may be easily implemented in our proposed simulation framework. The authors of [7] are presenting the results of FM channel field measurements conducted at 86 MHz and are proposing a corresponding model. These results show that for the urban area, the power delay profiles (PDPs) had a strong single multipath with surviving multi-paths near the first one. A strong

line-of-sight component was obtained in rural areas. Another candidate model, suitable for Hilly Terrain Regions (HTRs), was proposed by the authors of [8]. Here, a directional model based on COST-259 at 2 GHz one is proposed. Moreover, a hardware emulator based on SAW (Surface Acoustic Wave) filters is also introduced.

The rest of the paper is structured as follows: section II gives the details about the simulation framework and in section III, the implemented propagation channel model is highlighted. Finally, section IV presents an estimation of the communication range for the two envisaged digital modulation schemes and for the simple LOS propagation channel. This estimation is obtained by analysing the BER variation with respect to the distance.

II. SIMULATION FRAMEWORK

The synoptic of the proposed simulation framework is presented in Figure 1. As can be seen, there are three main parts, namely, the one which consists in forming the baseband (BB) composite signal containing the audio part, limited to 5 kHz bandwidth and the data part including in the pictogram to transmit, and which modulates a 11 kHz subcarrier. This part is implemented in Simulink by using blocks from the "RTL-SDR book library" [9].

The pictograms are grey level images of small dimensions (100x100 pixels), each pixel being represented by 8 bits. The corresponding bit stream is sent with a low data rate (8 or 12 kbits/sec depending on the digital modulation scheme) and is organized in frames. The payload of each frame contains the information corresponding to a column of the image to be transmitted.

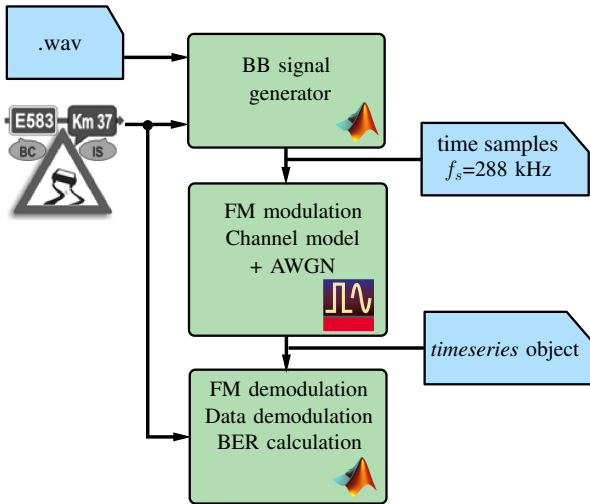


Fig. 1. Synoptic of the proposed simulation framework.

The main advantage of such implementation is that this part is fully compatible with the most common SDR hardware, consequently the experimental part is easy to be implemented.

The second part in the simulation framework is implemented by using Keysight's ADS. Here, the baseband signal from

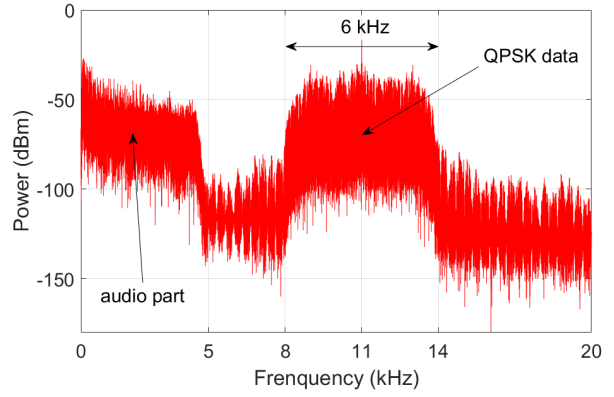


Fig. 2. Frequency spectrum of an imported baseband signal. The signal is including the audio part (limited to 5 kHz) and the data part which modulates in QPSK the 11 kHz sub-carrier.

Simulink modulates an FM carrier ($f = 100$ MHz). Figure 2 presents the frequency spectrum of the imported baseband signal. The bit rate was setup to 8 kbits/sec and the Nyquist matched filter's roll-off factor was considered to $\beta = 0.5$.

Then, the RF signal is conveyed through the propagation channel model which may be implemented in different manners, from the simplest free space path loss to more realistic multipath ones modelling fading phenomena. Moreover, different kinds of antenna models may also be employed. The simulations presented in this paper are performed by considering isotropic antennas. After the receiving antenna, an AWGN (Additive White Gaussian Noise) having the power spectral density of -173 dBm/Hz is considered.

Figure 3 corresponds to the frequency spectrum of the RF signal obtained by the FM modulation of the 100 MHz carrier frequency. The baseband signal is the one depicted in Figure 2 and the modulator's sensitivity was chosen to 100 kHz/V.

The received signal is then processed by the third part of the proposed simulation framework. Here, the FM demodulation is performed by using a Complex Delay Line Frequency Discriminator (CDLFD) [9]. Then, the data signal around 11 kHz subcarrier is separated from the audio part by filtering. The demodulation of the data signal is performed by using a carrier synchronization stage operating at symbol rate and which is presented in details in [4]. The resulting data stream is compared to the delayed version of the initial one and the BER

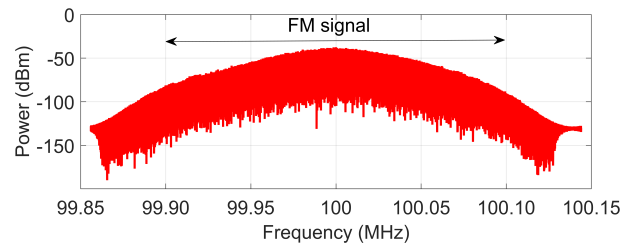


Fig. 3. Frequency spectrum of the RF signal obtained in Keysight's ADS by performing FM modulation of a 100 MHz carrier.

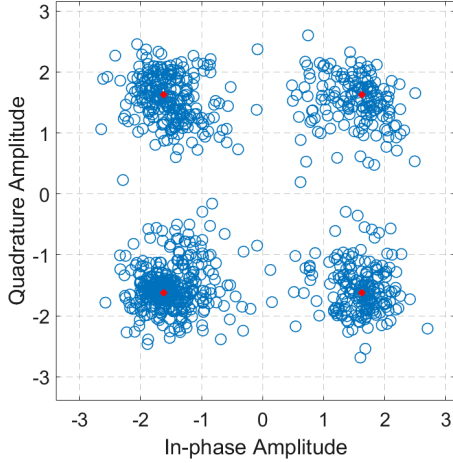


Fig. 4. Constellation of the received signal in the case of a QPSK transmission. The distance between the emitter and the receiver is 28 kilometers.

is calculated. To increase the accuracy of the obtained BER values, the data corresponding to a pictogram is sent several times such that the number of processed bits is sufficient to obtain a confidence level greater than 99 %.

Figure 4 is presenting the constellation (QPSK modulation) of the signal corresponding to 28 km between the emitter and the receiver in the case of a LOS transmission scenario and of a two-ray propagation channel. Figure 5 depicts the corresponding decoded pictogram.

The main advantage of the proposed simulation framework is the use of MathWorks - Simulink Keysight - ADS co-simulation. Consequently, all the baseband processing takes advantage of the Simulink capabilities and the accuracy in the model of the RF part (i.e., propagation channel and even the FM modulation part which may go down to circuit level) relies on Keysight's ADS software capabilities.



Fig. 5. Example of a decoded pictogram, extracted from a received FM signal containing a QPSK modulated subcarrier. The distance between the emitter and the receiver is considered 28 km and the $EIRP = 30$ dBm.

III. PROPAGATION CHANNEL MODEL

In order to validate the proposed simulation framework, the simplest multipath propagation channel, described in details in [10], was implemented. In our considered scenario, the communications occur beyond the critical distance d_{FF} (far-field region), defined as:

$$d_{FF} = \frac{4\pi \cdot h_E \cdot h_R}{\lambda_0} \quad (1)$$

where h_E and h_R are the emitting and the receiving antenna heights respectively and λ_0 is the wavelength in vacuum.

The received power level, $(P_R)_{dBm}$, may be approximated by the equation (2):

$$P_R = EIRP + G_R + 20 \cdot \log_{10}(h_E \cdot h_R) - 40 \cdot \log_{10}(d) \quad (2)$$

In this equation, $(EIRP)_{dBm}$ is the equivalent isotropic radiated power, $(G_R)_{dBi}$ is the receiving antenna's gain and d is the distance between the two antennas. As can be remarked from this equation, in these conditions, the received power decreases by 40 dB each decade which is accurate in far-field region $d \gg d_{FF}$.

To validate this propagation model, the following scenario was implemented in Keysight's ADS. Two antennas placed at $h_E = 10$ meters and at $h_R = 3.5$ meters respectively are exchanging FM modulated signals having a carrier frequency of $f = 100$ MHz (corresponding to a wavelength $\lambda_0 = 3$ meters). The considered $EIRP = 30$ dBm and, as stated, the receiving antenna's gain is $G_R = 0$ dBi. In this scenario, from equation (1), the far-field condition is accomplished for distances $d \gg d_{FF} = 146.6$ meters.

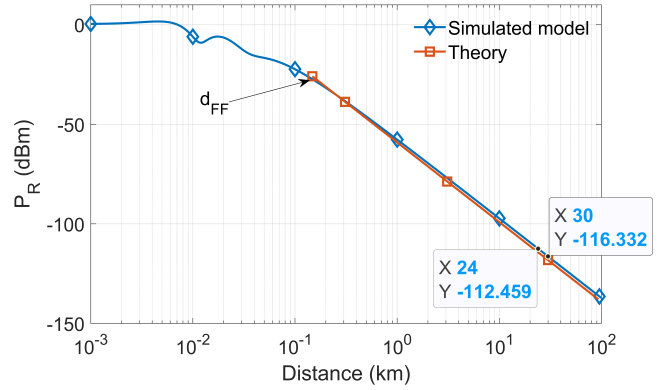


Fig. 6. Variation of the received power with respect to the distance d in the case of a two-ray propagation channel. Comparison between the theory and simulation results for $d \geq d_{FF}$.

Figure 6 presents the variation of the received power level with respect to the distance obtained from equation (2) and from the proposed simulator. As expected, the simulation result is very close to the theoretical one. The difference between the two plots may be explained by the fact that in simulation, the influence of the ground on the reflection coefficient is considered. Indeed, a realistic value for the ground's relative permittivity $\epsilon_r = 15$ and for the conductivity $\sigma = 0.005$ S/m are set up.

IV. SIMULATION RESULTS

To validate the proposed tool, a series of simulations were performed to extract the BER variation with respect to the distance in the case of sending the image notifications by the means of two digital modulation schemes, i.e., QPSK and 8-PSK respectively. The EIRP was set to 30 dBm and the employed propagation channel was the one presented in the previous section.

Figure 7 depicts the BER variation with respect to the distance for the two considered modulations. In this particular case, the maximum estimated distance for which the images are received with an acceptable quality ($BER < 10^{-3}$ - arbitrary value) is about 27.5 kilometres in the case of using QPSK modulation. As expected, when using 8-PSK, the corresponding distance decreases to about 21.5 kilometres, since 8-PSK need a higher SNR for the same target BER.

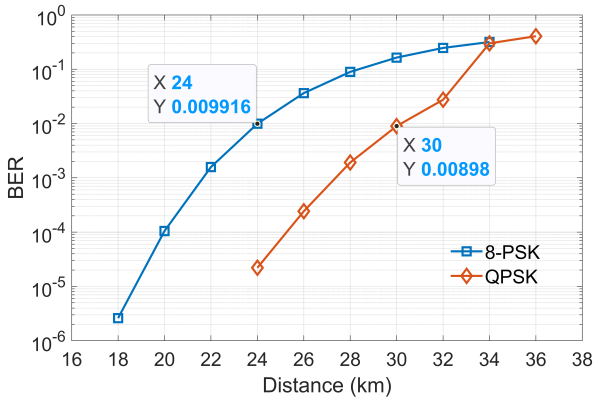


Fig. 7. BER variation with respect to the distance in the case of a LOS two ray propagation channel model.

In order to verify the obtained results, the power difference needed to obtain a target $BER \approx 10^{-2}$ when employing QPSK and 8-PSK was compared with the theory. More in details, from a theoretical point of view, on an AWGN channel, to obtain the BER values depicted in Figure 7, in the case of the 8-PSK modulation scheme, the signal's power level needs to be $\Delta P = 4.59$ dB higher than the one necessary to transmit with approximately the same BER but employing the QPSK modulation.

Indeed, for ideal conditions, the difference of E_b/N_0 , (i.e., the energy per bit over the noise power spectral density) when employing QPSK or 8-PSK is given by equation (3):

$$\Delta(E_b/N_0) = (E_b/N_0)_{8-PSK} - (E_b/N_0)_{QPSK} = 2.83 \text{ dB} \quad (3)$$

Consequently, considering that the noise power level is identical in the two scenarios, the signals' power difference is:

$$\begin{aligned} \Delta P &= SNR_{8-PSK} - SNR_{QPSK} \\ &= \Delta(E_b/N_0) + 10 \cdot \log_{10} \left(\frac{3}{2} \right) = 4.59 \text{ dB} \quad (4) \end{aligned}$$

On the other hand, by considering the power variation depicted in Figure 6, for the same distances (i. e. 24 km

for 8-PSK and 30 km for QPSK), the difference between the received power levels is $\Delta P_{channel} = 3.87$ dB, value which is very close to the ideal one, ΔP , to within 1 dB. In other words, the same increase of power level to change from QPSK modulation to 8-PSK one while keeping the same target BER is obtained both in theory and from the proposed simulation framework.

V. CONCLUSION

This paper presented a simulation tool which is intended to estimate in an accurate manner the communication range of small size image transmissions in the FM band to warn drivers from potential traffic dangerous situation. This tool may include a realistic propagation channel, may also include realism in the simulated RF part and it is compatible with the existing developed software which is based on the SDR paradigm. The proposed framework was validated by performing pictograms transmission on a two-ray propagation channel and by extracting the BER variation with respect to the communication range. Future work will be done to implement more realistic FM propagation channels and perform experimental tests in order to confirm the obtained results. Moreover, it is intended to extend these results to other modulation schemes.

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