

# Performance Evaluation of Bluetooth in a High Voltage Environment

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**Abstract**— The paper provides some experimental results of Bluetooth system performance in presence of some impulses in the High Voltage (HV) Laboratory at the Dresden University of Technology. The performance is evaluated by the measured BER of an established link between two Bluetooth modules. An impulse voltage generator creates a homogeneous electric field at voltages from 200 kV up to 500 kV. Some experiments has shown the Bluetooth link is extremely influenced by the high voltage impulses in the range above 450 kV that is equivalent to a lightning appearing in the nature. The examined BER has increased due to malfunction of the receiver and the raised noise level in that environment.

**Keywords**— Bluetooth modules, RSSI - Received Signal Strength Indicator, High Voltage Impulse, Lightning

## I. INTRODUCTION

Cable replacement by a Bluetooth device significantly enhances the applications demand like mobility, flexibility, maintenance free and simplified installation but also introduces problems in comparison to wire line based communications, e.g. interferences and noise. An effective application of Bluetooth technology could be the power substation control systems, high voltage lines or measurement systems of high voltage laboratory where enormous cables are usually used.

The characteristics of high voltage or heavy electric environment differ from the office environment for various electrical devices producing ambient electromagnetic noise. These scenarios are like the Bluetooth communications in industrial environment. The operating temperatures vary from -20 to +100 °C and alter also from the office environment. In this paper we reported the measurement results of Bluetooth communications in high voltage laboratory when the high voltage impulses or lightning impulses were generated. The output of Marx impulse generator was set from 200 kV up to 500 kV and the corresponding electric field strength changes alternatively from 100 to 250 kV/m due to the fact the plate was 2 m above from ground. We measured consequently the BER and RSSI when transmitting and receiving Bluetooth modules were placed in the presence of high voltage effects. Another measurement setup was performed to convert the received power indicator RSSI into the dBm scale whereas no effects of high voltage were applied. Our additional interest was to figure out the upper boundary

of high voltage whereby Bluetooth modules are still applicable.

The paper specializes in man-made impulsive noise produced by the high voltage equipment. This unwanted impulse noise is often more important for determining the system degradation than the Gaussian noise, especially at frequencies from the VHF range and higher. The spectral analysis has been discussed in [5]. It was shown that the greatest amount of impulse noise energy from high voltage equipment is concentrated within the initial 150 MHz. Although at 800 MHz, in a close distance up to 10 m from the high voltage equipment, a strong electromagnetic field can still be detected when an electrical breakdown happens. Since Bluetooth works in the unlicensed frequency range of 2.4 GHz, the greatest amount of the impulse energy is filtered out. The receiver's immunity from this impulse noise also depends on the out-of-band blocking ability. However, interference influence of high voltage equipment over Bluetooth devices is still unclear since no previous work has been conducted about this. Therefore, prior to transmit Bluetooth data in such environments the performance evaluation test is necessary. This paper reported the achieved BER in the high voltage laboratory was greater than the correspondent BER in office environment because of various noise sources.

The remainder of the paper is organized as follows. In section II measurement setup and techniques are given and in section III a simplified approach for converting the correspondent RSSI value into dBm value is represented. The characteristics of impulse voltage are outlined in section IV. Finally, some results in section V and some conclusions in section VI complete the paper.

## II. MEASUREMENT SETUP AND TECHNIQUES

Two Bluetooth USB modules with half wavelength dipole antennas are connected to two laptops. Since the modules eb502 from A7 Engineering adopt CSR Bluetooth chips [3][6], the BlueTest software that is a part of CSR BlueSuite can be used to perform BER test after changing the Bluetooth device drivers on both laptops. The data transmission (TX-DATA1) was performed in BlueTest on the transmitter side, alternatively the data quality estimation (BIT ERR1) was executed on the receiver side.

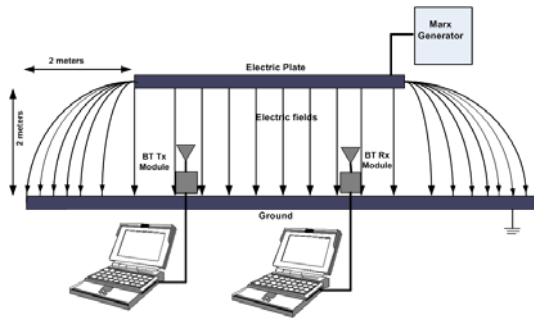


Fig. 1. Schematic setup with two kinds of interference sources

Then we transmitted the PRBS9 payload in a designated frequency band. Furthermore, the same setup but different configuration of Bluetest might be applicable for RSSI measurements. This term and signal power has been used interchangeably. After the Bluetooth RSSI measurement was carried out, we compared the received signal power and two threshold levels defined as the Golden Receive Power Range [1].

Fig. 1 shows the schematic setup with two Bluetooth USB modules controlled by two laptops. The electric plate connected with the Marx generator is creating homogeneous impulsive electric fields and the correspondent arrow lines toward the ground are represented. During the measurements, the places of transmitting and receiving modules have been kept constant. Both modules are placed under the affect of homogeneous impulsive electric field. Two long pieces of USB cables are used with modules to keep the laptops in save distance. The BER and RSSI are recorded for variable transmitting power at each voltage value from the 200-500 kV range. Using this setup we can measure either BER or RSSI for a particular moment. Moreover, the measured BER and RSSI were not time corresponding each other because of the multipath. In order to minimize the fading effect and to get more precise results, we placed the modules in short separation distance. Then we took the average over a large number of samples and we collected the correspondent RSSI at the beginning and at the end BER measurement of each transmitted power.

### III. RSSI CONVERSION APPROACH

In order to convert the received power level from RSSI value into dBm, the analytical approach from [4] was applied. Additionally, a comparison with the measurement results from the spectrum analyzer was carried out and the similarity was confirmed again.

The slave unit was connected to the spectrum analyzer through a 3 dB power splitter fed by a dipole antenna with 0 dB gain. The setup of slave unit used for the measurement can be found in Fig. 2. The separated master unit was controlled by another laptop.

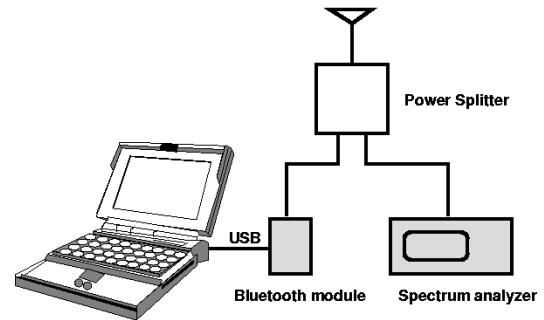


Fig. 2. Slave unit converting RSSI into dBm

The recorded received power in dBm from spectrum analyzer represents the corresponding value of RSSI. However the measurement environment had a negative impact on the results as the signal fluctuates randomly. Therefore it may be difficult to record accurate corresponding RSSI and dBm results at the same time. Then we set the transmitting and receiving antenna in 1 m separation distance to reduce the received signal fluctuation in the office environment. During the experiments we made sure the signal variation was negligible and it was about 0.2 dBm.

### IV. IMPULSE VOLTAGE CHARACTERISTICS

A Marx generator is used to generate high voltage impulses with applied charging voltage on capacitors, therefore at the maximum charging voltage the minimum time between impulses is 30 s (i.e. 2 impulses per minute). This interval is dictated by the maximum charging current, the maximum energy of the impulse capacitors in the impulse generator and the resistor energy absorption capacitors.

In our experiments we mainly used two impulse waveforms: long of 250/2500 $\mu$ s and short of 1.2/50 $\mu$ s. Their main parameters are the peak voltage value ( $U_p$ ), the peak time ( $T_p$ ), the rise time ( $T_1$ ), the back half-value time ( $T_2$ ), the impulse duration ( $T_d$ ), and the cut time ( $T_c$ ). Reasonably, the separation time between two impulses depends on the respective electric field strength  $E$ . In order to simulate a lightning, the high voltage impulse has to be shortened after the rise time  $T_1$ . The table I outlines the measured parameters of the impulse waveforms with or without lightning.

Fig. 3 shows the impulse waveform of electric field radiation with and respectively without lightning. It is clearly seen that the the back half-value time is defined when the half of the impulse amplitude is achieved. The impulse waveform of 1.2/50 $\mu$ s with lightning achieves its rise time after 2.2  $\mu$ s. The back half-value time is 2.4  $\mu$ s as represented in Fig. 4. In opposite, for the impulse of 250/2500 $\mu$ s the rise time is 100  $\mu$ s and the back half-value time is 100.2  $\mu$ s (Fig. 5).

TABLE I

IMPULSE WAVEFORMS PARAMETERS: (S.- SHORT, L. - LONG, WO. - WITHOUT, W. - WITH)

S. Waveform	$U_p$ kV	$T_1$ $\mu s$	$T_2$ $\mu s$
WO. lightning	200 – 500	2.4	4.6
W. lightning	200 – 500	1.3	2.35
L. Waveform	$U_p$ kV	$T_p$ $\mu s$	$T_2$ $\mu s$
WO. lightning	200 – 500	200	500
W. lightning	200 – 500	188	189

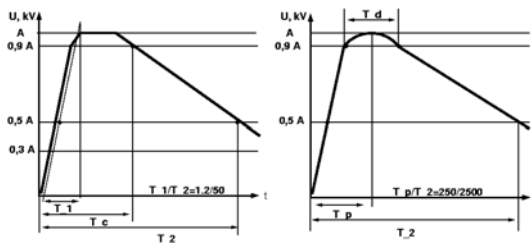


Fig. 3. Voltage impulse waveform of amplitude A for short and respectively long impulse without lightning

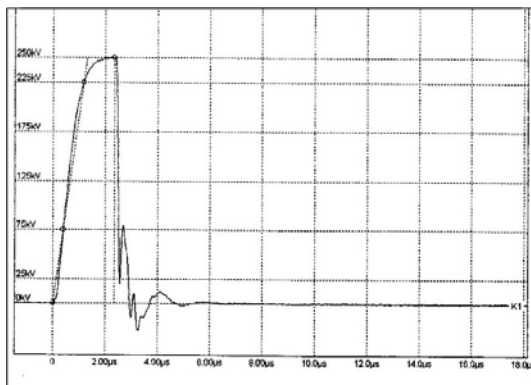


Fig. 4. Short voltage impulse with lightning

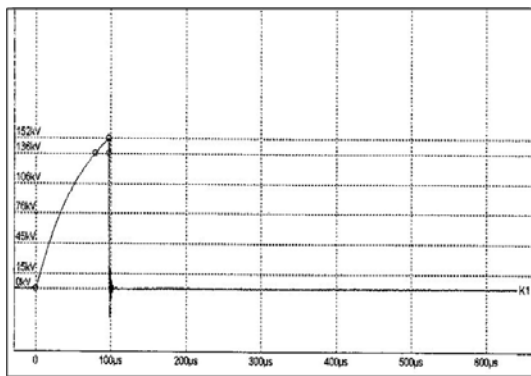


Fig. 5. Long voltage impulse with lightning

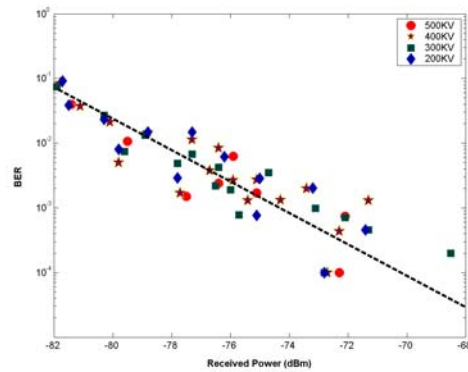


Fig. 6. Bit error rate of impulses without lightning

V. PERFORMANCE EVALUATION

The Bit Error Probability (BEP) is an important parameter, which estimates the performance of a digital radio receiver against an interfering signal or background noise. To estimate the BEP in reference to GFSK scheme, the general form of BEP ( $P_e$ ) developed for FSK can be modified as follows [2]

$$P_e = Q_1(a, b) - \frac{1}{2} e^{-(a^2+b^2)/2} I_0(ab) \tag{1}$$

where

$$a = \sqrt{\frac{\epsilon_b}{2N_o} (1 - \sqrt{1 - |\rho|^2})}$$

and

$$b = \sqrt{\frac{\epsilon_b}{2N_o} (1 + \sqrt{1 - |\rho|^2})}$$

Here  $Q_1(a, b)$  is the Marcum Q function,  $I_0(ab)$  is the modified Bessel function of order zero,  $E_b$  is the energy per bit,  $N_o$  is the noise power spectral density in dBm/Hz and  $p$  is the symbol cross-correlation coefficient. For non-coherent receivers, the  $p$  can be computed by

$$\rho = \frac{\sin(\pi h)}{\pi h}$$

where  $h$  is the modulation index.

Fig. 6 describes the experimental results for four types of impulse voltages. The dot line depicts the average BER and its decrease is almost linear with increasing power level on the receiver side in high voltage environment. The receiver sensitivity level of our Bluetooth module was -85 dBm for 0.1% BER. It is clearly shown that the BER 0.1% is met at around -82 dBm. Therefore the receiver sensitivity level reduces with 3 dB in presence of impulse noise and high voltage electric field.

Fig. 7 depicts the BER when short and long impulses with lightning are applied. They have greater impact on BER than the voltage impulses without lightning, since the rise time and the cut time are very short. The curve also shows that the average BER decreases linearly with increasing the received

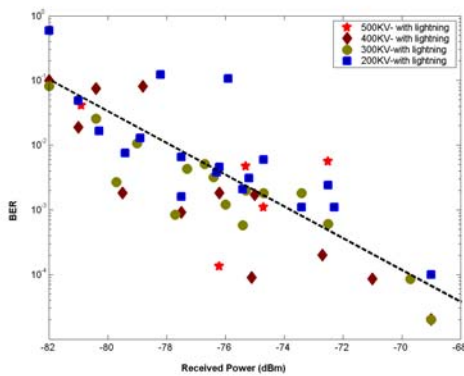


Fig. 7. Bit error rate of impulses with lightning

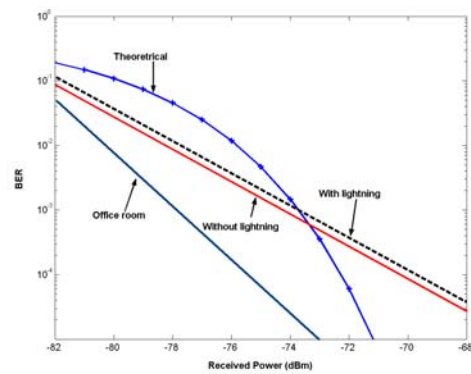


Fig. 9. Bit error rate for four different cases

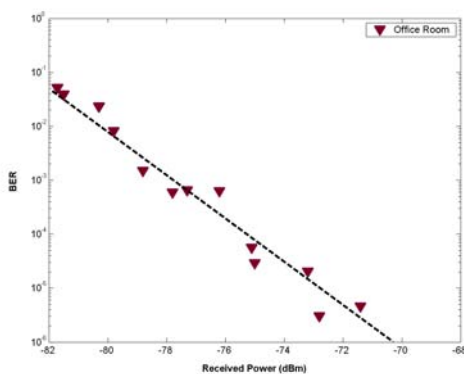


Fig. 8. Bit error rate in office room

power level. The 0.1% BER was met when the received power level is -82.5 dBm, i.e. the sensitivity level was reduced with 2.5 dB in presence of lightning impulse. At lightning voltage of 400 kV the Bluetooth device still work and exchange data. When a voltage of 450 kV is applied, the device was found to be out of order a few minutes after being restarted.

Fig. 8 represents the measurement results performed in the office environment. The BER is less spread in comparison to Fig. 4 and 5. It was found that the BER of 0.1% meets the receiver sensitivity level of -85 dBm. Moreover, the BER decreased linearly with the increased power level on the receiver side.

Fig. 9 compares the achieved BER under different conditions with a theoretically calculated result. It is shown that the experimental BER differs significantly from to the theoretical expected values when the impulsive man-made noise appears. At the time of lightning the data transmission experienced a greater BER in comparison to voltage impulse and office environment. The lightning and impulse voltage BER decreased with 0.5 dB separation. Also the sensitivity level in the office environment differs with 3 dB from high voltage environment. The slope of decrease of BER was found a bit larger than in the

office environment. For example it was about 0.005% BER/dB whereas the value of 0.007% BER/dB was estimated in the high voltage laboratory.

## VI. CONCLUSION

The paper reported the performance of Bluetooth communications by means of BER in high voltage laboratory where high impulse voltage, lightning voltage and impulsive noise present. The appropriate measurement setups were performed to measure BER and RSSI, converting RSSI to dBm values and measured signal to noise ratio.

The results show that the high voltage and lightning has an impact on the receiver performance. The typical impulse waveform does not really affect the data transmission when the recommended protection conditions from [7] are taken into account. The BER limit was found to be met at receiver sensitivity of 3 dB less in comparison to the office environment. The reason could be the receiver's malfunction and the increased noise level. The lightning affects the data transmission increasing BER as originally expected. Bluetooth modules can still exchange data in the worst case under lightning voltage of 400 kV. However the Bluetooth link is extremely influenced by the high voltage impulses in the range above 450 kV that is equivalent to a lightning appearing in the nature. The reported results might be useful for the manufacturers in order to increase the resistance of wireless devices.

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