- **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

Course Programme

Digital Communications, Advanced Course (ETTN01), 7.5 hp, 191106 – 200115

First lecture: Wednesday 6 November (week 45), 15.15 – 17.00 in E:2311.

Project starts in week 47.

Laboratory lesson: LAB (4 hours) starts on Friday13 December 2019 (week 50 = 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 15 January 2020, 08.00 – 13.00, Eden 025

2:nd opportunity: Monday 20 April 2020, 08.00 – 13.00, E:2311

3:rd opportunity: Wednesday 19 August 2020, 0800 – 13.00, E:3308

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: Juan Vidal Alegría, Room E:2364, mail: juan.vidal_alegria@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:3139

Time plan for the project and lab:

Soon

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

Week	Contents
1	Lecture (6/11): Introduction. 5.1 – 5.1.2 (pages 329-341).
2	Lecture (11/11): 5.1.2 – 5.1.7 (pages 336 – 360).
	Exercise (12/11): Problems 5.1, 5.11, Example 5.2 on page 334, 5.6i, 5.9.
	Lecture (13/11): Project info and start-up procedure , 5.2 (pages 360 – 377).
	Exercise (14/11): 5.15a, 5.19, 5.16b, Example 5.4 on page 343, 5.13a, 5.14.
3	Lecture (18/11): 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 (19/11): 5.20, 5.18a, 5.21, 5.23, Example 5.20 on page 373, 5.30.
	Lecture (20/11): 3.4.1 (pages 161 – 163), Problem 5.34, 3.4.3 (pages 167-170).
	Exercise (21/11): Example 5.23 on page 384, 4.34i), 5.34, 5.33.
4	Lecture (25/11): 8.1 – 8.2.1(pages 501– 512). OFDM introduction.
	Exercise (26/11): 3.16, Example 5.4 on page 343. 5.34 ((5.133) – (5.138)).
	Lecture (27/11): OFDM lecture notes pages 1-45.
	Exercise (28/11): 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.

5 <u>Lecture (2/12):</u> 9.1 – 9.2 (pages 581 – 596).

<u>Exercise (3/12):</u> OFDM problems X1, X2, X3, X4, X5,.

<u>Lecture (4/12):</u> 9.2 (591 – 596), Problem 5.34, 7.3(pages 480 – 486).

<u>Exercise (5/12):):</u> OFDM problems X6, X7, X8, X9, X10, X11

6 **Lab starts this week**

<u>Lecture (9/12):</u> 7.3.21-7.3.2 (pages 484 - 490).

<u>Exercise (10/12):</u> 9.2, 9.3, 9.4, 9.5.

<u>Lecture (10/12):</u> Summary of the course.

<u>Exercise (11/12):</u> 9.6, 9.7, 9.8, 9.10

7 <u>Lecture (16/12):</u> Project presentations

<u>Exercise (17/12):</u> 7.7, 7.9, 7.10a.

<u>Lecture (18/12):</u> Project presentations

<u>Exercise (19/12):</u> Project presentations

Lecture 1: MAP receiver and signal space

MAP receiver

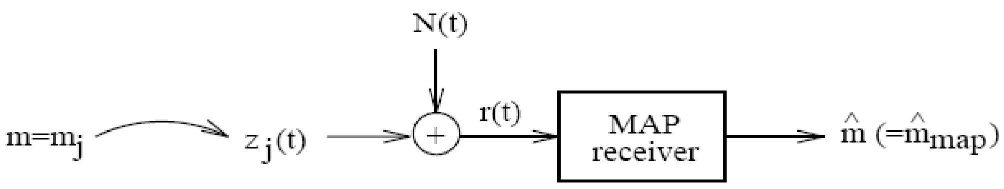
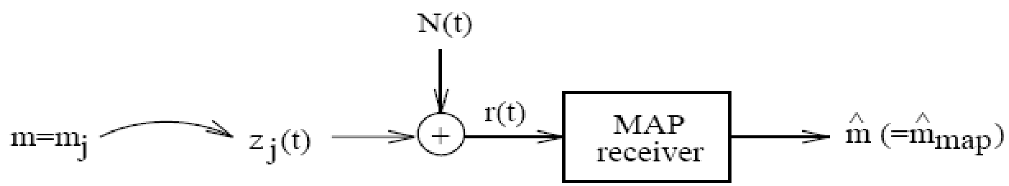


Figure 5.1: Reception of one of M possible waveforms $\{z_\ell(t)\}_{\ell=0}^{M-1}$ in AWGN.

In this course we study the MAP receiver in detail

Lecture 1: MAP receiver and signal space

MAP receiver



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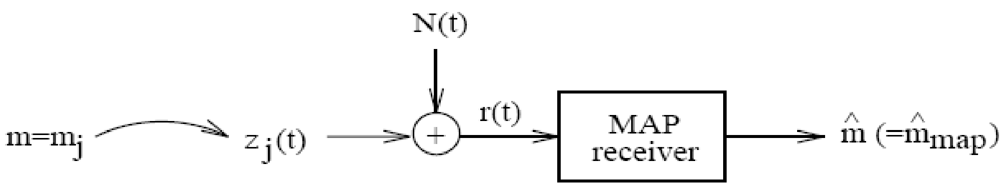
Lecture 1: MAP receiver and signal space

MAP receiver



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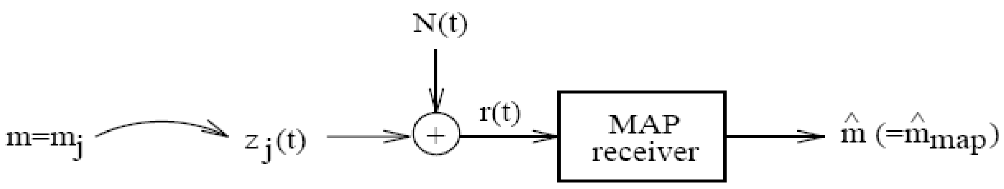
Lecture 1: MAP receiver and signal space

MAP receiver



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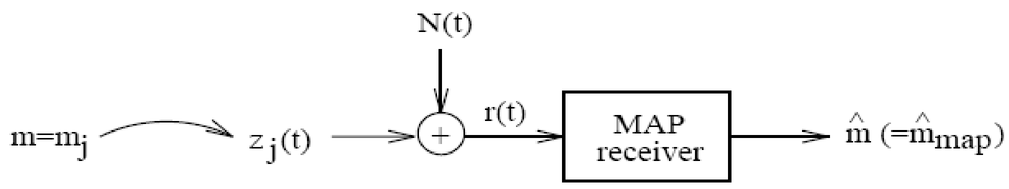
Lecture 1: MAP receiver and signal space

MAP receiver



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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

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

MAP is defined as

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

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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"

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

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

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

Why am I not here?

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

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 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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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……"

ML-rule

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

m_1 = "Fredrik is sick"

MAP is defined as

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

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

ML is defined as

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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……"

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

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

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

ML is defined as

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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……"

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"

MAP is defined as

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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……"

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"

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

MAP is defined as

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

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

ML is defined as

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

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

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

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

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

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

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

m_1 = "Fredrik is sick"

MAP is defined as

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Lecture 1: MAP receiver and signal space

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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

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

m_1 = "Fredrik is sick"

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

m_2 = "Fredrik is dead"

MAP is defined as

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

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

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Why am I not here?

Explanation m = "Fredrik is……"

MAP-rule

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

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"

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

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

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"

MAP is defined as

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

Which one is more logical?

Lecture 1: MAP receiver and signal space

MAP receiver

The ML rule is, in general, totally crazy

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

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

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

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

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

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

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 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

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

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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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

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

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

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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

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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Which one is more logical?

Lecture 1: MAP receiver and signal space

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

Implication (to us):

MAP is defined as

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

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

Implication (to us): NONE

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Which one is more logical?

Lecture 1: MAP receiver and signal space

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

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

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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

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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

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

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

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) ∝ 0.999…999/10000
P(murder|observation) ∝ 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

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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: 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

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

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Lecture 1: MAP receiver and signal space

MAP receiver

Hypotetical case: Lottery with 1000000 tickets

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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

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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

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

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

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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

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

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

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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

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

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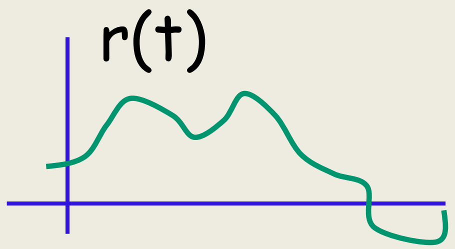
Which one is more logical?

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)



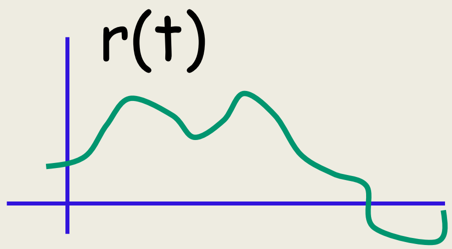
m=+1

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.