Frame Synchronisation for Frequency Redundant Transmission of Data over Power Lines

Michael Arzberger, Klaus Dostert
Institute for Industrial Information Systems
University of Karlsruhe
Hertzstrasse 16, D-76187 Karlsruhe, Germany
Phone: +49 721 608 4597, Fax: +49 721 755788
e-mail: Michael.Arzberger@etec.uni-karlsruhe.de
dostert@ iiit.etec.uni-karlsruhe.de

ABSTRACT

Systems for packet oriented transmission of data over power lines use characteristic patterns - so-called preambles - to mark the beginning of a data frame. Transmission over noisy channels, such as power lines calls for robustness for the detection of these preambles. On one hand this robustness is achieved by the use of spread spectrum techniques, on the other hand by introduction of error-tolerant preamble detection algorithms. Besides the basic selection of a detection strategy, the choice of a suitable preamble sequence and careful choice of thresholds play an important role for the overall performance of the frame synchronisation. This paper will evaluate different strategies for preamble detection, examine the dependencies on the mentioned parameters, and make proposals towards an optimum.

1 INTRODUCTION

Besides the necessary synchronisation of clocks in the receiver for symbol detection in packet oriented mainsborne communication systems also the synchronisation of the data frames is of primary interest. Dedicated frame synchronisation methods must be developed to enable the receiver determining the start of a data frame.

As the power line channel generally can not provide for a defined idle-state, the leaving of which could be used to determine the start of a data frame, the beginning of a frame must be marked with unique patterns, so-called preambles, preceding each data frame. The structure of such a data packet, composed by a leading preamble followed by the data frame is shown in Fig. 1.

As errors in preamble detection cause the loss of a complete data frame or a dead-lock to the receiver for the duration of one data frame, the reliability of preamble detection must be superior to data detection. On the other hand, sequences used as preambles should be as short as possible to maintain efficiency.

Before a closer look at the preambles is given, the basic data transmission procedure is described.

1.1 SPREAD SPECTRUM MODULATION

When using power lines as communication links, robustness against interference is of higher importance than bandwidth efficiency. By means of spreading techniques, enhanced robustness in comparison with narrowband modulation can be established. A possible modulation-scheme is modified fast frequency-hopping as described in [1]. Each data bit is represented by a predefined sequence of C time-limited harmonic waveforms with different frequencies, so-called chips. The sequence of chips denoting a data bit is called a symbol. The duration T_S of a symbol composed of C chips with the duration $T_C = \frac{T_S}{C}$ corresponds to the duration of a data bit.

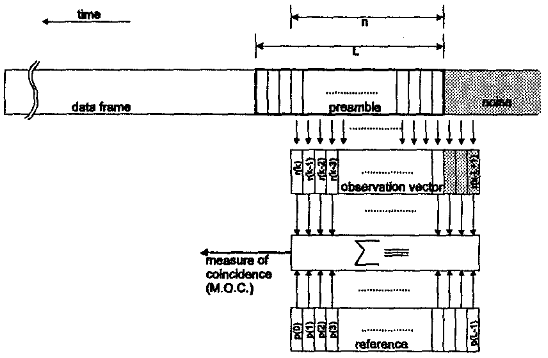

Figure 1: Packet structure and detection procedure

1.2 RECEIVER STRUCTURE

The typical structure of a receiver is shown in Fig. 2. The received signal is fed into M optimum envelope demodulators tuned to the frequencies $f_1...f_M$. As coherent demodulation in hostile environments such as power lines is generally impractical, noncoherent envelope demodulation is performed. Each envelope demodulator consists of two correlators, the outputs of which are sampled at the end of each chip. The two waveforms used as references for the correlators are discrete sine- and cosine representations. The clock used to sample the correlator outputs and clear the accumulators with rate $1/T_C$ is called chip clock. It must be synchronous with the chip clock in the transmitter. An appropriate synchronisation procedure is described in [2] and will be summarised in the next section. The sampled results of each pair of correlators are combined to derive the envelope and fed into the chip decision unit, that selects the chip with the maximum envelope. After each clock period T_C the chip decision unit delivers information about the frequency of the received chip and the corresponding envelope magnitude represents a measure for the energy of a received chip.

With knowledge of the relative position of a chip within a symbol, the following chip-mapper can decide whether the recent chip corresponds to a symbol for a "L" or a "H" bit. However, the binary result ($c_B(k \cdot T_c)$ in Fig. 2) of this decision still has the chip rate $1/T_C$.

The bit decision logic recombines C of the mapped chips to a data bit. This recombination is done by majority decision. To avoid ambiguities, the number C of chips per data bit must be odd. The final output of the bit decision unit is the data with the rate $1/T_S$.

0-7803-3567-8/96/$5.00 © 1996 IEEE

For the task of frame sychronisation each of the following signals within the receiver can be used (see Fig. 2):

- The M-ary signal at the output of the chip decision unit $c_c(k{\cdot}T_C)$,
- the binary signal at the output of the chip-mapper $c_B(k{\cdot}T_C)$,
- the binary data signal $d(l{\cdot}T_S)$ at the output of the bit decision unit.

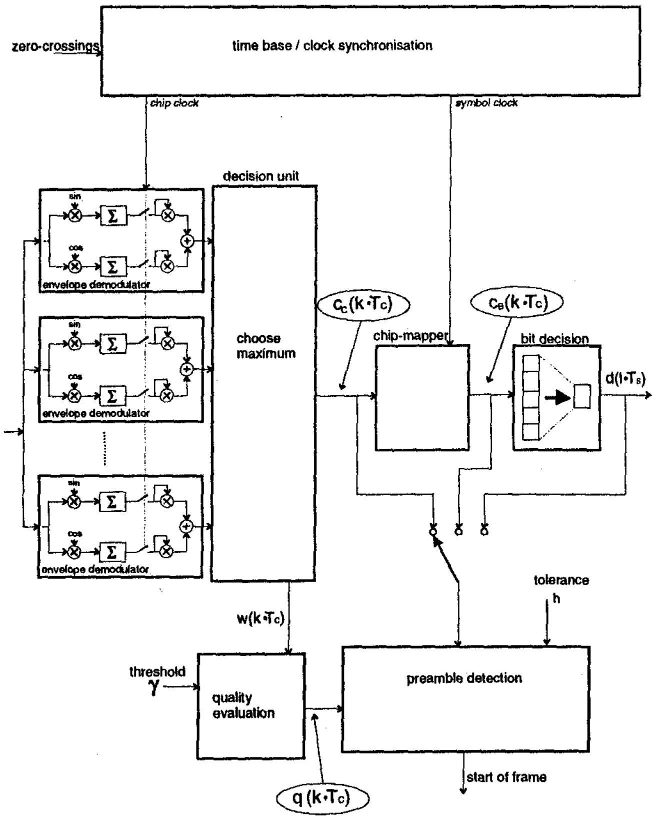

Figure 2: Receiver structure

1.3 Synchronisation of Symbols and Chips

A pragmatic procedure for synthesis of a global synchronised clock system for transmitters and receivers based on the zero-crossings of the mains voltage is described in [1] and [2]. The interval T_P between two zero-crossings of the mains voltage is divided into K time slots of equal duration $T_S = \frac{T_P}{K}$. Each of these time slots will be used for the symbol corresponding to one data bit. Ambiguity of phase, which may occur when receiver and transmitter are connected to different phases of three phase power supply networks can be overcome by using only integer multiples of six for the number K of time slots per period. If these symbol time slots are divided further into C sub-intervals for the chips of a symbol, the position of each chip within a symbol is unique, even under the aforementioned ambiguities.

This uniqueness of the relative chip position within a symbol is essential for proper operation of the chip-mapper, which uses this relative position to assign a chip to the appropriate data bit.

2 Preamble Detection

2.1 Preamble Detection out of the Data Bits

In the following we consider a detection strategy, that calculates a measure of coincidence $\Lambda(\vec{p},\vec{r}(k))$ for each discrete time step k. The compared row-vectors are a predefined preamble sequence $\vec{p}$ of length L, and an observation vector $\vec{r}(k)$ containing the recently received bit $r(k)$ and L-1 already received bits $r(k)...r(k$-L+$1)$. Detection of a preamble occurs whenever the measure of coincidence (MOC) exceeds a certain threshold. The MOC must steadily grow with increasing similarity of the two compared vectors $\vec{p}$ and $\vec{r}(k)$. Robustness against bit errors is introduced by choosing the value of detection threshold appropriately.

A measure of coincidence $H(k)$ can be derived by counting the equivalent bits in the corresponding positions of the vectors $\vec{p}$ and $\vec{r}(k)$. This measure, further referred to as count of equivalence, can be written as

$$H(k) = \sum_{i=0}^{L-1} p(i) \equiv r(k-i); \text{ where} \equiv \text{denotes logical equivalence} \qquad (1)$$

As proposed $H(k)$ steadily grows with increasing similarity to the maximum value $H_{max}=L$. To achieve detection, even if up to h bits of the received preamble are corrupted, the following detection rule is used:

$$H(k) \geq L-h. \qquad (2)$$

2.2 Preamble Detection Based on Chips

Obviously the performance of the strategy mentioned above grows with the length of the preamble sequence. More precisely, the number of observations taken to find a decision is of major importance. Besides longer preamble sequences, a higher number of observations can be derived by observing a signal with a higher clock rate. Such signals are available at the output of the chip decision unit (M-ary) or at the output of the chip-mapper (binary). Each element out of these streams, a bit or a chip, is comprehensively referred to as a "character" in the following. Both new methods of detection will be evaluated in the next section.

2.2.1 Binary Detection

The binary signal $c_B(k{\cdot}T_C)$ (see Fig. 2) of the chips assigned to an "L"- or "H"-bit is used as input for the detector. The advantage in comparison with detection using bits, the possibility to observe C times more characters, is degraded by the fact that the preamble sequence is still determined by a sequence of bits, not chips. As the frequency hopping scheme assigns a predefined sequence of chips to each data bit, there is a certain periodicy in the generated sequence of chips. This unavoidable property causes degrading side-effects discussed later.

2.2.2 M-ary Detection Using the Stream of Chips

The problems arising from the constraints in choosing a preamble sequence can be avoided by using the M-ary signal $c_c(k{\cdot}T_C)$ (see Fig. 2) at the output of the decision-unit for preamble detection. This will lead to an observation vector $\vec{r}$ containing M-ary information on the frequencies of the received chips.

The MOC given by (1) must be adapted. The binary equivalence $\equiv$ of bits is replaced by a M-ary equivalence $\underset{M}{\equiv}$ of chips. Now a generalised MOC is obtained

$$H(k)=\sum_{i=0}^{L-1} p(i)\underset{M}{\equiv} r(k-i). \tag{3}$$

The operator $\underset{M}{\equiv}$ delivers a logical one in case of equivalence of both operands, a zero in all other cases. A generalised law for preamble detection can be written as

$$\sum_{i=0}^{L-1} p(i)\underset{M}{\equiv} r(k-i)\geq L-h. \tag{4}$$

2.3 ADDITIONAL QUALITY EVALUATION

At this point the quality of the received characters plays no role in the decision strategy. Each character is treated as „valid". This is not advisable, especially not in cases where the characters can actually be generated by noise. For this reason it is useful to monitor the quality of a character.

The output of the envelope demodulator selected by the decision-unit ($w(k \cdot T_C)$ in Fig. 2) can be used to produce the binary quality signal $q(k \cdot T_C)$. It is compared with a threshold γ. The value 1 is delivered for valid characters, which exceed the threshold, the value zero otherwise.

The modified MOC rates only the valid characters and provides:

$$H(k)=\sum_{i=0}^{L-1} [\, p(i)\underset{M}{\equiv} r(k-i)]\cdot q(k-i). \tag{5}$$

2.3.1 ERRONEOUS QUALITY DECISIONS

Of course the quality decision itself can be erroneous in two ways:

- First order error: A signal is detected although there was actually nothing sent. The probability of this event is P_{FC}.
- Second order error: No signal is detected although it is present. The probability for this error is P_{FR}.

The following table shows the probabilities for the case of ideal (error-free) decision and the simplified case of no quality decision at all.

	Ideal decision	No decision
P_{FC}	0	1
P_{FR}	0	0

2.4 IMPACT OF RECEPTION ERRORS ON PREAMBLE DETECTION

A chip error occurs when the receiver's chip decision unit (see Fig. 2) identifies the frequency erroneously. The probability P_{CE} of such a chip error can be calculated according to [3]. Assuming corruption by additive white Gaussian noise with the spectral power density N_0 and M-ary envelope detection we have:

$$P_{CE}=1-\sum_{i=0}^{M-1}(-1)^i\begin{pmatrix} M-1 \\ i \end{pmatrix}\frac{1}{i+1}e^{-\frac{iE_C}{(i+1)\cdot 2N_0}} \tag{6}$$

$\frac{E_C}{N_0}$ is the ratio of chip energy and noise power density, named energy-to-noise-ratio ENR of a chip. As a data bit is composed out of C chips, we have the following relation $\frac{E_C}{N_0}=\frac{E_B}{C \cdot N_0}$, where E_B denotes the bit energy.

Observing preamble detection based on bits, preamble detection is influenced by bit errors. As the bit decision unit (see Fig. 2) recombines C chips to a data bit by using a majority decision, a bit error appears only if more than half of all chips are corrupted by chip errors. With the given chip error probability P_{CE} the bit error probability P_{BE} is given by

$$P_{BE}=\sum_{i=\lceil C/2 \rceil}^{C}\begin{pmatrix} C \\ i \end{pmatrix}\left(P_{CE}\right)^i\left(1-P_{CE}\right)^{C-i}. \tag{7}$$

As mentioned before, bits and chips can be regarded as characters in the same way. For the following considerations it is useful to define the probability P_E of a character error. In case of detection based on bits, P_E is the bit error probability, in case of detection based on chips, P_E is the chip error probability.

2.5 ERRORS IN PREAMBLE DETECTION

Three different kinds of events that are leading to an erroneous preamble detection will be treated in the following:

- The false alarm,
- the loss of a valid preamble,
- the premature detection of an incomplete preamble.

2.5.1 FALSE ALARM

This is the event of detecting a preamble, although actually no preamble has been sent. The false alarm occurs if L-h characters detected from a purely random received signal match with the preamble reference. Having M possible states of the chip frequency information and the probability P_{FC} for erroneously rating a character as „valid", a random match to a chip in the preamble reference occurs with the probability $\frac{1}{M}\cdot P_{FC}$. The probability that this random matching occurs a least L-h times is the probability P_{FA} of a false alarm, i.e.

$$P_{FA}=\sum_{i=0}^{h}\begin{pmatrix} L \\ i \end{pmatrix}\left(1-\frac{1}{M}\cdot P_{FC}\right)^i\cdot\left(\frac{1}{M}\cdot P_{FC}\right)^{L-i} \tag{8}$$

Note that P_{FA} is independent of the actual preamble structure.

2.5.2 LOSS OF A RECEIVED PREAMBLE DUE TO CHARACTER ERRORS

This event, shortly called loss, occurs if at least h valid characters of a completely received preamble do not match the stored preamble reference because they are corrupted by noise. The probability P_{PL} of this preamble loss is derived easily from the probability P_E of character errors:

$$P_{PL}=1-\sum_{i=0}^{h}\begin{pmatrix} L \\ i \end{pmatrix}\left(P_E+P_{FR}\right)^i\cdot(1-P_E-P_{FR})^{L-i} \tag{9}$$

2.5.3 CHOICE OF A THRESHOLD FOR QUALITY DECISION

In [5] a way for determining an optimum threshold γ is shown. This optimum strongly depends on the noise power density and the received signal energy. As on power lines the noise power density is time-variant within wide limits, it is impossible to determine an optimum threshold. Nevertheless (8) indicates, that the probability of false alarms is improved with any value of the probability of first order errors P_{FC} below one. However the probability of loss increases according to (9) with any non-zero value of P_{FR}. For this, it is reasonable to choose a low threshold, in order to keep P_{FR} as low as possible.

2.5.4 Premature Detection of a Partly Received Preamble

Entering the preamble detector it takes L steps until the preamble sequence is completely contained in the observation vector $\vec{r}$. As shown in Fig. 1 we consider the n-th step of this character by character reading. At a timestep k, n characters originating from a real preamble and L-n random characters generated by pure noise, are contained in the observation vector. The generalised MOC (3) can be split into two parts H_{PN} and H_{PR}. H_{PN} denotes the contribution of the L-n random characters r_N to the MOC:

$$H_{PN}(n) = \sum_{i=n}^{L-1} \left[p(i) \underset{M}{\equiv} r_N(k-i) \right] \cdot q(k-i). \qquad (10)$$

H_{PR} is the contribution to the MOC of the n possibly corrupted characters originated by the preamble:

$$H_{PR}(n) = \sum_{i=0}^{n-1} \left[p(i) \underset{M}{\equiv} r(k-i) \right] \cdot q(k-i). \qquad (11)$$

Assuming error-free transmission, the n received characters are exactly the characters $p(L\text{-}1\text{-}n)...p(L\text{-}1)$ of the preamble sequence and we have

$$H_{PP}(n) = \sum_{i=0}^{n-1} p(i) \underset{M}{\equiv} p(L+1-n+i). \qquad (12)$$

H_{PP} resembles the aperiodic autocorrelation sequence and will be called count of autoequivalent characters (COAEC) in the following.

The premature detection in a position n occurs if the received characters originating from a preamble deliver a fictive contribution $H_{PR}(n)=j$ to the MOC and the contribution of the random characters is high enough to fulfil the detection law (4). The probability of a premature detection in position n is then:

$$P_{FP}(n,h,L,P_E) = \sum_{j=0}^{min(L-h,n)} P\left\{ H_{PR}(n) = j \right\} \cdot P\left\{ H_{PN}(n) \geq L-h-j \right\} \qquad (13)$$

Following [4] we can take into account that r corrupted characters within the $H_{PP}(n)$ characters matching the preamble decrease the MOC by r. Also r corrupted characters within the n-$H_{PP}(n)$ mismatching characters increase the MOC by r. The probability P_{FP} can be derived as

$$P_{FP}(n) = \sum_{j=max(0,L-h)}^{n} \left\{ \sum_{r=max(0,H_{PP}(n)-j)}^{min(j,H_{PP}(n))} \left[\binom{H_{PP}(n)}{r} \cdot \binom{n-H_{PP}(n)}{j+r-H_{PP}(n)} \cdot \right. \right.$$

$$\left. (1-P_E-P_{FR})^n \cdot \left(\frac{P_E+P_{FR}}{1-P_E-P_{FR}} \right)^{2r+j-H_{PP}(n)} \right]$$

$$\left. \sum_{i=max(0,L-h-j)}^{L-n} \left[\binom{L-n}{i} \left(\frac{1}{M} \cdot P_{FC} \right)^i \cdot \left(1 - \frac{1}{M} \cdot P_{FC} \right)^{L-n-i} \right] \right\} \qquad (14)$$

Using the COAEC's margins $H_{PP}(0)=0$ and $H_{PP}(L)=L$, P_{FP} delivers the probability of a false alarm for the position n=0 (no preamble character contained in the observation vector) and the probability of detection 1-P_{PL} for the position $n=L$ (observation vector contains preamble completely).

The composition of the preamble sequence contributes to the probability P_{FP} only through the COAEC $H_{PP}(n)$.

Fig. 3 shows an example for the values of the COAEC and the probability of premature detection for a binary preamble sequence of length 16 and two different probabilities of character errors $P_E=10^{-4}$ and $P_E=10^{-2}$.

Corresponding to a low threshold, the probabilities of errors in quality decision are assumed to be $P_{FC}=0{,}9$ and $P_{FR}=10^{-3}$. Additionally P_{FP} is shown for the case of no quality decision. The probability of a character error corresponds, according to (6) ENRs of approximately 15 dB and 12 dB. The maximum tolerated number of corrupted bits per preamble is h=2. It is seen that there is a strong dependence between the COAEC and the probability of premature detections, which will be used as follows to derive appropriate preamble sequences.

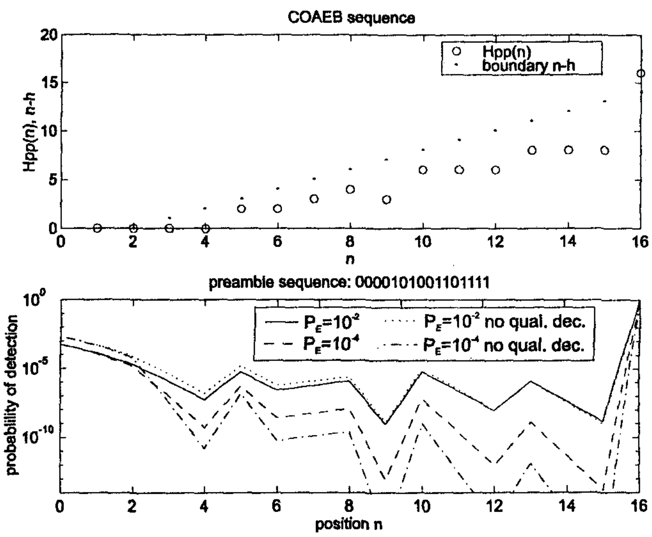

Figure 3: Impact of the preamble sequence on premature detection

2.6 Choice of Preamble Sequences

An ideal preamble detection meets two requirements:

- No premature detections.
- Safe detection of a completely received preamble.

Assuming error-free transmission, premature detection in a wrong position $n<L$ is avoided if the following equation is fulfilled for all $n<L$

$$H_{PP}(n) < L-h-H_{PN}(n), \quad \forall n < L. \qquad (15)$$

Sure detection for $n=L$ (complete reception) is guaranteed by

$$H_{PP}(L) \geq L-h. \qquad (16)$$

Again using the margin $H_{PP}(L)=L$, this equation is always fulfilled - assuming error free transmission.

Using the upper bound L-n for H_{PN}, equation (15) can be simplified and expresses a necessary requirement for the avoidance of premature detection:

$$H_{PP}(n) < n-h, \quad \forall n < L. \qquad (17)$$

As mentioned, the MOC in case of transmission errors H_{PR}, becomes lower or higher than $H_{PP}(n)$ depending on the characters corrupted by errors. An increase of the MOC is critical, as it may cause a premature detection if the bound *n-h* is exceeded by H_{PR}. The probability for this is small if the gap between $H_{PP}(n)$ and the threshold *n-h* is large (see Fig. 3). Therefore the following requirements for the composition of a preamble sequence hold:

1. Necessary: Each value of the COAEC must be less than n-h.
2. Desirable: The difference between the COAEC and the bound n-h should be as large as possible.

The second requirement implies that a preamble sequence should contain no periodic components, because they lead to peak values of $H_{PP}(n)$. The binary preamble sequence shown in Fig. 3 meets these requirements. The sequence was derived by calculating the COAECs for all possible sequences of length 16 and sequentially discarding those not meeting the requirements. As numerous sequences can be found this way, a third desirable requirement was additionally used: The characters should be uniformly distributed.

2.7 Comparison of the Preamble Detection Methods

With the figures „probability of false alarms" and „probability of loss", the proposed schemes of preamble detection are compared in the following:

2.7.1 Probability ofFalse Alarms

A plot of the probability of false alarms for the proposed detection schemes is shown in Fig. 4. For all plots the maximum tolerated number of corrupted characters per preamble is denoted in bits. Therefore the maximum tolerated number of corrupted **chips** per preamble is *C* times the maximum tolerated number of corrupted **bits** per preamble. The number of chips per bit is *C*=3, the preamble length is 16 bit, corresponding to 48 chips. As expected, the probability of false alarms in case of detection based on chips (binary or M-ary) is significantly superior to detection based on bits.

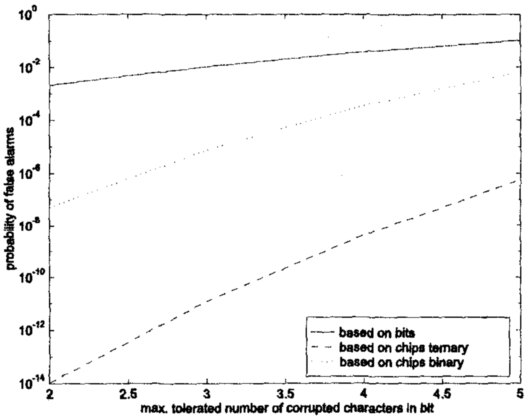

Figure 4: Probability of false alarms for the proposed detection strategies vs. maximum tolerated number of corrupted characters per preamble

2.7.2 Probability of Loss:

The probability of loss versus the ENR is depicted in Fig. 5 for detection based on chips and bits. The probability of errors in transmission was calculated following (6) and (7). The probability of loss deteriorates if detection based on chips is used. For equal probability, the detection based on chips needs an approximately 3 dB higher ENR.

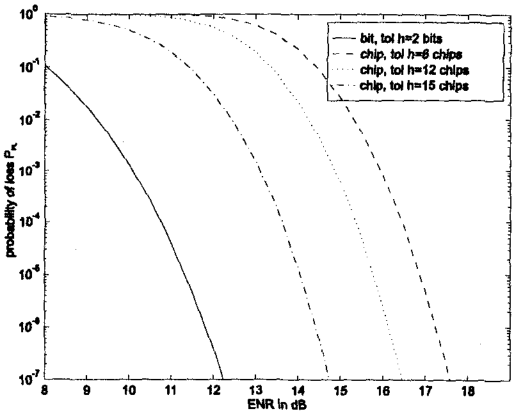

Figure 5: Probability of preamble loss P_{PL} versus ENR

3 Conclusions

For the construction of powerful preamble sequences and detection schemes, no overall optimum can be found. The proposed use of chips for detection combined with M-ary measures of coincidence significantly improves the probability of false alarms without extending the sequence used as preamble. Monitoring the quality of each received character also yields an improved false alarm behaviour, but thresholds for quality discrimination must be chosen very carefully. So, if an improvement of the probability of false alarms is paramount, detection based on chip information should be preferred.

However the improvement of the false alarm behaviour leads to a deterioration due to preamble loss errors. A trade-off between both effects is necessary.

The structure of a sequence chosen for a preamble neither influences the probability of false alarms nor the probability of loss, but has strong effect on premature detections. Degradation due to premature preamble detections can be avoided by observing the mentioned requirements concerning the sequence.

4 References

[1] K. M. Dostert: "Frequency-Hopping Spread-Spectrum-Modulation for Digital Communications over Electrical Power Lines", IEEE Journal on selected areas in communications, vol. 8, No. 4, pp. 700-710, May 1990.

[2] G. Threin: "Datenübertragung über Niederspannungsnetze mit Bandspreizverfahren", VDI Fortschrittberichte, Reihe 10, Nr. 156, VDI-Verlag, Düsseldorf 1991.

[3] J. G. Proakis: "Digital Communications", Third edition, McGraw-Hill, New York, 1995.

[4] R. A. Scholtz: "Frame Synchronization Techniques", IEEE Trans. On Communications, vol. COM-28, No. 8, pp. 1204-1212, Aug. 1980.

[5] J. Johann: "Modulationsverfahren", Springer-Verlag, Berlin, 1992.