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Design of optimum sync and detection patterns for frame synchronisation

A. Nowbakht and J.W.M. Bergmans

Frame synchronisation for a packet transmission system, in which the sync pattern is preceded by a known preamble, is considered. The correlation receiver uses an extended (or shortened) version of the sync pattern, which is called the detection pattern. This leads to a new criterion for designing optimum pairs of sync and detection patterns. The obtained patterns result in a normalised improvement of up to 3.91 dB over the known optimum patterns.

Introduction and system model: The common packet transmission scheme is considered, in which every frame contains a sync pattern prior to the user data. We assume an additive white Gaussian noise (AWGN) channel. The frame synchronisation system at the receiver consists of a correlator followed by a threshold detector (see Fig. 1). The correlator outputs a correlation sequence and, whenever an element of this sequence surpasses a given threshold, the detection of the sync pattern is flagged.

Fig. 1 Block diagram of frame synchronisation system model

In practice, a common scenario is the one in which the sync pattern is preceded by a known preamble and the search for the sync pattern is enabled once the preamble has been detected. A sync pattern design criterion was proposed in [1] for this case. It consisted in selecting the sync patterns that minimised the maximum (absolute) value of the correlation sequence before the correlation peak. The correlation sequence is the sliding correlation of the sync pattern with the concatenated preamble/sync pattern. The patterns obtained performed significantly better than the known optimum autocorrelation sequences (sync patterns minimising the maximum (absolute) value of the autocorrelation sequence before the autocorrelation peak) because the optimum autocorrelation sequences are only optimal if the sync pattern is not preceded by a preamble.

We show that the performance can still be improved significantly by considering the joint optimisation of sync pattern and correlation receiver. We allow the correlator to use extended sync patterns, i.e. to extend the sync pattern by preceding it with the last bits of the known preamble. We also allow shortened sync patterns, i.e. to consider only the last part of the sync pattern. We denote the pattern used by the correlator as the detection pattern. The detection pattern is unambiguously defined by its length, the sync pattern and the preamble (in the case it is an extended sync pattern). Our sync pattern design criterion is essentially the same as the one proposed in [1] but for each possible sync pattern we consider a range of possible lengths for the detection pattern. We select the pairs of sync patterns and detection pattern lengths that minimise the maximum value of the correlation sequence before the correlation peak. To the best of our knowledge the possibility of considering detection patterns of different length from that of the sync pattern has not been exploited systematically before.

Frame format: We use bold type to denote a sequence $\mathbf{x}$ of length M and non-bold type to denote its elements $x[n]$ for $n=0, \dots, M-1$ (we start indexing at zero). Each frame $\mathbf{f}$ consists of three parts: preamble $\mathbf{p}$, sync pattern $\mathbf{s}$ and data $\mathbf{d}$ (in this order). The frame can alternatively be specified as $\mathbf{f}=(\mathbf{p}, \mathbf{s}, \mathbf{d})$. Let N , N_p , N_s and N_d denote the frame, preamble, sync pattern and data lengths, respectively, so that $N=N_p+N_s+N_d$. We consider $\mathbf{f}$ to be binary, i.e. $\mathbf{f} \in \{-1, 1\}^N$.

Correlation receiver: The correlator generates $\mathbf{q}_{s,w}$, the correlation sequence of the received sequence $\mathbf{r}=\mathbf{f}+\mathbf{n}$ with a stored sequence $\mathbf{w}$ of length L denoted as the detection pattern. We stress the dependence

of the correlation sequence on the choice of $\mathbf{s}$ and $\mathbf{w}$ by using them as sub indices. We define the $\mathbf{w}$ for $L>N_s$ as $\mathbf{w}=\mathbf{s}_L \equiv (p[N_p-(L-N_s)], \dots, p[N_p-1], \mathbf{s})$ for $L>N_s$. For $L \leq N_s$ we define $\mathbf{w}$ as $\mathbf{w}=\mathbf{s}_L \equiv (s[N_s-L], \dots, s[N_s-1])$ for $L \leq N_s$. This means that, for $L>N_s$, the sync pattern is extended by prefixing it with the last bits of the preamble to form $\mathbf{w}$, whereas for $L \leq N_s$ the sync pattern is shortened by considering the beginning $(s[0], \dots, s[N_s-L-1])$ as the last part of the preamble. Note that our correlator coincides with the one used in the literature for $L=N_s$, since then $\mathbf{w}=\mathbf{s}$, i.e. the detection pattern coincides with the sync pattern.

We write the correlation sequence $\mathbf{q}_{s,w}$ as $q_{s,w}[i] = \sum_{k=0}^{L-1} w[k] r[i+k-(L-1)]$ for $i=0, \dots, N-1$.

Since $\mathbf{r}=\mathbf{f}+\mathbf{n}$ we can write $\mathbf{q}_{s,w}=\mathbf{c}_{s,w}+\mathbf{n}_w$ where $\mathbf{c}_{s,w}$ is the correlation sequence of the frame $\mathbf{f}$ with $\mathbf{w}$, i.e. $c_{s,w}[i] = \sum_{k=0}^{L-1} w[k] f[i+k-(L-1)]$ for $i=0, \dots, N-1$, and $\mathbf{n}_w$ is the correlation sequence of the noise sequence $\mathbf{n}$ with $\mathbf{w}$. We consider the elements of $\mathbf{n}$ to be statistically independent Gaussian random variables with zero mean and standard deviation σ . Therefore $\mathbf{n}_w$ is additive Gaussian noise of standard deviation

$$\sigma_w = \|\mathbf{w}\|\sigma = \sqrt{L}\sigma \quad (1)$$

at the output of the correlator.

Detection distance: We define the detection distance as the normalised difference of the value of $\mathbf{c}_{s,w}$ at the correlation peak and the maximum value at any prior instant, i.e. $D = \sqrt{N_s}/\sqrt{L} (c_{s,w}[i_o] - \max\{c_{s,w}[i]: i < i_o\})$, where $i_o = N_p + N_s - 1$ is the position of the last bit of the sync pattern in the frame. (The sync and detection patterns are designed so that $c_{s,w}[i_o] > \max\{c_{s,w}[i]: i < i_o\}$.) The normalisation factor $\sqrt{N_s}/\sqrt{L}$ is introduced in order to be able to make a fair comparison between detection distances D corresponding to different lengths L . This factor compensates for the different noise variances at the correlator output corresponding to different detection pattern lengths L (see (1)).

The correlation peak $c_{s,w}[i_o] = L$ since it is the autocorrelation of the detection pattern. Therefore the detection distance is written as $D = \sqrt{N_s}/\sqrt{L} (L - \max\{c_{s,w}[i]: i < i_o\})$. Note that D is a function of the preamble, the sync pattern and the detection pattern.

Now we proceed to search for sync patterns $\mathbf{s}$ and detection pattern lengths L that maximise D . The maximum detection distance that can be achieved for a given sync pattern length N_s and range of detection pattern lengths $a < L < b$ is given by:

$$D_{\max} = \max_{a < L < b} \max_{y \in \{-1, 1\}^{N_s}} \left\{ \sqrt{\frac{N_s}{L}} \cdot (L - \max\{c_{y,y_L}[i]: i < i_o\}) \right\}$$

or equivalently by:

$$D_{\max} = \max_{a < L < b} \left\{ \sqrt{\frac{N_s}{L}} \cdot \left(L - \min_{y \in \{-1, 1\}^{N_s}} \max\{c_{y,y_L}[i]: i < i_o\} \right) \right\}$$

The above maximisation can be performed by exhaustive search for practical sync pattern lengths N_s .

Table 1: Optimal pairs of sync and detection patterns with lowest correlation sidelobes

Preamble $\mathbf{p}$	N_s	Sync $\mathbf{p} \cdot \mathbf{s}$	L	Detection $\mathbf{p} \cdot \mathbf{w}$	$D_{\max}$
+ - + -	8	70	11	270	8.528 (6)
+ + - -	8	3A	13	0C3A	9.414 (6)
+ + + +	8	89	7	09	8.552 (8)
+ - + -	12	598	15	2598	12.522 (10)
+ + - -	12	B70	17	0CB70	13.443 (12)
+ + + +	12	0A6	12	0A6	14 (14)
+ - + -	16	5E60	19	25E60	16.518 (14)
+ + - -	16	32D0	22	0C32D0	17.056 (14)
+ + + +	16	149D	16	149D	18 (18)
+ - + -	20	51F26	26	2A51F26	21.049 (18)
+ + - -	20	B2B50	26	0CB2B50	21.049 (18)
+ + + +	20	052E6	20	052E6	22 (22)

Results: Table 1 lists the optimal pairs of sync and detection patterns according to our optimisation criterion (found by exhaustive search) for $N_s = 8, 12, 16, 20$ and $1 < L < 40$. The first column indicates the basic period of the preamble, where we have used + (or -) as a shorthand notation for +1 (or -1). We consider the preamble to be built up by repeating an integer number of times the basic period. The last column lists the achieved detection distances and between parentheses are the detection distances obtained when performing the optimisation for $L = N_s$, i.e. when the sync pattern is used as detection pattern. We observe gains of up to $20 \log_{10} (9.414/6) = 3.91$ dB.

Conclusions: The optimal design criterion for sync patterns for the common case where the sync pattern is preceded by a known preamble was published in [1]. We present a somewhat more general approach where the correlation receiver is allowed to use a different pattern from the sync pattern to correlate with the received sequence. This leads to a new joint optimisation criterion for sync patterns and correlation receiver. We have obtained a new table of optimal pattern

pairs, which shows that our strategy can lead to improvements of up to 3.91 dB over the known optimal sync patterns, for sync pattern lengths $N_s = 8, 12, 16, 20$.

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