Design of optimum sync and detection patterns for frame synchronisation
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Design of optimum sync and detection patterns for frame synchronisation

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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 autocorrelation peak is found, the detection pattern is flagged.

In practice, a scenario is the one in which the sync pattern is shortened by considering the beginning (of the correlation peak and the preamble (in this order). The frame can be extended by preceding it with the last bits of the known 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.

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Detection distance: We define the detection distance as the normalised difference of the value of $e_{\text{max}}$ at the correlation peak and the maximum value at any prior instant, i.e. $D = \sqrt{N_f / N_s} (c_{s,w}[i] - m(c_{s,w}[i]; i < i_o))$. The normalisation factor $\sqrt{N_f / N_s}$ 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 (4)).

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

Now we proceed to search for sync patterns $s$ 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:

$$D_{\text{max}} = \max_{a < L < b} \max_{i \in \{1,\ldots,i_o\}} \left( \frac{N_f}{N_s} (L - \max[c_{s,w}[i]; i < i_o]) \right)$$

or equivalently by:

$$D_{\text{max}} = \max_{a < L < b} \left( \frac{N_f}{N_s} (L - \min_{i \in \{1,\ldots,i_o\}} \max[c_{s,w}[i]; i < i_o]) \right)$$

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

<table>
<thead>
<tr>
<th>Preamble $N_s$</th>
<th>Sync $p \times s$</th>
<th>$L$</th>
<th>Detection $p \times w$</th>
<th>$D_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ + + + + +</td>
<td>0</td>
<td>20</td>
<td>00</td>
<td>0.825 (6)</td>
</tr>
<tr>
<td>+ + + + + +</td>
<td>3A</td>
<td>13</td>
<td>0C3A</td>
<td>9.414 (6)</td>
</tr>
<tr>
<td>+ + + + + +</td>
<td>89</td>
<td>7</td>
<td>09</td>
<td>8.552 (8)</td>
</tr>
<tr>
<td>+ + + + + +</td>
<td>598</td>
<td>15</td>
<td>2598</td>
<td>12.522 (10)</td>
</tr>
<tr>
<td>+ + + + + +</td>
<td>17</td>
<td>0C870</td>
<td>13.443 (12)</td>
<td></td>
</tr>
<tr>
<td>+ + + + + +</td>
<td>17</td>
<td>0A68</td>
<td>14 (14)</td>
<td></td>
</tr>
<tr>
<td>+ + + + + +</td>
<td>16</td>
<td>056E0</td>
<td>16.518 (14)</td>
<td></td>
</tr>
<tr>
<td>+ + + + + +</td>
<td>16</td>
<td>15</td>
<td>16.108 (14)</td>
<td></td>
</tr>
<tr>
<td>+ + + + + +</td>
<td>20</td>
<td>051F26</td>
<td>21.049 (18)</td>
<td></td>
</tr>
<tr>
<td>+ + + + + +</td>
<td>20</td>
<td>0B2B50</td>
<td>21.049 (18)</td>
<td></td>
</tr>
<tr>
<td>+ + + + + +</td>
<td>20</td>
<td>0526E0</td>
<td>22 (22)</td>
<td></td>
</tr>
</tbody>
</table>

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

Correlation receiver: The correlator generates $q_{s,w}$, the correlation sequence of the received sequence $r = f + n$ with a stored sequence $w$ of length $L$ denoted as the detection pattern. We stress the dependence of the correlation sequence on the choice of $s$ and $w$ by using them as sub indices. We define the $w$ for $L > N_s$ as $w = s_N \equiv [p[N_p - (L - N_s)], \ldots, p[N_p - 1], s]$ for $L > N_s$. For $L \leq N_s$ we define $w = s_N \equiv [0, N_s - L, \ldots, s[1]$ for $L \leq N_s$. This means that, for $L > N_s$, the sync pattern is extended by prefixing with the last bits of the preamble to form $w$, whereas for $L = N_s$ the sync pattern is shortened by considering the beginning $[0, \ldots, s[N_s - 1)]$ as the last part of the preamble. Note that our correlator uses the one used in the literature for $L = N_s$, since then $w = s$, i.e. the detection pattern coincides with the sync pattern.

We write the correlation sequence $q_{s,w}$ as $q_{s,w}[i] = \sum_{k=0}^{L-1} w[k] r[i+k-(L-1)]$ for $i = 0, \ldots, N_s - 1$. Since $r = f + n$ we can write $q_{s,w} = c_{s,w} + n_s$ where $c_{s,w}$ is the correlation sequence of the frame $f$ with $w$, i.e. $c_{s,w}[i] = \sum_{k=0}^{L-1} w[k] f[i+k-(L-1)]$ for $i = 0, \ldots, N_s - 1$, and $n_s$ is the correlation sequence of the noise sequence $n$ with $w$. We consider the elements of $n$ to be statistically independent Gaussian random variables with zero mean and standard deviation $\sigma$. Therefore $n_s$ is additive Gaussian noise of standard deviation $\sigma_w = \|w\|\sigma = \sqrt{L\sigma}$ (1) at the output of the correlator.

Detection distance: We define the detection distance as the normalised difference of the value of $e_{\text{max}}$ at the correlation peak and the maximum value at any prior instant, i.e. $D = \sqrt{N_f / N_s} (c_{s,w}[i] - m(c_{s,w}[i]; i < i_o))$. The normalisation factor $\sqrt{N_f / N_s}$ 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 (4)).

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