Design of a Transceiver for 3G DECT Physical Layer

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The Big Picture

2G DECT
Binary GFSK
1.152 Mbps

3G DECT
M-ary DPSK
3.456 Mbps

DECT - Digital Enhanced Cordless Telecommunications
Overview

• 2G DECT specifications and 2G transceiver
• 3G DECT specifications
• Issues in receiver design
• Digital FM demodulator
• Coherent detector for DPSK symbols
• Results and Conclusion
2G DECT Specifications

• Multi-Carrier TDMA TDD system

• RF carriers separated by 1.728 MHz (=B) each in 1880 MHz to 1938 MHz band

- Bit rate, $R_b = 1/T_b = 1.152$ Mbps
- GFSK modulation with $BT_b=0.5$
2G DECT Specifications (contd.)

- Nominal frequency deviation of ±288 kHz
- Allowed deviation limits: 70% to 140% of nominal
GFSK Transceiver

Bit Stream @1.152 Mbps

Acquisition/Synchronisation/Data Detection

In Software

Samples @ 2.304 MHz

ADC → PLL → Hard limiter → BPF → SAW filter → PA

Gaussian LPF BT_b = 0.5

VCO @IF

BPF (non-linear)

F_c-IF

FM demod

@ 2.304 MHz
TDMA Frame Structure in DECT

- **S-field**: Synchronisation Field
- **A-field**: Control Information
- **B-field**: Data Packet

<table>
<thead>
<tr>
<th>Frame</th>
<th>Slot</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ms</td>
<td>5 ms</td>
</tr>
<tr>
<td>0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23</td>
<td></td>
</tr>
</tbody>
</table>

- **Guard Band**
- **Guard Band**
3G Physical Layer Specifications

- Modulation Schemes: $\pi/2$ DBPSK, $\pi/4$ DQPSK, $\pi/8$ D8PSK

Constellation for differential PSK modulation
3G Physical Layer Specifications (contd.)

- Root-Raised Cosine with 50% excess bandwidth
- Symbol rate is 1.152 Msps
- Zero ISI at the output of the matched filter in the receiver

Normalized time-domain waveform

Power spectrum (frequency in MHz)
3G Physical Layer Specifications (contd.)

• Allowed combination of modulation schemes

<table>
<thead>
<tr>
<th>Configuration</th>
<th>S-field</th>
<th>A-field</th>
<th>B-field</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>GFSK</td>
<td>GFSK</td>
<td>GFSK</td>
</tr>
<tr>
<td>1b</td>
<td>$\pi/2$-DB</td>
<td>$\pi/2$-DB</td>
<td>$\pi/2$-DB</td>
</tr>
<tr>
<td>2</td>
<td>$\pi/2$-DB</td>
<td>$\pi/2$-DB</td>
<td>$\pi/4$-DQ</td>
</tr>
<tr>
<td>3</td>
<td>$\pi/2$-DB</td>
<td>$\pi/2$-DB</td>
<td>$\pi/8$-D8</td>
</tr>
</tbody>
</table>

• S and A fields always employ $\pi/2$-DBPSK
  $\Rightarrow$ can be detected in a non-coherent GFSK receiver
DPSK Transceiver

Signal processing in digital domain

In Software

Samples @ 3.456 MHz

IF\textsubscript{1} + IF\textsubscript{2}

IF\textsubscript{2} = 9.504 MHz

ADC
BPF\textsubscript{2}
SAW

IF\textsubscript{c} - IF\textsubscript{1}

Bit Stream

Bit to symbol mapping

Root-raised cosine filter $\alpha=0.5$

$\text{Cos}(2\pi f_{\text{IF}}t)$

$\text{Sin}(2\pi f_{\text{IF}}t)$

$F_{\text{c}} - f_{\text{IF}}$

BPF (linear)

$F_{\text{c}} - f_{\text{IF}}$

ADC
BPF\textsubscript{2}
SAW

IF\textsubscript{1} + IF\textsubscript{2}

IF\textsubscript{2} = 9.504 MHz

Bit Stream

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$\text{Cos}(2\pi f_{\text{IF}}t)$

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$F_{\text{c}} - f_{\text{IF}}$

BPF (linear)
Bandpass Sampling - choice of IF2

- IF2 = 9.504 MHz = (5+0.5)*B; B = 1.728 MHz
  ⇒ minimum sampling rate, \( F_s = 2B = 3.456 \text{ MHz} \)
I-Q Demodulation

- Carrier Frequency and Carrier Phase synchronization
- Clock Frequency and Clock Phase synchronization

\[ r(n) \quad \text{@3.456 Msps} \]

\[ \cos(n \pi/2) \quad \sin(n \pi/2) \]

\[ g_k(n) \]

\[ y(n) \quad \text{@1.152 Msps} \]
Data Detection in the receiver

a) non-coherent differential

- Transmitted constellation points
- Received constellation points (in noise), $y(n)$

\[ \theta > 0 \Rightarrow \text{bit 1} \]
\[ \theta < 0 \Rightarrow \text{bit 0} \]

b) coherent differential

- Transmitted constellation points
- Received constellation points (in noise), $y(n)$

\[ \varphi = 90\,\text{degrees} \Rightarrow \text{bit 1} \]
\[ \varphi = -90\,\text{degrees} \Rightarrow \text{bit 0} \]
Performance of Different Demodulation Schemes

![Graph showing performance comparison of different demodulation schemes. The graph plots log(BER) vs. Eb/N0 and includes lines for coherent BPSK, coherent differential BPSK, and non-coherent differential BPSK.]
Tasks in the receiver

• Slot boundary acquisition on power-up/sync loss

• Clock recovery in every slot

• Frequency and phase offset estimation

• Data detection with adaptive carrier phase tracking
Signal Processing in Digital Domain

- Bandpass samples at 3.456 MHz
- S & A fields
- B field (if GFSK)
- S-field only
- B-field

- Digital FM demodulator
  @ 2.304 MHz

- Carrier frequency and phase offset estimator
  Start of S-field
- Symbol clock phase (kT_b/12, k=0,1…11)

- Coherent data detector with adaptive phase correction
  Demodulated GFSK data

- Acq & Sync/data (for GFSK)

- Demodulated DPSK data
FM Demodulation

• An FM signal

\[ r(t) = A \cos(2\pi f_c t + \phi(t)) ; \quad \phi(t) = 2 \pi k_f \int m(\tau) d\tau + 2\pi \Delta f t \]

= \[ A \cos (\phi(t)) \cos(2\pi f_c t) - A \sin (\phi(t)) \sin(2\pi f_c t) \]

\[ x_c(t) \quad \quad \quad \quad \quad \quad \quad \quad x_s(t) \]

• Instantaneous phase

\[ \phi(t) = \tan^{-1}(x_s(t)/x_c(t)) \]

• Instantaneous frequency

\[ \frac{d\phi(t)}{dt} = 2\pi k_f m(t) + 2\pi f \]
Digital FM Demodulator

• $r(t)$ sampled @ 3.456MHz
  \[ r(n) = x_c(n) \cos(n\pi/2) - x_s(n) \sin(n\pi/2) \]

• $x_c(n) = r(2n+1)(-1)^n$
  \[ x_c(n) = r(2n)(-1)^n \]
  \[ \Rightarrow x_c(n) \text{ and } x_s(n) \text{ are not samples at same time instant.} \]

Implementations constraints

• Output of Demodulator should be @ 2.304MHz.
  \[ \Rightarrow \text{Interpolate } x_c(t) \text{ and } x_s(t) \text{ by 4 and then decimate by 3} \]

  \[ \text{ALSO} \]

• For $\tan^{-1}(\ )$ samples of $x_c(t)$ and $x_s(t)$ should be at same time instant
  \[ \Rightarrow \text{Decimate with different phases} \]
Digital FM Demodulator (contd.)

Tan^{-1}( ) calculation

- Calculation of $\phi(n) = \tan^{-1}(x_s(n)/x_c(n))$ is computation intensive

$\Rightarrow$ Table Look-up method

Trade-off between computational complexity and memory requirement
Soft FM demodulator block diagram

\[
\begin{align*}
\text{Demux} & \quad r(n) \\
(-1)^n & \quad x_c(n) \\
\downarrow & \quad x_{ci}(n) \\
\downarrow & \quad x_{cd}(n) \\
\frac{x_{sd}(n)}{x_{cd}(n)} & \quad \tan^{-1} \quad \phi(n) \\
& \quad g(n)
\end{align*}
\]
Signal Processing in Digital Domain

- Bandpass samples at 3.456 MHz
- S-field only
- S & A fields
- B field (if GFSK)

Coherent detector with adaptive phase correction

Carrier frequency and phase offset estimator

Digital FM demodulator

Start of preamble

Symbol clock phase ($kT_b/12, k=0,1…11$)

Acq & Sync/data (for GFSK)

Demodulated GFSK data

Demodulated DPSK data

@ 2.304 MHz
• $g_k(n)$ - root-raised cosine matched filter

$$\Rightarrow g_k(n) = g(nT - kT_b / 12), k = 0, 1, 2, \ldots, 11, \text{ from clock recovery}$$
Symbols in S-field

• $y(n) = (I_n + jQ_n) \ e^{j(n\alpha + \theta)}$, where $\alpha = 2\pi \cdot \delta f \cdot T_s$

• S-field (1-0 pattern) always DBPSK

  $\Rightarrow y(n) = [I_o + jQ_o] [e^{i\theta}, e^{j(\pi/2 + \theta)}, e^{j\theta}, \ldots], \ \delta f = 0, \ \theta \neq 0$
Estimation of $\delta f$

- $y(n) = A.[I_o+jQ_o].[e^{j\theta}, e^{j(\pi/2+\alpha+\theta)}, e^{j(2\alpha+\theta)}, ...]$

- $y_1(n) = y(2n) = A.(I_o+jQ_o).e^{j(2n\alpha+\theta)}$

- $y_2(n) = y(2n+1) = A.(I_o+jQ_o).e^{j\pi/2}.e^{j((2n+1)\alpha+\theta))}$

- For $i=1,2$
  
  $y_i(n).y_i^*(n-1) = A^2e^{j2\alpha} = A^2 [\cos(2\alpha)+jsin(2\alpha)]$

- Average $y_i(n).y_i^*(n-1)$ over the preamble to get an estimate of $\alpha$, denoted by
Estimation of $\theta$

- Compensate for $\delta f$

\[
y_d(n) = y(n)e^{-jn\hat{\alpha}} = [I_n + jQ_n]e^{j(\alpha - \hat{\alpha})n + \theta} \approx [I_n + jQ_n]e^{j\theta}
\]

- Form two sequences $z_e(n)$, $z_o(n)$

$\Rightarrow z_e(n)$

\[
z_e(2n) = y_d(2n)e^{-j\pi/2}
\]

\[
z_e(2n+1) = y_d(2n+1)
\]

$\Rightarrow z_o(n)$

\[
z_o(2n) = y_d(2n)
\]

\[
z_o(2n+1) = y_d(2n+1)e^{-j\pi/2}
\]
Estimation of $\theta$ (contd.)

- $z_e(n)$ will be points from one of the following, $z_o(n)$ will be from the other

- The average of $z_e(n)$ or $z_o(n)$ will be small; the other sequence is used to estimate, $\hat{\theta}$
Data detection with Phase Tracking

\[ y(n) \]

\[ u(n) \]

\[ v(n) \]

\[ d(n) \]

\[ e^{-j(n\hat{\alpha} + \hat{\theta})} \]

\[ w^*(n) \]

\[ e(n) = \hat{d}(n) - v(n) \]

\[ v(n) = w^*(n)u(n) \]

\[ w(n) = w(n-1) + \mu u(n) e^*(n) \]
Performance of the LMS Algorithm

![Graph showing the performance of the LMS algorithm.]
Performance of the LMS Algorithm (contd.)
Performance of the Receiver Algorithm

MU = 0.2
with freq. estimate
Performance of the Receiver Algorithm

MU = 0.2
\( \Delta f = 10 \text{ kHz} \)

- Ideal
- with freq. estimate
- no freq. estimate
Conclusions

• Transceiver hardware design for 3G DECT physical layer was presented

• Issues involved in the receiver design were discussed

• Carrier synchronization algorithms were discussed

• Performance results of the receiver were presented