A low SNR approach to Substation Communication using Powerline for EMI reduction

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***Abstract*— Use of space time code concatenated with BCH (Bose Choudhari Hocquenghem) code is analyzed for performance in powerline channel with impulse noise. Performance of BCH-Space time code is worked in this paper for application of narrowband power line communication. BCH code (63, 36) with t=5 is designed and implemented in TMS320C6713 Digital Signal Processor, which is interfaced with Matlab version 7.4, where power line channel and impulse noise are simulated. These results are compared with Turbo coded OFDM scheme for powerline channel. From the results, reduction in carrier power requirement is found for BCH Space time code. Space time code has now become popular in wireless communication, as application in multipath channel. Since power line can provide different uncorrelated paths to realize multipaths effect, it is possible to apply space time code for powerline channel. In this paper, powerline is modelled as a multipath channel and impulse noise as Middleton class-A noise, on Matlab 7.4 platform. The BCH code of n=63, k=36, t=5, is designed and tested in a Digital Signal Processor (DSP) TMS320C6713. Interfacing is done using JTAG from processor to Matlab where power line, impulse noise and space time code are simulated. The performance of the system as communication system for narrowband PLC is tested for different channel and noise conditions. The results are used to find SNR requirement at a Pe (Probability of error) of the order of 10-5 and for carrier signal strength to be within EMI (Electro Magnetic Interference) and EMC(Electro Magnetic compatibility) limits. Use of a BCH code with more better error correcting capacity, will further reduce the SNR requirement, hence will reduce carrier power.**

I. Introduction

Electric power industry has confronted many new challenges in the deregulated environment. There has been increased pressure on the electricity utilities to utilize network assets more effectively and provide a reliable and high quality power supply with real time monitoring. This requirement also calls for the concept of smart grid. In order to improve service reliability, the existing substation should be automated for faster fault location and clearance, cooperating with the feeder automation. And in the past decade, new communication schemes have been designed to integrate data from relays and Intelligent Electronic Devices (IEDs) and capitalize on the protection, control, metering, fault recording communication functions available in digital devices [1,4,9]. This refers to substation monitoring wherein the critical requirement utility substations operate a range of potentially volatile equipment, which needs constant proactive monitoring to ensure that potential problems are identified and handled at the earliest stage. Generally, station bus is used to connect all equipments inside the substation. Many sensor technologies are available to monitor the myriad equipment located within a substation. The challenge lies in transferring the data collected by the sensor from the transformer cost-effectively and efficiently back to the control house, or regional control center without compromising security, speed or reliability.

Advances in powerline communications (PLC) technology provide an important new option, enabling a cost-effective, reliable and above all, real time remote monitoring platform to ensure that substation equipment is kept at the optimum performance levels.

Running hard wire cables out to the transformers to read monitoring equipment is difficult to accomplish due to underground high voltage wiring. With a substation's field consisting of gravel and concrete, trenching is also extremely expensive and time-consuming. Where a suitable right-of-way between the control house and remote sensors exists, the fiber plus the required SCADA and media converters are cost-prohibitive. The magnetic and electrical fields, along with the high voltage equipment, can interfere with wireless signals, resulting in unknown signal strength and reliability. The use of powerline communications equipment could potentially avoid tens of thousands of dollars to install dedicated copper or fiber communication lines in existing substations, if Intelligent Electronic Devices (IEDs) need to be connected.

The powerline communication systems used in substation environment should follow regulatory norms of EMI (Electromagnetic Interference) and EMC (Electromagnetic compatibility). EMC is the ability of a device or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances in the form of interferences to any other system in that environment, even to itself. Without producing intolerable disturbances, meaning that the equipment does not bother other equipment. The emission of EM signals by the equipment does not cause electromagnetic interference problems in other equipment that is present.

A communication system used for power line channel can be designed to have electromagnetic compatibility, provided

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care is taken to make it function with lower signal power to be within EMI norms. Different approaches such as OFDM (Orthogonal Frequency Division Modulation) and Spread Spectrum system are studied and implemented for Broadband power line communication. Regulatory limits for narrowband PLC and broadband PLC are slightly different. Powerlines radiate causing EMI at higher frequencies causing difficulty in broadband applications. It is to be recalled that broadband applications of powerline as a channel, cater to internet applications in the range of 2 to 30 MHz but narrowband applications cater to automation within 500 KHz. Design of present day MODEM (Modulator –Demodulator), can be enhanced with latest technology that requires lesser carrier power and comply with regulatory limits. A combination of a modulation and channel coding that reduces SNR (Signal to Noise Ratio), will be the key point for further progress in the field of narrowband PLC. This paper is to suggest digital communication scheme for narrowband application in substation automation.

II POWER LINE CHANNEL

The channel provided by power line has a transfer function that is both time variant and frequency variant. This means powerline channel is a harsh channel for sending high frequencies. Investigation into the behaviour of powerline channel has led to powerline channel being treated as a multipath channel [1], [2].

A. Modelling Power Line Channel

Powerline channel can be modelled by echo mode as in case of a fading channel, as there are reflecting paths caused on line due to impedance mismatches arising due to random switching on and off of other points.

$$H(f) = \sum_{i=1}^{N} g_i \cdot e^{-(a_0 + a_1 \cdot f^k) \cdot d_i} \cdot e^{-j2\Pi f \tau_i} \tag{1}$$

Equation (1) gives the transfer function that is used to model the powerline channel. It takes into account the time variant and frequency variant behaviour of the powerline channel, obtained by echo model of a multipath channel. g_i in (1) represents the gain of each path at i^{th} instant, exponent of second term in (1) represents the attenuation of H(f) with respect to frequency and the exponent of third term in (1) represents the delay (phase changes) in the received multipaths at i^{th} instant. N represents the number of multipaths in fading channel and number of disturbance points in a power line channel. d_i are lengths of disturbance points along the power line. [2] gives more details of (1).

B. Modelling impulse noise

$$f(x) = \sum_{m=0}^{\infty} \frac{A^m}{m!} e^{(-A)} \left[\frac{1}{\sqrt{2\Pi \sigma_m^2}} \right] \cdot e^{\left(\frac{-x^2}{2\sigma_m^2} \right)} \tag{2}$$

Equation (2) suggests that Middleton Class A noise model [16], [13] that refers to cumulative sum of Gaussian distributions where $(\sigma_m)^2$ is noise variance, with $(\sigma_m)^2 = \sigma^2 (m/A+T) / (1+T)$, index $T = (\sigma_G)^2 / (\sigma_{GI})^2$ is the GIR (Gaussian-to-Impulsive noise power Ratio) with Gaussian noise power $(\sigma_G)^2$ and impulsive noise power $(\sigma_{GI})^2$. And $\sigma^2 = (\sigma_G)^2 + (\sigma_{GI})^2$ is the total noise power. The noise x followed by (4) always includes the background Gaussian noise with power $(\sigma_G)^2$.

In [2], several noise sources that can be found on low- or medium-voltage power grids are explained, such as, for example (i) colored thermal noise, (ii) periodic asynchronous impulse noise related to switching operations of power supplies, (iii) periodic synchronous impulse noise mainly caused by switching actions of rectifier diodes. Reference to different literature, suggests that analysis of power line with impulse noise justifies the check for power line communication performance.

C. Space time code.

A multipath channel is also called as fading channel, due to characteristic of fading phenomenon of multipath channel. Fading is the property of instantaneous variation of signal power in a multipath channel. In [3], inventions of S.M. Alamouti, the so-called Alamouti space–time block codes are presented, which are accepted for wireless (fading) channel.

As in [3], A ‘2 transmit one receive antenna (2x1) space-time communication system’ has the transmission scheme as given by Table I.

Table I Transmit scheme for 2x1 space time code

	Time instant t1	Time instant t2
Transmitter point 1	symbol 1	-Conj(symbol 2)
Transmitter point 2	symbol 2	Conj(symbol 1)

s_0, s_1 are symbols transmitted in two time slots as per Table 1. ‘r’ is received signal; H_0 and H_1 are transfer functions of path 1 and path 2 respectively, also called as channel states. s_{0e} and s_{1e} are estimates of symbols s_0 and s_1 at time slots t_1 and t_2 at the receiver, which are determined by (3) and (4).

$$s_{oe} = conj\,(H_0) \times r_0 + H_1 \times conj\,(r_1) \tag{3}$$

$$s_{1e} = conj\,(H_1) \times r_0 - H_0 \times conj\,(r_1) \tag{4}$$

Recovery of symbols s_0 and s_1 are further found by minimum distance of s_{oe} and s_{1e} with symbols s_0 and s_1.
The detailed mathematical support to derive receiving scheme is given in [3]. It is seen that recovery at the receiver requires the knowledge of channel states. i.e. signal estimation and detection at the receiver requires the knowledge of the channel states (Channel State Information). In the work presented in this paper, channel estimation is performed by adding known dummy pilot symbol along with data symbols.

C. Multipaths for a Powerline Channel

The two transmitting antennas in the Alamouti’s space time coding scheme can be realized in power line channel, by injecting modulated signal to two different paths formed utilizing a single phase system [4] as shown in Fig.1 Equivalent to two fading paths in a wireless channel, the two different paths chosen for signal transmission in power line are statistically uncorrelated and thus make it possible to use the space time scheme.

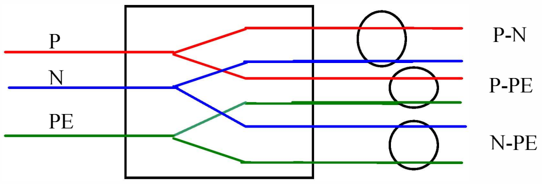

Fig. 1 Splitter used for MIMO paths in a single phase powerline [4]. P-Phase, N-neutral, PE-Protective Earth

Similarly, two uncorrelated paths can be obtained in a three phase system [5], as shown in Fig.2.

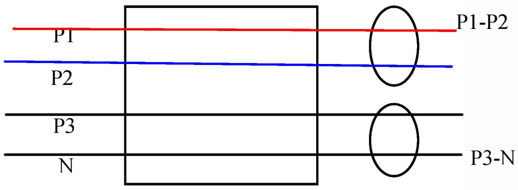

Fig. 2 MIMO paths in a three phase powerline [5]. P1-Phase 1, P2-Phase 2, P3-Phase 3, N-Neutral

From Fig. 1 and Fig. 2 it thus becomes clear that a power line channel can be realized as a '2x1 space time communication system', by injecting and receiving the signal using P-N and P-PE in case of a single phase powerline system and by injecting and receiving the signal using P1-P2 and P3-N.

D. Design of Turbo code

The recursive systematic convolutional (RSC) encoder [7, 8] is obtained from the non recursive nonsystematic (conventional) convolutional encoder by feeding back one of its encoded outputs to its input. The generator matrix for two memory RSC encoder used in this paper is given by G = [1 $(1+D^2)/(1+D+D^2)$]. The numbers of states generated are four. For decoding BCJR decoding is used. The BCJR algorithm works on a trellis representing the finite-state machine and its complexity is proportional to the number of trellis states. The algorithm calculates the aposteriori L values called the APP L values, of each information bit.

E. Design of OFDM

In OFDM, data over narrowband carriers is transmitted in parallel at different frequencies. Spectral efficiency is achieved by using these parallel subchannels that are as closely spaced as possible in frequency without overlapping/ interfering, by being orthogonal. Typically, ISI (Intersymbol Interference) comes from multi-path delays. By its very nature OFDM defeats multipath distortion. Designs that have led to integrated chips and modems that have been introduced into the market, providing high speeds over the power line at low costs for BPL(Broadband over Power Line) [11]. Out of many forms of modulation that could be used over the power line, OFDM is identified as the most suitable, because of its immunity to the frequency selective fading channels, which is studied by simulation studies.

In OFDM scheme of modulation, data symbols are first mapped for the desired modulation (binary or M-ary). The mapped data symbols are now viewed as being in frequency domain and are further modified to parallel streams to convert frequency points to time domain points using IFT (Inverse Fourier Transform). Cyclic prefix (padding last few bits of IFT to initial stream of IFT output). IFT output is transmitted on channel after passing through DAC (Digital to analog converter). The received output is the convolution of the IFT signal and channel impulse response. At the receiver, cyclic prefix is removed, passed through DAC (Digital to analog converter) and FT (Fourier Transform) block to get back the data as frequency points.

F. Design of BCH(Bose Choudhari Hocquenghem) code

BCH codes are cyclic codes discovered independently by Hocquenghem in 1959 and later by Bose and Roy-Choudhari independently in 1960. BCH codes form large class of multiple random error correcting codes and are the most powerful algebraic codes, i.e. they have a good algebraic structure[6]. Berlekamp introduced the first truly efficient algorithm for decoding both binary and non binary BCH codes in 1967. This was further developed by Massey and is usually called Berlekamp- Massey decoding algorithm[6].

III RESULTS

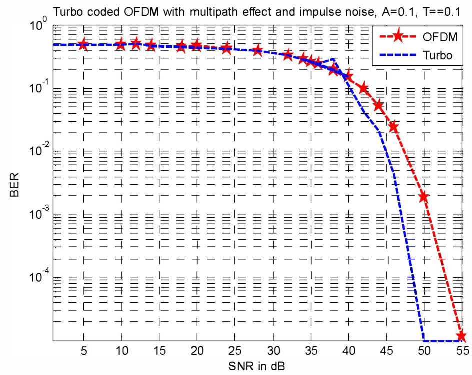

Fig.3 BER vs SNR for Turbo coded OFDM for powerline channel with impulse noise

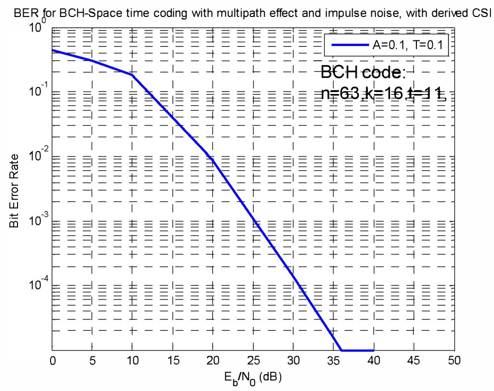

Fig.4 BER vs SNR for BCH(n=63, k=16, t=11) coded Space time code for powerline channel with impulse noise.

Results obtained by (i) Turbo coded OFDM as shown in Fig. 4 and (ii) BCH coded space time code as shown in Fig 5, are compared in this paper.

Recursive systematic convolutional (RSC) encoder as explained in section D, with simple rectangular interleaver is used to design four state Turbo code [6]. Decoding is performed by BCJR algorithm [7]. OFDM with 32 subcarriers is realized using ifft and fft blocks. Powerline channel is modelled using echo model using (1). Convolution of the output of Turbo coded OFDM signal and channel impulse response using (1), is performed and the impulse noise using (2) is added to obtain received signal. BER (Bit error rate) vs SNR (Signal to noise ratio) graph is shown in Fig. 3. An iteration of 5 is used for Turbo code. The Turbo coded OFDM scheme is realized on Matlab 7.9 platform.

Similarly a BCH code of t= 5 error correcting code with n= 63, k=36 is designed and decoding is performed with Berleykamp Massey algorithm. 2x1 space time code is thought to be realised using details in Fig. 1 and Fig.2. PSK (Phase shift Keying) modulated is used to modulate space time encoded data. 1000 frames of 63 bits are sent over powerline channel, for each SNR value in Fig. 4. A zero is padded to each frame of 63 bits, to facilitate space time encoding, that requires two bits to encode at any time instant as in Table I. Dummy pilot symbols added along with data symbols for each frame thus forming frame size as 128. Channel transfer function realised using (1), is assumed same for one frame but changes randomly for each frame. After verifying on a 'C' platform, BCH encoder and decoder are realized in TMS320C6713 digital signal processor, using code composer studio (ccs) v 3.1, in order to check the realizability of BCH code in real time. Power line channel realized in Matlab 7.4 is interfaced with ccs and monitored in Matlab.

Echo model consisting of five paths with disturbing path lengths from 5 to 50 meters for (1), is used to simulate powerline channel and A=0.1, T=0.1 for (2), is used to simulate impulse noise, for both case of results in Fig. 3 and Fig.4.

III CONCLUSIONS

From the results of Fig.3 and Fig.4 it is thus concluded that BCH coded Space time code performs better than Turbo coded OFDM, for the same environment of powerline channel with impulse noise. Graphs show the coding gain of 15 dBs at P_e of 10^{-5}.

To obtain results of Fig.5, there is overload of 64 pilot bits plus 27 parity bits per a frame of 64 bits (with n=63, k=36 BCH code). In comparison with this, there will be overload of about 64 bits for each 32 bits as code rate of Turbo code is 1/3, plus overload of about 100 bits for each of these 32 frequency points in ifft signal at transmitter, as there is need to add guard band bits and to add equal number of complex conjugate points and need to add cyclic prefix. The space time code scheme can be realized using splitter arrangement in a single phase powerline and without any splitter in a three phase powerline. The performance of Turbo coded OFDM method can be improved by use of channel equalizer and performance of BCH coded space time code can be improved by use of improved method for channel state estimation.

For a powerline channel, study of impulse disturbances are sufficient with A=0.1, T=0.1 and A=0.1, T=0.01. As per the results shown in this paper, for A=0.1 and T=0.01, the SNR requirement will be more than 35 dBs. SNR requirement for P_e of 10^{-5} for a BCH coded space time code can further be reduced by using higher error correcting capacity BCH code.

As per the results shown in this paper, consider the performance point of $P_e = 10^{-5}$ and assuming psd (power spectral density) of white noise as 10^{-6}, than say at a maximum value of SNR of 40 dBs for a heavily disturbed channel, the signal power will be 100mW and carrier signal strength of 10 mV. The present EMC regulations for narrowband powerline communication are 134 dBμV or 63mV. SNR requirement for P_e of 10^{-6} for a BCH coded space time code can further be reduced by using higher error correcting capacity BCH code.

Thus a communication scheme for a narrowband power line communication for substation automation is suggested that allows to follow EMI/EMC regulations. The scope of the work is to measure psd of noise in a substation environment, implement the proposed BCH space time in real time and use a suitable BCH code for the carrier signal strength to be within regulatory limits.

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