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OFDM-based Power Line Communication system for Smart Meter Data Transmission

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***Abstract*—In this paper, the effectiveness of using power line as communication channel for the transmission data from energy meter is developed. The power line channel is modelled as a combination of the transfer function of multipath signal environment and Additive White Gaussian Noise (AWGN). OFDM served as the encoding method for the PLC network interface that ensures high speed data delivering. Forward Error Correction (FEC) technique was employed in the reduction of the high signal error rate caused by noisy channel. In order to evaluate the performance of OFDM-based PLC system, MATLAB software is used to model and simulate a practical multipath power line communication channel model and provides the Bit Error Rate (BER) against signal-to-noise ratio (SNR) curves for OFDM with different modulation schemes (BPSK, QPSK and QAM)). The simulation results showed that BPSK is the most preferred modulation techniques for its considerable performance. The results also indicated that with Convolutional Channel Encoding, there is a significant improvement in BER values.**

Keywords—Smart metering, Noise, Power line, OFDM, Matlab Simulink, PLC, BPSK, QAM, QPSK, SGCN, BER

I. INTRODUCTION

Traditionally, energy consumed by customers is mostly gotten by manually taking periodic readings from the display of electro-mechanical meters installed at their premises. As this method is labour intensive, electronically read measurements that can be transmitted through a communication media are preferred. This can be achieved by different methods of retrofitting on to existing meters [1 - 3]. The main challenge with retrofitting is its limited capability for future expansion; hence it is preferred to install electronic energy meters. The electronic (smart) meters combined with low cost communications and enterprise software, are enabling a wholly new approach to metering [4].

Smart meters deploy advanced information and communication technology to control the electrical consumption [5]. An important characteristic is the communication infrastructure used for data communication. Amongst the popular possibilities include telephone wires, Ethernet cabling, fibre optic cabling, as well as wireless and satellite technologies. However, each of these information transmission techniques has its limitations involving cost and availability to reach the maximum number of users.

Over the past few years, the increasing ubiquity of the data transmission is creating a rapidly growing demand for larger bandwidth to the home and office. This search for new ways of transferring information has introduced Power line Communications (PLC) [7, 8]. PLC technology use existing electrical power lines as a transmission medium to provide data communications capabilities by coupling modulated carrier signal onto the power line. The benefits of implementing this emerging technology are significant, starting from the fact that there is no need for new infrastructure, which is both time consuming and expensive to install. In addition, bearing in mind that no new wires are required, PLC techniques have become even more appealing. A major benefit of using power line as data transmission channel is that the customers' premises are connected to the power grid [8].

A major challenge associated with the transmission of data over the power lines are the susceptibility of channel to noise and interferences as they were not initially designed to carry data but power [9]. Many attempts have made to mitigate such problems over the last two decades through empirical studies of PLC channel and noise [10 - 13].

In this paper, an orthogonal frequency division multiplexing scheme is employed in the efficient transmission of smart meter data over the power line. The power line channel is modelled as a combination of the transfer function of multipath signal environment and Additive White Gaussian Noise (AWGN). MATLAB software is used to model and simulate the developed system.

II. POWER LINE NOISE

Power lines are susceptible to a range of interfering signals which impedes reliable high-speed PLC data transmission. Noise in power lines usually originates from electrical devices connected to the network or in its proximity [14, 15]. It can occur due to the normal operation of some electrical machinery and devices.

Noise in PLC can be classified as background and impulsive noise. Background noise is stationary and can be modelled by the Gaussian distribution. An impulsive noise originates from variation sources such as heating processes, microwave ovens, electric motors and any other electrical sources. According to researches, Middleton Class A based on the Poisson-Gaussian model is most suitable in describing the statistical characteristics of impulsive noise in PLC channels [16 – 20]. The model incorporates both background and impulsive noises. The model given as:

$$p(z) = \sum_{m=0}^{\infty} e^{-A} \frac{A^m}{m!} \frac{1}{2\pi\sigma_m^2} \exp\left(-\frac{z^2}{2\sigma_m^2}\right) \quad (1)$$

with the variance σ_m^2 defined as:

$$\sigma_m^2 = \left(\sigma_g^2 + \sigma_i^2\right) \frac{\left(\frac{m}{A}\right)+\Gamma}{1+\Gamma} \quad (2)$$

where A is the impulsive index, $\sigma_g^2 + \sigma_i^2$ denotes the power of background noise and impulsive noise respectively, and Γ is the ratio background noise power to impulsive noise power.

III. Smart Metering

Smart metering comprises a range of functionalities made possible by the introduction of electronic utility meters, low cost communications and enterprise software. Thus, utility company can now remotely and accurately read and manage meters. A typical smart meter is made up of five functional blocks as indicated in Fig. 1 [4]. This works by sampling the current and voltage waveforms, and then processing the samples to obtain electrical parameters. Furthermore, additional processing and memory capacity is required to perform analysis on the data. This function requires continuous conditional testing of input data and would thus increase the burden on a smart meter's CPU (Central Processing Unit).

IV. Power Line Channel Model

In power line networks, the link between the customer's house and the substation is a bus topology and also varies in length. The numerous in-house wirings are tied up at a junction box, thus causing impedance mismatches in the power line network. These lead to a multipath propagation scenario with frequency selectivity attenuation problem. The channel transfer function is also time-varying and depends on the location of the receiver since different appliances are constantly being switched on or off causing changes in the transfer function. Models of the power line channel transfer function that describes the multipath propagation effects have been proposed by Philipps and Zimmermann and Dostert [21]. The channel transfer function that describes the signal propagation in power lines in the frequency range from 500 kHz to 20 MHz is given by the following:

$$\boldsymbol{H(f)} = \sum_{i=1}^{N} \underbrace{\boldsymbol{g_i}}_{weight} \underbrace{\boldsymbol{e^{-(a_0+a_1 f^k)d_i}}}_{attenuation} \underbrace{\boldsymbol{e^{-j2\pi\tau_i}}}_{delay} \quad (2)$$

where N is the number of relevant propagation paths, g_i and d_i are the weighting factors and length of the i_{th} path respectively, frequency-dependant attenuation is defined by the parameters a_0, a_1 and the exponent k, and τ_i is the path delay given as:

$$\tau_i = \frac{d_i\sqrt{\varepsilon_r}}{c_0} = \frac{d_i}{v_p} \quad (3)$$

where ε_r is the dielectric constant of the insulating material, c_0 is the speed of light and v_p is the propagation speed.

V. Digital Modulation Techniques

Digital Modulation is in great demand as it provides information capacity, high data security, quicker system availability with great quality communication. There are three major classes of digital modulation techniques used for transmission of digitally represented data namely, amplitude shift keying (ASK), frequency shift keying (FSK) and phase shift keying (PSK).

ASK that represents digital data as variations in the amplitude of a carrier wave. The carrier signal will be transmitted when the signal value is 1; otherwise, 0 is transmitted.

FSK transmits information through discrete frequency changes of a carrier signal. It uses a pair of discrete frequencies to transmit binary information. Binary symbol 1 is called the mark frequency and symbol 0, the space frequency.

PSK transmits digital data by modulating the phase of a constant frequency, the carrier wave. It is achieved by varying the cosine and sine signals at a precise time. There are mainly of two types, namely Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK), according to the number of phase shifts.

A. Binary phase-shift keying (BPSK)

In BPSK technique, the sine wave carrier takes two phase reversals such as 0 and π. The expression for BPSK is given as:

$$S_n(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f t + (1-n)\pi), \; n = 0, 1 \quad (4)$$

where E_b is the energy per bit, and T_b is the bit duration.

The bit error rate (BER) of BPSK under additive white Gaussian noise (AWGN) is calculated as:

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \quad (5)$$

where P_b is probability of bit-error and N_0 is the noise power spectral density.

B. Quadrature phase-shift keying (QPSK)

In QPSK technique, the sine wave carrier takes four phase reversals such as 0, $\frac{\pi}{2}, \pi, \frac{3\pi}{2}$. The expression for QPSK is given as:

$$S_n(t) = \sqrt{\frac{2E_b}{T_b}} \cos\left(2\pi f t + (2n-1)\frac{\pi}{4}\right), \quad n = 0, 1, 2, 3 \quad (6)$$

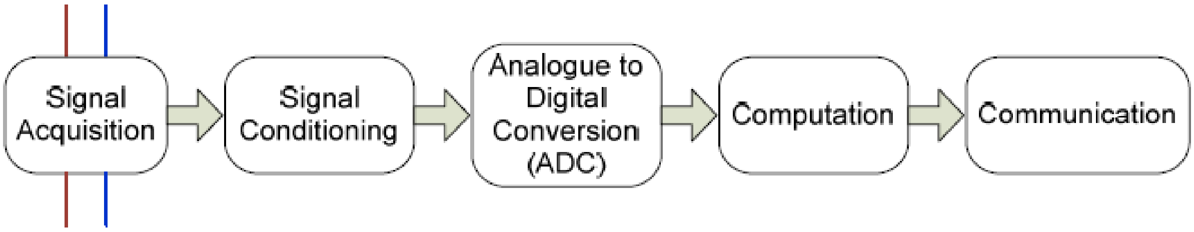

Fig. 1: Smart meter block diagram

The probability of bit-error for QPSK is the same as for BPSK given in (5)

C. *Quadrature amplitude modulation (QAM)*

QAM is based on the application of ASK and PSK to two carrier waves of the same frequency but with a phase difference of $\frac{\pi}{2}$. One of the carrier waves lags the other by $\frac{\pi}{2}$. Their amplitudes are referred to as the in-phase component $I(t)$ and quadrature component $Q(t)$ respectively. Thecomposite waveform is mathematically expressed as:

$$S_n(t) = \sin(2\pi ft)I(t) + \cos(2\pi ft)Q(t) \qquad (7)$$

VI. OFDM

Orthogonal Frequency Division Multiplexing (OFDM) is a digital multi-carrier encoding technique that splits a single carrier modulation into multiple subcarriers within the same single channel. Instead of transmitting a high-rate stream of data with a single carrier, it makes use of a large number of closely spaced orthogonal subcarriers that are transmitted in parallel. Each subcarrier is modulated with a conventional digital modulation scheme (such as BPSK, QPSK and QAM) at low symbol rate. The combination of these subcarriers allows data rates similar to asingle-carrier digital modulation technique of the same bandwidths. Fig. 2 shows a simplified OFDM transmitter model.

S_n is a serial stream of binary digits. By inverse multiplexing, these are first de-multiplexed into N parallel streams, and each one mapped to a symbol stream using a digital modulation technique (constellation mapping). A set of complex time-domain samples is gotten from an inverse FFT computation done on each set of symbols. The samples are then mixed in quadrature. The digital-to-analogue converters (DACs) convert the real and imaginary components into analogue signals which are then used to modulate the sine and cosine waves at carrier frequency, f_c, respectively. The resulting signals are then mixed to give the transmission signal $S(t)$.

The receiver (Fig. 3) picks up the signal $r(t)$, and quadrature-mixed down to base band using sine and cosine waves at the carrier frequency. This also creates signals centred on f_c, which are filtered out by low-pass filters. The resulting baseband are digitized using analog-to-digital converters (ADCs) and converted to frequency domain using forward FFTs. This returns N parallel streams, which are converted to a binary stream using appropriate encoder. The streams are then re-combined into a serial stream,$\hat{S}(t)$, which is an estimate of the original binary stream at the transmitter.

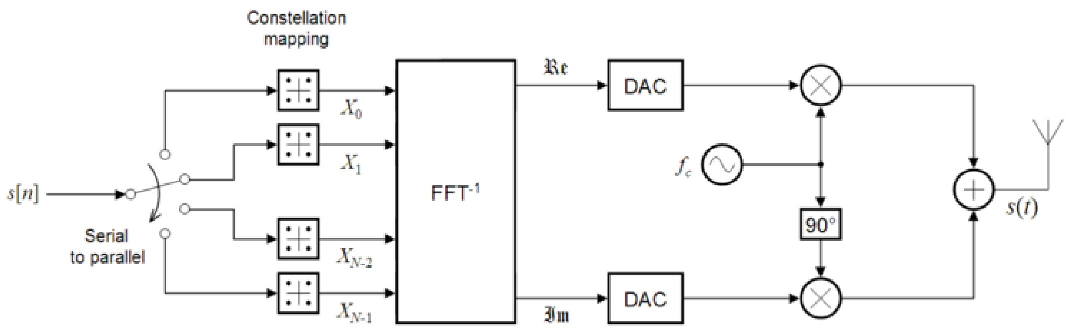

Fig. 2: Block diagram of a simplified transmitter OFDM model

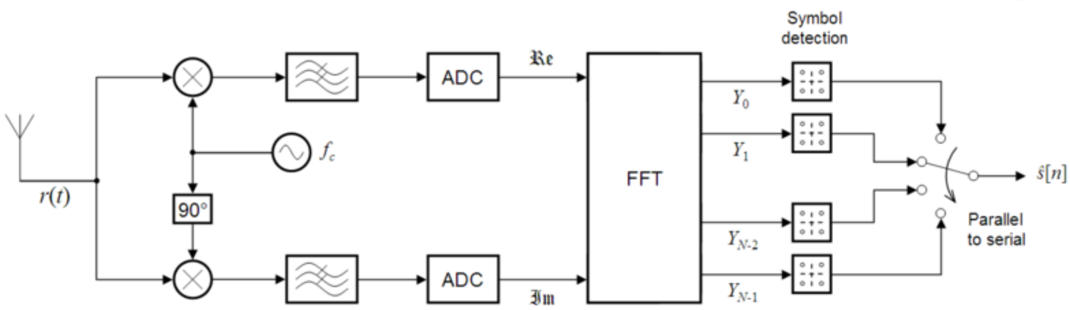

Fig. 3: Block diagram of a simplified OFDM receiver model

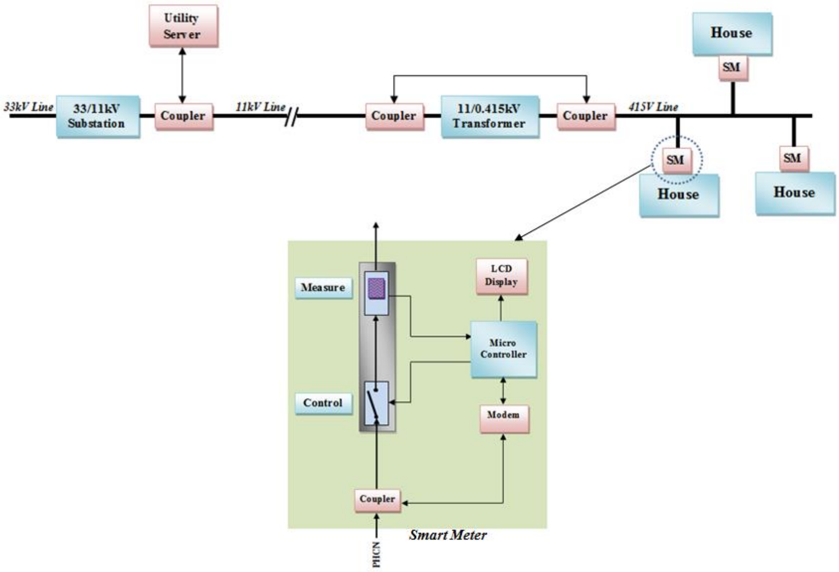

Fig. 4: PLC system Architecture for smart metering

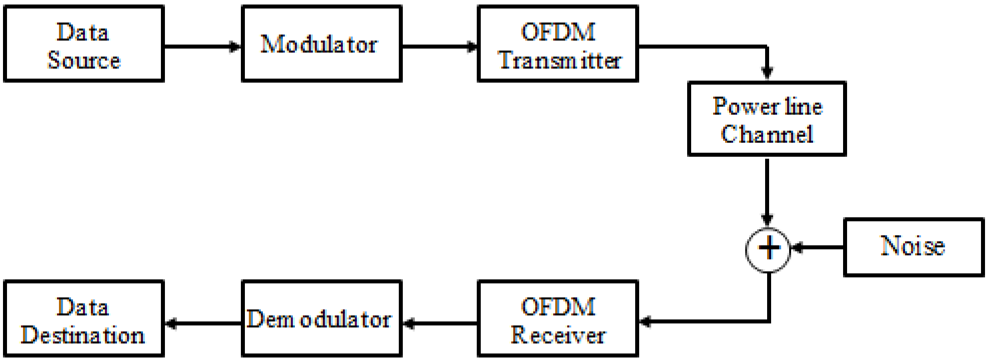

Fig. 5: Block diagram of OFDM-based PLC system

VII. PLC NETWORK MODEL

The PLC network is designed to meet certain requirements as both data and electricity need to be transmitted along the power lines. This requires a number of intermediate network devices positioned at the substation, at the distribution transformer, and in the home in the form of smart meters as shown in Fig. 4.

At the Substation, high frequency modulated data from utility company is coupled unto 50Hz power supply. The Transformer transmits data from medium to low voltage lines. Couplers act as High Pass filters that make coupling of data unto power line a reality. Couplers also bypass the distribution transformers and allow only high frequencies to pass through. The smart meter is the last node in a PLC system. OFDM in the modem is the encoding method that is used for the PLC network interface and helps provide physical and data link layer encryption. Fig. 5 shows a block diagram of the OFDM-based PLC system.

VIII. RESULT

The proposed OFDM-based PLC system for smart metering data transmission was modelled and simulated in Simulink environment of MATLAB 2019a with parameters presented in Table 1.

Table 1: Simulation parameters

Parameters	Values
Number of subcarriers	64
Modulation types	BPSK/QPSK/QAM
FFT block size	128
Number of occupied subcarriers	52
Length of CP	32
Numbers of bits	52×10^6

To investigate the effect of modulation schemes on the developed system, BER values for different SNRs were obtained for BPSK, QPSK and QAM modulation schemes and plotted as presented in Fig. 6. It is observed that BPSK had the lowest bit error rate (BER) thus, a better scheme than QPSK and QAM.

Furthermore, the different modulation schemes were with convolutional coding was investigated is shown in Fig. 7. It is observed that although there is a great improvement in BER values with the introduction of convolutional coding for the three modulation schemes, BPSK still offers a better performance than QPSK and QAM. The effect of convolutional coding rate for the system was also investigated and result is shown in Fig. 8. It is observed that a coding rate of ½ offers best performance.

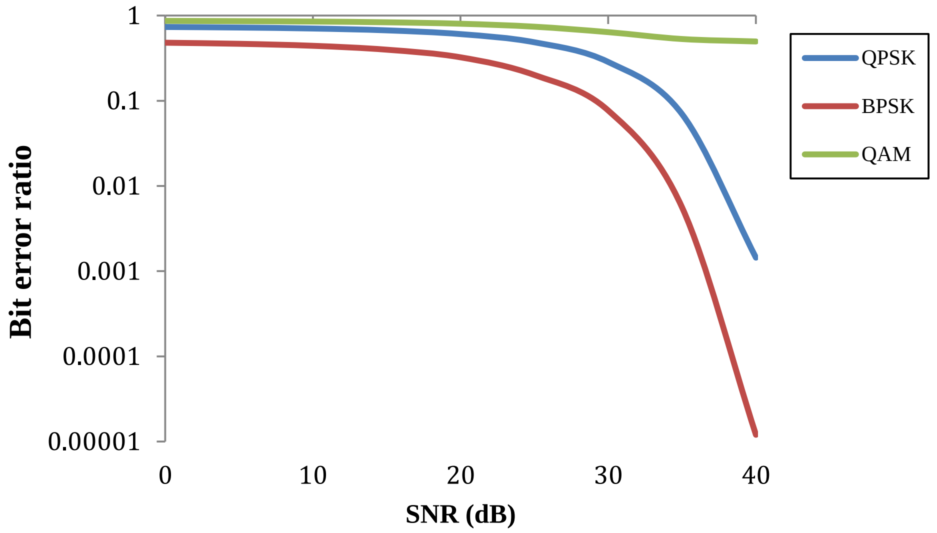

Fig. 6: BER curve of PLC channel using OFDM with BPSK, QPSK and QAM

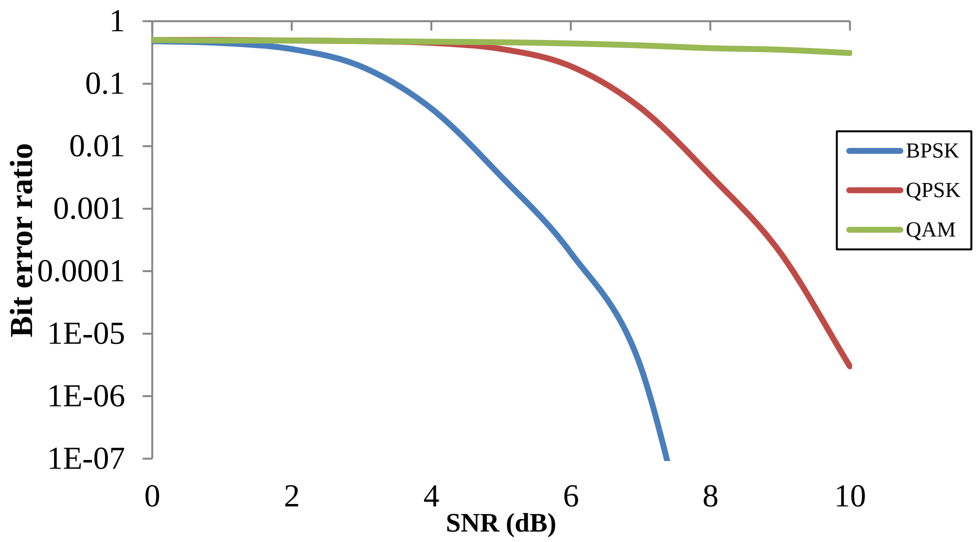

Fig. 7: Convolutional Coded-OFDM with Different Modulation

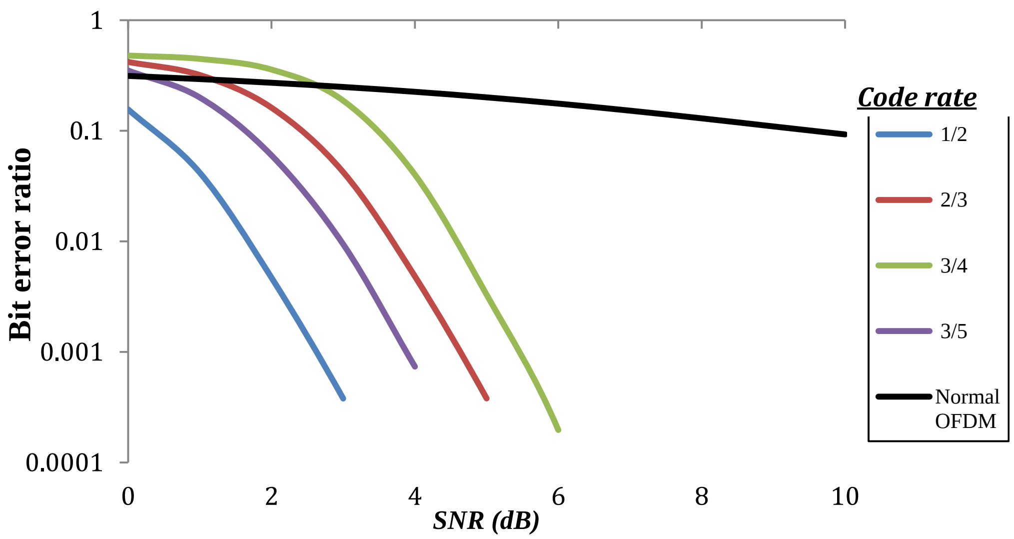

Fig. 8: Convolutional Coded-OFDM at Code Rates

IX. Conclusion

In power line communication, electric power lines are used for communication purposes along with transmitting electrical energy. Since power network is already in place, deployment of PLC technology has the obvious advantage of reducing communication infrastructure cost. However, the power grid is designed optimally for delivery of power and not data. The power line channel generally appears as a harsh environment for the low-power high-frequency communication signals. In this work, PLC communication channel which is a combination of communication model, power line model and noise model was developed. The communication model was realized as an OFDM system, power lines were modelled from the transfer function of multipath signal environment and noise model were modelled as Additive White Gaussian Noise (AWGN). The results of the simulations done to investigate the effect of different digital modulation schemes on the OFDM-based PLC system, BPSK had the least bit error rate among the modulation techniques considered even though they were individually combined with convolutional coding.

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