Adaptive CPFSK Modulation for Power Line Communications

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ABSTRACT

Power-line communication (PLC) has an advantage that it can use existing facilities for communication, but it may not be suitable for wide-band signal transmission due to the nature of the power-line. In this paper we consider the use of adaptive CPFSK modulation scheme robust to harsh power-line channel condition. The modulation parameters are initialized and adjusted during the data transmission without interrupt by using line probing technique. The performance of the proposed scheme is analyzed and verified by computer simulation.

I. INTRODUCTION

In recent, power-line communication (PLC) has been considered as one of possible solutions for rapidly increasing demand for multimedia services, because it can use incumbent power-line network without additional wiring. However, since the power-line is designed for transmission of the electricity, it does not provide channel characteristics of good quality suitable for high-speed communications. In particular, the characteristics of the power-line significantly vary depending upon the switch status (i.e., on/off) of the electrical loads [1]. As a result, it may be desirable to employ a modulation scheme robust to time-varying channel characteristics.

Recent studies have considered the use of continuous phase modulation (CPM), spread spectrum (SS) and multi-carrier modulation (MCM) as an efficient modulation scheme for PLC. Since the SS scheme requires large bandwidth to obtain a large processing gain, it may not appropriate for high-speed communications and it has inferior performance compared to the MCM [2]. The MCM modulates each sub-channel independently, it may be suitable for frequency selective PLC channel, appropriate for high-speed communication. However, the implementation complexity is high compared to single carrier modem and it may require an expensive analog-front-end due to high peak-to-average power ratio (PAR). Also, the MCM is shows weakness to impulsive noise in PLC environment [3]. Although the CPM has low spectral efficiency, it features low system complexity and favorable performance due to low PAR and robustness to amplitude variation and impulsive noise [3]. The CPM decreases the sidelobe of the power spectrum by means of continuously connecting the phase that contains the information. In this paper, we use CPFSK modulation, a sort of CPM, as a robust modulation scheme in the variation of signal amplitude.

The adaptive modulation scheme has been studied to utilize bandwidth efficiently in voice-band modem using telephone line from late 1980’s. In wireless QAM system, it is possible to achieve nearly optimum performance by changing modulation level, the channel coding rate and the transmit power [4][5]. In MCM, an adaptive modulation that allocates subcarrier bit and assign suitable amount of power for channel condition [6][7]. Although the CPFSK has been studied as a robust modulation scheme under harsh channel condition, there is few research on an adaptive modulation of CPFSK.

In this paper, an adaptive CPFSK modulation scheme is designed so as to maximize the transmission rate, while providing the desired bit error rate (BER) without any interruption of the transmission when the channel condition is changed.

II. CHANNEL PROBING

It is well understood that the characteristics of the power-line channel is abruptly changed due to the operation of the electrical loads. To obtain the optimum performance, it is required to estimate the channel condition so as to adjust the modulation parameters. As a practical method, the use of line probing (LP) has been applied to QAM-based voice band modems [5]. Since the CPFSK modulation scheme is much simpler than QAM, the line probing idea can be easily applied to PLC environment.

It is desirable for the LP signal to be generated in a simple way, while having a minimum PAR. Since we consider the use of the bandwidth between 4 and 12 MHz and the symbol rate of up to 1Mbaud, it may suffice to use tone signals spaced by 0.5MHz. The PAR of the LP tone signal can be minimized by controlling the phase of each tone. For ease of implementation, we consider the use of tone signals with 0° and 180° phase. Fig. 1 depicts the frequency response of the designed LP signal, yielding a PAR of 2.56dB.

For line probing, the periodic LP signal with a period of L is repeatedly transmitted. Let $r_i(n)$ be the received signal corresponding to the i -th period of the LP signal $s(n)$,

$$r_i(n) = s(n) + v_i(n) \tag{1}$$

where $v_i(n)$ denotes the additive noise term. Taking the discrete Fourier transform (DFT) of $r_i(n)$, we have

$$\begin{aligned} R_i(k) &= \sum_{n=0}^{L-1} r_i(n)\exp(-j2\pi knT) \\ &= S(k) + V_i(k) \end{aligned} \tag{2}$$

where $S(k)$ and $V_i(k)$ denote the DFT of $s(n)$ and $v(n)$, respectively. Letting $\bar{R}(k)$ be the time average of $R_i(k)$,

$$\begin{aligned} \bar{R}(k) &= \frac{1}{M}\sum_{i=0}^{M-1} R_i(k) \\ &= S(k) + \frac{1}{M}\sum_{i=0}^{M-1} V_i(k) \end{aligned} \tag{3}$$

the power spectrum of the signal component can be estimated as

$$\begin{aligned} \hat{G}_S(k) &= \left|\bar{R}(k)\right|^2 \\ &= \left|S(k)\right|^2 + \left|\frac{1}{M}\sum_{i=0}^{M-1} V_i(k)\right|^2 + \frac{2}{M}\mathrm{Re}\left[S(k)\sum_{i=0}^{M-1} V_i(k)\right] \end{aligned} \tag{4}$$

Assuming that the additive noise is a zero-mean random process and uncorrelated with the signal, $\hat{G}_s(k)$ is an unbiased estimate with variance inversely proportional to M .

The power spectrum of the noise can be estimated by eliminating the power spectrum of the signal from the power of the received signal. The power spectrum of the received signal can be estimated as

$$\begin{aligned} \bar{G}_R(k) &= \frac{1}{M}\sum_{i=0}^{M-1} G_{R_i}(k) \\ &= \left|S(k)\right|^2 + \frac{1}{M}\sum_{i=0}^{M-1}\left|V_i(k)\right|^2 + \frac{2}{M}\sum_{i=0}^{M-1}\mathrm{Re}\left[S(k)V_i^*(k)\right] \end{aligned} \tag{5}$$

The power spectrum of noise signal can be estimated as

$$\begin{aligned} \hat{G}_V(k) &= \bar{G}_R(k) - \hat{G}_S(k) \\ &= \frac{1}{M}\sum\left|V_i(k)\right|^2 - \left|\frac{1}{M}\sum V_i(k)\right|^2 \end{aligned} \tag{6}$$

Fig. 2 depicts a block diagram of the channel estimation module. Since we are considering the use of 4- or 2- level CPFSK with a symbol rate of up to 1 Mbaud, the information required for determining the modulation parameters can be obtained by the LP method.

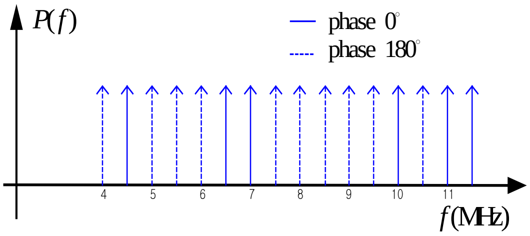


Fig.1 Frequency response of the LP signal

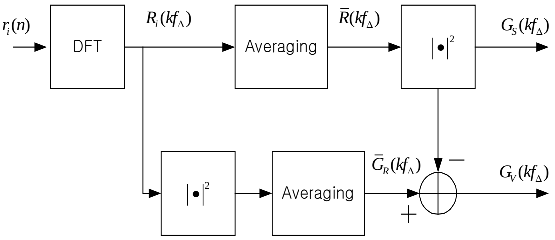


Fig. 2 Block diagram of channel estimation module

III. ADAPTIVE CPFSK MODULATION

A carrier-modulated CPM signal $s(t)$ can be expressed as [9]

$$s(t)=\sqrt{\frac{2E}{T}}\cos[2\pi f_c t+\phi(t:I)+\phi_o] \qquad (7)$$

where E represents the symbol energy, T is the symbol duration time, f_c is the carrier frequency and $\phi(t:I)$ is the information phase represented as

$$\begin{aligned}\phi(t:I)&=2\pi f_d T\sum_{k=-\infty}^{n-1} I_k+2\pi f_d(t-nT)I_n \\ &=\theta_n+2\pi h I_n q(t-nT)\end{aligned} \qquad (8)$$

Here f_d is the peak frequency deviation, h is the modulation index equal to $2f_dT$, θ_n denotes the phase accumulation of the symbols up to time $(n-1)T$, i.e.,

$$\theta_n=\pi h\sum_{k=-\infty}^{n-1} I_k \qquad (9)$$

and $q(t)$ is the impulse response of the phase shaping pulse defined as

$$q(t)=\begin{cases}0\ , & (t<0)\\ t/2T, & (0\le t\le T)\\ 1/2, & (t>T)\end{cases} \qquad (10)$$

The use of $h=1.0$ keeps the FSK tone signals orthogonal, appearing to be optimum in additive white gaussian channel. However, this may not be optimum in the frequency selective power-line channel. The use of h less than 1.0 may result in a BER performance better than the use of $h=1.0$. If the received FSK tone signals have equal power with the use of power control, the use of $h=1.0$ provide better performance than any other h .

Although negligible SNR gain is obtained by controlling the FSK modulation level, the modulation level control can be used to avoid performance degradation due to frequency selective nulls. But, the SNR gain can be obtained by controlling the symbol rate R_s, since the detection bandwidth W is proportional to R_s. That is, the received SNR $\gamma(R_s,M)$ according to the symbol rate R_s and modulation level M can be approximated as [10]

$$\gamma(R_s,M)\simeq\gamma(R_s/2,M)-3dB \qquad (11)$$

$$\gamma(R,M)\simeq\gamma(R,M/2) \qquad (12)$$

It can be seen that halving the symbol rate cans provide 3dB SNR gain because the noise bandwidth is also halved.

To provide optimum performance, the received SNR γ_i of each tone in the available bandwidth is estimated using the LP method in the beginning. The LP finds out the signal bandwidth that provides the maximum average SNR. Since the channel is not ideal, we apply the power control to each tone. After the bin power control, the average SNR can be represented as

$$\hat{\gamma}_{av}=\gamma_{av}+10\log_{10}\frac{R_{s,\max}}{R_s}\ \ \text{(dB)} \qquad (13)$$

where $R_{s,\max}$ is the maximum symbol rate, R_s is the current symbol rate, γ_{av} is the average SNR and $\hat{\gamma}_{av}$ is the achievable average SNR due to the symbol rate control in the receiver. If the difference between γ_i 's in the selected bandwidth is larger than the maximum amount of the gain adjustment, ΔG, it may be desirable to find out another bandwidth that has the average SNR with the next largest value. This procedure goes until the difference is less than ΔG. If such a bandwidth is not found, the procedure is repeated with a halved symbol rate. Here the value of ΔG needs to be determined by considering the effect of the sidelobe of the tone to the adjacent tones and the dynamic range of the power amplifier. If

$$|\gamma_i-\hat{\gamma}_{av}|\le\Delta G,\ \ 1\le i\le M, \qquad (14)$$

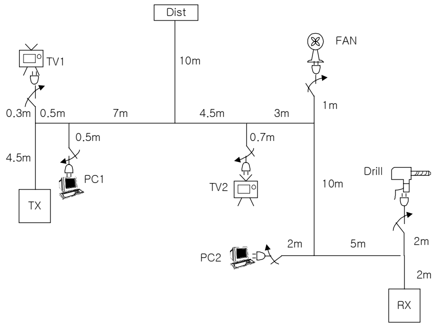
the transmit signal power is controlled so that the received signal has tones with equal power. Since the transmit power should be unchanged after the power control, the gain g_i for each tone should satisfy

$$\frac{1}{M}\sum_{i=1}^{M} g_i^2=1 \qquad (15)$$

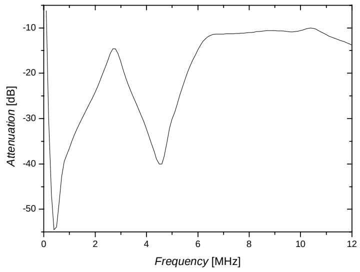
If $\hat{\gamma}_{av}$ is less than the SNR required for specified BER, it is required to control the symbol rate.

IV. PERFORMANCE EVALUATION

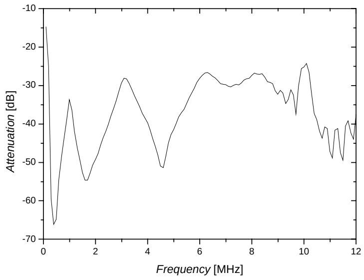
To evaluate the performance of the proposed adaptive modulation scheme, we consider a CPFSK based PLC modem with a maximum transmission of 2Mbps, when the available bandwidth is 4~12MHz. The PLC modem employs 4- or 2-level CPFSK modulation at a symbol rate of 0.25, 0.5 or 1Mbaud depending upon the channel condition. Fig 3 depicts the structure of the power-line network considered for performance evaluation. Fig. 3 (b) and (c) illustrate the frequency responses of the channel when only PC 1 is on and others are all off, and all the loads are switched on, respectively.



(a) Example of the power-line network



(b) PC1 on, others off



(c) All switches on

Fig. 3 Example of the power-line network

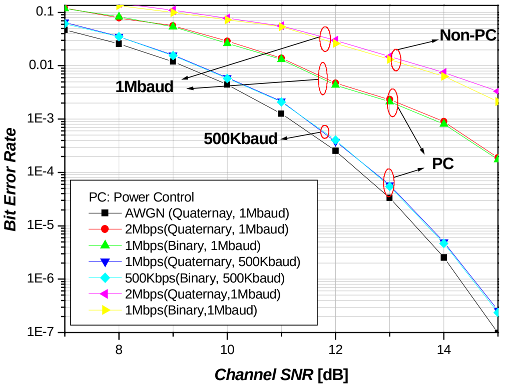


Fig. 4 BER performance

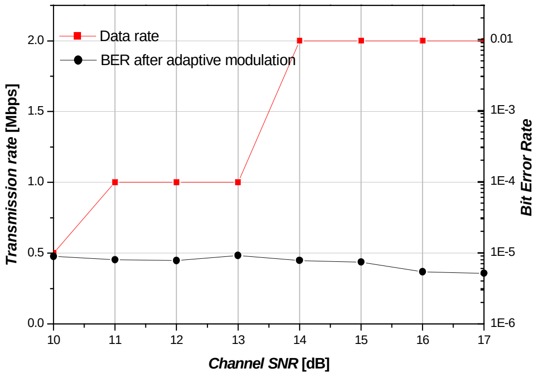


Fig. 5 Performance of adaptive modulation scheme

Fig. 4 depicts the BER performance when the proposed scheme with $\Delta G = 5dB$ is applied to the channel shown in Fig. 3. It can be seen that the use of bin power control significantly improve the receiver performance and that the use of halved symbol rate can provide an SNR gain of 3dB. It can also be seen that there is a performance gap of approximately 3dB compared to the AWGN case. This is because bin power control can not compensate channel distorsion completely.

Fig. 5 depicts the receiver performance in terms of the transmission rate and BER when the proposed scheme is applied to the channel condition Fig. 3(b). It can be seen that the adaptive CPFSK system provides the required 10^{-5} BER performance by adjusting the symbol rate and modulation level according to the SNR condition.

V. CONCLUSION

In this paper, we have proposed an adaptive CPFSK modulation scheme that can transmit the data at a maximum rate of 2Mbps without interrupt under time-varying power-line channel condition. The modulation parameters are initialized by estimating channel information using the line probing technique. The modulation parameters are adjusted to provide a desired BER performance without interrupting the data transmission when the channel condition is suddenly changed. Simulation results show that the adjustment of each tone power, symbol rate and modulation level can provide performance quite robust to time-varying power-line channel condition.

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