Digital Communications, Advanced Course

- Very fast development of high performing digital communication systems.

- The last 20 years has shown an impressive development, and the next 20 years will be even more dramatic!

- Modern communication systems requires state-of-the-art software and hardware technology and they are among the most advanced technical systems that we have today.

Communication trends

- **Different users and applications require different bit rates and error protection (imply adaptive systems).**
- **Mobile broadband, machine-type-communications, Internet-of-things, tactile Internet, device-to-device communications,……..**
- **To increase the performance the communication system should be able to adapt to the current quality of the communication link.**

  The system should always work close to maximum performance!
- **MIMO and OFDM are examples of advanced methods.**
- **LTE and Digital TV are examples of advanced systems.**
- **The demand for higher and higher bitrates drives the development of more advanced and sophisticated communication system solutions.**

- **In this course we will study modern advanced digital communication methods and systems.**
- **Stationary as well as mobile communication system solutions.**
- **This course gives a breath and a depth so that you can <u>understand</u> today's advanced communication system, and also <u>*many future systems*</u>.**

Project work in this course

- 2 students/group.
- A communication application/technical problem/problem area, relevant for the course, is investigated.
- The choice of project is mainly done by the project group.
- Articles and conference papers from IEEE´s database ”IEEE Xplore” **http://ieeexplore.ieee.org/Xplore/DynWel.jsp**

  is recommended to get additional technical information.
- Written report, oral presentation, and be opponent to another group.
- 1-2 hours of discussion/feedback on report/project by a (top) student of MWIR-year 2

Some examples of applications/systems studied in previous projects:

- Mobile telephony/broadband (GSM, EDGE, LTE, 4G, 5G,...)
- Internet
- Modem (e.g., ADSL)
- WLAN (Wireless Local Area Network)
- Digital TV
- MIMO
- Massive MIMO
- OFDM+MIMO
- GPS (Global Positioning System)
- Bluetooth
- mmWave

A communication link:

- **Different requirements on error protection.**
- **Different requirement on bit rate (bps) and bandwidth (Hz).**
- **Different qualities of the communication link.**

- **What are the technical challenges/problems and limitations?**
- **How do we solve these?**

Course Programme

Digital Communications, Advanced Course (ETTN01), 7.5 hp

First lecture: Monday 30 October (week 44), 15.15 – 17.00 in E:2311.

Project starts in week 44.

Laboratory lesson: LAB (4 hours) starts on Tuesday 5 December 2017 (week 49 = Study week 6).

Application to the laboratory lesson is made on the homepage of this course where you book one available time-slot. Applications can be made one week before the lab starts, or maybe earlier, check Messages!

Messages will be distributed on the homepage of this course, http://www.eit.lth.se/kurs/ettn01 . Check messages at least twice a week!

Written Examination:

1:st opportunity: Wednesday 10 January 2018, 14.00 – 19.00, Sparta D

2:nd opportunity: Monday 9 April 2018, 08.00 – 13.00, E:2311

3:rd opportunity: Not yet scheduled. Likely in August 2018

Course Literature:

- "Introduction to Digital Communications", compendium August 2006.
- Lecture notes on OFDM
- Manual for the laboratory lesson.

The lecture notes on OFDM, and the manual for the laboratory lesson will be available on the homepage of this course, (they are not available yet).

You are allowed to use the compendium and the lecture notes on OFDM during the written examination.

This course is defined by the pages and problems given in the course outline given below in this course program, and by the laboratory lesson.

Lecturer: Fredrik Rusek, Room E:2377, mail: Fredrik.Rusek@eit.lth.se

Teaching assistant: Muhammad Umar Farooq, Room E:2367, mail: muhammad.umar_farooq@eit.lth.se

Lectures: Mondays 15.15 – 17.00 in E:2311

Wednesdays 15.15 – 17.00 in E:2311

Exercise class : Tuesdays 13.15 – 15.00 in E:2517

Thursdays 10.15 – 12.00 in E:2517

Time plan for the project and lab:

Soon

Preliminary Course Outline for the course Digital Communications, Advanced Course (ETTN01), 2017:

Week	Contents
2	Lecture (13/11): Introduction. 5.1 – 5.1.2 (pages 329-341). Lecture (14/11): 5.1.2 – 5.1.7 (pages 336 – 360). Exercise (15/11): Problems 5.1, 5.11, Example 5.2 on page 334, 5.6i, 5.9.
3	Lecture (20/11): Project info and start-up procedure , 5.2 (pages 360 – 377). Exercise (21/11): 5.15a, 5.19, 5.16b, Example 5.4 on page 343, 5.13a, 5.14. Lecture (22/11): 5.4.1 (pages 380 – 392), Example 5.34, Figure 5.26 on page 393, 5.4.4 – 5.4.6 (pages 396 – 405). Exercise (23/11): 5.20, 5.18a, 5.21, 5.23, Example 5.20 on page 373, 5.30.
4	Lecture (28/11): 3.4.1 (pages 161 – 163), Problem 5.34, 3.4.3 (pages 167-170). Exercise (29/11): Example 5.23 on page 384, 4.34i), 5.34, 5.33. Lecture (30/11): 8.1 – 8.2.1(pages 501– 512). OFDM introduction. Exercise (1/12): 3.16, Example 5.4 on page 343. 5.34 ((5.133) – (5.138)).
5	Lecture (5/12): OFDM lecture notes pages 1-45. Exercise (6/12): 8.1, 8.4, 8.6a,b,c,e, 8.7a,b,c,e, 2.32a,b, 8.8a, Example 8.4 on page 512. Lecture (7/12): 9.1 – 9.2 (pages 581 – 596). Exercise (8/12): OFDM problems X1, X2, X3, X4, X5,.
6	**Lab starts this week!** Lecture (12/12): 9.2 (591 – 596), Problem 5.34, 7.3(pages 480 – 486). Exercise (13/12):): OFDM problems X6, X7, X8, X9, X10, X11 Lecture (14/12): 7.3.21-7.3.2 (pages 484 - 490). Exercise (14/12): 9.2, 9.3, 9.4, 9.5.
7	Lecture (19/12): Summary of the course. Exercise (20/12): 9.6, 9.7, 9.8, 9.10 Exercise (22/12): 7.7, 7.9, 7.10a.

To be able to understand more advanced communication system solutions, e.g., systems where coding is used and/or mobile systems, <u>we need to get more knowledge</u> about uncoded systems!

Lecture 1: MAP receiver and signal space

MAP receiver

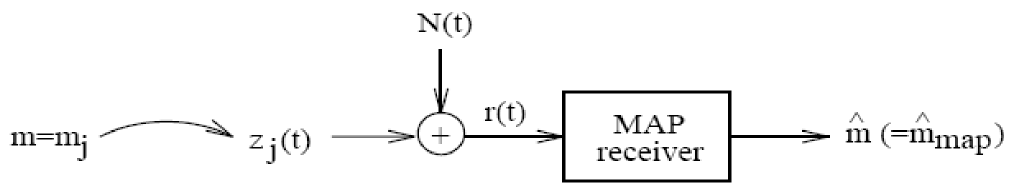
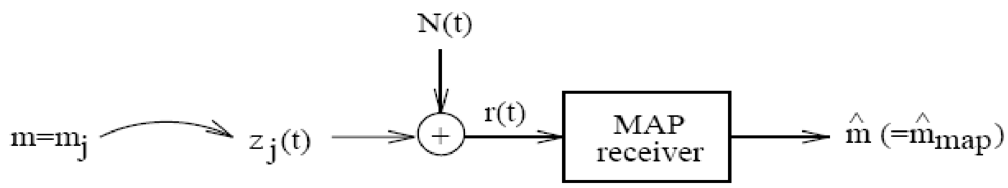


Figure 5.1: Reception of one of M possible waveforms $\{z_\ell(t)\}_{\ell=0}^{M-1}$ in AWGN.

In this course we study the MAP receiver in detail

Lecture 1: MAP receiver and signal space

MAP receiver



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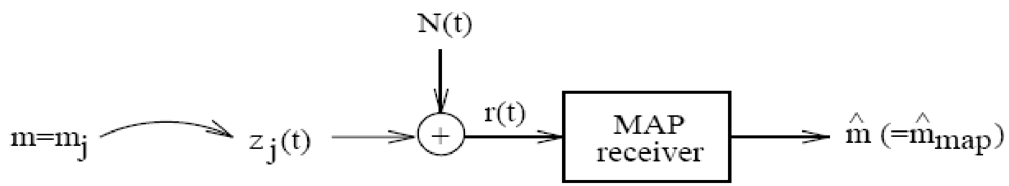
Lecture 1: MAP receiver and signal space

MAP receiver



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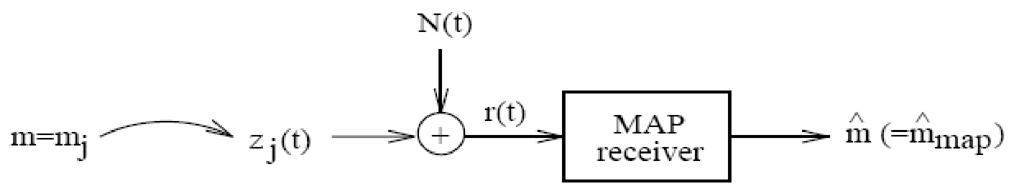
Lecture 1: MAP receiver and signal space

MAP receiver



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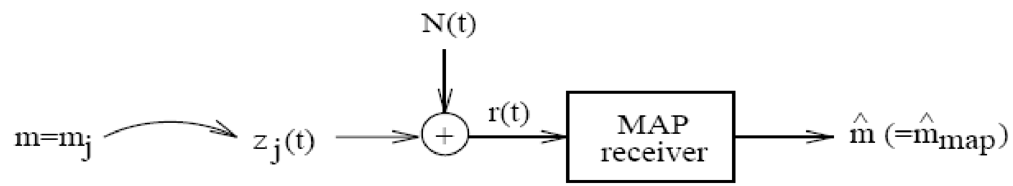
Lecture 1: MAP receiver and signal space

MAP receiver



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Which one is more logical?

Lecture 1: MAP receiver and signal space

MAP receiver

Suppose that on the next lecture, I will not show up

MAP is defined as

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MAP receiver

Suppose that on the next lecture, I will not show up

Observation r(t) = "fredrik is not here"

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MAP receiver

Suppose that on the next lecture, I will not show up

Observation r(t) = "fredrik is not here"

Why am I not here?

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MAP receiver

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Why am I not here?

Observation r(t) = "fredrik is not here"

Explanation m = "Fredrik is……"

MAP is defined as

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MAP receiver

Suppose that on the next lecture, I will not show up

Observation $r(t)$ = "fredrik is not here"

Why am I not here?

Explanation m = "Fredrik is……"

ML-rule

$p(r(t)|m_1) = 0.9$

m_1 = "Fredrik is sick"

MAP is defined as

$$\hat{m} = \underset{m}{\operatorname{argmax}}\, p(m|r(t))$$

$$= \underset{m}{\operatorname{argmax}}\, p(r(t)|m)p(m)$$

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Why am I not here?

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Explanation m = "Fredrik is……"

ML-rule

$p(r(t)|m_1) = 0.9$
m_1 = "Fredrik is sick"
$p(r(t)|m_2) = ?$
m_2 = "Fredrik is dead"

MAP is defined as

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Explanation m = "Fredrik is……"

ML-rule

$p(r(t)|m_1) = 0.9$
m_1 = "Fredrik is sick"
$p(r(t)|m_2) = 1$
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Why am I not here?

Explanation m = "Fredrik is……"

ML-rule

$p(r(t)|m_1) = 0.9$
m_1 = "Fredrik is sick"
$p(r(t)|m_2) = 1$
m_2 = "Fredrik is dead"

$$\boxed{\text{Fredrik is dead} = \text{argmax}_m \, p(r(t)|m)}$$

MAP is defined as

$$\hat{m} = \underset{m}{\text{argmax}}\, p(m|r(t))$$

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Which one is more logical?

Lecture 1: MAP receiver and signal space

MAP receiver

Suppose that on the next lecture, I will not show up

Observation r(t) = "fredrik is not here"

Why am I not here?

Explanation m = "Fredrik is……"

MAP-rule

$p(m_1|r(t)) \propto p(r(t)|m_1)p(m_1)$

m_1 = "Fredrik is sick"

MAP is defined as

$$\hat{m} = \underset{m}{\operatorname{argmax}}\, p(m|r(t))$$

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Which one is more logical?

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MAP receiver

Suppose that on the next lecture, I will not show up

Why am I not here?

Observation r(t) = "fredrik is not here"

Explanation m = "Fredrik is……"

MAP-rule

$p(m_1|r(t)) \propto p(r(t)|m_1)p(m_1) \approx 0.9 \times 0.1 = 0.09$

m_1 = "Fredrik is sick"

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MAP receiver

Suppose that on the next lecture, I will not show up

Why am I not here?

Observation r(t) = "fredrik is not here"

Explanation m = "Fredrik is……"

MAP-rule

$p(m_1|r(t)) \propto p(r(t)|m_1)p(m_1) \approx 0.9 \times 0.1 = 0.09$

m_1 = "Fredrik is sick"

$p(m_2|r(t)) \propto p(r(t)|m_2)p(m_2)$

m_2 = "Fredrik is dead"

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Observation $r(t)$ = "fredrik is not here"

Explanation m = "Fredrik is……"

MAP-rule

$p(m_1|r(t)) \propto p(r(t)|m_1)p(m_1) \approx 0.9 \times 0.1 = 0.09$

m_1 = "Fredrik is sick"

$p(m_2|r(t)) \propto p(r(t)|m_2)p(m_2) \approx 1 \times 0.0001 = 0.0001$

m_2 = "Fredrik is dead"

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Which one is more logical?

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MAP receiver

$$\boxed{\text{Fredrik is sick} = \text{argmax}_m\, p(r(t)|m)}$$

MAP-rule

$p(m_1|r(t)) \propto p(r(t)|m_1)p(m_1) \approx 0.9 \times 0.1 = 0.09$
m_1 = "Fredrik is sick"
$p(m_2|r(t)) \propto p(r(t)|m_2)p(m_2) \approx 1 \times 0.0001 = 0.0001$
m_2 = "Fredrik is dead"

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Which one is more logical?

Lecture 1: MAP receiver and signal space

MAP receiver

The ML rule is, in general, totally crazy

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Which one is more logical?

Lecture 1: MAP receiver and signal space

MAP receiver

The ML rule is, in general, totally crazy

- According to what rule do we do everyday decisions?
- According to which rule should a court make their decisions?

MAP is defined as

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ML is defined as

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Which one is more logical?

Lecture 1: MAP receiver and signal space

MAP receiver

The ML rule is, in general, totally crazy

- According to what rule do we do everyday decisions? MAP
- According to which rule should a court make their decisions? MAP

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Which one is more logical?

Lecture 1: MAP receiver and signal space

MAP receiver

True court case: Sally clark case, England 1998

MAP is defined as

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Which one is more logical?

Lecture 1: MAP receiver and signal space

MAP receiver

True court case: Sally clark case, England 1998

Observation: Sally Clark, mother of two, had two babies that died in infancy

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Which one is more logical?

Lecture 1: MAP receiver and signal space

MAP receiver

True court case: Sally clark case, England 1998

Observation: Sally Clark, mother of two, had two babies that died in infancy

P(observation|natural causes) = 1/10000 according to expert in child deaths

MAP is defined as

$$\hat{m} = \underset{m}{\operatorname{argmax}}\, p(m|r(t))$$

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Lecture 1: MAP receiver and signal space

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True court case: Sally clark case, England 1998

Observation: Sally Clark, mother of two, had two babies that died in infancy

P(observation|natural causes) = 1/10000 according to expert in child deaths
P(observation|murder) = 1 according to common sense

MAP is defined as

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P(observation|murder) = 1 according to common sense

Implication (to us):

MAP is defined as

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Lecture 1: MAP receiver and signal space

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P(observation|murder) = 1 according to common sense

Implication (to us): NONE

MAP is defined as

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Which one is more logical?

Lecture 1: MAP receiver and signal space

MAP receiver

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P(observation|natural causes) = 1/10000 according to expert in child deaths
P(observation|murder) = 1 according to common sense

Implication (to us): NONE **Implication to court:**

MAP is defined as

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ML is defined as

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Which one is more logical?

Lecture 1: MAP receiver and signal space

MAP receiver

True court case: Sally clark case, England 1998

Observation: Sally Clark, mother of two, had two babies that died in infancy

P(observation|natural causes) = 1/10000 according to expert in child deaths
P(observation|murder) = 1 according to common sense

Implication (to us): NONE **Implication to court: Lifetime jail sentence**

MAP is defined as

$$\hat{m} = \underset{m}{\operatorname{argmax}}\, p(m|r(t))$$

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Which one is more logical?

Lecture 1: MAP receiver and signal space

MAP receiver

True court case: Sally clark case, England 1998

CLEARLY ML

Observation: Sally Clark, mother of two, had two babies that died in infancy

P(observation|natural causes) = 1/10000 according to expert in child deaths
P(observation|murder) = 1 according to common sense

Implication (to us): NONE **Implication to court: Lifetime jail sentence**

MAP is defined as

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Which one is more logical?

Lecture 1: MAP receiver and signal space

MAP receiver

True court case: Sally clark case, England 1998

MAP ?

Observation: Sally Clark, mother of two, had two babies that died in infancy

P(observation|natural causes) = 1/10000 according to expert in child deaths
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MAP is defined as

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Which one is more logical?

Lecture 1: MAP receiver and signal space

MAP receiver

True court case: Sally clark case, England 1998

MAP ?

Observation: Sally Clark, mother of two, had two babies that died in infancy

P(observation|natural causes) = 1/10000 according to expert in child deaths
P(observation|murder) = 1 according to common sense
P(mother is murderer) = 1/1000…000
P(mother is not murderer) = 0.9999…999

MAP is defined as

$$\hat{m} = \underset{m}{\operatorname{argmax}}\, p(m|r(t))$$

$$= \underset{m}{\operatorname{argmax}}\, p(r(t)|m)p(m)$$

ML is defined as

$$\hat{m} = \underset{m}{\operatorname{argmax}}\, p(r(t)|m)$$

Which one is more logical?

Lecture 1: MAP receiver and signal space

MAP receiver

True court case: Sally clark case, England 1998

MAP ?

Observation: Sally Clark, mother of two, had two babies that died in infancy

P(observation|natural causes) = 1/10000 according to expert in child deaths
P(observation|murder) = 1 according to common sense
P(mother is murderer) = 1/1000…000
P(mother is not murderer) = 0.9999…999

P(natural causes|observation) $\propto$ 0.999…999/10000

MAP is defined as

$$\hat{m} = \arg\max_{m} p(m|r(t))$$

$$= \arg\max_{m} p(r(t)|m)p(m)$$

ML is defined as

$$\hat{m} = \arg\max_{m} p(r(t)|m)$$

Which one is more logical?

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P(natural causes|observation) $\propto$ 0.999…999/10000
P(murder|observation) $\propto$ 1/1000…000

MAP is defined as

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$$= \underset{m}{\operatorname{argmax}}\, p(r(t)|m)p(m)$$

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Lecture 1: MAP receiver and signal space

MAP receiver

True court case: Sally clark case, England 1998 MAP: NOT GUILTY

Observation: Sally Clark, mother of two, had two babies that died in infancy

P(observation|natural causes) = 1/10000 according to expert in child deaths
P(observation|murder) = 1 according to common sense
P(mother is murderer) = 1/1000…000
P(mother is not murderer) = 0.9999…999

P(natural causes|observation) ∝ 0.999…999/10000
P(murder|observation) ∝ 1/1000…000

MAP is defined as

$$\hat{m} = \underset{m}{\operatorname{argmax}}\, p(m|r(t))$$

$$= \underset{m}{\operatorname{argmax}}\, p(r(t)|m)p(m)$$

ML is defined as

$$\hat{m} = \underset{m}{\operatorname{argmax}}\, p(r(t)|m)$$

Which one is more logical?

Lecture 1: MAP receiver and signal space

MAP receiver

True court case: Sally clark case, England 1998 **MAP: NOT GUILTY**

Aftermath: Released in 2003, after some math professors took a look at the case.

Sally died from alhcolism somewhat later

MAP is defined as

$$\hat{m} = \underset{m}{\operatorname{argmax}}\, p(m|r(t))$$

$$= \underset{m}{\operatorname{argmax}}\, p(r(t)|m)p(m)$$

ML is defined as

$$\hat{m} = \underset{m}{\operatorname{argmax}}\, p(r(t)|m)$$

Which one is more logical?

Lecture 1: MAP receiver and signal space

MAP receiver

Hypotetical case: Lottery with 1000000 tickets

MAP is defined as

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Which one is more logical?

Lecture 1: MAP receiver and signal space

MAP receiver

Hypotetical case: Lottery with 1000000 tickets

P(someone presents the winning ticket|person bought a ticket) = 1/1000000

MAP is defined as

$$\hat{m} = \underset{m}{\operatorname{argmax}}\, p(m|r(t))$$

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Which one is more logical?

Lecture 1: MAP receiver and signal space

MAP receiver

Hypotetical case: Lottery with 1000000 tickets

P(someone presents the winning ticket|person bought a ticket) = 1/1000000
P(someone presents the winning ticket|person printed the winning ticket at home on a printer) = 1

MAP is defined as

$$\hat{m} = \underset{m}{\operatorname{argmax}}\, p(m|r(t))$$

$$= \underset{m}{\operatorname{argmax}}\, p(r(t)|m)p(m)$$

ML is defined as

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Lecture 1: MAP receiver and signal space

MAP receiver

Hypotetical case: Lottery with 1000000 tickets

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P(someone presents the winning ticket|person printed the winning ticket at home on a printer) = 1

ML: ??

MAP: ??

MAP is defined as

$$\hat{m} = \underset{m}{\operatorname{argmax}}\, p(m|r(t))$$

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Lecture 1: MAP receiver and signal space

MAP receiver

Hypotetical case: Lottery with 1000000 tickets

P(someone presents the winning ticket|person bought a ticket) = 1/1000000
P(someone presents the winning ticket|person printed the winning ticket at home on a printer) = 1

ML: Jail

MAP: ??

MAP is defined as

$$\hat{m} = \underset{m}{\operatorname{argmax}}\, p(m|r(t))$$

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Lecture 1: MAP receiver and signal space

MAP receiver

Hypotetical case: Lottery with 1000000 tickets

P(someone presents the winning ticket|person bought a ticket) = 1/1000000
P(someone presents the winning ticket|person printed the winning ticket at home on a printer) = 1

ML: Jail

MAP: Prior probability of fraud must be evaluated

MAP is defined as

$$\hat{m} = \underset{m}{\operatorname{argmax}}\, p(m|r(t))$$

$$= \underset{m}{\operatorname{argmax}}\, p(r(t)|m)p(m)$$

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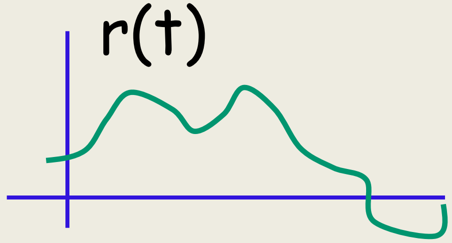
Lecture 1: MAP receiver and signal space

MAP receiver

To analyze a digital communications system, it is difficult to work with a continuous time signal

It is hard to evaluate a probability of the form p(r(t)|m)



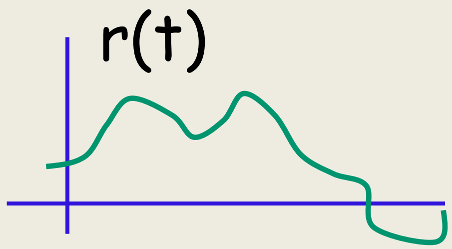
m=+1

Lecture 1: MAP receiver and signal space

MAP receiver

To analyze a digital communications system, it is difficult to work with a continuous time signal

It is hard to evaluate a probability of the form $p(r(t)|m)$



$m=+1$

We are used to evaluate probabilites of the form $p(r|m)$

$r=1.4312$ $m=+1$

Lecture 1: MAP receiver and signal space

MAP receiver

To analyze a digital communications system, it is difficult to work with a continuous time signal

Concept of signal space:

- Transfer all continuous signals into discrete vectors
- Transformation should be such that no information is lost
- Transformation is done via a set of basis functions
- For two systems with identical signal spaces, all properties (E_b, BER, etc) are idetincal
- However, bandwidth – properties are not. They depend on the basis functions
- Allows for a simpler description and analysis of the system.