The Nature of Robust and Reliable Communications:

Theory and Applications

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Open your mind

Robust and Reliable Communications needs an Open Mind!

Connect the points in one strike with not more than four lines

**Solution:**

![Diagram showing the solution to connect the points with four lines]
What counts

Imagination is more than knowledge.

\[ E = mc^2 \]

Albert Einstein (1879-1955)
Introduction

Changes in Wireless Communications

(1) Globalization
(2) Tendency to open the telecom market
(3) Harmonization interests for a world standard
(4) Rapid growth of mobile user population
(5) Bandwidth hungry applications

In the future a gap in capacity is unavoidable!
Introduction

Requirements for Future Wireless Communications

(1) Mobile multi-user schemes [wireless terrestrial/satellite]
   a) Voice
   b) Data
   c) Telemetry
(2) World coverage.
(3) High degree of availability.
(4) Resources on demand (billing).
(5) Flexibility: Type and quality of future services are not known in advance. The killer application is missing.
(6) Cheap and economic in use.

→ It is not possible to estimate it precisely enough!
Introduction

Expected Interference

Unknown interference everywhere and always present.

(1) Broadband and narrowband interference
(2) Impulsive and permanent interference
(3) Intensional jamming
(4) Men made noise (non-Gaussian noise).
(5) Combinations of the above types of interferences
(6) High dynamic changes of the above compositions of interference sources

⇒ It is not possible to predict it now!
Introduction

Challenges due to the Changes

The predicted gap in capacity can be bridged by exploiting sophisticated interference combating techniques!

(1) Robust communication techniques
(2) Reliable communication systems
Optimum System:

Conventional Digital Communication System

A conventional communication system is used to explain the problem with optimum systems.

Outline:
Bipolar NRZ pulses, AWGN, detector is optimized to AWGN (Matched-Filter/Correlator). The MF maximizes the SNR prior to the decision. High SNR makes the decision more reliable.
Optimum System:

Problem description and definitions

\[ r = d + n = D_n \cdot s + n \quad \rightarrow \quad Z_n = [r,s] = D_n \cdot [s,s] + [n,s] \]

Gaussian interference

”Linear property of correlation“
The **interference reduction effect** is gained from the **white nature of the interference** itself.
Optimum System:

Now we are looking for the **most harmfull type of interference** that confuses the detector and results in wrong decisions.

Variations:

\[ Z_n = \alpha_1 \cdot D_n \cdot [s,s] + \alpha_2 \cdot [n,s] = \alpha_1 \cdot D_n + \alpha_2 \cdot [n,s] \]

A wrong decision is based on the opposite polarity of the transmitted data bit. Only the SONI in the interference term (X) can do that. Additionally \( \alpha_2 > \alpha_1 \) must hold.

\[ n = -D_n \cdot s \]

The decision variable for the most harmfull interference is:

\[ Z_n = \alpha_1 \cdot D_n + \alpha_2 \cdot [-D_n \cdot s, s] = D_n \cdot (\alpha_1 - \alpha_2) \]
**Optimum System:**

The most harmfull interference waveform is one which produces an additive component in the decision variable containing the **same information** as the desired waveform.

**Physical Interpretation:** The worst case occurs when the interference presents the detector a signal (SONI) which is a delayed replica of the SOI. That’s **multipath** interference!

\[
\begin{align*}
\alpha_1 &< \alpha_2 \\
\text{Delay large enough for phase canceling}
\end{align*}
\]

"Unresolvable Error"
**Optimum System:**

**Problem:** In a multipath environment the conventional detector (optimized for AWGN) can not distinguish between the SOI and SONI (resolve the multipath components). The BEP raises significantly!

The need of a detection philosophy that resolves the multipath components is obvious.
Optimum System:

Remark:

The bad behavior in a multipath environment is not a great surprise, because the conventional detector (optimized for AWGN) is trained to find the polarity of a DC level and to average out all disturbances. Disturbances are treated as interference.

If, like in the multipath case, the detector finds an additional DC level, it considers that as something usefull and make no attempt to reduce it.
The way out of the dilemma

Robust Systems:
Spread-Spectrum Technology
The Inventor of Spread-Spectrum Technology

Hedy Lamarr and George Antheil. Photo of Hedy Lamarr courtesy of the Academy of Motion Picture Arts & Sciences. Photo of George Antheil courtesy of the Estate of George Antheil.
**Fact:** We have control about the transmitted signal (SOI).

Remember the IR mechanism in AWGN is based on the white nature of the interference itself and the averaging operation corresponding to the integration. E.g. „chopping behavior“.

How can that mechanism be realized for multipath interference?

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### Preparing the SOI

\[ d(t) = D_n \cdot p(t) \]

\[ s(t) = p(t) \]

\[ c(t) \]

Transmitter  Channel
Robust System: Spread-Spectrum Technology

**Spread-Spectrum Signal:** \( c(t) \).

\[ L = 7 \ldots \text{Number of chips/symbol} \]

\[ \int_{T_0} T_c c(t) \cdot dt = 0 \ldots \text{OK} \]

\( \rightarrow \) DC-less

\[ \int_{0}^{T_0} c(t) \cdot dt = 0 \ldots \text{OK} \]

\( \rightarrow \) Synchronization possible

\( \rightarrow \) Generalized IR-processing corresponding to „chopping“-operation.
Robust System: Spread-Spectrum Technology (MRR)

The interference reduction effect is gained from the white nature of the spread-spectrum signal.
Robust System: Spread-Spectrum Technology

„Resolveability of the multipath components due to the 2-valued Auto-Correlation-Function“

Components resolveable!
Robust System: Spread-Spectrum Technology (RAKE)

Input:

Delay: 3 \cdot T_c

Ref:

Result:

Correlator matched to direct path

Correlator matched to echo

\[ Z_n = Z_1 + Z_2 = [s_1, s_1] + [s_1, n_1] + [s_2, n_2] + [s_2, s_2] = 0.5 + 0 + 0 + 0.5 = 1 \]
Robust System: Spread-Spectrum Technology

Remarks to the spread-spectrum philosophy

The spread-spectrum concept is a **generalization** of the „**whitening procedure**“ for any interfering waveform.

We have **learned from nature** to prepare our communication system to make it more robust and reliable against unpredictable kinds of interfering waveforms.

„**PN-property**“

Sloopy speaking: Before the integration is performed, the SOI has no zero-crossings and the SONI has many zero-crossings, that garantees:

\[
[s, s] \text{ approaches } 1 \quad \text{and} \quad [n, s] \text{ approaches } 0
\]
General Remarks on Optimum Systems and Robust Systems
Robustness and Reliability

\[ \lambda_2 \]

\[ \lambda_2^* \]

\[ \lambda_1^* \]

\[ \lambda_1 \]

\[ G \rightarrow G^* = \max \{ G \} \ldots \text{Optimum} \]

\[ G \rightarrow G \geq G' \ldots \text{Robust} \]
Robust and Reliability

Interference Reduction (IR)

\[ x(t) \rightarrow \text{IR} \rightarrow y(t) \]

IR-Processor

\[ \text{SNR}_x \rightarrow G_c \rightarrow \text{SNR}_y \]

\[
G_c = \frac{\text{SNR}_y}{\text{SNR}_x} > 1 \quad \text{... Conversion-Gain}
\]
Robust and Reliability

IR-Processor

\[ S \ldots \text{SOI} \]
\[ I \ldots \text{SONI} \]

\[ P_X = P_S + P_I \]

\[ P_Y = P_S - \Delta P_S + P_I - \Delta P_I \]

\[ \text{SNR}_X = \frac{P_S}{P_I} \]

\[ \text{SNR}_Y = \frac{P_S - \Delta P_S}{P_I - \Delta P_I} \]

\[ \Delta P_I = P_I \text{ and } \Delta P_S \ll \Delta P_I \]

**Goal:** Remove the SONI without distorting the SOI.

\[ \Delta P_I = P_I \ldots \text{Interference Suppression.} \]

\[ \Delta P_I \approx P_I \ldots \text{Interference Reduction.} \]
Usefull Properties for Future Wireless Applications
Exploiting the pseudo-random property of the spread-spectrum signal.
Exploiting the pseudo-random property of the spread-spectrum signal.
Multipath - MRR

Multipath Rejection Receiver [passive MF]

Input Signal

SOI

Amplitude

SONI

Correlator

Time

Amplitude

Time

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Multipath - MRR

Multipath Rejection Receiver [active MF]

- **Input Signal**
- **SOI**
- **Correlator**
- **SONI**

Amplitude vs. Time plots for each component.
(Radio-) Resource-Management: Threshold decides if MP-component is included in the decision variable.

Exploiting the pseudo-random property of the spread-spectrum signal.
Remark-Coding: The „coder“ processes bits to form symbols and prepare the information with parity bits (redundancy = bandwidth expansion) to reduce the SEP.

Remark-SST: The SST processes waveforms and protect the information from unknown channel attacks (interference whitening = bandwidth expansion) to improve the SNR.
Spread-Spectrum: (R)evolution

Single Code Transmission: Combat unpredictable kinds of interference including multipath interference rejection.

RAKE-Receiver: Resolve multipath components.

CDMA: Multi exploitation of the channel.

Multi Code Transmission: Enhance efficiency.
Spread-Spectrum: (R)evolution con’t

Multi-User Detection: Combat the multi-user interference.

Multi Carrier Code Transmission (MC-CDMA):

Combat the multi-user interference using the collision avoidance principle.

Radio Resource Management:

Exploites the flexibility of the spread-spectrum philosophy.
The next step beyond spread-spectrum

Robust & Reliable Systems:
Spread-Spectrum Technology
+ Nonlinearity
Overall Structure of an Efficient Robust System

Remark-Coding: The „coder“ processes bits to form symbols and prepare the information with parity bits (redundancy = bandwidth expansion) to reduce the SEP ($P_e$).

Remark-SST: The SST processes waveforms and protect the information from unknown channel attacks (interference whitening = bandwidth expansion) to improve the SNR.

Remark-NL: The NL processes waveforms to reduce the interference magnitude.

Higher Layer: Operations on symbols.
Physical Layer: IR-Operations on waveforms.
An Efficient Robust & Reliable Communication System

Example: Broadband and narrowband interference present at the same time.

Area for reliable chip decisions

\[ \Delta \ldots \text{Adjustable Threshold} \]

Input Signal Sample:

AWGN: Represents broadband interference.

Continuouse Wave: Represents narrowband interference.
An Efficient Robust & Reliable Communication System

Nonlinearity \( \rightarrow \) RCA-Nonlinearity

RCA ... Reliable Chip Accumulator

Area for reliable chip decisions

\[
\begin{align*}
\text{Output} & \rightarrow 1 \\
-\Delta & \\
\text{Area for reliable chip decisions} & \\
\end{align*}
\]

\[
\begin{align*}
\text{Input} & \rightarrow -1 \\
\Delta & \\
\text{Area for reliable chip decisions} & \\
\end{align*}
\]
An Efficient Robust & Reliable Communication System

Performance

Remarks:
The new robust and reliable system outperforms its counterpart (comparable complexity).
From Robustness follows Reliability.

**Robustness**  ➙  **Reliability**

1. Low complexity (simple)
2. Small size
3. Light weight
4. Simple algorithms
5. Flexible services
6. Scalable performance
7. Adaptive interference reduction
8. Easy resource management

1. Less power consuming
2. Low error-probability
3. Long lifecycle
4. High availability
5. Independent of environment
6. Stable algorithms
7. Scalable performance
8. Adaptive interference reduction

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Thank you for your attention.
Alois M.J. Goiser is a member of the Faculty of Electrical Engineering and Information Technology at the University of Technology Vienna, Austria. Currently he holds the position of an associate professor. He is the head of the “Robust and Reliable Communications”-group at the Institute of Communications and Radio Frequency Engineering.

He is involved in spread-spectrum applications since 1988. His research interests are interference reduction schemes in general, CDMA-networks, multi-user detection, synchronization of RAKE-receivers. His focus is on low-complexity digital transceivers for robust and reliable communications.

He was the technical program chair of Eurocomm2000 and has published more than 80 technical papers, one book and contributions to books. He headed many projects with industry and the European Community.