PLC Systems for Electric Vehicles and Smart Grid Applications

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Abstract—**In this paper an extensive set of measurements, simulations and testing of a commercial modem are performed in an electric vehicle to evaluate the performance of PLC. The noise of the motor drive is measured and characterized in the time and frequency domains. Also, the noise generated by the AC/DC converter is measured and described. The symbol-error-rate performance of a multicarrier communication scheme is analyzed via simulation by employing the above modeled channels and noise.**

Keywords—Power Line Communication; Electric Vehicle; Channel Modeling

I. INTRODUCTION

Power line communication (PLC) has recently gained widespread interest, from both industry and the scientific community, as a viable alternative technology for broadband communications. Commercial modems are nowadays capable of reaching theoretical speeds of 500 Mb/sec, by using advanced communication techniques. Therefore, a growing number of applications can benefit from the increasing potential of the PLC technology.

The use of PLC to enable in-vehicle communications and networking is an attractive field of application and research. Modern vehicles are provided with a large number of devices and features that require data communication. Some examples include data transfer between sensors and actuators, traction control, and, to a large amount, infotainment. Currently, the most widely spread solution for providing communications links of guaranteed performance quality, is based on employing a dedicated data bus for each link (Controller Area Network, Local Interconnect Network, Media Oriented Systems Transport, FlexRay).

It is commonly recognized, at this time, that PLC can not substitute all the types of communication links. This is due to robustness, safety, and standardization issues that have not been completely assessed and resolved so far. For example it is not recommended, presently, to use PLC for providing ABS functionality. On the other hand, PLC may indeed be employed for proving auxiliary features such as the entertainment, air conditioning control, diagnostic signals etc.

The in-vehicles applications of PLC systems have been investigated in recent years, and the many results [1] – [18] reveal the interest in the topic. The authors have recently developed new methods and tools for the analysis and modeling of PLC systems [19], poining attention also to the use of PLC for naval applications [20]. A first analysis of the PLC channel onboard a fully electric vehicle has been presented in [21] by the authors.

In this paper, an elaborate study of different power line channels is presented, with the main purpose of assessing the channel characteristics and consequently demonstrating the feasibility of using PLC onboard electric vehicles. Additional work would be needed to design and implement a complete PLC-based system. For example, proper coupling has a crucial role in a PLC-based system since security and safety-related sub-systems (i.e. ABS and ESP) produce high current transients that can potentially harm the PLC system. The vehicle under study was not equipped with such advanced safety systems, but this does not lessen the validity of our conclusions since channel evaluation is the necessary step for determining communication feasibility.

Another aspect analyzed in this work concerns the possibility of directly plugging to the power grid for recharging some of these hybrid and electric vehicles (called Plug in Electric Vehicles, PEV). This fact implicates the need for the management of the PEVs increase and their effect on the Smart Grid, but it can also be seen as a potential: the power link between the grid and the PEV can be exploited for communications purposes with the aim of providing new services (trip information, vehicle's diagnosis, entertainment, etc.) by using the PLC technology.

Additional fundamental activity we carried out to support and validate the conclusions drawn from our measurement campaign was a field test of a commercial modem: DCB1M by YAMAR Electronics [22].

II. MEASUREMENTS

A. In vehicle channel

The measurement setup and the particular electric vehicle under examination have been introduced in [21]. The use of a Vector Network Analyzer (VNA) allowed a simple measurement setup [21], since it can be connected directly to the transmitting and receiving ends because of the dimensions of the vehicle. Its frequency range was set to [100kHz – 30 MHz], with 1024 frequency samples. In order to perform accurate measurements, the VNA was calibrated to take into account the effects of coaxial cables connecting the VNA to both ends. The VNA measures the insertion gain S_{12} which is related to the transfer function as shown in Ref. [18].

It is evident that the channel insertion gains change according to the power status of the vehicle. For this reason we took measurements with the ignition key in different positions: in particular it can be in the "off" position; in "position I" (in which the battery is connected to a limited set of auxiliary devices); in "position II" (battery connected to all the devices and the inverter is turned on). In addition, some loads were turned on (i.e. the front lights) as clearly explained in the figures. The different channels depend on the choice of the terminations where the VNA is connected, and for that we considered the following four connection points: rear light; cigarette lighter; rear indicator; rear break light; courtesy light.

Figures 1 to 5 show the transfer functions of the five channels analyzed (Channel #1 is already shown in [21]). An in depth analysis of the frequency responses is performed in section III.

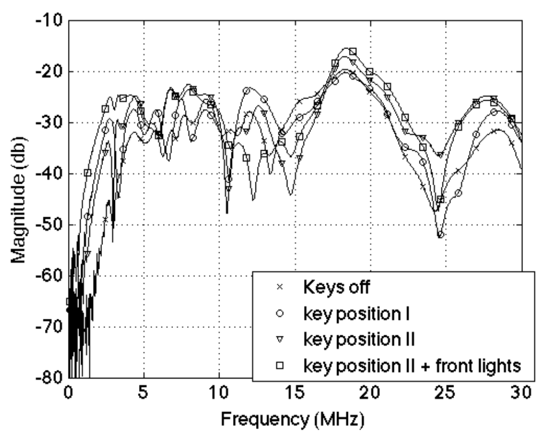

Figure 1. Channel #1 (rear light – cigarette lighter)

B. Grid to vehicle channel

In this case the vehicle has been plugged to the power grid for battery charging at a socket located in the basement of the laboratory. To create a setup representing a data transmission, one of the two terminals has been connected to the cigarette lighter of the vehicle and the other one at the same socket where the charging cable is connected. A low pass filter between the mains and the socket is used to avoid the influence on the measurement of the mains grid. Once the vehicle is plugged, the ignition key can be set in the previously described different positions, while no additional conditions (lights on etc.) have been measured because this particular data transmission will in most cases take place only when the vehicle is parked and full off.

Figure 6 shows the transfer function of the grid – vehicle channel (labeled as Channel #6) in the different keys position for the broadband PLC, while Figure 7 shows the transfer function relative to the CENELEC band limits.

Regarding the narrowband channel depicted in Figure 7, attenuations of more than 40db are observed in the CENELEC A and B bands, and up to 300 kHz, resulting in a unusable channel for communication. On the other hand in the frequencyinterval from 300 kHz to 500 kHz, the attenuation is between 30db and 40db. Then these frequencies, which are reserved for future Smart Grid applications, may support a narrowband communication under common noise scenarios.

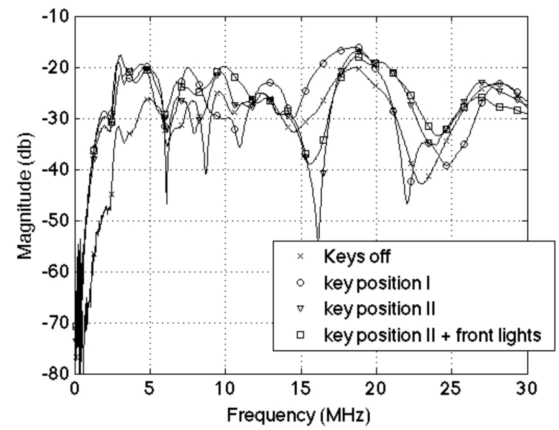

Figure 2. Channel #2 (rear indicator – cigarette lighter)

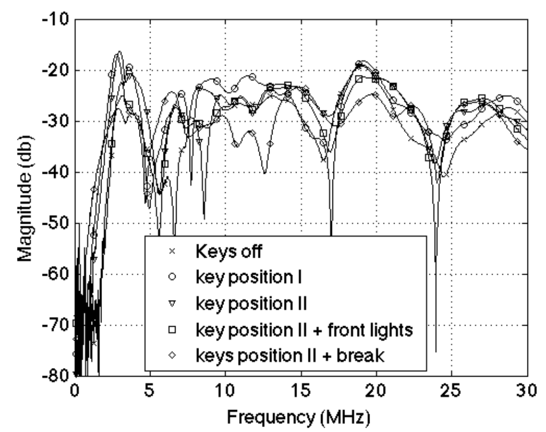

Figure 3. Channel #3 (rear break light – cigarette lighter)

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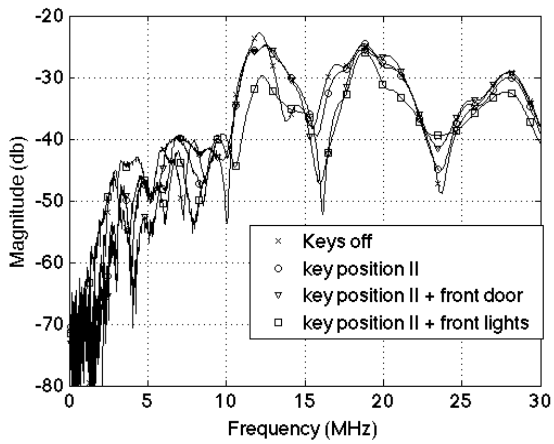

Figure 4. Channel #4 (rear light – courtesy light)

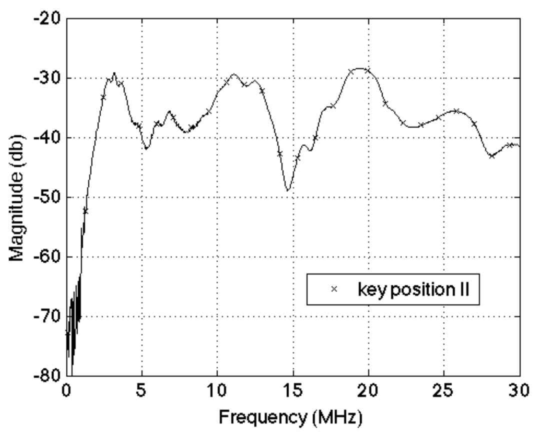

Figure 5. Channel #5 (courtesy light – cigarette lighter)

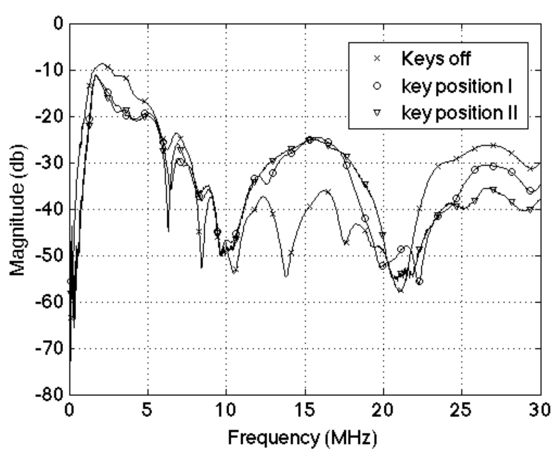

Figure 6. Channel #6

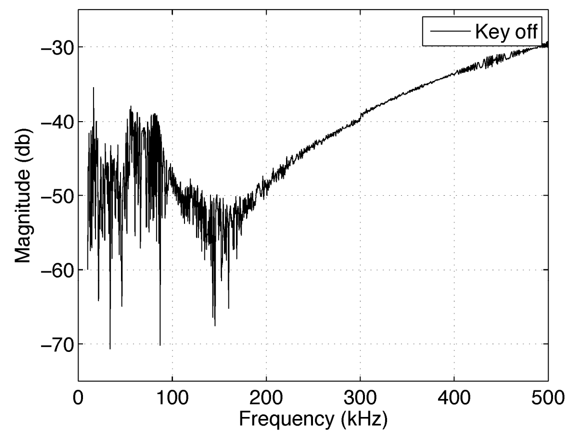

Figure 7. Insertion gain of the channel in the narrow frequency band [20 - 500]kHz.

C. Noise Measurements

The unique feature that hybrid or full electric vehicles have is the electric engine. For this reason, the power grid of such vehicles is in principle different if compared to internal combustion engine vehicles; it is characterized by the presence of an additional sub-grid feeding the motor drive and fed by the battery pack. The presence of the motor drive creates a certain amount of noise caused by the semiconductors switching. A similar situation holds for the noise introduced into the grid by the AC/DC converter which works during battery charging.

As it is well known, in order to evaluate the possibility of implementing a PLC based data transmission, noise characterization is fundamental. In this study, we have focused our attention on the two above mentioned sources, which inject a conducted noise in the power grid that is considerably higher than the background noise (the latter being around -130 dbm/Hz according to our measurements).

The noise generated by the motor drive and by the AC/DC converter (during charging) has been recorded during a significant time interval at different terminals, using a 12 bit, 200MS/s, digitizer with an input impedance of 50 Ohms. The recorded time domain noise has been post processed, in order to determine the Power Spectral Density (PSD) in the range of interest. The same procedure has been performed for the noise measured at all the terminals, and no significant difference has been evidenced; this is due to the electrically small dimensions of the vehicle.

Figure 8 shows the PSD of the measured noise generated by the motor drive, while Figure 9 and shows the noise of the AC/DC converter. These noises can be considered as periodic impulsive noises, hence the PSD analysis is statistically significant. The effects of these noises on the communication and their properties are further analyzed in the following sections.

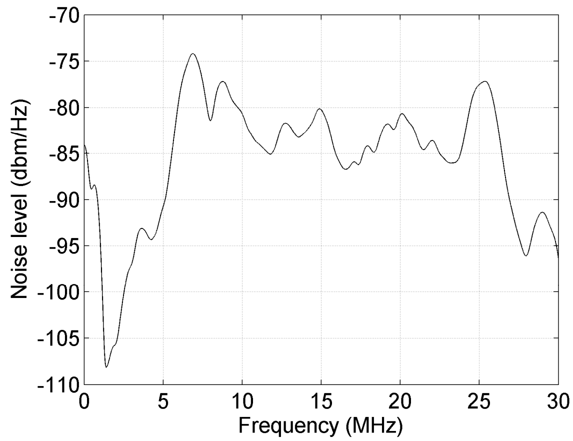

Figure 8. Power spectral density of the noise generated by the motor drive

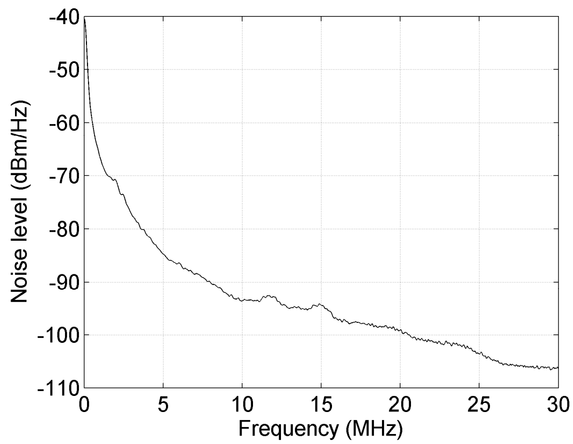

Figure 9. Power spectral density of the noise generated by the AC/DC converter.

III. STATISTICAL ANALYSIS

A. In vehicle channel

To better evaluate the channels performances we have calculated the Cumulative Density Function (CDF) relative to each channel in the different configurations.

Figure 10 shows the CDF for all the channels relative to the internal communications paths, whose frequency responses are represented in Figures 1-5. The conclusions which can be drawn by analyzing Figure 10 is the following: the best channel for data communication is Channel #2, which presents in most of its configurations a lower attenuation, while the worst is Channel #4. In particular, considering a threshold M = -40 db, in Channel #2 the probability that the attenuation is stronger than M is around 0.05, while for the two worst configurations of Channel #4 the probability is 0.3.

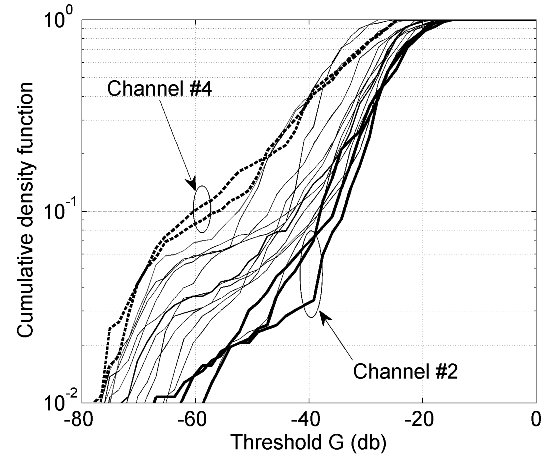

Figure 10. CDF of channels #1 to channels #5

B. Grid to vehicle channel

Figure 11 shows the CDF for Channel #6 (power grid to vehicle), which presents intermediate characteristics between Channel #2 and Channel #4.

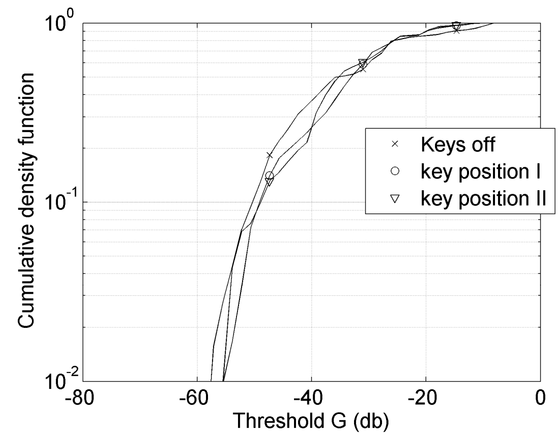

Figure 11. CDF of channel #6

IV. MODELLING AND SIMULATIONS

The model used to perform the simulations has been introduced in [21]. It is based on the knowledge of the power grid topology, and cables characteristics; then the unknown voltages and currents are expanded in the wavelet domain in order to obtain a linear and sparse system which can be accurately solved in a low CPU time.

A. In vehicle channel

The procedure is the following: from a random stream of data an OFDM frame is generated, then the corresponding time series is transmitted in the channel #i (i=1..5) using a certain injected PSD. In this step we consider that the inter symbol interference (ISI) is completely eliminated by the guard interval, and a stationary frequency response of channel #i. The measured noise of figure 8, properly resampled, is then added in the time domain to the received signal. The so obtained data at the receiver have been equalized in frequency according to the transfer function of the channel #i. In this step we consider perfect synchronization, and no equalization mismatch. The result is then compared to the transmitted QAM constellation allowing the calculation of the symbol error rate. This whole process has been performed for a statistically significant set of data. The rationale for using 1000 data carriers is based on the fact that commercial standards for broadband PLC use a comparable number of carriers (HomePlug AV, IEEE P1901).

The cumulative results presented in Figure 12 again confirm the results obtained by qualitatively looking at the CDF graph, with Channel #2 being the best channel (characterized by lower Symbol Error Rate in our simulated data transmission) and Channels #4 and #5 being the worst performing channels.

B. *Grid to vehicle channel*

Simulations for this configuration have been performed according to the same procedure explained in section IV A, i.e. using 1024 random symbols modulated according to a 16 QAM scheme, adding the noise to the signal at the received, and demodulate to calculate the Symbol Error Rate. The main difference is that in the previous case the channel transfer function was analytically calculated by the model, while in this case the transfer function considered is the one measured.

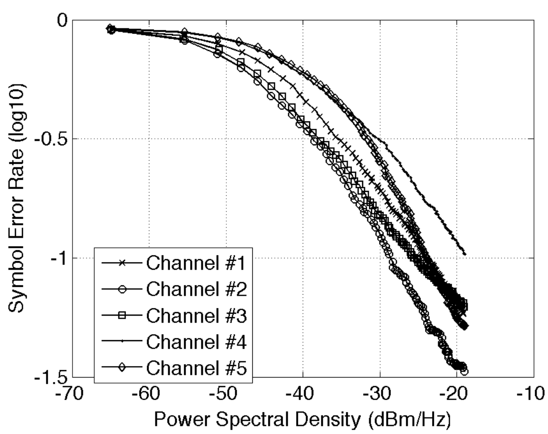

Figure 12. Symbol Error Rate for channels #1 to #5

Figure 13 shows the Symbol Error Rate as a function of IPSD. This particular channel performance lies in between Channel #2 (the best one) and Channel #4, the worst one.

As an overall comment, it can be noted that in the considered vehicle the signal coming from the 220V power grid across the battery charge plug has to pass through two converters, the AC/DC one needed for the recharging of the 96V power battery pack and the DC/DC 96-12V converter for the access to the inner vehicle loads (lamps, lighter, courtesy lamps etc). Then it is reasonable that in the measured data the signal attenuation to reach the inner vehicle loads is relevant. To reduce this inconvenient specific electric connections to bypass the two converters could be included in the electric scheme.

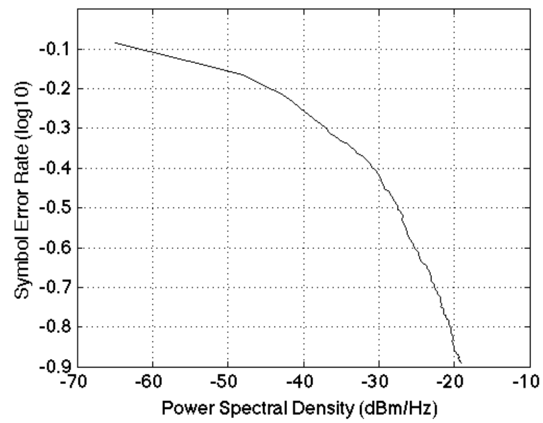

Figure 13. Symbol Error Rate for channel #6

V. Modem Testing

Field tests using a modem dedicated for vehicle PLC were carried out in order to evaluate the performance of PLC inside an electrical vehicle (EV) environment.

The DCB1M modem by Yamar Electronics was used for the testing. The modem is shown in Figure 14. Employing the DC-BUS technology, this modem can operate in extremely noisy environments. The modem is based on phase modulation combined with forward error correction mechanism that is adaptive to channel conditions. This provides several operational modes for communication at bit rates ranging from 1.3Mbps with no data protection down to 230Kbps with maximum protection.

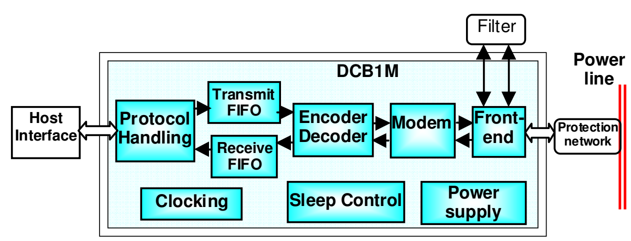

Figure 14. Block diagram of the DCB1M

The setup used for this test is depicted in Figure 15. Two modems, labeled DCB1 (Tr.) and DCB2 (Rec.) were placed in different locations in the vehicle. For the testing, the DCB1M modem, DCB1, repeatedly transmitted predefined sequence of data that was received and analyzed in DCB2 modem side.

The communication measurements were conducted between two extreme locations inside the vehicle: from the cigarette lighter (CL) to the backlights. Various modulation and coding schemes were used. Since this EV has different noise characteristics when driving forward, or backward, we tested the communication performance going both ways. The bit error-rate performance for transmission of 10^5 packets consisting of 250 bits each, are reported in the following table.

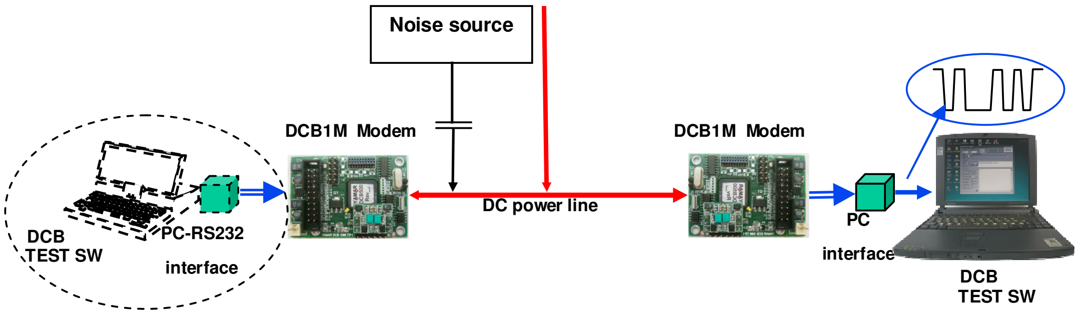

Figure 15. SETUP for DCB1M MODEM TESTING

Codec rate	Throughput [Mbps]	BER FWD.	BER REV.
1	1.3	1.7E-03	6.5E-03
¾	1	9.4E-06	1.8E-04
½	0.6	0	0
1/3	0.45	0	0
¾	0.5	0	4.8E-05
½	0.3	0	0
1/3	0.225	0	0

Field testing conclusions: DCB1M has been proven to sustain reliable communications at bitrates of 600Kbps (and below) in the EV under test. In this EV, driving forward generated less noise than driving backward. As predicted above, communication with in sufficient error-protection is not practical as it the channels in the vehicle are error-prone.

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