Design of a Robust modem for Power Line Communications

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ABSTRACT

We design a power line communication (PLC) modem robust to frequency-selective and time-varying channel condition. We consider the use of an adaptive CPFSK modulation scheme at a transmission rate of up to 2Mbps and TDMA scheme for multiple access. We propose a synchronization scheme for robust and fast frame synchronization and the channel change detector for adaptive modulation. The performance of the designed modem is verified by computer simulation. Numerical results show that the use of the proposed modem can transmit data without interruption even in the case of sudden change of the channel condition.

I. INTRODUCTION

Since the power-line network is known ubiquitous and inexpensive, there have been a large number of studies on the use of power-line for communications. In particular, the power line communication (PLC) has been considered as one of major schemes for home-networking. It is well understood that the power line has unpredictable characteristics. The gain variation is very large depending upon the position and kind of the load [1]. The gain variation due to capacitive loads can be as much as -100dB/km. The PLC channel has time-varying attenuation characteristics due to sudden change of loads. The nature of power-line may not be appropriate for high-speed communications [2]. Periodic noise synchronized with electric appliances and non-periodic impulsive noise due to the switching can last up-to 100μsec severely degrades the performance [2].

Low-speed modems using simple schemes such as FSK which has low spectral efficiency, are developed at the beginning [3]. Recently, there have been a number of modem development based on the spread spectrum (SS) and orthogonal frequency division multiplexing (OFDM) methods. 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 OFDM [4]. OFDM scheme modulates each sub-channel independently, it may be suitable for frequency selective PLC channel, appropriate for high-speed communications. However, implementation complexity compared to single carrier modem and it may require an expensive analog-front-end due to high PAR. Although OFDM is known robust to continuous wave interference but it shows weakness to impulsive noise in PLC environment [5].

Although FSK has low spectral efficiency, but it has many advantages such as low implementation complexity, low PAR and robustness to amplitude variation, quite suitable for applications to PLC. Moreover it has robustness to impulsive noise [5]. The use of non-coherent detection and diversity was applied to the design of FSK modem for PLC [6]. It was reported that the use of an appropriate hopping pattern can double the transmission rate [7]. The performance can further be improved by combining the coding and diversity to overcome the interference and impulsive noise [8].

Most of previous works have concentrated on the use of novel modulation scheme, diversity, and coding schemes to be robust to unpredictable channel condition, but not adaptive ones. As a result, it may not provide reliable communications whenever the channel undergoes sudden change. Although the use of adaptive frequency allocation and rate control method was considered in [9], no analytic design method was described. Moreover, it needs to consider

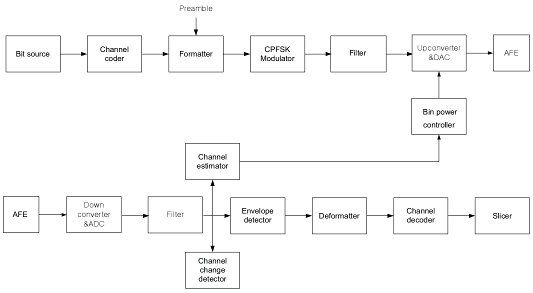
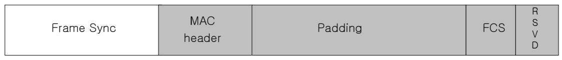
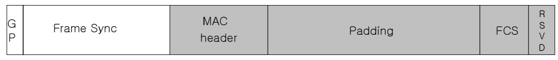


Figure 1: The designed PLC transceiver



(a) downlink control slot structure



(b) uplink control slot structure

Figure 2: The structure of main control slot

multiple access schemes efficient for PLC environment. In this paper, we consider the use of adaptive schemes for CPFSK modem to provide stable transmission by adjusting the modulation parameters in real time. By employing the line probing method, the modem parameters are initialized optimally to the given channel condition [10]. We use a channel change detector to adjust the modulation parameters whenever the channel condition suddenly changes, transmitting data without interruption. We consider the use of TDMA scheme to support multiple users in a conservative manner. Among multiple access protocols, TDMA scheme is employed to avoid the problems such as the carrier sensing and hidden node problem in the carrier sensing multiple access [11]. Full duplex transmission is provided by using a time dividing duplex (TDD). In a TDMA scheme, it is required to reliably provide the frame synchronization. We propose a novel frame synchronization method.

This paper is organized as follows. The structure of designed PLC modem is described in Section II. Section III describes a frame synchronization algorithm. We design a simple but efficient channel change detector in Section IV, and conclusions are drawn in Section V.

II. ADAPTIVE CPFSK MODEM

Fig 1. depicts the structure of the designed PLC modem. Each frame consists of eight slots. The first slot in the frame is used as the control slot to provide frame synchronization and adaptive modulation. As depicted in fig. 2, the control slot includes the training symbols for frame synchronization and MAC header for initialization in the downlink. A guard interval is inserted in the beginning of the uplink slot to avoid possible collision between the uplink and the downlink slot. Padding is used to just keep the fixed slot size and CRC (Cyclic redundancy code) is used as FCS. The rest of seven slots are used for user data transmission and these slots include the information about adaptive modulation.

During the initialization process, the modem determines the modulation parameters based on the line probing result. The symbol rate, modulation level (i.e., the number of tones) and carrier frequency are chosen to transmit the data with a BER lower than the desired one, while maximizing the transmission rate [10]. Since the channel gain is frequency selective, the transmit power of each tone is also controlled so that the received tones have equal power.

The transmitter sends the data with modulation parameters set by the initialization process. Since the channel is abruptly changed, it is required to adjust the modulation parameter to maintain the transmission without interrupt. We employ a channel change detector to detect a sudden change of the channel condition. Whenever the channel change is detected, the modulation parameters are adjusted using a simplified line probing module running in a background mode.

III. FRAME SYNCHRIZATION

It is first required to establish the frame synchronization for reception of data in a TDMA system. In conventional schemes, known tone signals are used for frame synchronization. However, it may not be applicable to the PLC environment because it is not easy to determine the threshold level for tone detection according to the unpredictable channel condition. We propose a robust frame synchronization scheme as depicted in Fig. 3.

A pseudo-noise (PN) sequence with period N is transmitted M times for the purpose of frame synchronization. Then, the output of the matched filter can have M repeated peaks. Assuming that the received signal is over-sampled at a rate of T/L, where L is the over-sampling ratio, the output of the matched filter at $t = nT + lT/L,\ l = 0,...,L-1$ can be represented as

$$z[n,l] = \boldsymbol{c}^{*T}\boldsymbol{r}[n,l]. \quad (1)$$

$\boldsymbol{c}$ is a N-dimensional vector given by

$$\boldsymbol{c} = [c_1, c_2, ..., c_N]^T \quad (2)$$

where

$c_i = e^{(j\phi(iT+L/2-1))}, \phi(t) = \pi \sum_{k=-\infty}^{i-1} I_k + \pi(t-iT)I_i/T$ for $iT \le t \le (i+1)T$ and I_i, $i = 1,2,...,N$ is obtained by mapping PN sequence into the amplitude levels ± 1. $\boldsymbol{r}[n,l]$ is a N-dimensional vector representing A/D converted samples whose element is given by

$$\boldsymbol{r}[n,l] = [r((n-N+1)T + \frac{lT}{L}), r((n-N+2)T + \frac{lT}{L}), ..., r(nT + \frac{lT}{L})]^T. \quad (3)$$

Here, the superscript T denotes the transpose of a vector. Note that the received signal $r(t)$ is frequency-shifted to the baseband before the A/D conversion.

Let $d_w(m), m = 1,2,...,M$ be the position of the maximum of $|z[n,l]|$ in the m-th block, each of which comprises LN samples. Define the test function by

$$T_D(m) = \mathrm{sgn}(a + (m-1)NL - |d_w(1) - d_w(m)|) \quad (4)$$

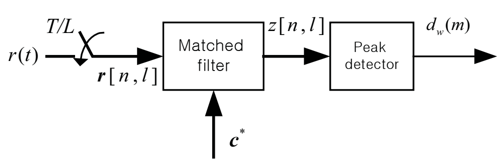


Figure 3: Block diagram of the proposed frame synchronizer

where $\mathrm{sgn}(x) = 1$ for $x \ge 0$ and zero, otherwise. Then, a frame synchronization can be declared if

$$\prod_{m=2}^{M} T_D(m) = 1. \quad (5)$$

Let $w[n,l]$ be the absolute value of the matched filter output and $\delta T/L$ be the timing offset between the received PN signal and the vector $\boldsymbol{c}$. It can be shown that if $-L/2 < \delta < L/2$,

$$\begin{aligned} w[n,l] &= \left|\sum_{i=1}^{N} c_i^* \cdot r[n,l]\right| \\ &= \left|\sum_{i=1}^{N} c_i^* \cdot (c_i \exp(jI_i \frac{\delta}{L}\pi) + v[n,l])\right| \end{aligned} \quad (5)$$

is Rician distributed, i.e.,

$$f_W(w) = \frac{w}{N\sigma_v^2}\exp(-\frac{w^2 + N^2\cos^2(\frac{l\pi}{L}) + \sin^2(\frac{l\pi}{L})}{2N\sigma_v^2}) \cdot I_o(\frac{w\sqrt{N^2\cos^2(\frac{l\pi}{L}) + \sin^2(\frac{l\pi}{L})}}{N\sigma_v^2}) \quad (6)$$

where assume $Var(\mathrm{Re}(v[n,l])) = Var(\mathrm{Im}(v[n,l])) = \sigma_v^2$, which is the variance of the additive noise term, and $I_o(\cdot)$ is the zeroth-order modified Bessel function of the first kind. For $|\delta| \ge L/2$, it can be shown that $w[n,l]$ is Rayleigh distributed, i.e.,

$$f_w(w) = \frac{w}{\frac{N}{2} + N\sigma_v^2}\exp(-\frac{w^2}{N + 2N\sigma_n^2}). \quad (7)$$

When we denote the event which PN sequence is located in each block as H_1 and the alternative case as H_0. The true detection probability P_D of the frame synchronization can be represented as

$$P_D = \prod_{m=2}^{M} \mathrm{Prob}\{\mathrm{T_D}(m) = 1|\ H_1\}. \quad (8)$$

The probability of false alarm P_F can be represented as

$$P_F = \prod_{m=2}^{M} \mathrm{Prob}\{T_D(m) = 1|\ H_0\} \quad (9)$$

and $\mathrm{prob}\{T_D(m) = 1|\ H_0\} = (2a+1)/LN$ since $d_w(m)$ is uniformly distributed. P_F can be rewritten as

$$P_F = \left(\frac{2a+1}{LN}\right)^{M-1}. \quad (10)$$

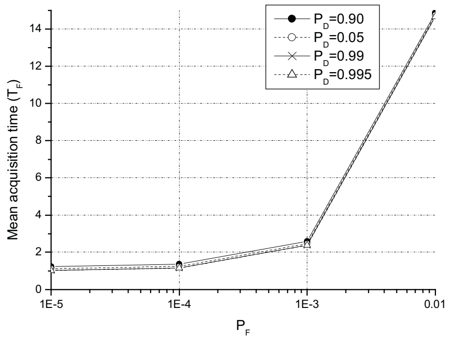


Figure 4: The mean acquisition time as a function of P_D, P_F

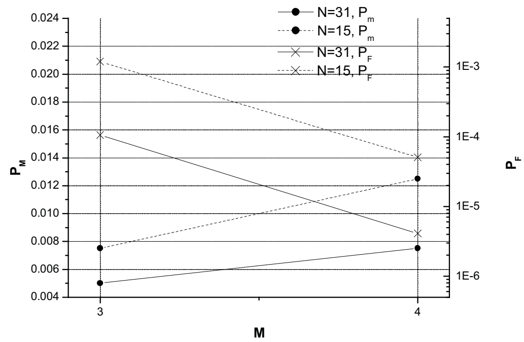


Figure 5: Frame synchronization performance

Using the flow graph technique [12], the mean acquisition time can be expressed by

$$T_{ACQ} = \frac{1}{P_D}\left(\frac{1}{2}P_D P_F K\left(\frac{K}{N}-1\right)+2-P_D\right)T_F \tag{11}$$

where K is the number of symbols per frame and T_F is frame length. Fig. 4 depicts T_{acq} as a function of P_D, P_F when the penalty time is $5T_F$. If we select P_D=0.99 for fixed P_F, T_{acq} is saturated and if we make P_F less than 10^{-3} for P_D=0.99, T_{acq} is shorter than 2.38 T_F. Fig. 5 depicts P_D and P_F as a function of N and M in an AWGN channel when $a=2$ and SNR= 13 dB.

IV. CHANNEL CHANGE DETECTOR

The problem for detecting a channel change can be formulated as testing two simple hypotheses problem. Let hypotheses H_1 be the case when the channel gain is suddenly changed by more than $\pm G$ dB with respect to the normal gain. And hypotheses H_0 be the case when the channel gain variation is less than $\pm G$ dB. The structure of the proposed channel detector is shown in Fig. 6. The signal power of the received signal is estimated from the over-sampled signal. Since the purpose of the proposed channel detector is to detect a sudden gain change under non-Gaussian noise condition, the use of a conventional linear filter may not be effective for this purpose.

We consider the use of a nonlinear filter to preserve the change of the power, while reducing the noise effect. The use of order statistic filters (OSFs) has been successfully applied to signal processing, where it needs to preserve sharp change of the signal, while being robust to non-Gaussian noise [13]. In this paper , we consider the use of the median filter, which is a simple form of the OSF, as a postprocessor of the signal power measurement.

The received signal for each symbol can be represented as

$$q[n] = \sum_{l=1}^{L}\left|s[n,l]+v[n,l]\right|^2 \cong \left|\hat{s}[n]+\hat{v}[n]\right|^2 \tag{12}$$

when $\hat{s}[n]$ and $\hat{v}[n]$ denote the equivalent values corresponding to the symbol-spaced sample. It can be shown that $q[n]$ is approximately distributed as

$$\begin{aligned} f_Q(q) &= \frac{1}{2\pi}\int_{-\infty}^{\infty}\psi_q(j\omega)e^{-j\omega q}d\omega \\ &= \frac{1}{2\pi}\int_{-\infty}^{\infty}\frac{1}{\sqrt{1-2j\sigma_v^2\omega}}e^{\frac{2js^2[n]}{\sigma_v^2}\omega}d\omega \end{aligned} \tag{13}$$

where σ_v^2 is the variance of v and $\psi_q(j\omega)$ is characteristic function of $q[n]$. Assuming that the noise is uncorrelated with the signal, the mean and variance of $q[n]$ under each hypotheses are given by

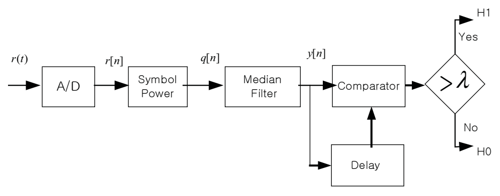


Figure 5: The structure of channel change detector

$$\mu_q[n] = E\{q[n]\} = \begin{cases} \hat{P}_S + \sigma_v^2; H_0 \\ \alpha^2 \hat{P}_S + \sigma_v^2; H_1 \end{cases} \quad (14)$$

$$\sigma_q^2 = E\{(q[n] - \mu_q[n])^2\} = \begin{cases} 4\hat{P}_S \sigma_v^2; H_0 \\ 4\alpha^2 \hat{P}_S \sigma_v^2; H_1 \end{cases} \quad (15)$$

where $\hat{P}_S^2 = E\{|s[n]|^2\}$ and α denotes the change of the channel gain.

The pdf of the median filter output $f_Y(y)$ and the cdf $F_Y(y)$ can be represented as

$$f_Y(y) = \frac{\partial F_Y(y)}{\partial y} = \frac{W!}{M!M!} F_q^M(y)\left[1 - F_q^M(y)\right] f_q(y) \quad (16)$$

$$F_Y(y) = \sum_{i=M+1}^{W} {}_W C_i \cdot F_q^i(y) \cdot \left[1 - F_q(y)\right]^{W-i} \quad (17)$$

where W is a window size of the median filter and $M = (W-1)/2$. Fig. 6 depicts the pdf of $y[n]$ obtained by the analysis and simulation when the power level of channel is changed by -6dB under hypothesis H_1 , the SNR is 13dB and the power of data symbol is normalized as one. It can be seen that the simulation results agree well with the analysis.

To detect the change of the gain, we need to compare the power level apart by an amount of T_{delay} symbols to remove the transient effect. In the Fig. 7, the detection probability is depicted in terms of T_{delay}

We design the detector to minimize the false detection probability P_F while satisfying the desired detection probability $\overline{P}_M$. That is, the detector is designed to minimize the Lagrangian F represented as

$$\begin{aligned} F &= P_F - \lambda\left(P_D - \overline{P}_D\right) \\ &= \int_{R_1} \left(f_Y(x \mid H_1) - \lambda f_Y(x \mid H_0)\right) dx + \lambda \overline{P}_D \end{aligned} \quad (18)$$

where $\overline{P}_D = 1 - \overline{P}_M$ is the desired detection probability equal to $f_Y(y \mid H_i)$ denotes the pdf under hypotheses $H_i, i = 0,1$, and R_1 is the detection region corresponding to H_1 .

Then, the test statistic is given by

$$\frac{f_Y(x \mid H_1)}{f_Y(x \mid H_0)} < \lambda \quad (19)$$

where λ can be determined by

$$\overline{P}_D = \Pr ob\left\{ \frac{f_Y(x \mid H_1)}{f_Y(x \mid H_0)} \le \lambda; H_1 \right\} \quad . \quad (20)$$

Once the channel gain change is detected, it needs to make a confirmation for reliable detection. The confirmation can be done by examining the test statistic

$$\begin{aligned} &T_C(i) = q[n - i - T_D] - q[n + i] \\ &for \;\; i = 1, 2, \cdots, I_C \end{aligned} \quad (21)$$

where I_C is confirmation number. Fig. 8 plot the detection and false alarm probability in terms of threshold. The mean acquisition time can be formulated as a simple equation

$$\begin{aligned} T_{acq} &= 0.75 T_f P_f' + 1.5(1 - 0.5 P_f)(1 - P_D) \\ P_f' &= \frac{T_f}{8T_S} P_f \end{aligned} \quad (22)$$

where T_f is frame length and T_S is symbol duration. We assumed that channel change probability is uniform in a frame and first symbol power of a frame is compared with the power of previous frame's symbol to confirm surely. Fig. 9 plot the T_{acq} in terms of threshold. SNR=13dB, T_{dealy} =3, W =3 and L =8 assumed.

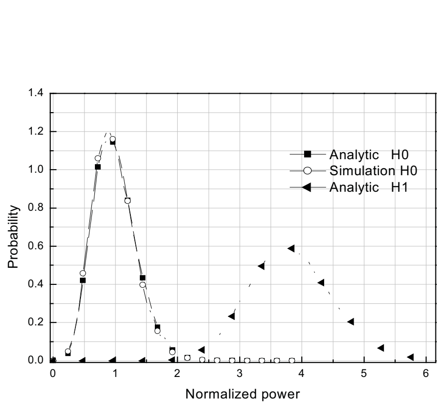


Figure 6: The pdf of median outputs

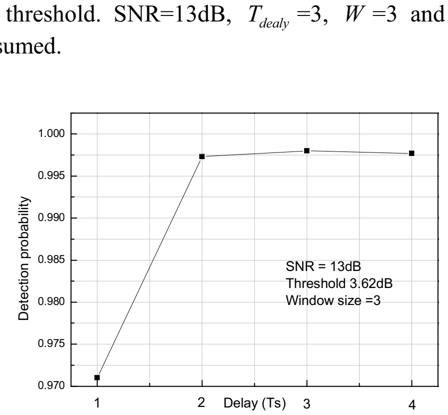


Figure 7: Performance in terms of T_{delay}

V. CONCLUSION

In this paper, we have proposed a CPFSK-based PLC modem that can provide performance robust to harsh power-line channel condition. By employing a channel change detector, the modulation parameter can be adjusted in real time according to the channel condition, with the aid of line probing technique. We also have designed a scheme for frame synchronization, that can provide reliable performance without exact a priori information on the channel condition. Finally, The analytic design and performance of the proposed modem are verified by computer simulation.

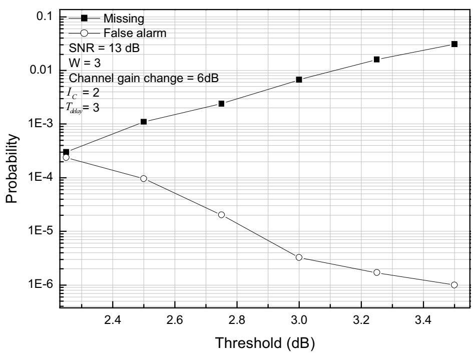


Figure: 8 Performance of the detector

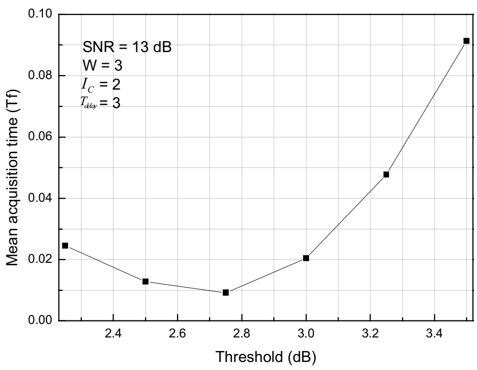


Figure: 9 Mean acquisition time of the detector

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