DETERMINATION OF MAXIMUM DATA TRANSMISSION DISTANCE IN POWERLINE NETWORKS IN DEVELOPING COUNTRIES

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ABSTRACT: Recently, Powerline communications has been considered for providing broadband access services and as a cost effective means of connectivity to non-urban and lowly populated areas. This indicates that it is a viable technology for developing countries like Tanzania where there is adequate penetration of the powerline networks. However, the use of the network for data transmission presents a number of problems that limits achievable transmission distances (hops). This paper looks at different modulation and coding techniques to maximize transmission distance.

1. INTRODUCTION

The recent development in communication has enabled different technologies to be considered for access in non-urban areas. These solutions include PSTN and wireless networks. The powerline network appears to be a candidate for communication to homes because the network and nodes are already available towards household. Basically powerline network in developing country like Tanzania covers a larger geographical area and it's divided into two parts; the first part is from end users to distribution transformers, with furthest customer being at 1.2km. Another part is from distribution transformers to primary substation and this covers about 4.0km. This makes the maximum separation between the customer and the primary substations to be 5.2km. Within the part from end users to distribution transformers the maximum number of customers (end users connected) is 70 customers per phase and this introduce the first challenge of communication through low voltage due to multi-path of signals and reflections. Figure 1 is a typical layout of powerline network in developing countries like Tanzania. The parameter DT is the distribution transformers and CM is the data switch at Customer meter.

The second challenge faced by PLC is noise. Three types of noise have already addressed by various PLC researchers, these are;

(i) The background colored noise caused by noise from distribution transformers and gaussian noise of PLC.
(ii) Radio frequency noise caused by AM broadcasting radio and
(iii) Impulsive noise, which are caused by switching of loads connected to PLC and lightning.

The third challenge is due to attenuation, caused by different cascaded cables and the route from end users to primary substation with branched end users and interconnected nodes. These factors make the transfer characteristics of PLC to be complex. To overcome such challenges when using powerline for communication purposes various techniques are to be adopted. These are suitable modulation and sophisticated channel coding.

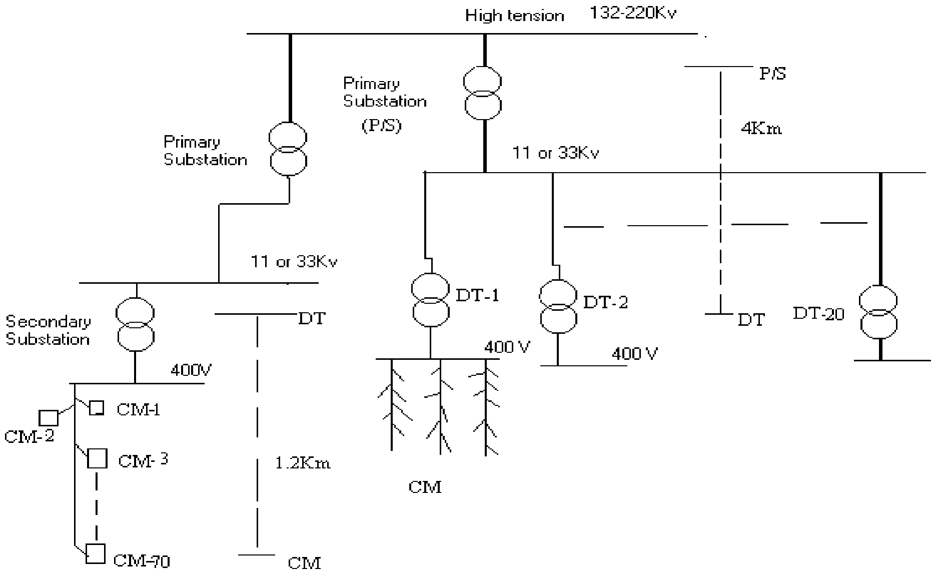

Fig 1: The Layout of Powerline network

2. DETERMINATION OF POWERLINE TRANSMISSION PARAMETERS

In developing countries like Tanzania, the powerline networks from primary substation to the end user bracket have the separation between the wires that is much greater than the radius of each conductor. Hence the capacitance, C, inductance, L and series resistance, R per unit length can be calculated using equations (1), (2) and (3) respectively, whereby a is the separation between conductor, r is the radius of a conductor and ε_o is the permitivity of free air, μ_o is the permeability of free space, μ_{al} and σ_{al} are permeability and conductivity of aluminum conductor respectively. f is the operating frequency (William, 1988) (Green, 1993). The conductance G is equal to zero.

$$C = \frac{\pi\varepsilon_o}{\cosh^{-1}(a/2r)} \tag{1}$$

$$L = \frac{\mu_o}{\pi}\cosh^{-1}(a/2r) \tag{2}$$

$$R = \frac{1}{\pi r}\sqrt{\frac{\pi f \mu_{al}}{\sigma_{al}}} \tag{3}$$

The power cable from bracket to the customer meter (CM) has the separation between two conductors that is much less than their radius. The capacitance and inductance per unit length can be expressed by equations (4) and (5) respectively. The parameter ε_r is relative permitivity and μ_r is relative permeability (Zimmermann *et al*, 1999).

$$C = \varepsilon_o \varepsilon_r \frac{r}{a} \qquad (4)$$

$$L = \mu_o \mu_r \frac{a}{r} \qquad (5)$$

From bracket to customer meters, the resistance R and conductance G of a conductor can be expressed by equations (6) and (7) respectively, where δ is skin depth.

$$R = \frac{1}{\pi r}\sqrt{\frac{\pi f \mu_{al}}{\sigma_{al}}} \qquad (6)$$

$$G = 2\pi f C \tan\delta \qquad (7)$$

3. TRANSFER FUNCTION PARAMETERS OF POWERLINE CHANNEL LINK

In all analysis and modelling the cabling are assumed to be matched, which is equivalent to regarding only the wave propagating from source to destination with no reflection. The cable attenuation for length, d at frequency f in different segments can be calculated using equation (8).

$$A(f,d) = \exp(-\sqrt{(R + j\omega L)(G + jwC)}\ d) \qquad (8)$$

The multi-path from primary substation to distribution transformer has been calculated using Zimmermann *et al*, 1999 and Matov *et al*, 2001, but instead of a single branch, the maximum number of branches in powerline network is considered. The result of the analysis is given in equation (9). The parameter t_{AZ} is the transmission factor from primary substation to farthest distribution transformer. ρ_{3M} is the reflection factor due to the load connected and is assumed to be matched with the cable from customer meter to the bracket. t_{3B} is the total transmission factor from branched network at distribution transformer and customer meters. g_{HT} is the weighting factor of the path along high tension grid.

$$g_{HT} = t_{AZ}\,\rho_{3M}^{(N-1)} t_{3B}^{(N-1)} \qquad (9)$$

N is the total number of branched distribution transformers. From distribution transformer to customer meter the multi-path is shown by equation (10).

$$g_{LV} = t_{BZ}\,\rho_{3M}^{(MN-1)} t_{CE}^{(MN-1)} \tag{10}$$

The parameter t_{BZ} is the transmission factor from distribution transformer to the customer meter. It has been assumed matched to the bracket to customer meter cable. t_{CE} is the total transmission factor between customer meter and customer pole. $M_{\max}$ is the maximum number of customer meter connected to the powerline cable. g_{LV} is the weighting factor of the signal propagation path from distribution transformer to customer pole. The interconnection between different cascaded cables is simulated as suggested by (Zimmermann *et al*, 1999) and (Langfeld *et al, 2001)* using equation (11).

$$P(t_d) = \exp(-j2\pi f t_d) \tag{11}$$

where $t_d = \frac{d_i}{v_p}$ and $v_p = \frac{c_o}{\sqrt{\varepsilon_r}}$

t_d is the path delay, d_i is path length c_o is speed of light in vacuum.

For interconnections from primary substation to distribution transformers, it is assumed that the distance between distribution transformers is even along the high-tension grid. In addition, it is assumed that the customers are equally distributed in the three phases of the grid. The maximum distribution transformers connected to any primary substation are assumed to be 20 as obtained from TANESCO. These are assumed to be distributed equally between phases. The maximum distance is considered to be 4km. The general equation representing this scenario is (12). N is the number of interconnected distribution transformers.

$$N = \frac{7d}{4000} \tag{12}$$

From distribution transformer to customer pole, the same assumptions as from primary substation to distribution transformer have been made. However, 200 customer meters per distribution transformer have been taken into consideration, which is maximum number in TANESCO network. For single phase 70 customer meters have been considered. The maximum distance from distribution transformer to furthest TANESCO customer is considered to be 1.2km and the result is given by equation (13), where d_a is the distance along low voltage grid.

$$M_{\max} = \frac{70 d_a}{1200} \quad (13)$$

The transfer function of the channel from primary substation to distribution transformer is given by equation (14) and from distribution transformer to customer pole, the transfer function is the same as in equation (14) with N and d replaced by $M_{\max}$ and d_a respectively.

$$H(f,d,N) = \sum_{i=1}^{N} \left| g_{HT}(f) \right|^{\varphi_{gHT}(f)} A(f,d) P(t_d) \quad (14)$$

For the segments from high-tension pole to distribution transformer, customer pole to bracket and bracket to customer meter do not have interconnections. In addition they have no branched network. Therefore, only cabling attenuation is considered. This is given by equation (15), where l is the length of the respective cable.

$$H(f,l) = \exp(-\sqrt{(R + j\omega L)(G + j\omega C)}\ l) \quad (15)$$

4. POWERLINE CHANNEL PERFORMANCE ANALYSIS

4.1 Customer Meter to Distribution Transformer

For direct sequence spread spectrum with BPSK modulation scheme, the probability error is given by equation (16)

$$P_e = Q(x) \quad (16)$$

$$x = \sqrt{\frac{2E_b}{N_o}}$$

The transmitted signal to noise ratio per bit and received probability error of 10^{-6} will be used to determine the maximum distance data can be transmitted noise

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} \exp(\frac{-u^2}{2}) du$, E_b / N_o is signal to noise ratio per bit and P_e is a probability error.

By considering data transmission through powerline network from distribution transformer to bracket, with channel transfer function $H(f, d_r, R)$, and the transfer characteristics H_{mb} from customer meter to bracket and H_{blv} from bracket to low voltage pole, the received signal to noise ratio from customer meter to distribution transformer is given by equation (17).

$$SNR_{LV} = \frac{2PG}{2\sigma_k^2 / (P_a \left| H(f, d_a, M_{\max}) + H_{mb}(f, l_m) + H_{blv}(f, l_{bp}) \right|^2)} \quad (17)$$

$$P_{eLV} = \sqrt{SNR_{LV}} \tag{18}$$

In addition, the corresponding probability bit error from customer meter to distribution transformer is given by equation (18). The parameter PG is the processing gain, which is the ratio between transmission frequency and data rate. σ_k^2 is the power spectral density of noise power. The signal to noise ratio at each instant considering the noise environment in PLC is given by equation (19), where σ_G^2 and σ_I^2 are power spectral density of gaussian (sum of background and narrow band, including other types of noise in the channel) and impulsive noise respectively.

$$\gamma_b = \frac{P_a}{2(\sigma_G^2 + \sigma_I^2)} \tag{19}$$

The ratio of impulsive noise to gaussian noise is considered equal to β. Equation (20) have been derived using equations (17) through (19).

$$Pe_{LV} = Q\left[\sqrt{\frac{2xPGx(1+\beta)x\left|H(f,d_a,MN)+H_{mb}(f,l_m)+H_{blv}(f,l_{blv})\right|^2 x\gamma_b}{(1+\frac{k_{imp}}{\lambda_{imp}}x\beta)}}\right] \tag{20}$$

The parameters β and γ_b are selected based on measurements done by (Zimmermann *et al*, 2000) and the proposed CENELEC standard with maximum power to be transmitted in Powerline network as 500mW. The simulation result obtained from equation (20) is presented in figure 2. The figure shows the dependence of probability error on distance in low voltage from customer meter to distribution transformer under different signal to noise ratio per bit.

The target is to minimize number of hops to distribution transformer. Considering distance of 400meters, two hops will be obtained. From figure 2 this can be obtained by applying signal to noise ratio of 80dB per bit. In addition, it can be observed that the probability error at this distance is 10^{-4} which is very high compared to the required performance of 10^{-8}. Also the sensitivity of required receiver at this distance has to be investigated.

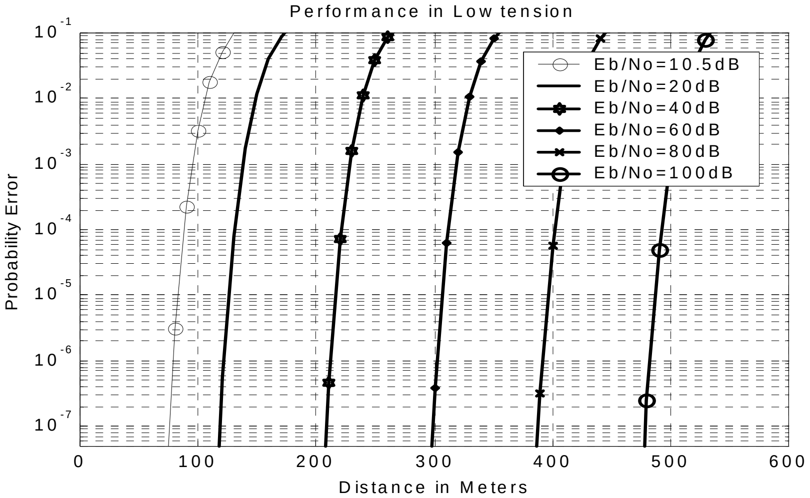

Fig 2:Performance of DSSS BPSK under different signal to noise ratio per bit from Distribution transformer to Customer meter

4.1.1 Receiver Sensitivity

The receiver sensitivity is chosen based on the selected BPSK modulation at desired BER. The graph of probability error vs. Eb/No is shown in figure 2 from Customer meter to Distribution transformer, where at 400meters Eb/No = 80dB. The transmitted signal to noise ratio (SNR) is obtained using equation (21), where R and B_T are data transmission rate and system bandwidth respectively. The value of R have been selected to get enough processing gain, which in case of 140kHz used and data rate of 10kbps the processing gain is equal to 14. For BPSK modulation the bandwidth is equal to half data rate based on nyquist results.

$$SNR = (E_b/N_o)(R/B_T) \tag{21}$$

$$= (80dB)(10kbps/5kHz)$$

$$= 74dB$$

Taking the maximum background noise (N_B) of $-120dB$ as suggested by (Zimmermann *et al*, 1999), the noise floor (N_r) at the receiver is calculated as in equation (22), where k_B is Boltzman's constant equal to $1.38x10^{-23}\,J/K$, T_A is the ambient temperature assumed to be $290K$, B_T is the required channel bandwidth in (Hz). The noise figure N_F is assumed to be $15dB$ as suggested by (Zyrem J. *et al*, 1998)

$$N_r = N_B + k_B T_A B_T + N_F \tag{22}$$

$$= 10^{(-140/10)} + (1.38x10^{-23}\,J/K)(290K)(5{,}000s^{-1}) + 15dB$$

$$= -125dB$$

The sensitivity P_r is given by equation (23).

$$P_r = N_r + SNR \qquad (23)$$
$$= -125dB + 74dB$$
$$= -51dB$$

Figure 3 is the graph showing the relationship between the received signal to noise ratio (SNR) with respect to distance at different signal to noise per bit (E_b/N_o) transmitted. From the graph it can be observed that by applying E_b/N_o of 80dB per bit the received SNR at a distance of 400m is 10dB, which is higher than the required receiver sensitivity of –51dB. Since the applied E_b/N_o is high, channel coding is needed to reduce the power and to increase channel performance.

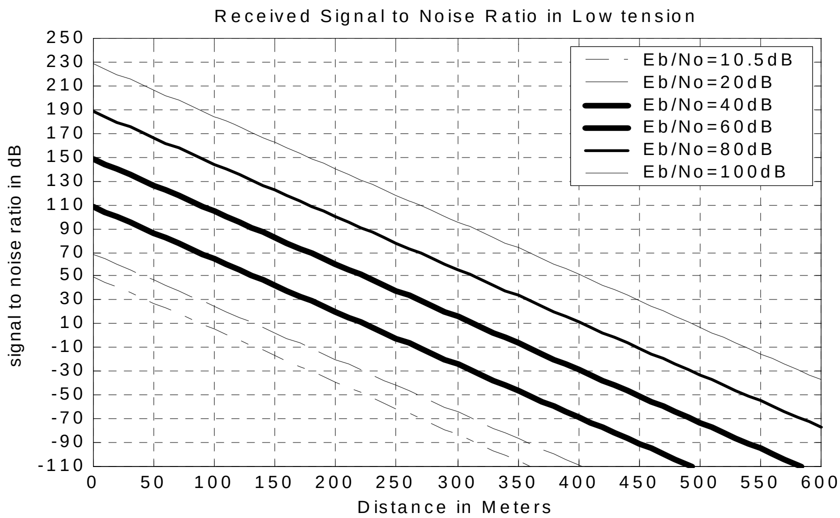

Fig 3:Hop distance from distribution transformer to primary substation under different signal to noise ratio

4.1.2 Coding Performance

By considering BCH code with (n, k) codes using BPSK modulation scheme, the probability error of powerline channel from distribution transformer to customer meters is given by equations (24) through (25).

$$q_{cLV} = Q\left(\sqrt{ \frac{2PG\,(1+\beta)\left| H(f,d,N) + H_m(f,l_m) + H_{bp}(f,l_{bp}) \right|^2}{(1+\frac{k_{imp}}{\lambda_{imp}}\beta)} \gamma_b \frac{k}{n} } \right) \qquad (24)$$

$$P_{eLVC} = \binom{n}{t+1} (q_{cLV})^{t+1} (1 - q_{cLV})^{n-t-1} \qquad (25)$$

$$P_{beLV} \;=\; \frac{(t+1)}{n}\, p_{eLVC} \qquad (26)$$

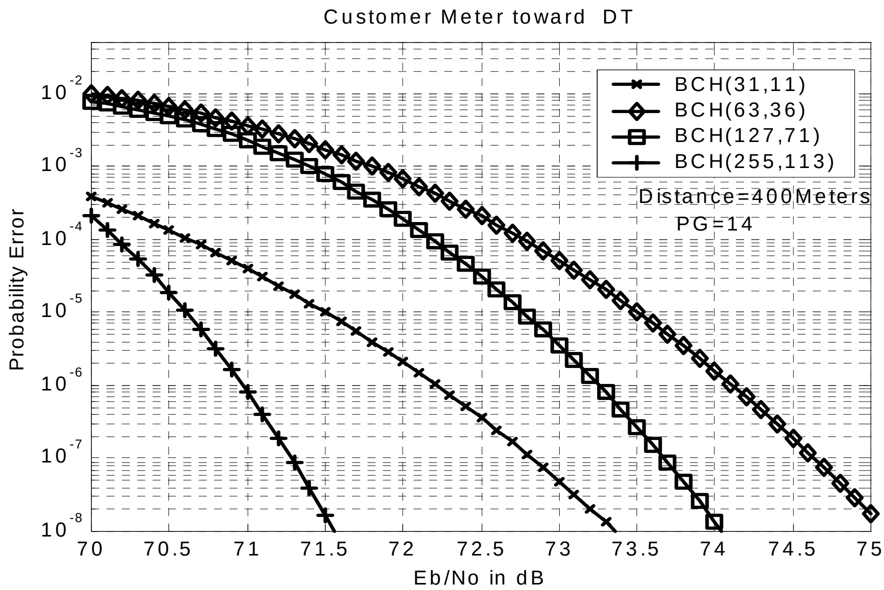

Fig 4: Performance of Coded DSSS BPSK under different code length from Distribution transformer to Customer meter.

The results of all these equations have been simulated using source code written in MATLAB software and the result is given in figure 4. Figure 4 shows the performance of powerline channel from customer meter to distribution transformers using different code rate of BCH and signal to noise ratio per bit and processing gain of 14. It can be seen that by applying BCH (255,113) and BCH (31, 11) at the maximum distance of 400 meters, the BER of 10^{-8} can be achieved at signal to noise ratio per bit of 73.4dB and 71.6dB respectively. Therefore, from customer meters to distribution transformers, which are 1.2km requires two regenerative repeaters at 400meters apart and from either end, BCH (31,11) code, DSSS-BPSK modulator and E_b/N_o of 71.6dB per bit.

4.2 **DISTRIBUTION TRANSFORMER TO PRIMARY SUBSTATION**

The data transmission through powerline channel from primary substation to distribution transformer, experiences two different transfer characteristics. These are transfer function from distribution transformer to high-tension pole H_{DtHT} and from high-tension pole to primary substation $H(f,d,N)$. Considering DSSS-BPSK modulator, the received signal to noise ratio is given by equation (27). In addition the corresponding probability error is given by equation (28). Using equations (19), (27) and (28), equation (29) can be derived.

$$SNR_{HT} = \frac{2PG}{2\sigma_k^2 / (P_a |H(f,d,N) + H_{DtHT}(f)|^2)} \tag{27}$$

$$p_{eHT} = \sqrt{SNR_{HT}} \tag{28}$$

$$Pe_{HT} = Q\left[\sqrt{\frac{2xPGx\ (1+\beta)x|H(f,d,N)+H_{DTHT}\ (f)|^2 x\gamma_b}{(1+\frac{k_{imp}}{\lambda_{imp}}x\beta)}}\right] \tag{29}$$

The simulation result obtained from equation (29) is presented in figure 4. The figure shows the dependence of probability error on distance in high-tension grid from primary substation to distribution transformer under different signal to noise ratio per bit. It can be observed that by applying signal to noise ratio per bit of 60dB, the distance of 4km can be obtained which is our target. But the performance at this distance is BER of 10^{-6} instead of 10^{-8}. Channel coding and the received signal strength have to be investigated.

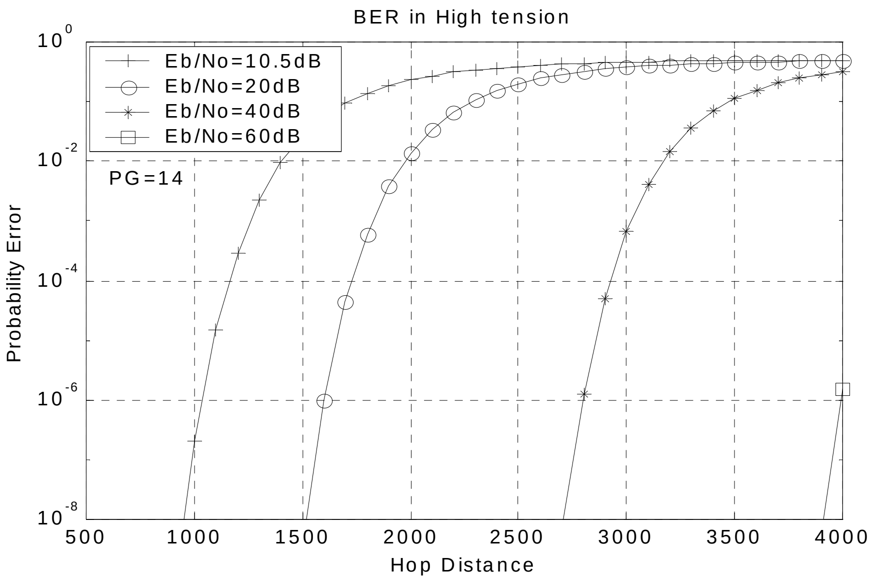

Fig 5: Performance of DSSS BPSK under different signal to noise ratio from Distribution transformer to primary substation.

4.2.1 **Receiver Sensitivity**

The receiver sensitivity is selected based on BPSK modulation at the desired BER. The graph of probability error vs. Eb/No is shown in figure 5. From Distribution transformer to primary substation at distance of 4km and BER of 10^{-6} the Eb/No = 60dB. The transmitted signal to noise ratio (SNR) is obtained using equation 30, where R and B_T are data transmission rate and system bandwidth respectively. For BPSK modulation data rate is twice bandwidth.

$$SNR = (E_b/N_o)x(R/B_T) \quad (30)$$

$$= (60dB)x(2)$$

$$=53\text{dB}$$

$$N_r = N_B + k_B T_A B_T + N_F \quad (31)$$

$$= 10^{(-140/10)} + 1.38x10^{-23} J/K\, x290Kx2x10^6 s^{-1} + 15dB$$

$$= -137.44dB + 15dB$$

$$= -122.44dB$$

The sensitivity P_r is evaluated as shown in equation (23), and the result is given in equation (32).

$$P_r = -122.44dB + 53dB \quad (32)$$

$$= -69.44dB$$

Figure 5 shows the dependence of received signal to noise ratio and distance in high tension grid from distribution transformer to primary substation under different signal to noise ratio per bit. From figure 5, it can be observed that by applying E_b/N_o of 60dB, the received signal at a distance 4km is about 10dB, which is above the required receiver sensitivity of –69.44dB.

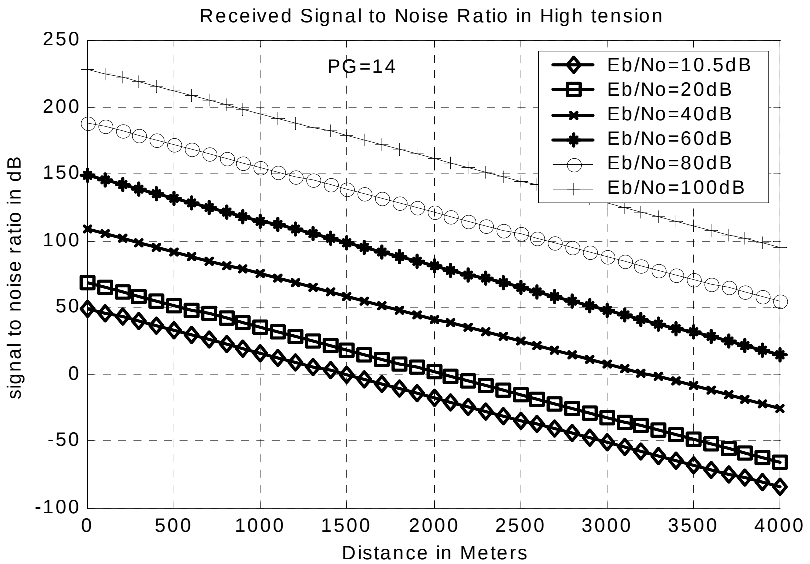

Fig 6: Performance of DSSS BPSK under different Signal to Noise Ratio from Distribution Transformer to Primary Substation

4.2.2 **Coding Performance**

By considering BCH code with (n, k) codes with BPSK modulation scheme, the probability error of powerline channel from distribution transformer to primary substation is given by equations (32) through (34), where t is the number of errors to be corrected in block codes.

$$q_c = Q\left(\sqrt{\frac{2PG(1+\beta)\left|H(f,d,N)+H_{DTHT}(f,l)\right|^2}{(1+\frac{k_{imp}}{\lambda_{imp}}\beta)}\gamma_b\frac{k}{n}}\right) \quad (32)$$

$$P_{eHTC} = \binom{n}{t+1}(q_c)^{t+1}(1-q_c)^{n-t-1} \quad (33)$$

$$P_{be} = \frac{(t+1)}{n}p_{eHTC} \quad (34)$$

Figure 6 shows the performance of the PLC from distribution transformer to primary substation under different code rate of BCH. It can be observed that by applying BCH (255, 113), signal to noise ratio of approximately 50dB and processing gain of 14, the desired performance of 10^{-8} can be obtained. Therefore, the required specifications from distribution transformers to primary substation are BCH (255,113) code, DSSS-BPSK modulator and E_b/N_o of 50B per bit.

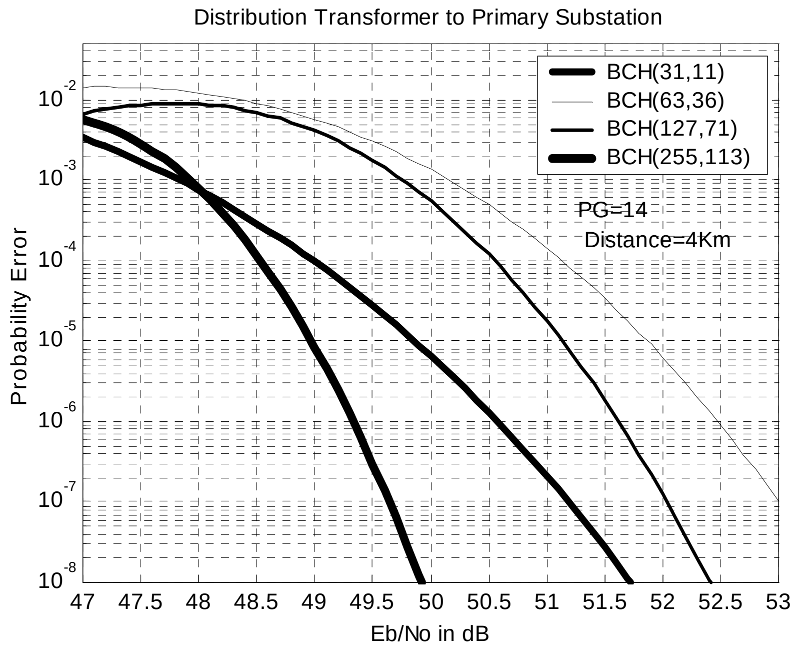

Fig 7: Performance of Coded DSSS BPSK under different code length from Distribution transformer to Primary substation.

2 5. CONCLUSION

It has been shown that, data transmission from customer energy meter to primary substation will require two hops. From customer meter to distribution transformer the hop distance is 400meters and from primary substation to distribution transformer the data can be transmitted to a maximum of 4km with acceptable fidelity. The appropriate modulation is direct sequence spread spectrum with BPSK as a carrier modulation and BCH code. For the selected transmission frequency of 140kHz, the processing gain for direct sequence is 14 and data rate is 10kbps. These specifications of frequency, data rate, signal to noise ratio per bit and code rate system can be tuned during implementation to meet a specified hop distance and performance.

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