Introduction to Massive MIMO technology

Aleksei Fedorov

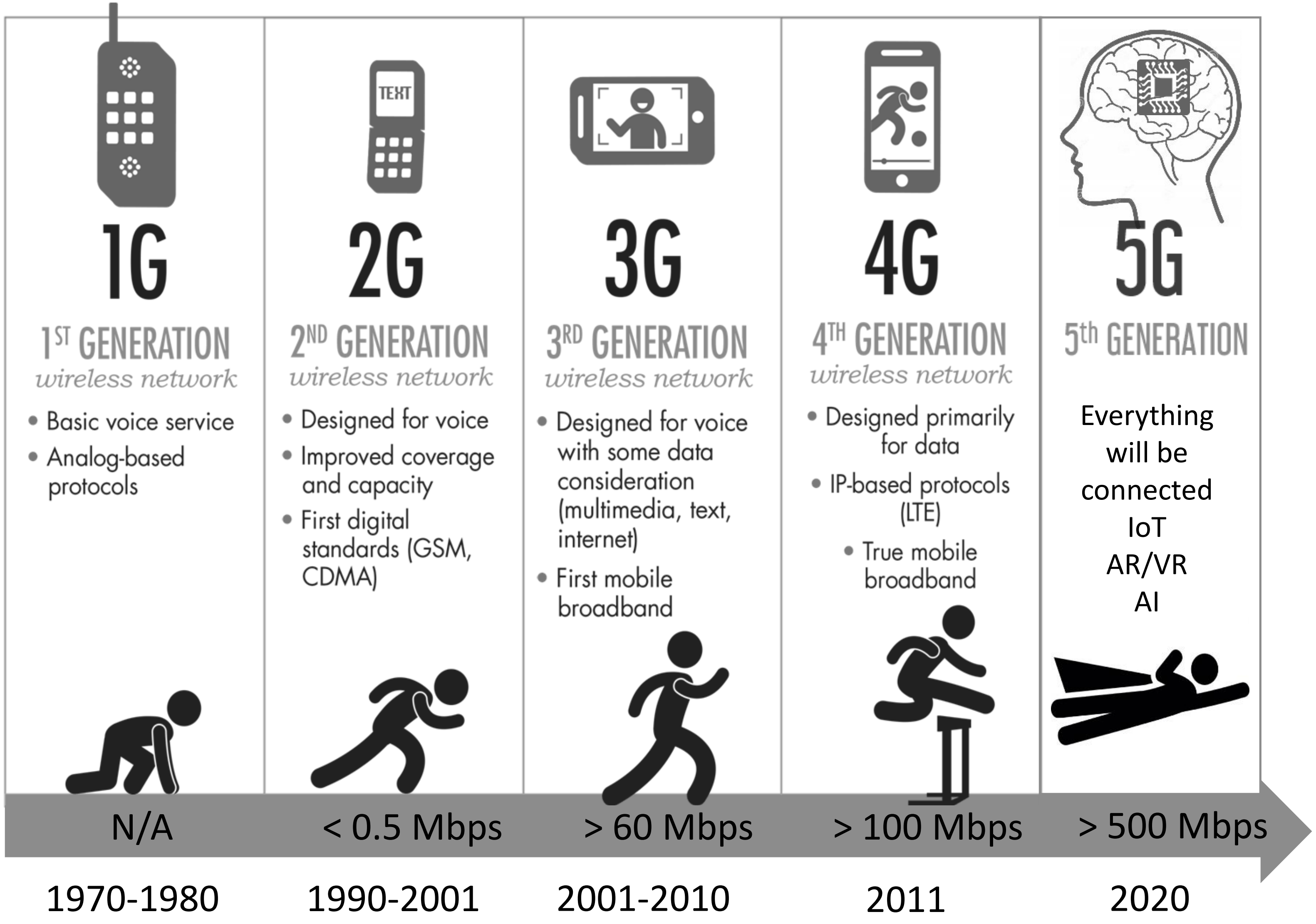
PhD candidate at Computer Science Department

University of Otago

Outline

- History of mobile communication
- Physical aspects of radio signals
- Introduction to LTE/4G
- Massive MIMO approach
- What we do

History of mobile communication



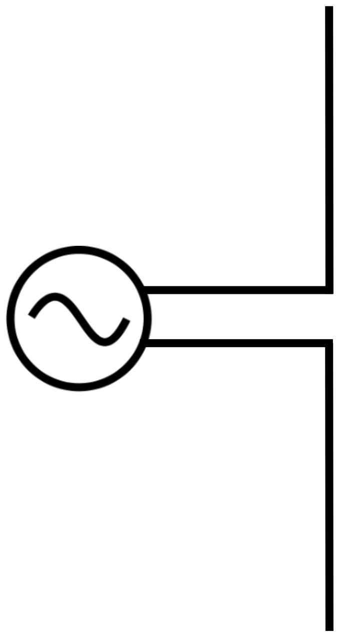
Physical aspects of radio signals

- What is a radio signal

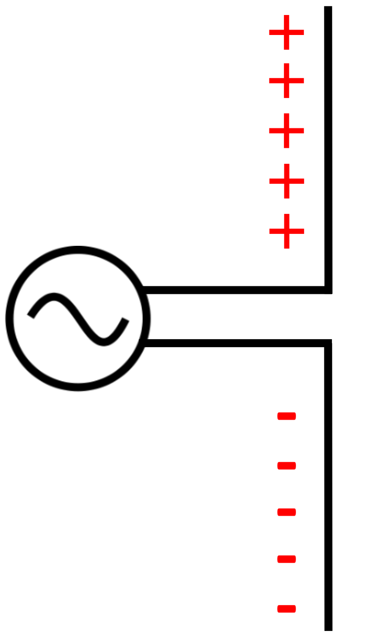
  Radio signal is an electromagnetic wave travelling through air

- How is it generated?

Generation of EM wave

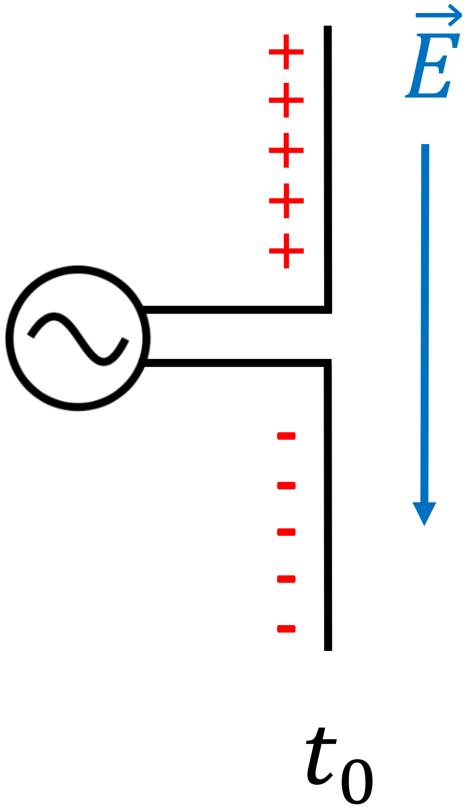


Generation of EM wave

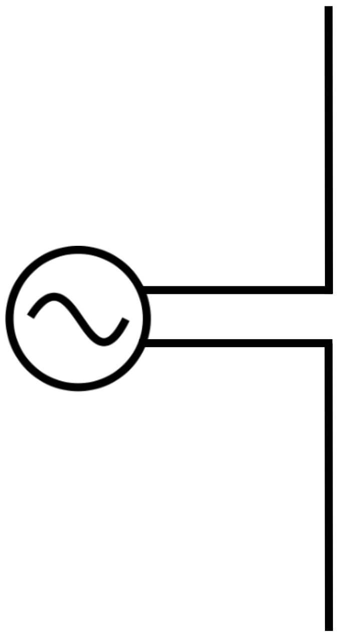


t_0

Generation of EM wave

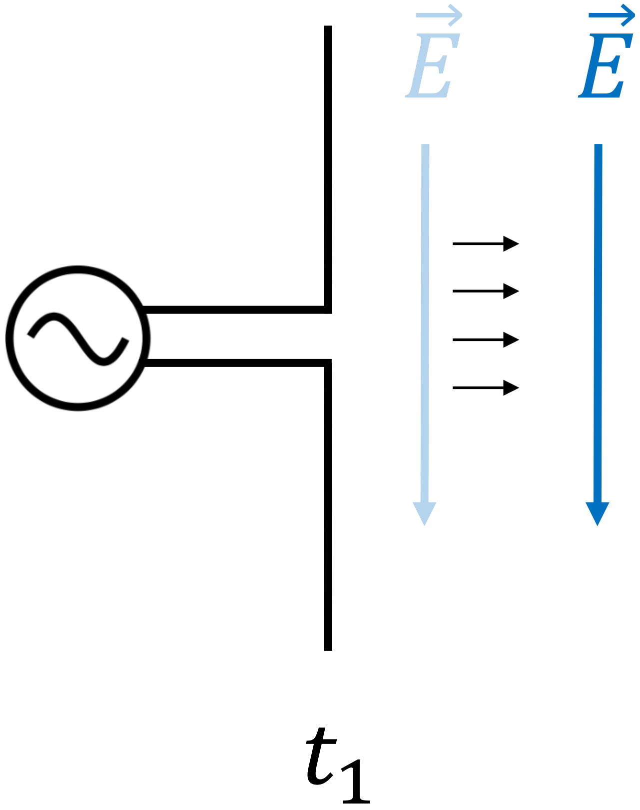


Generation of EM wave

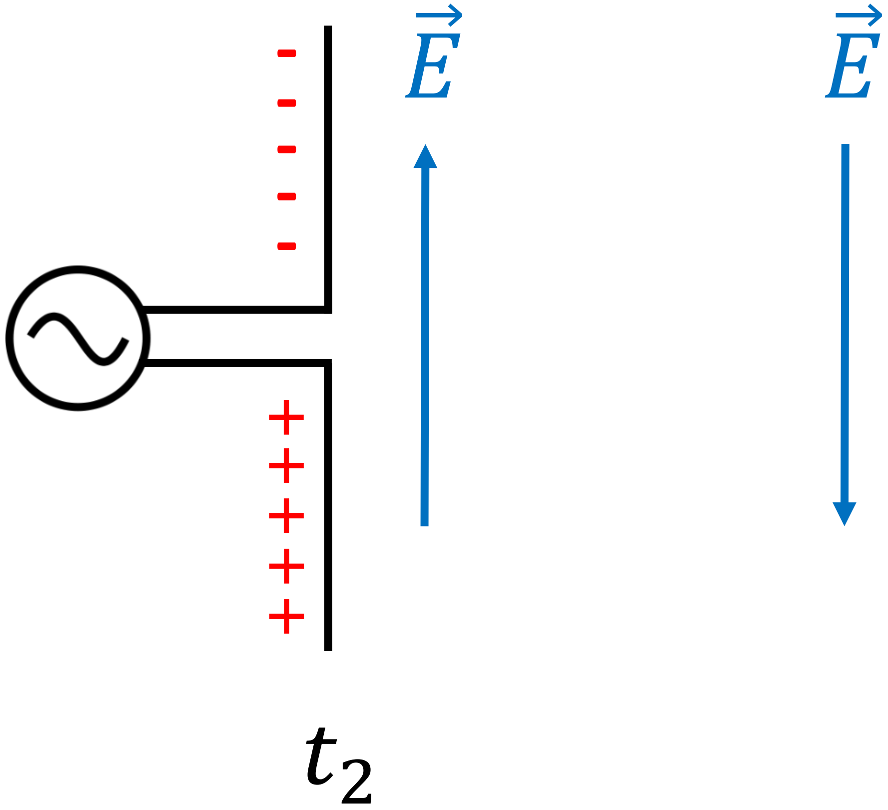


t_1

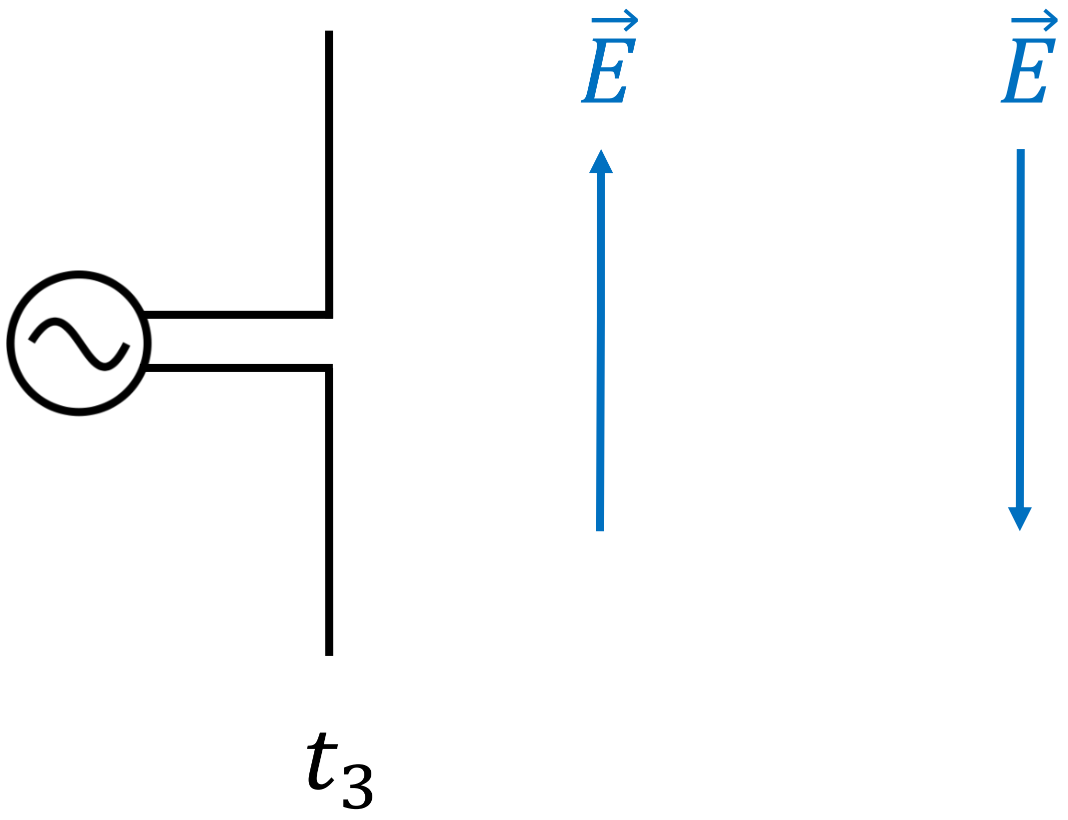
Generation of EM wave



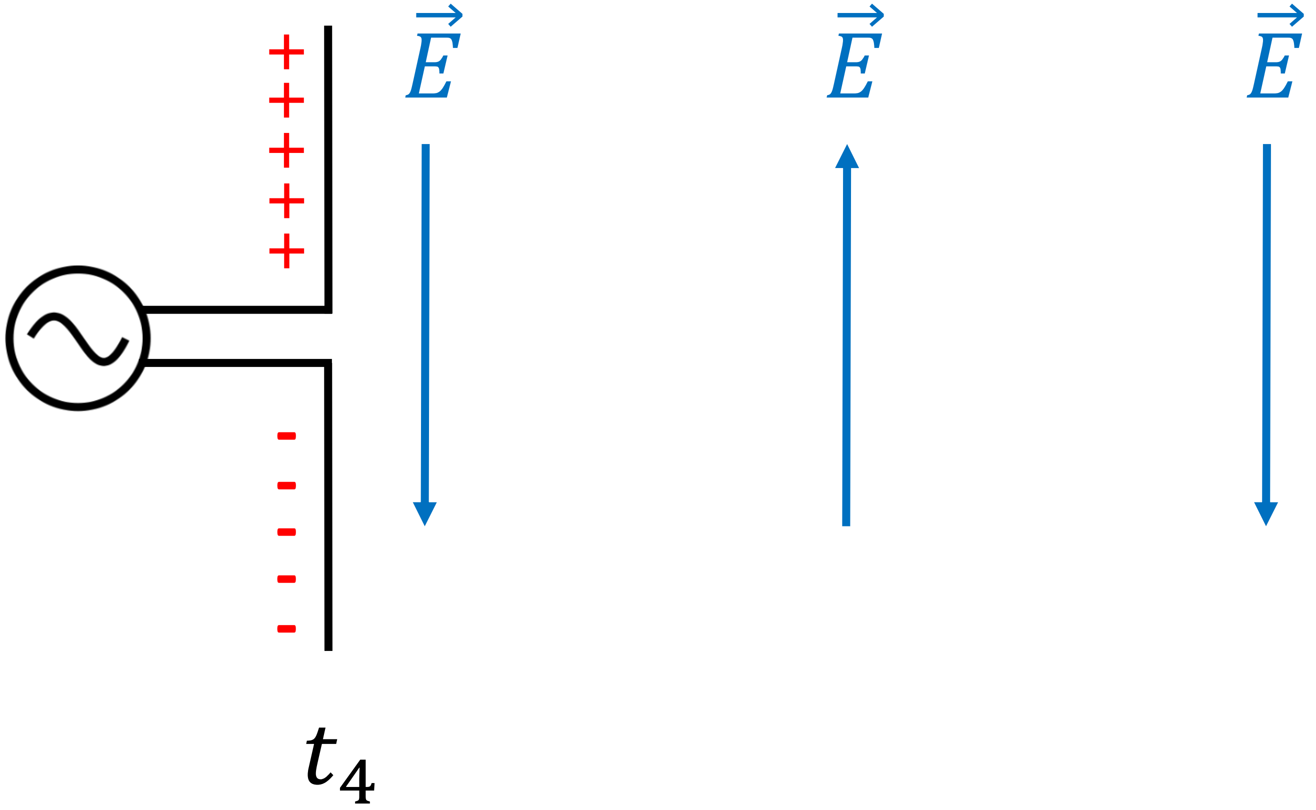
Generation of EM wave



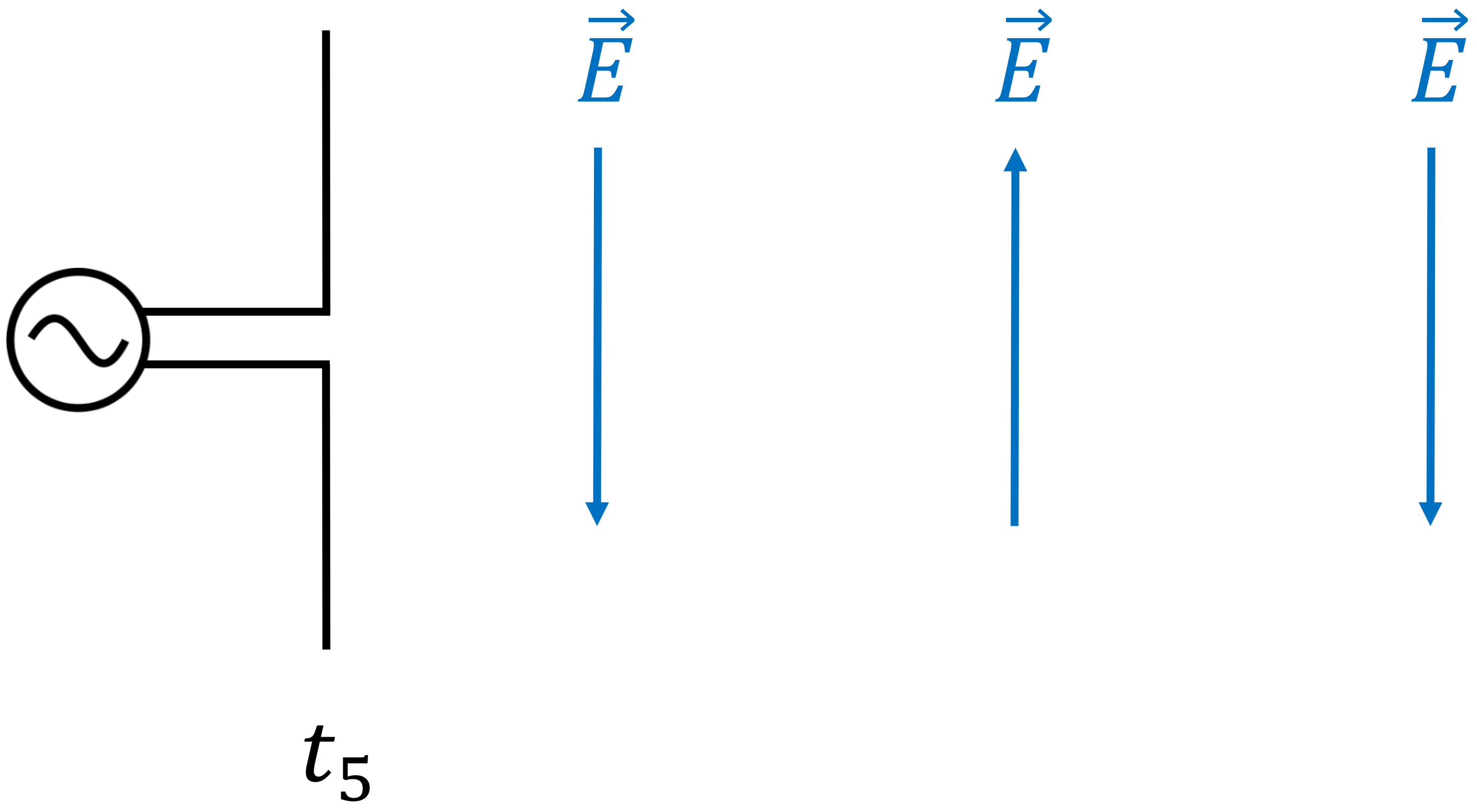
Generation of EM wave



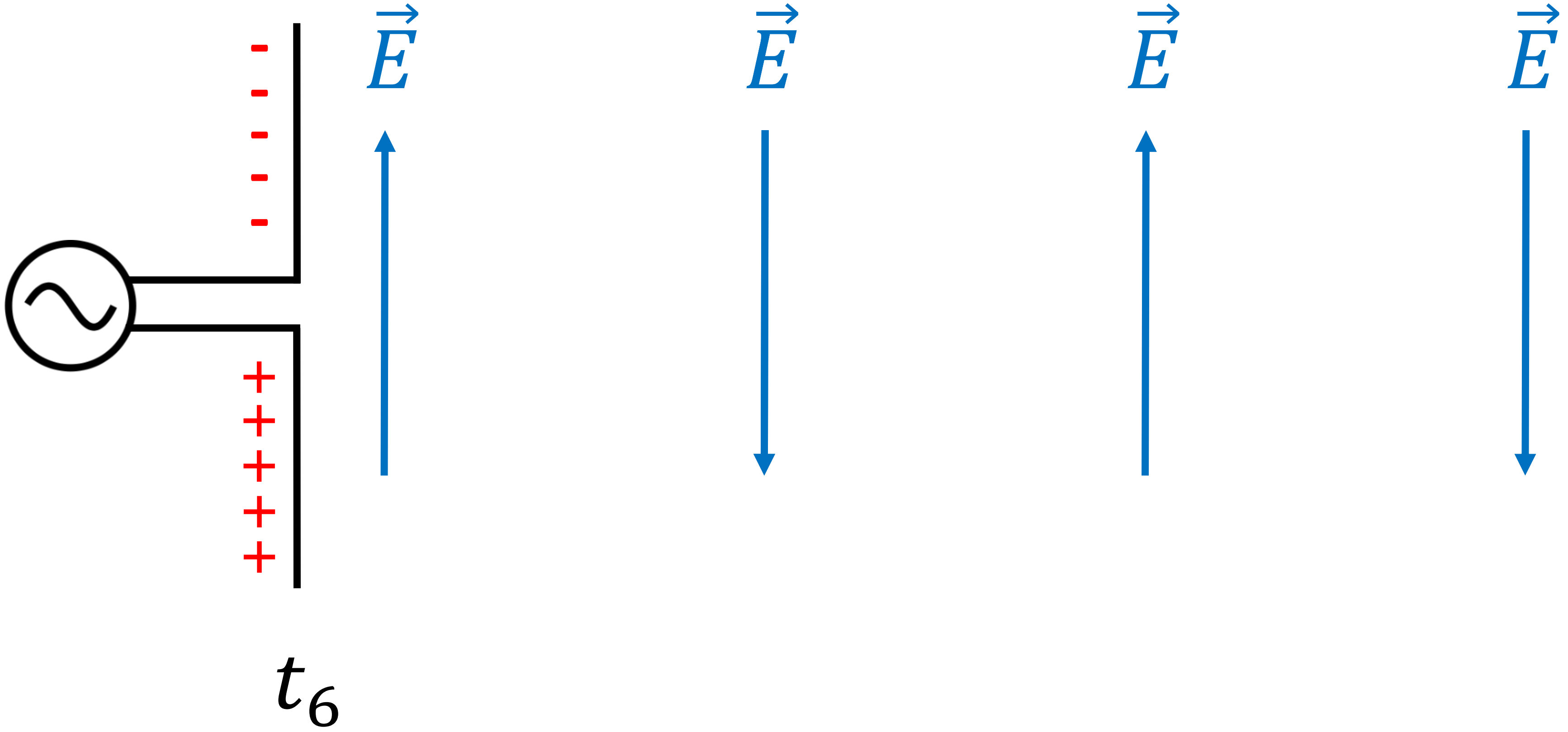
Generation of EM wave



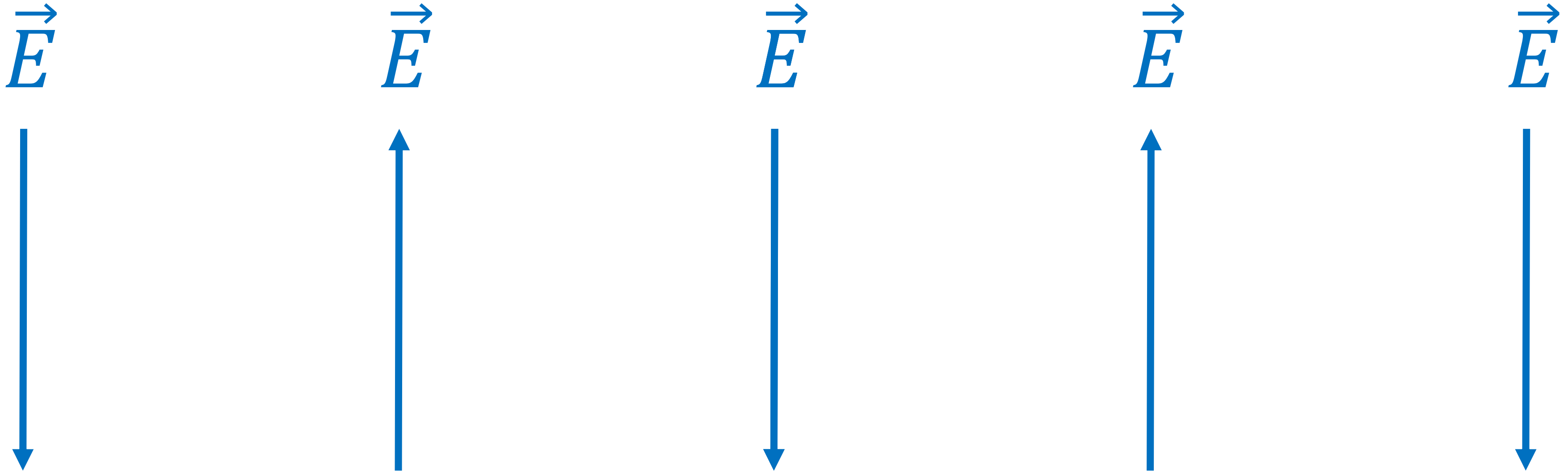
Generation of EM wave



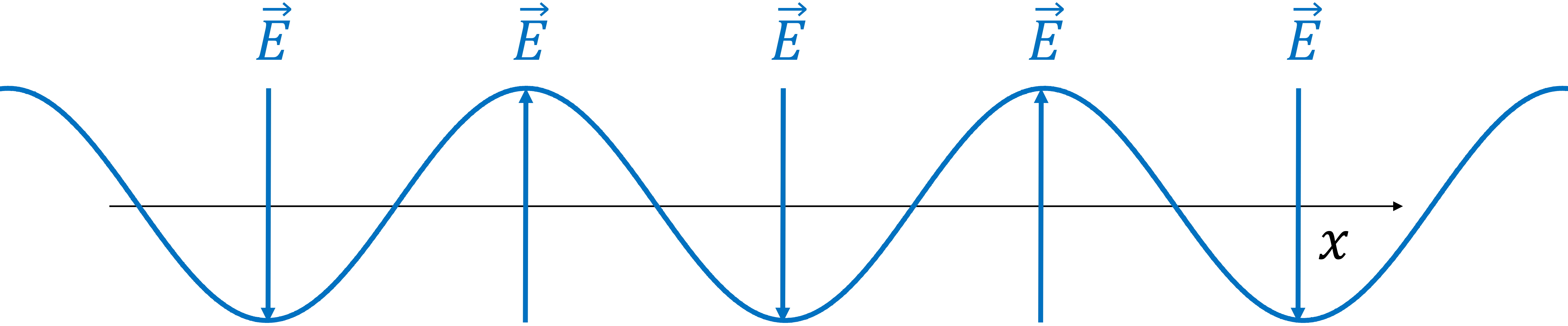
Generation of EM wave



Generation of EM wave

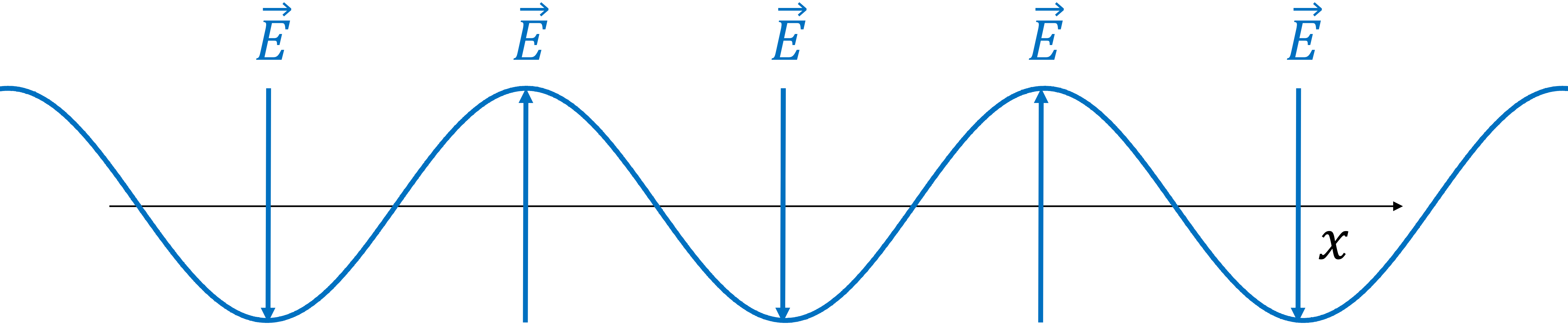


Generation of EM wave



$$\vec{E}(t) = \overrightarrow{\boldsymbol{E_0}} \cdot \exp\Big(j\,(2\pi\, \boldsymbol{\omega}\, t\ - \boldsymbol{\varphi})\Big)$$

Generation of EM wave



$$\vec{E}(t) = \overrightarrow{\boldsymbol{E_0}} \cdot \exp\big(j\,(2\pi\,\boldsymbol{\omega}\,t\;-\boldsymbol{\varphi})\big)$$

Physical aspects of radio signals

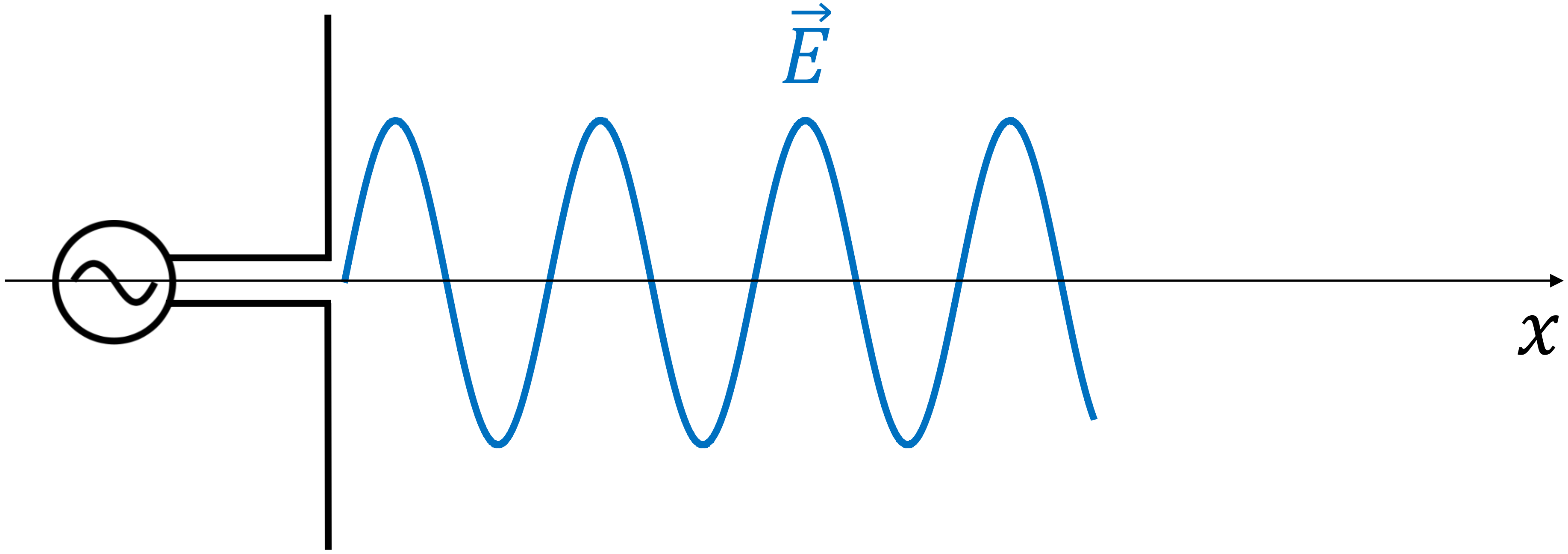
- What is a radio signal

  Radio signal is an electromagnetic wave travelling through air

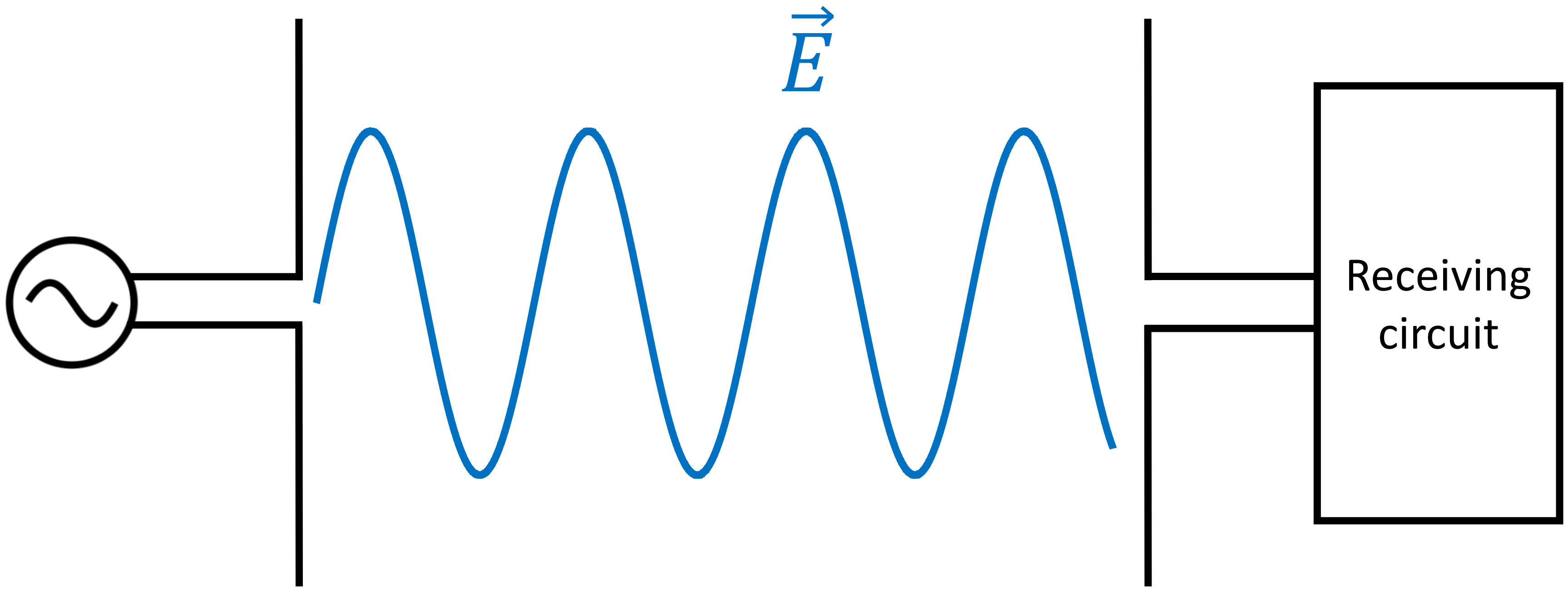
- How is it generated?

- How is it received?

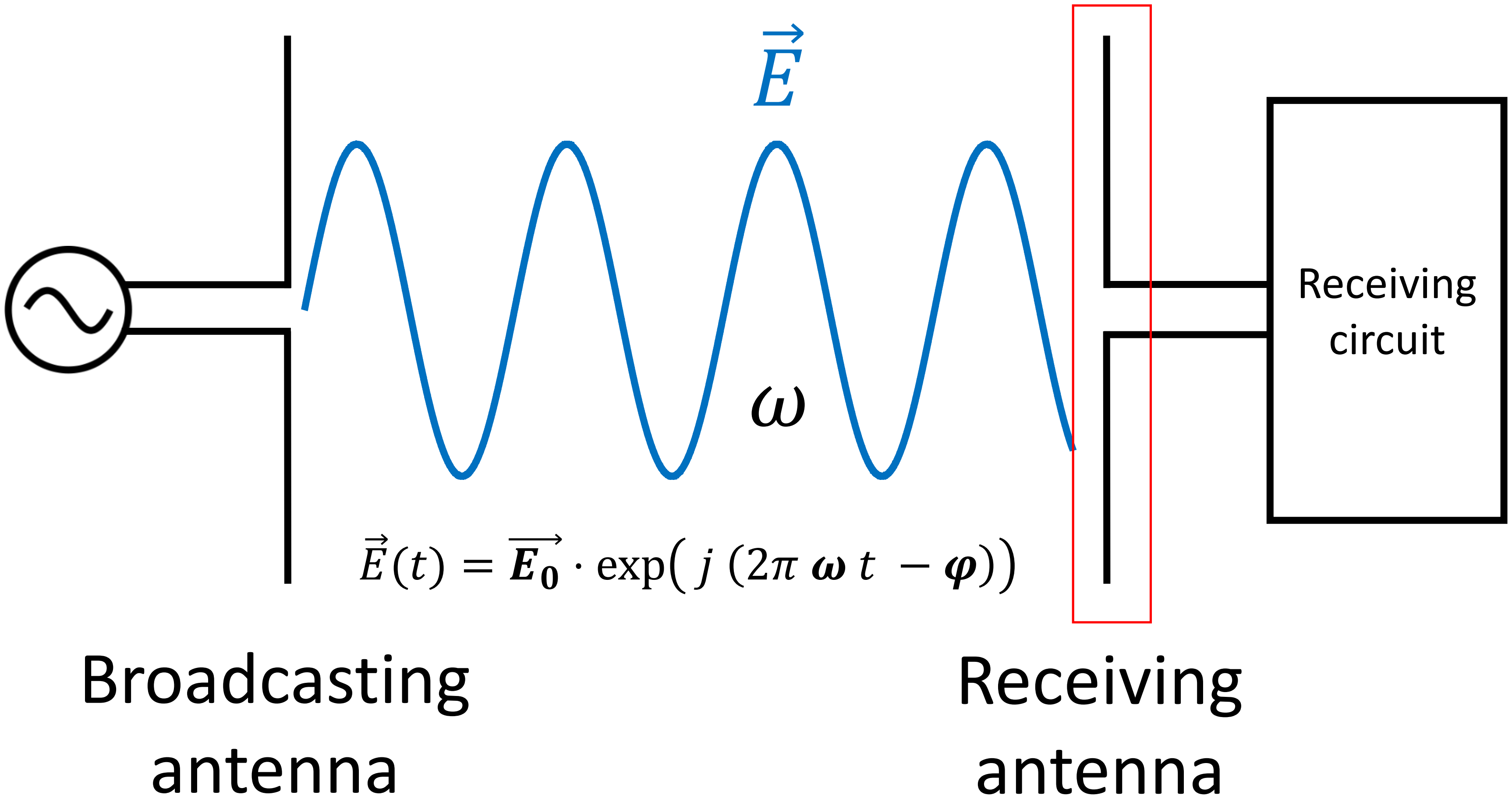
Reception of EM wave



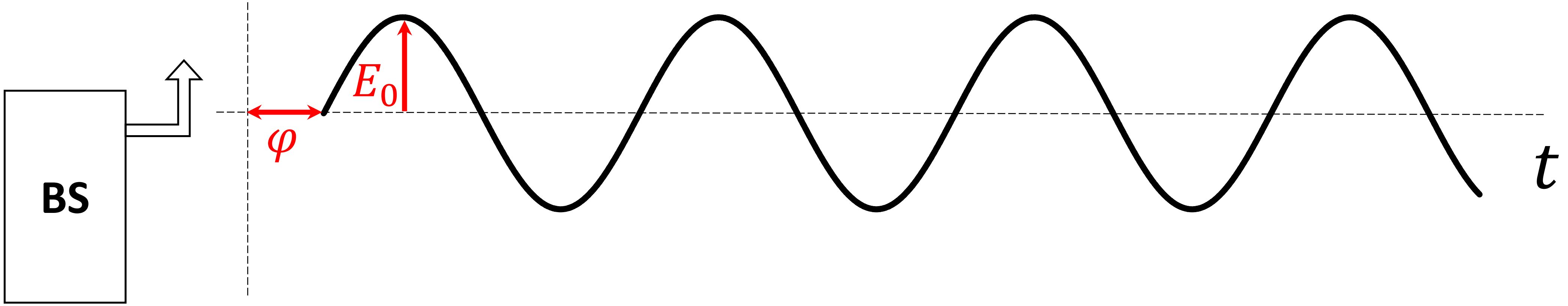
Reception of EM wave



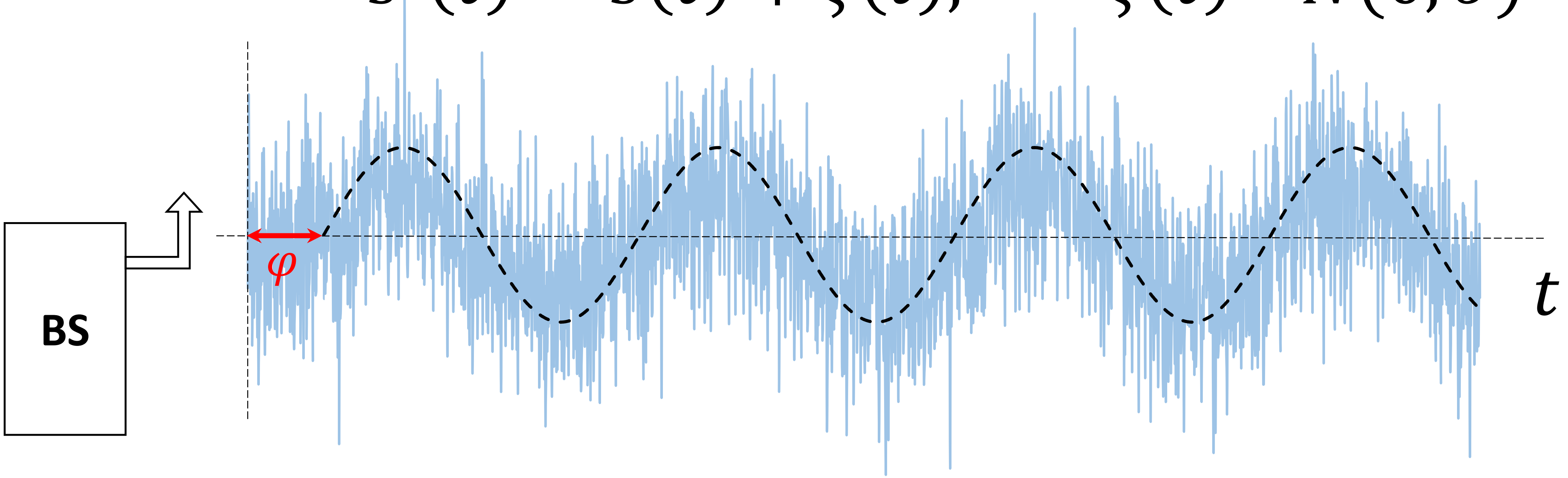
Reception of EM wave

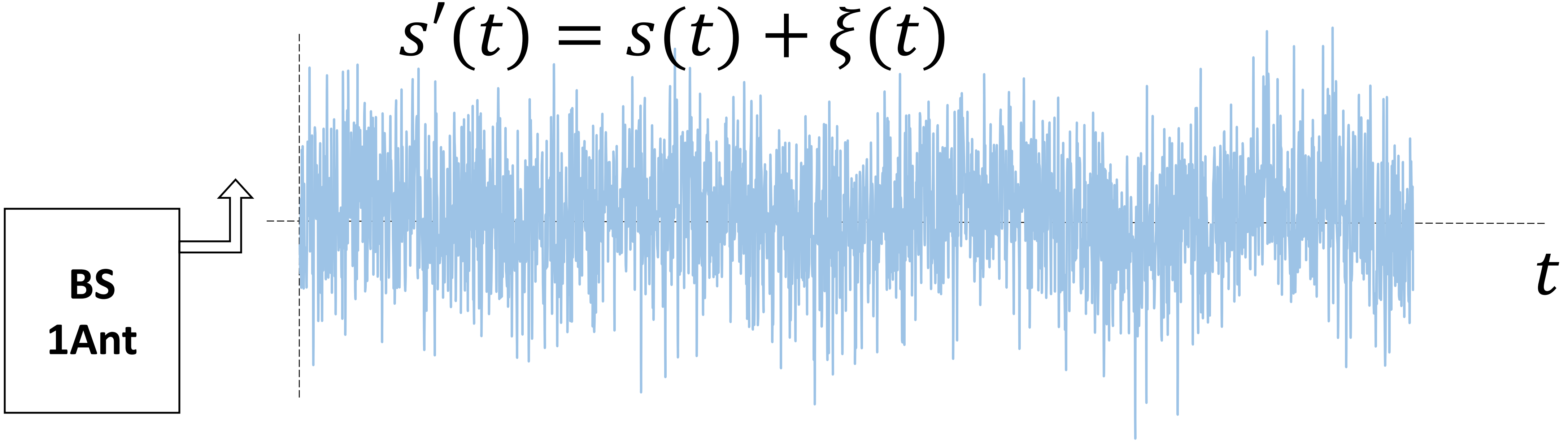


$$s(t) = E_0 \cdot \exp\big(j\,(2\pi\,\omega\,t - \varphi)\big)$$

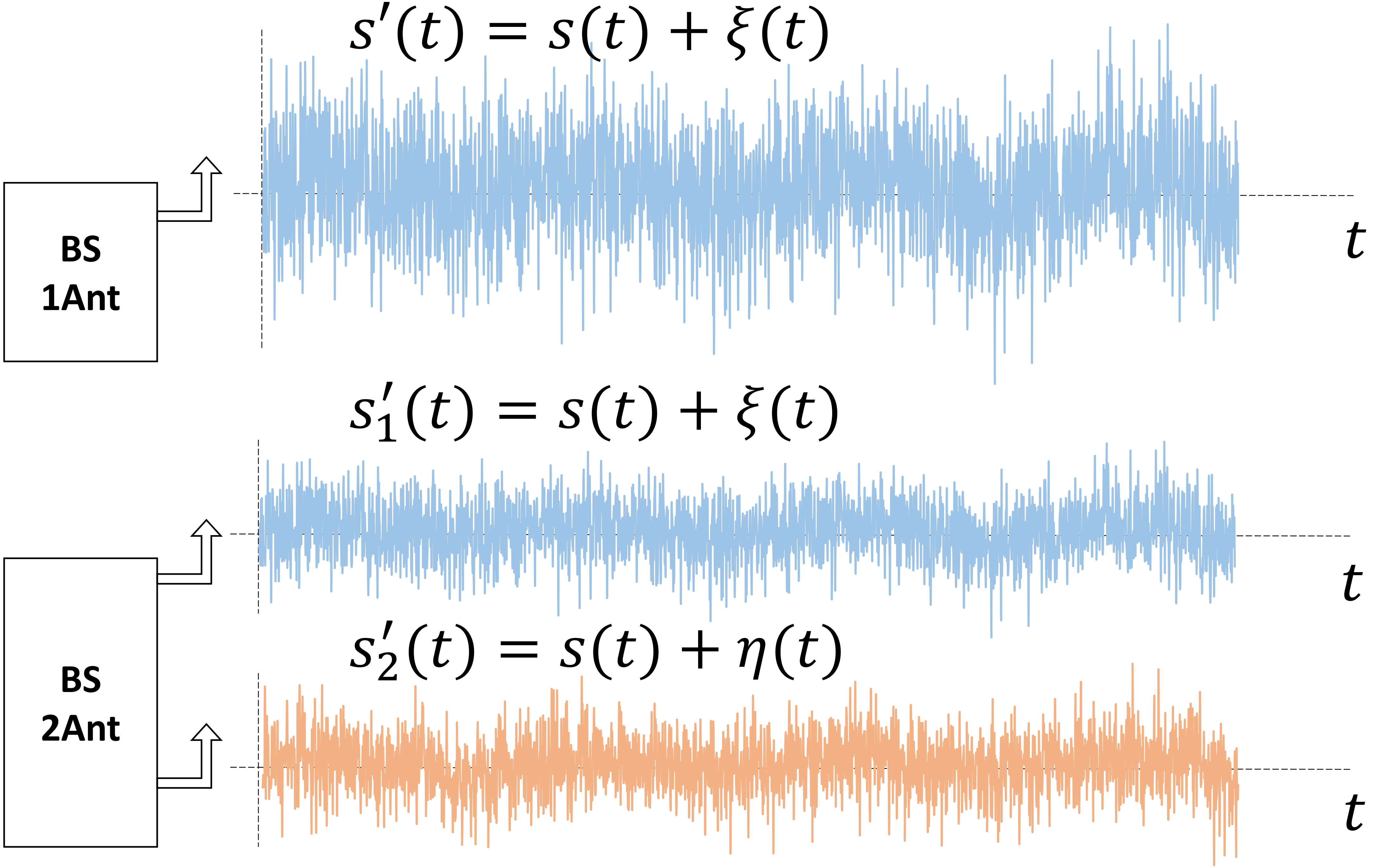


$$s'(t) = s(t) + \xi(t), \qquad \xi(t) \sim N(0, \sigma)$$

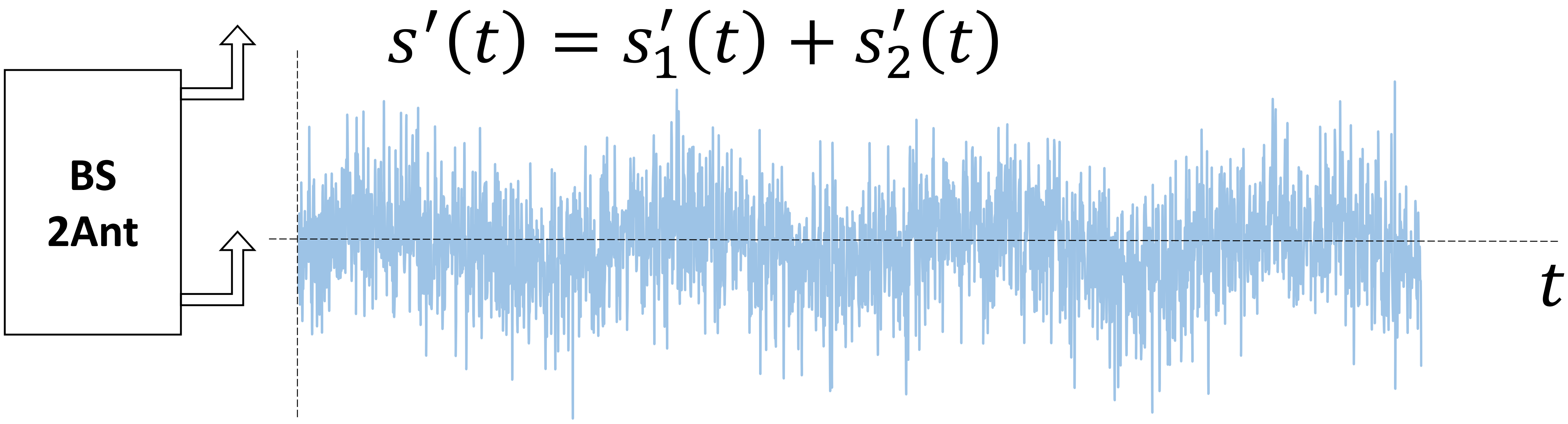




$s'(t) = s(t) + \xi(t)$
BS
1Ant
t

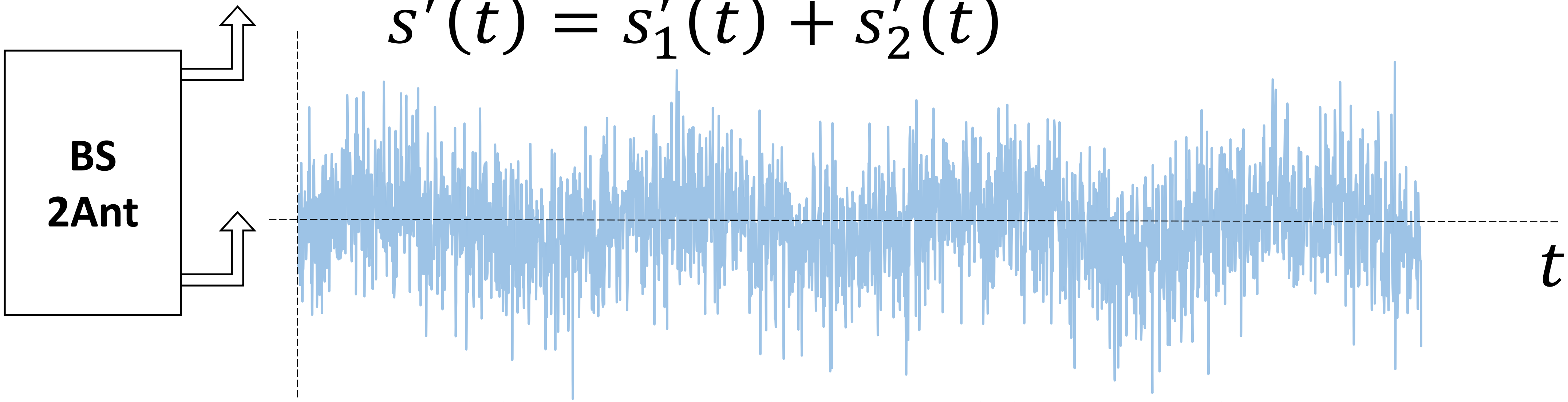


$s'(t) = s(t) + \xi(t)$
BS
1Ant
t
$s_1'(t) = s(t) + \xi(t)$
t
$s_2'(t) = s(t) + \eta(t)$
BS
2Ant
t



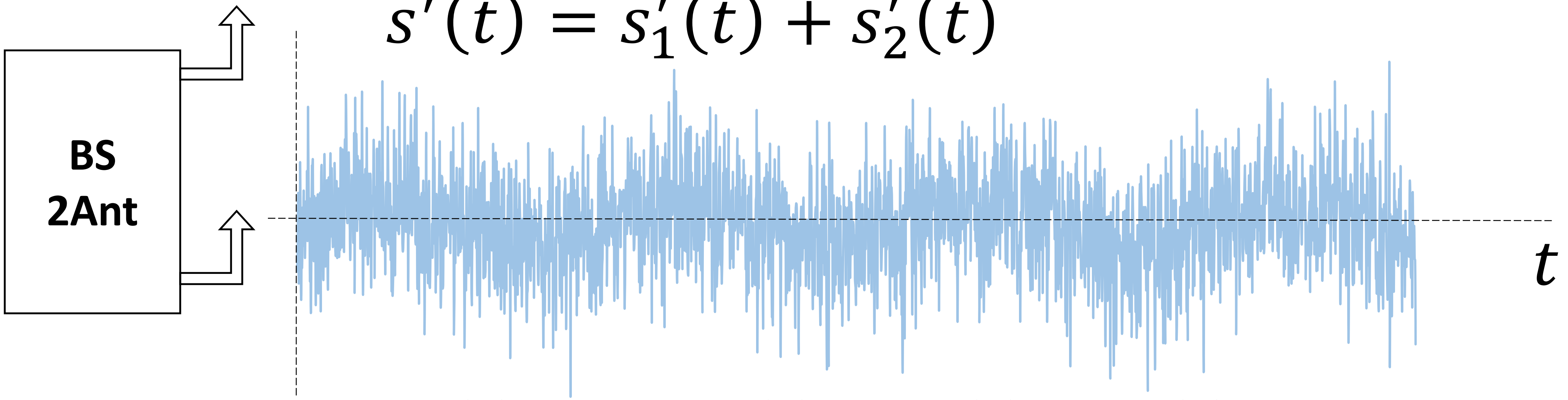
BS
2Ant
$s'(t) = s'_1(t) + s'_2(t)$
t

$$s'(t) = s'_1(t) + s'_2(t)$$



$$s'(t) = 2 \cdot s(t) + \eta(t) + \xi(t)$$

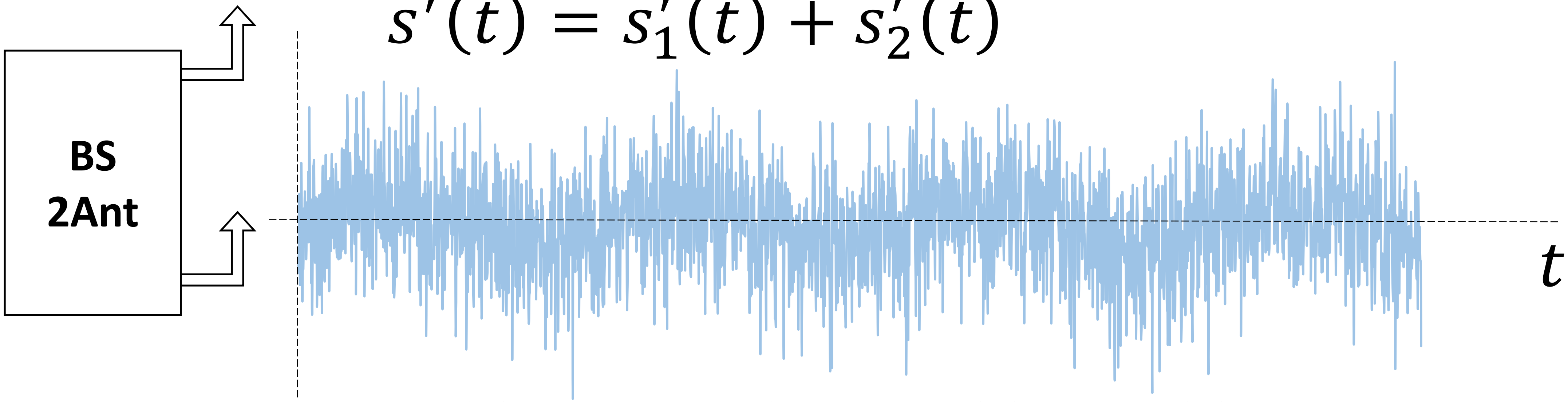
$$s'(t) = s_1'(t) + s_2'(t)$$



$$s'(t) = 2 \cdot s(t) + \eta(t) + \xi(t)$$

Noises $\eta(t)$ and $\xi(t)$ are independent

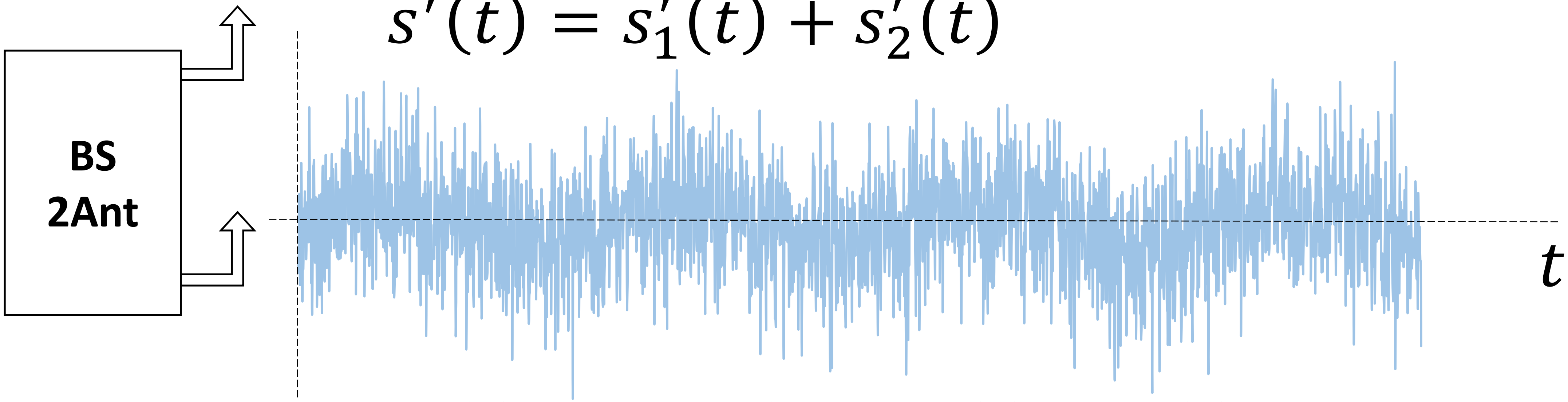
$$s'(t) = s_1'(t) + s_2'(t)$$



$$s'(t) = 2 \cdot s(t) + \eta(t) + \xi(t)$$

Noises $\eta(t)$ and $\xi(t)$ are independent $E[\,\xi\,\eta\,] = 0$

$$s'(t) = s_1'(t) + s_2'(t)$$

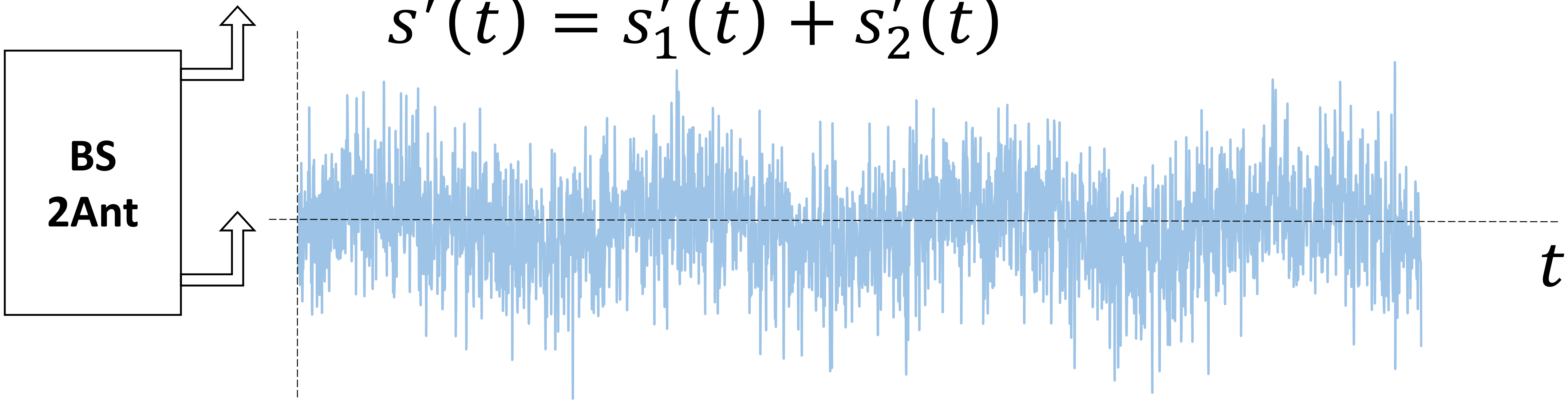


$$s'(t) = 2 \cdot s(t) + \eta(t) + \xi(t)$$

Noises $\eta(t)$ and $\xi(t)$ are independent $E[\,\xi\,\eta\,] = 0$

$$E[\xi] = E[\eta] = 0 \qquad E[\xi^2] = E[\eta^2] = \sigma^2$$

$$s'(t) = s_1'(t) + s_2'(t)$$

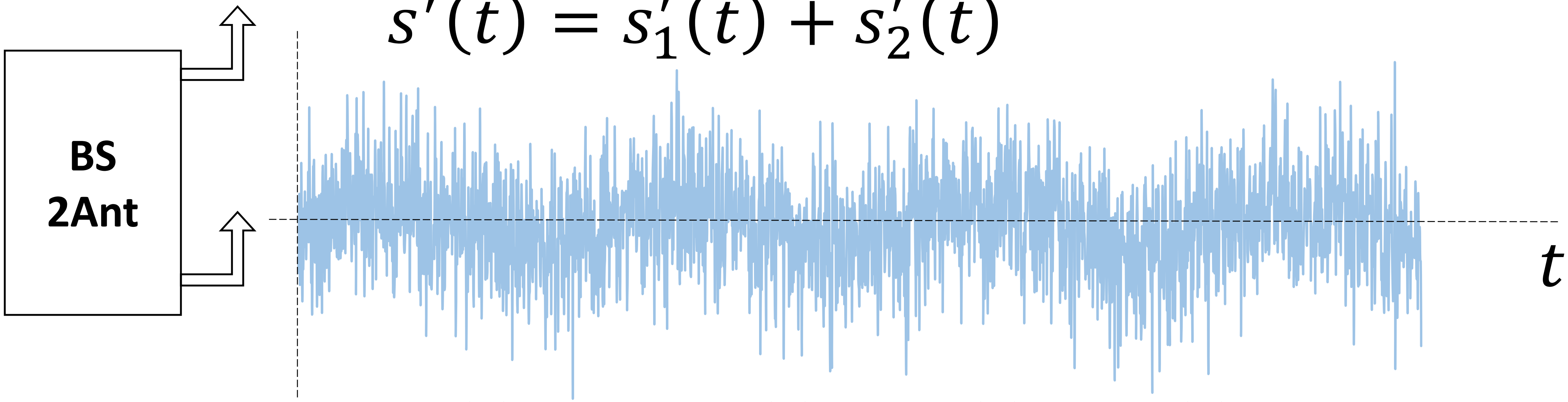


$$s'(t) = 2 \cdot s(t) + \eta(t) + \xi(t)$$

Noises $\eta(t)$ and $\xi(t)$ are independent $E[\,\xi\,\eta\,] = 0$

$$\xi(t) \sim N(0, \sigma) \qquad \eta(t) \sim N(0, \sigma)$$

$$s'(t) = s_1'(t) + s_2'(t)$$



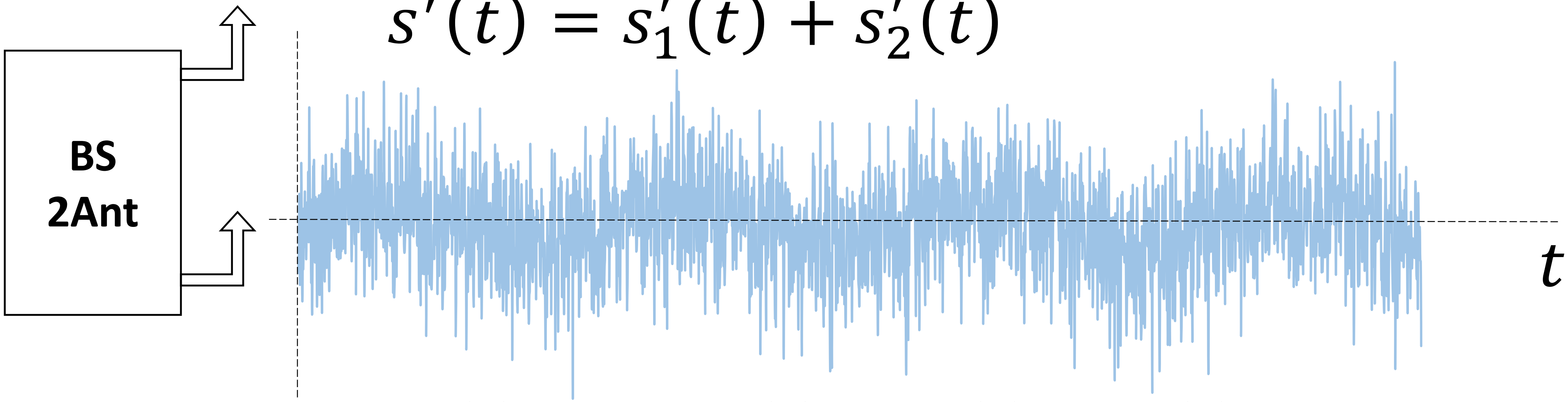
$$s'(t) = 2 \cdot s(t) + \eta(t) + \xi(t)$$

Noises $\eta(t)$ and $\xi(t)$ are independent $E[\,\xi\,\eta\,] = 0$

$$E[\xi] = E[\eta] = 0 \qquad E[\xi^2] = E[\eta^2] = \sigma^2$$

$$\zeta = \xi + \eta$$

$$s'(t) = s'_1(t) + s'_2(t)$$



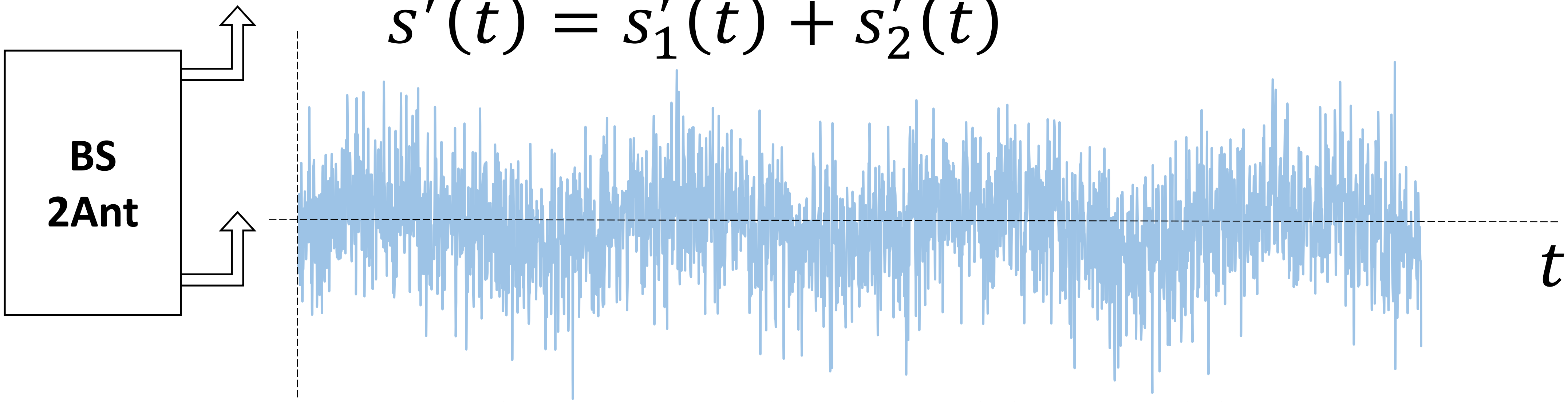
$$s'(t) = 2 \cdot s(t) + \eta(t) + \xi(t)$$

Noises $\eta(t)$ and $\xi(t)$ are independent $E[\,\xi\,\eta\,] = 0$

$$E[\xi] = E[\eta] = 0 \qquad E[\xi^2] = E[\eta^2] = \sigma^2$$

$$\zeta = \xi + \eta \qquad E[\zeta] = E[\xi + \eta] = E[\xi] + E[\eta] = 0$$

$$s'(t) = s_1'(t) + s_2'(t)$$



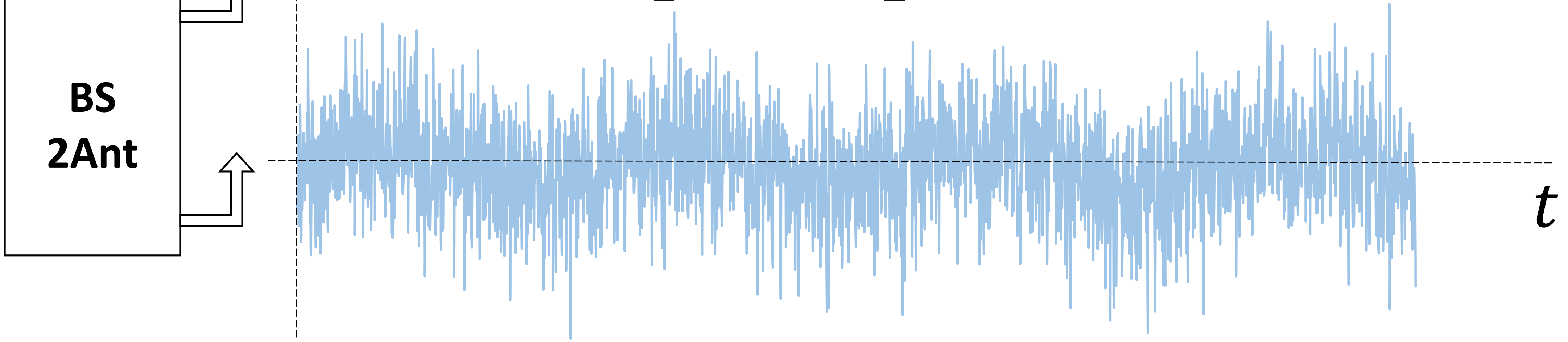
$$s'(t) = 2 \cdot s(t) + \eta(t) + \xi(t)$$

Noises $\eta(t)$ and $\xi(t)$ are independent $E[\,\xi\,\eta\,] = 0$

$$E[\xi] = E[\eta] = 0 \qquad E[\xi^2] = E[\eta^2] = \sigma^2$$

$$E[\zeta^2] = E[(\xi + \eta)^2] = E[\xi^2] + 2E[\xi\,\eta] + E[\eta^2] = ?$$

$$s'(t) = s_1'(t) + s_2'(t)$$



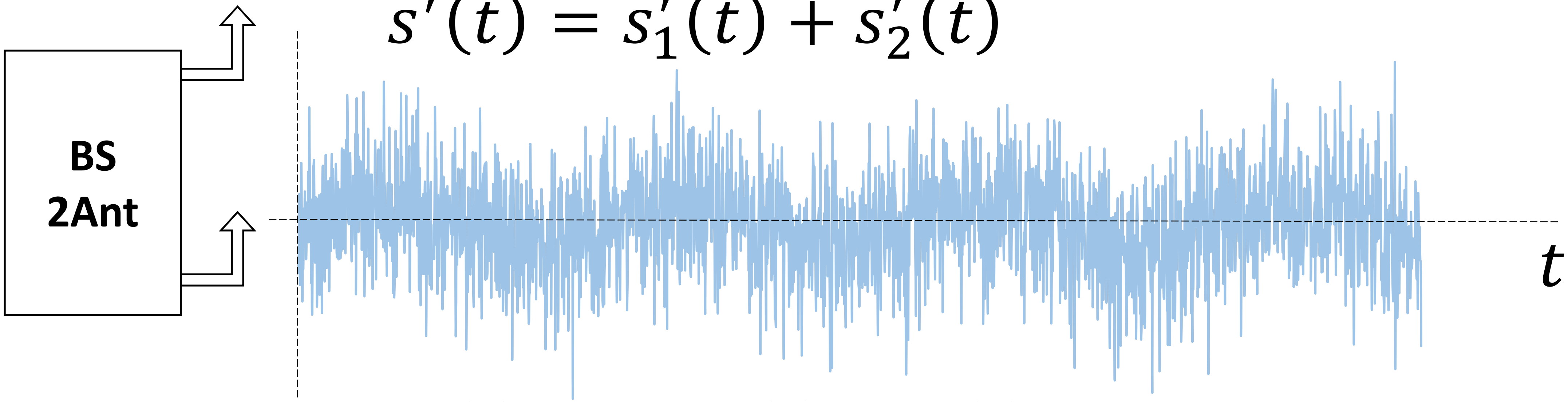
$$s'(t) = 2 \cdot s(t) + \eta(t) + \xi(t)$$

Noises $\eta(t)$ and $\xi(t)$ are independent $E[\,\xi\,\eta\,] = 0$

$$E[\xi] = E[\eta] = 0 \qquad E[\xi^2] = E[\eta^2] = \sigma^2$$

$$E[\zeta^2] = E[(\xi+\eta)^2] = \underset{\overset{\parallel}{\sigma^2}}{E[\xi^2]} + 2\underset{\overset{\parallel}{0}}{E[\xi\,\eta]} + \underset{\overset{\parallel}{\sigma^2}}{E[\eta^2]} = 2\sigma^2$$

$$s'(t) = s_1'(t) + s_2'(t)$$

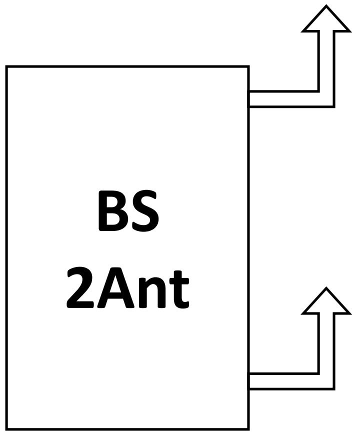


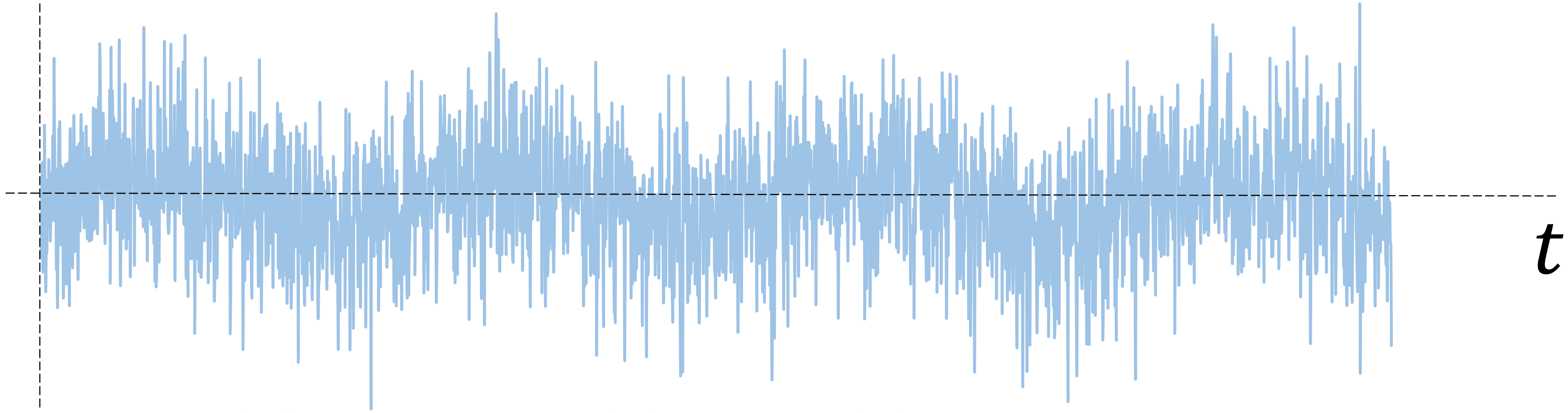
$$s'(t) = 2 \cdot s(t) + \zeta(t)$$

$$E[\zeta] = 0$$

$$E[\zeta^2] = 2\sigma^2$$

$$s'(t) = s'_1(t) + s'_2(t)$$





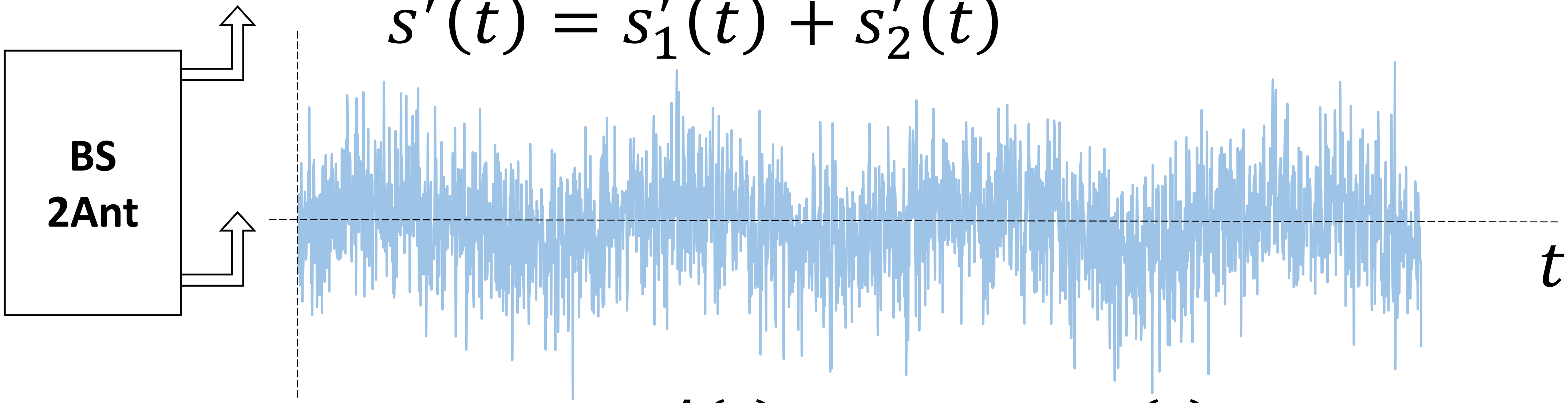
$$s'(t) = 2 \cdot s(t) + \zeta(t)$$

$$E[\zeta] = 0$$

$$E[\zeta^2] = 2\sigma^2$$

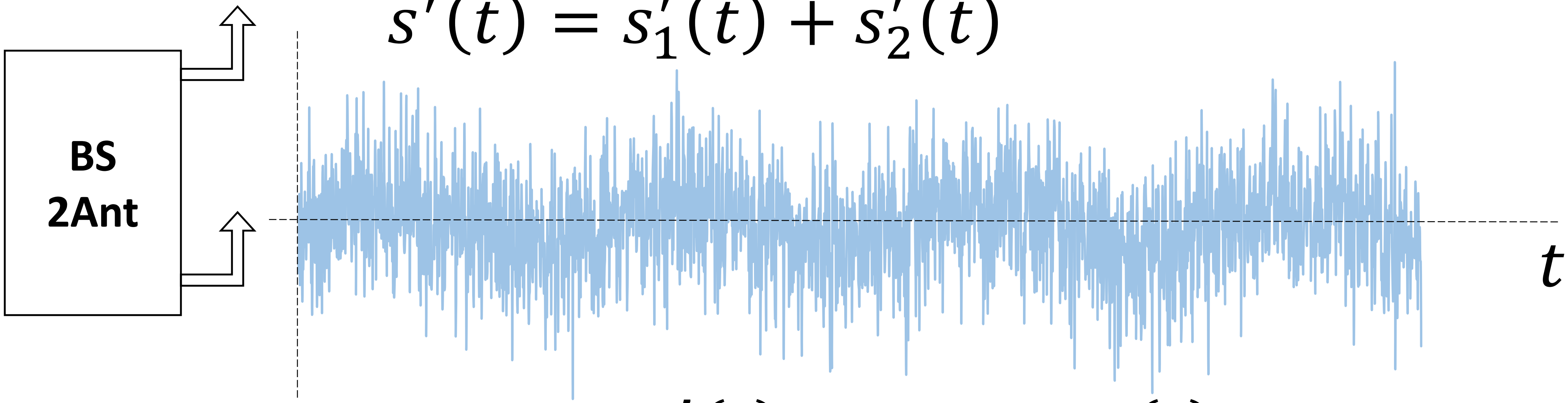
$$\zeta(t) \sim N\left(0, \sqrt{2}\,\sigma\right)$$

$$s'(t) = s'_1(t) + s'_2(t)$$



$$s''(t) = \frac{s'(t)}{2} = s(t) + \frac{\zeta(t)}{2} = s(t) + \varsigma(t)$$

$$s'(t) = s'_1(t) + s'_2(t)$$

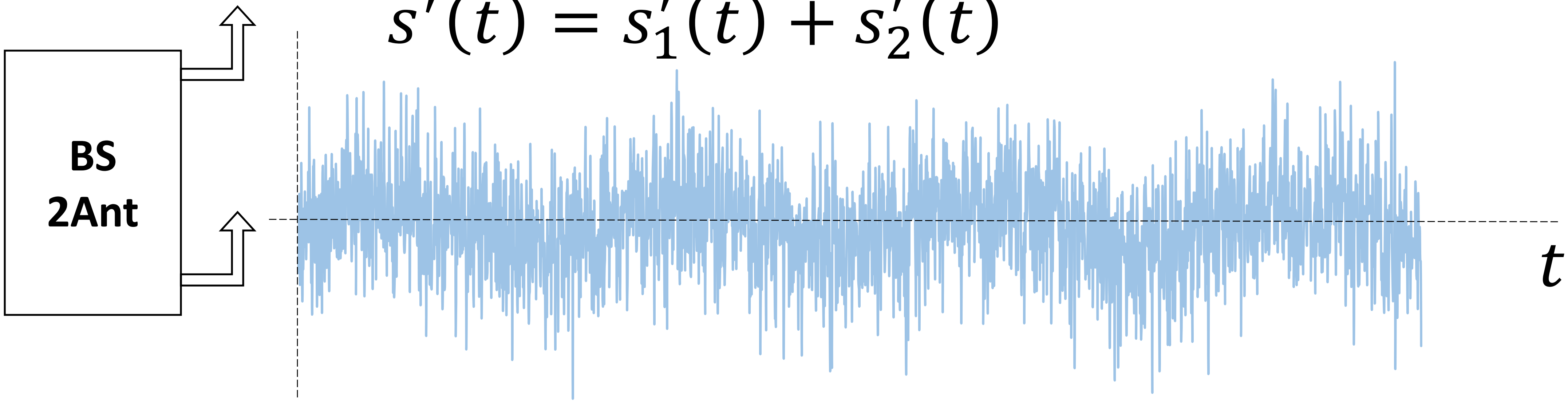


$$s''(t) = \frac{s'(t)}{2} = s(t) + \frac{\zeta(t)}{2} = s(t) + \varsigma(t)$$

$$E[\varsigma] = E\left[\frac{\zeta}{2}\right] = \frac{E[\zeta]}{2} = 0$$

$$E[\varsigma^2] = E\left[\left(\frac{\zeta}{2}\right)^2\right] = \frac{E[\zeta^2]}{4} = \frac{2\sigma^2}{4} = \frac{\sigma^2}{2}$$

$$s'(t) = s_1'(t) + s_2'(t)$$



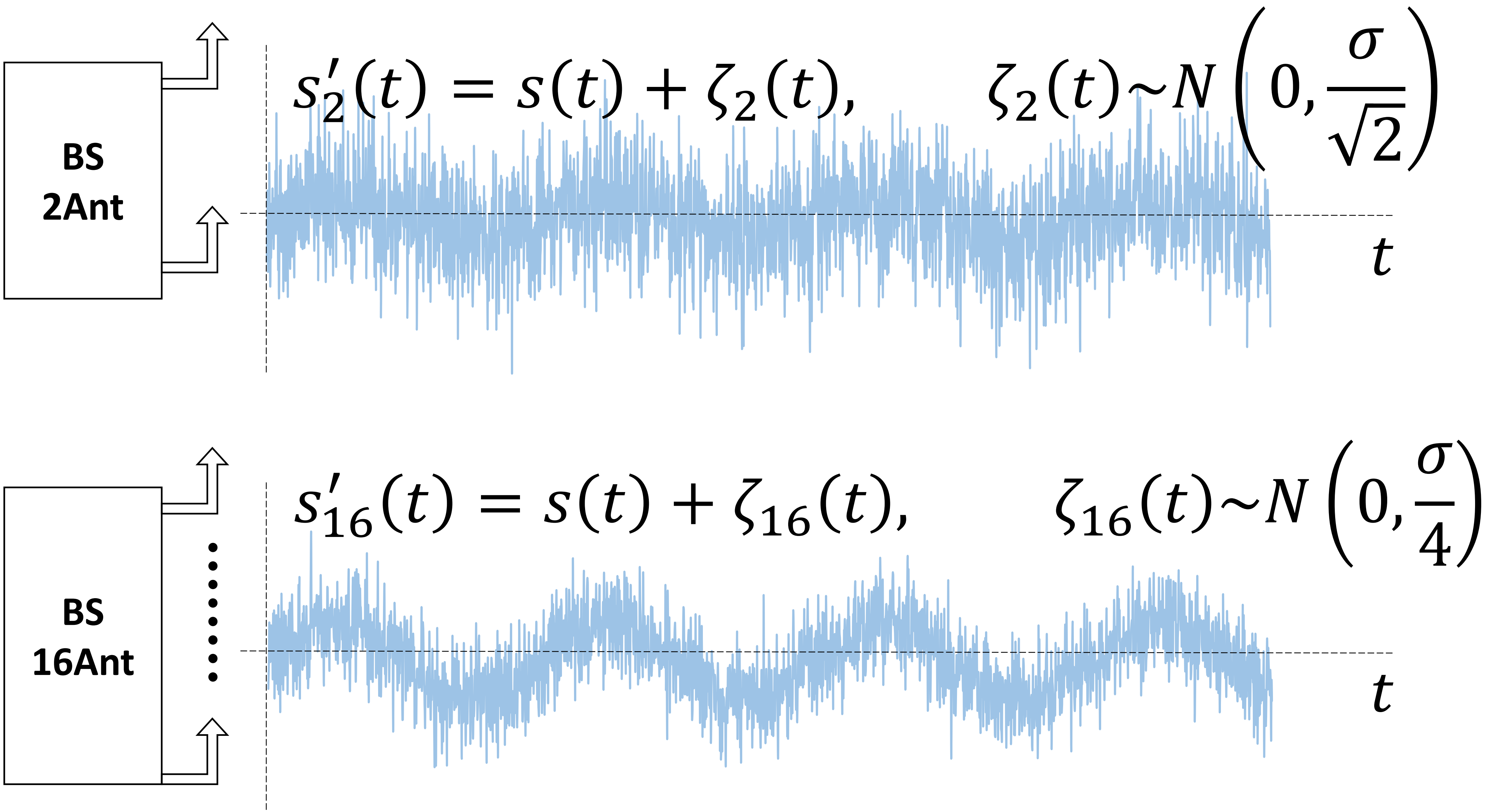
$$s''(t) = s(t) + \varsigma(t)$$

$$E[\varsigma] = 0$$

$$E[\varsigma^2] = \frac{\sigma^2}{2}$$

$$\varsigma(t) \sim N\left(0, \frac{\sigma}{\sqrt{2}}\right)$$

$$\boxed{s_1'(t) = s(t) + \xi(t) \quad \xi(t) \sim N(0, \sigma)}$$



BS
2Ant
$s'_2(t) = s(t) + \zeta_2(t), \qquad \zeta_2(t) \sim N\left(0, \frac{\sigma}{\sqrt{2}}\right)$
t
BS
16Ant
$s'_{16}(t) = s(t) + \zeta_{16}(t), \qquad \zeta_{16}(t) \sim N\left(0, \frac{\sigma}{4}\right)$
t

The number of antennas makes difference

- Theoretically, the more antennas we have, the better reception we obtain

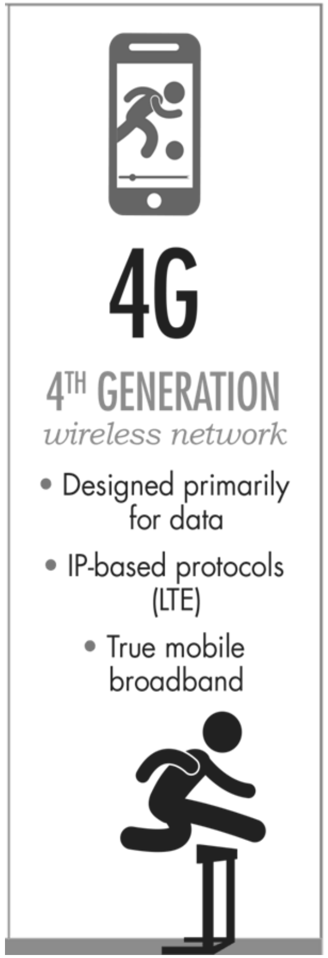
$$s'_{N_{ant}}(t) = s(t) + \zeta_{N_{ant}}(t)$$

$$\zeta_{N_{ant}}(t) \sim N\left(0, \frac{\sigma}{\sqrt{N_{ant}}}\right)$$

Outline

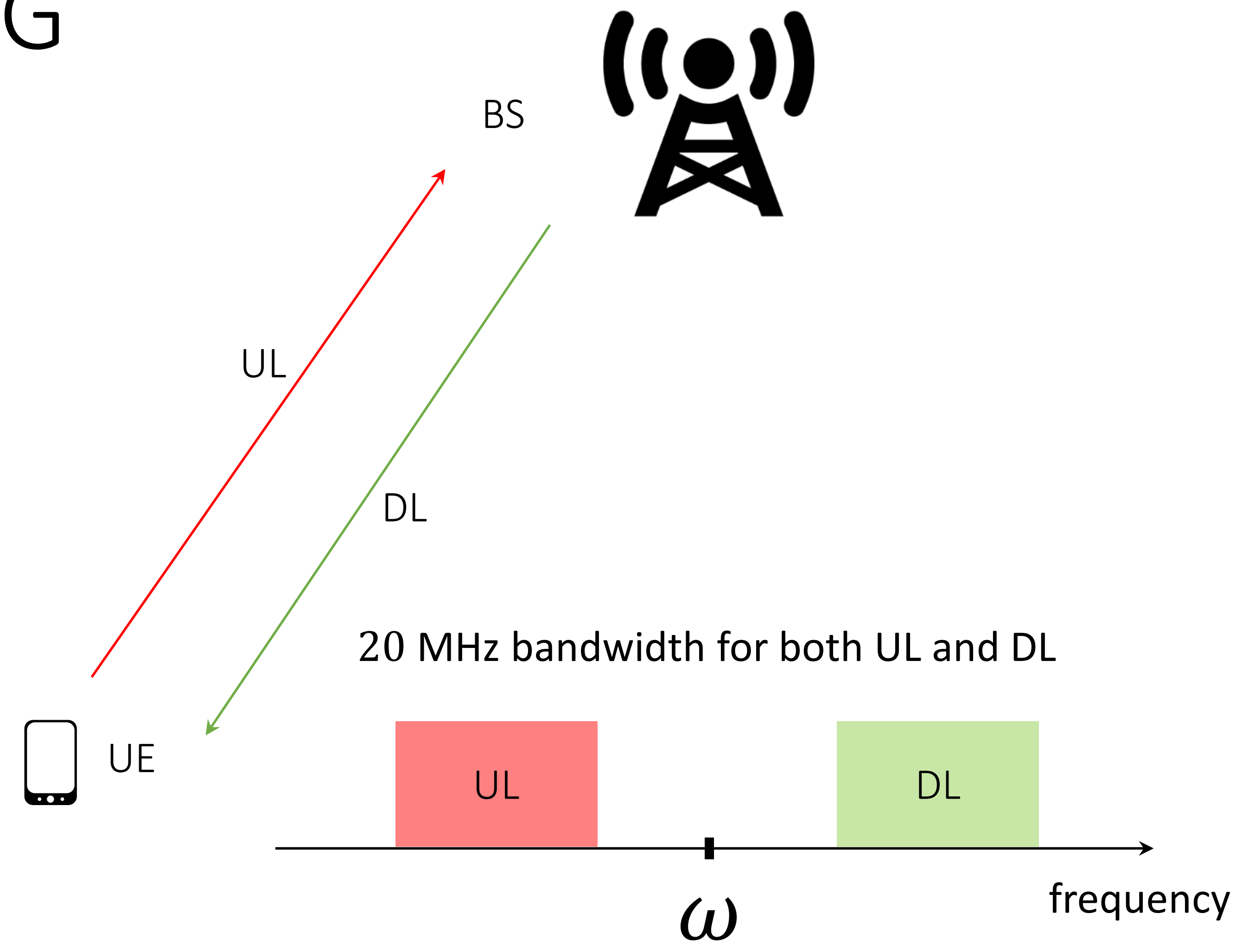
- History of mobile communication
- Physical aspects of radio signals
- **Introduction to LTE/4G**
- Massive MIMO approach
- What we do

Introduction to LTE/4G



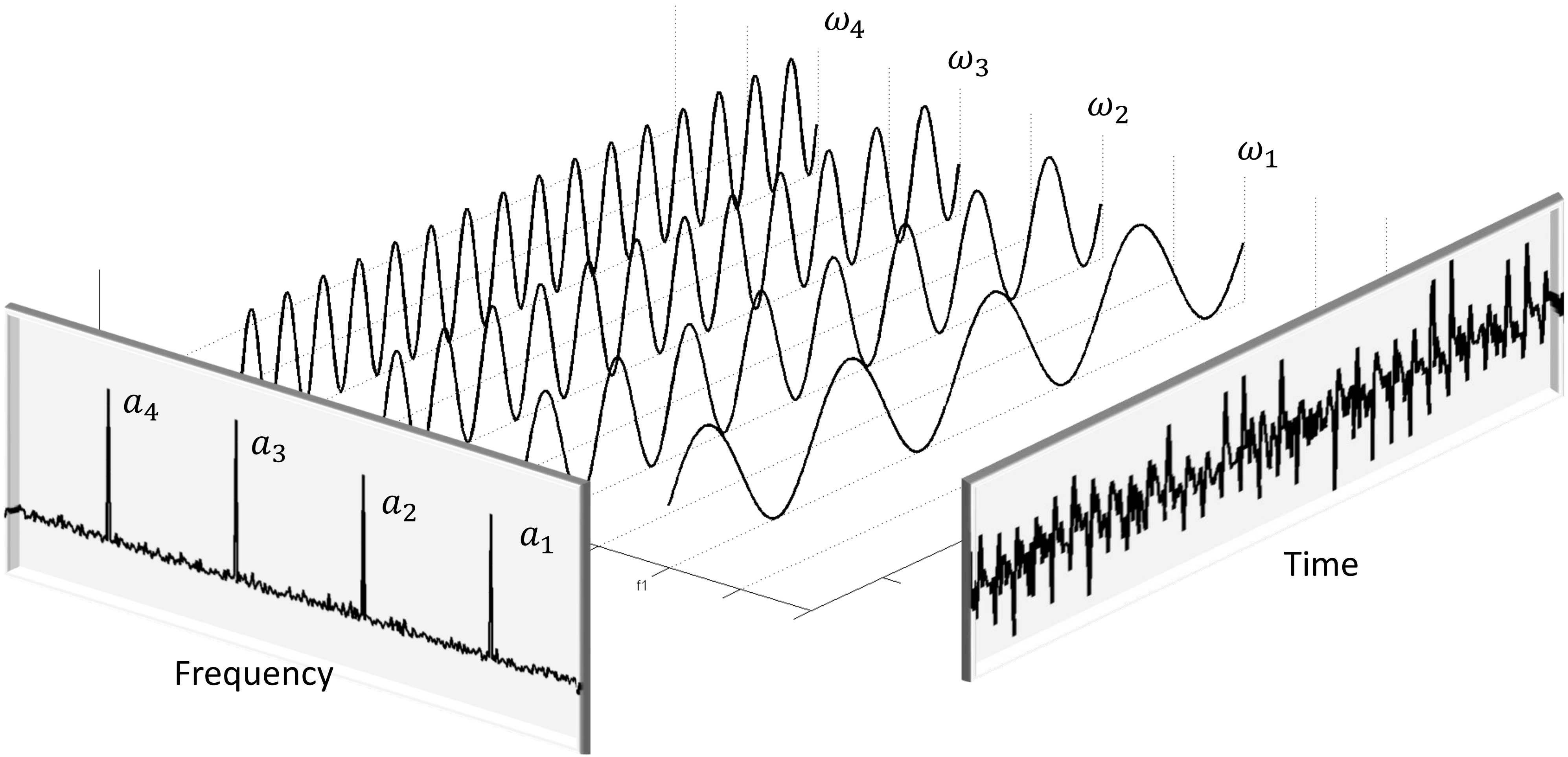
> 100 Mbps

2011



For Spark ω = 2.6 GHz

LTE uses OFDM



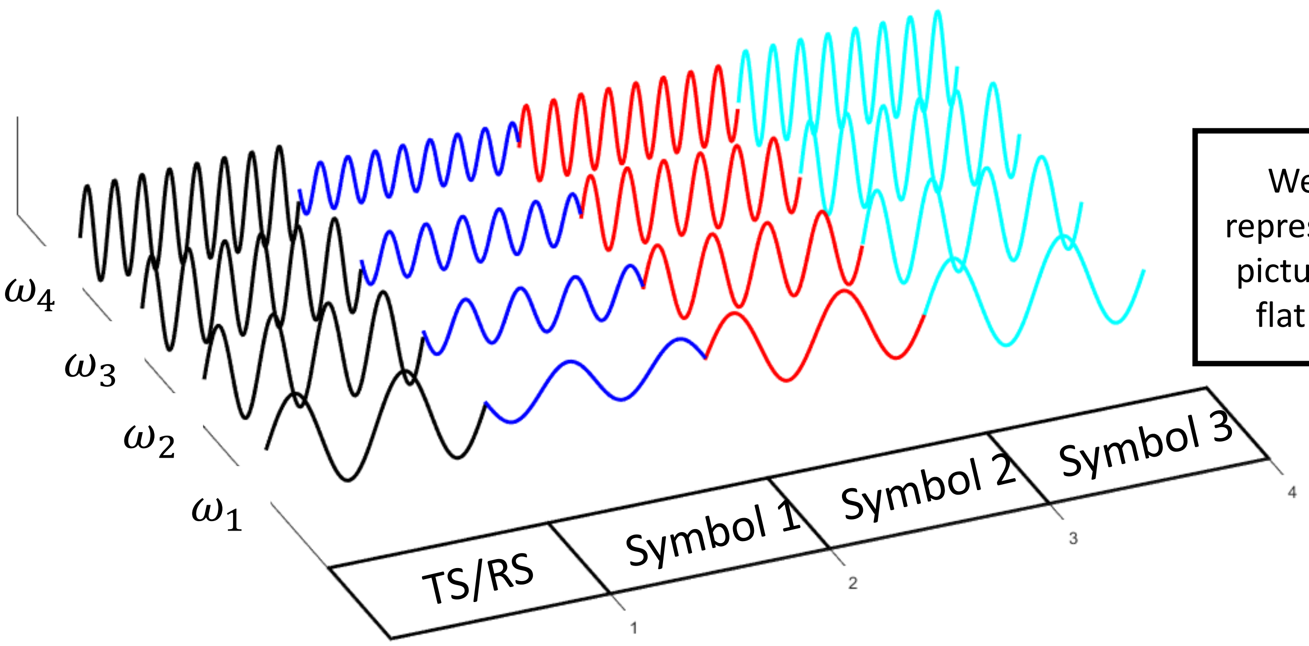
Orthogonal channels (subcarriers) can be shared among up to four users, or can be used by one user. Flexible approach for resource allocating

LTE uses OFDM

- OFDM – Orthogonal Frequency Division Multiplexing is a technique, which allows to increase a transmission rate without increasing the sampling rate of a communication system.

- The technique utilizes a number of orthogonal subcarriers (sine waves) to transmit data in a parallel manner

LTE Signal at Physical Layer



We can represent 3D picture as a flat table

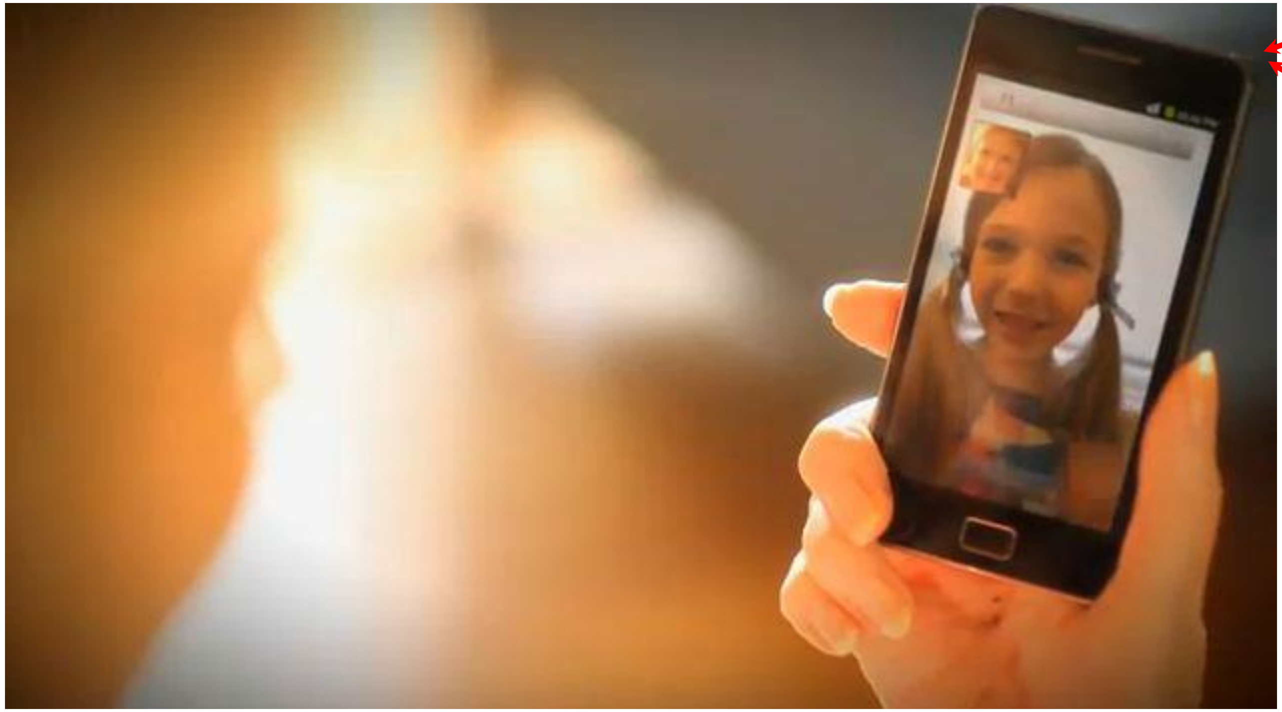
Reference Symbol	Symbol 1	Symbol 2	Symbol 3
RS1	a_1	a_5	a_9
RS2	a_2	a_6	a_{10}
RS3	a_3	a_7	a_{11}
RS3	a_4	a_8	a_{12}

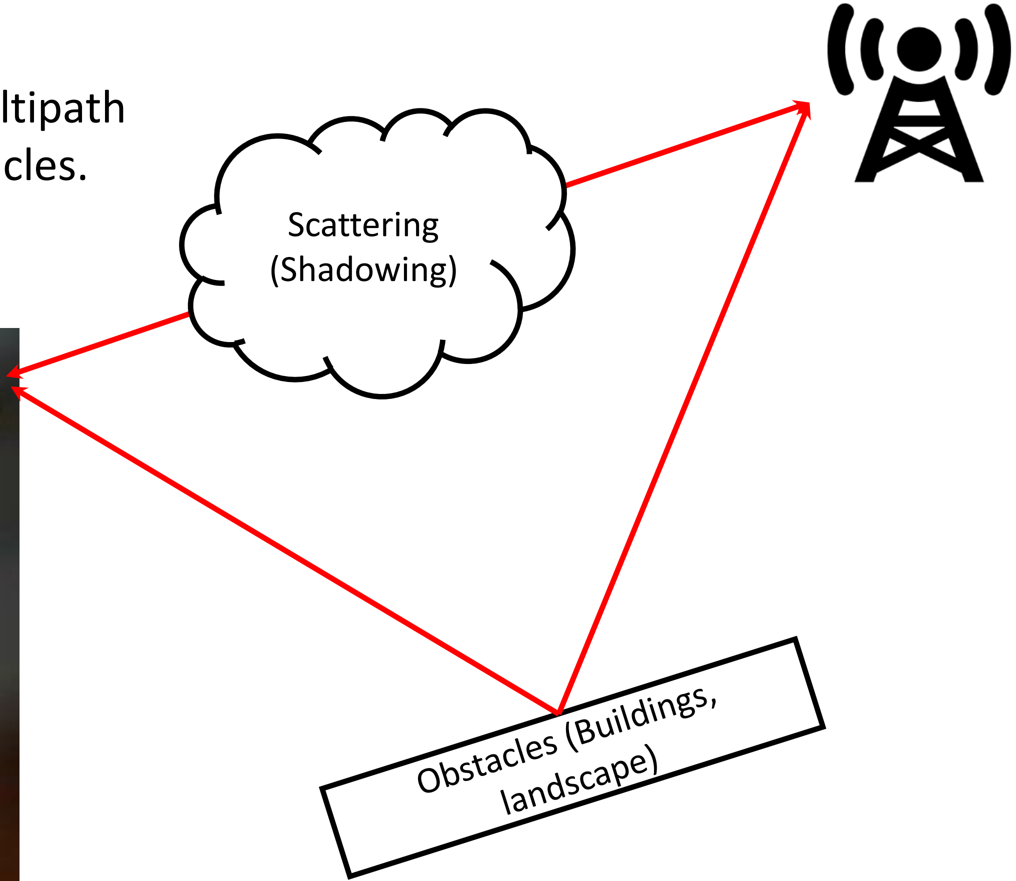
Such a spreadsheet is called as Resource Block (RB)

Reference Symbols are used to estimate the channel through which signals are transmitted

What is Multipath Propagation Channel?

Multipath effects occur in a wireless channel, which is called Multipath channel, where a transmitted signal reflects from different obstacles. Instead of one signal, the receiver receives several copies of the transmitted signal.





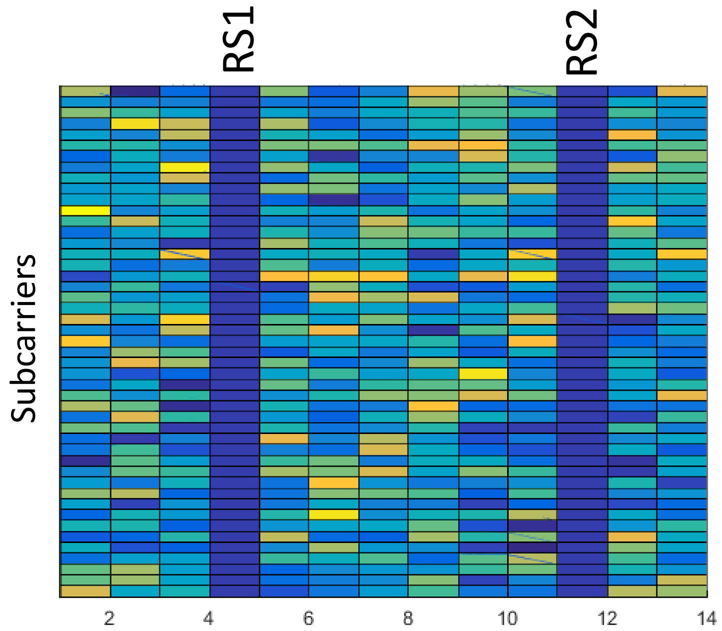
Video Call is loading channel in both sides
High network capacity must be performed in both sides

Channel estimation stage

Resource Block from example

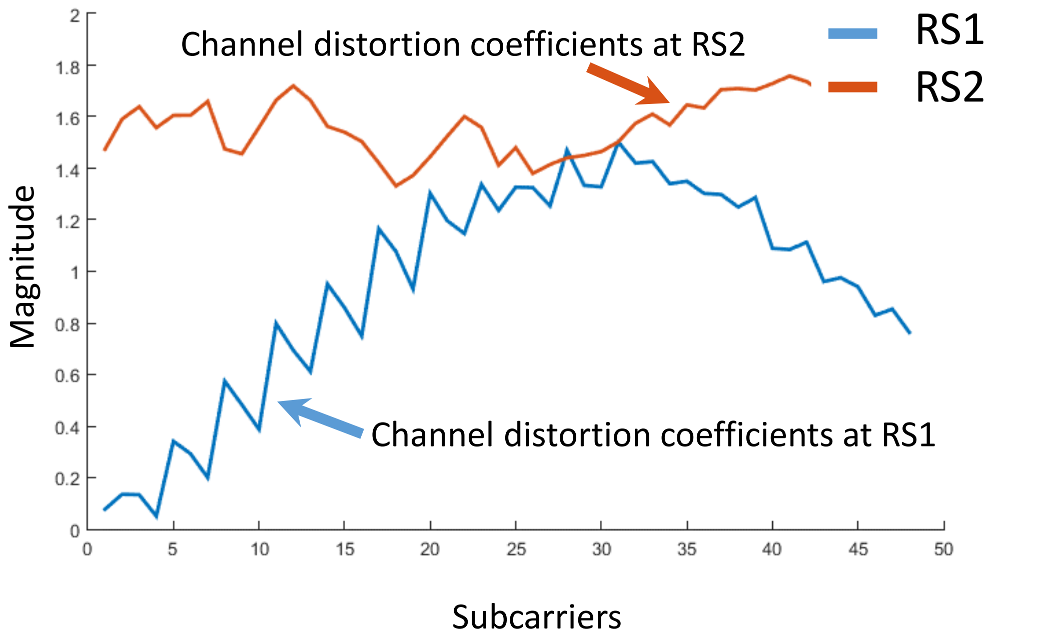
RS	Symbol 1	Symbol 2	Symbol 3
RS1	a_1	a_5	a_9
RS2	a_2	a_6	a_{10}
RS3	a_3	a_7	a_{11}
RS3	a_4	a_8	a_{12}

Typical Resource Block in LTE

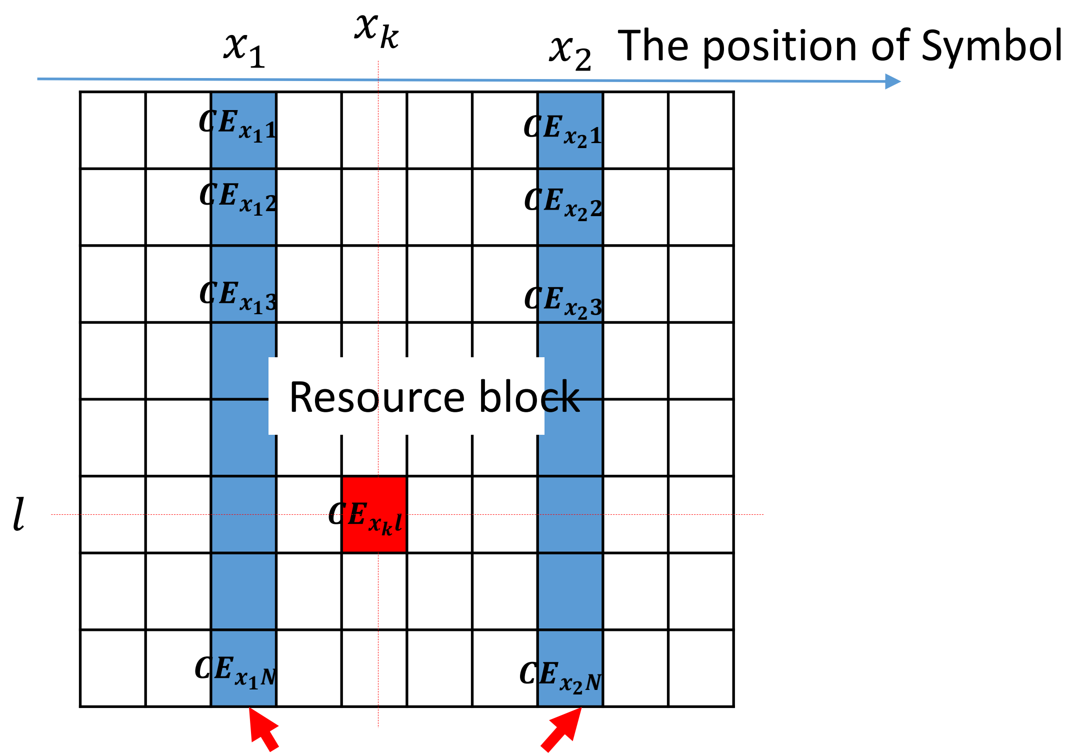


Data Symbols and Reference Symbols (blue blocks)

Channel estimation is performed by using RSs



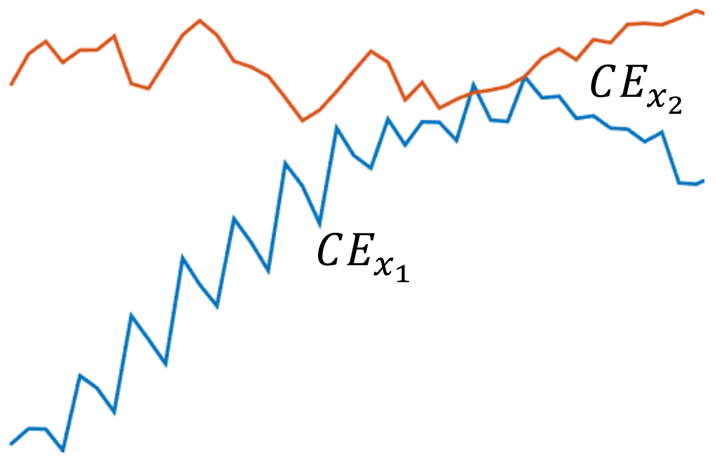
The main weak place in CE is approximation



We estimated the channel at these places

Linear approximation

$$CE_{x_k l} = \frac{CE_{x_2 l} - CE_{x_1 l}}{x_2 - x_1}(x_k - x_1) + CE_{x_1 l}$$



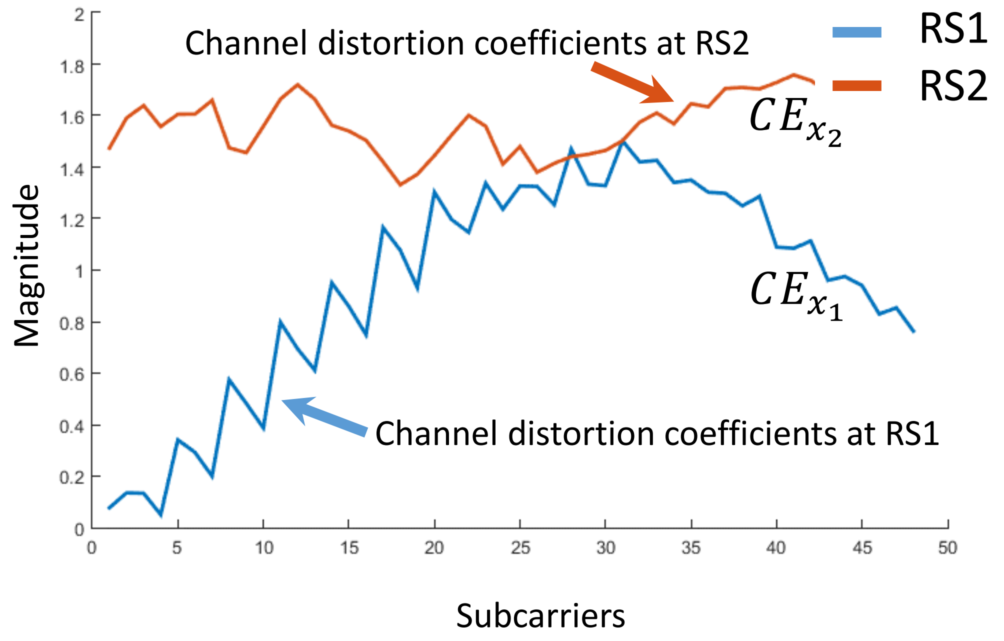
There are a lot of approaches in channel approximation, we will consider the easiest one: linear approximation

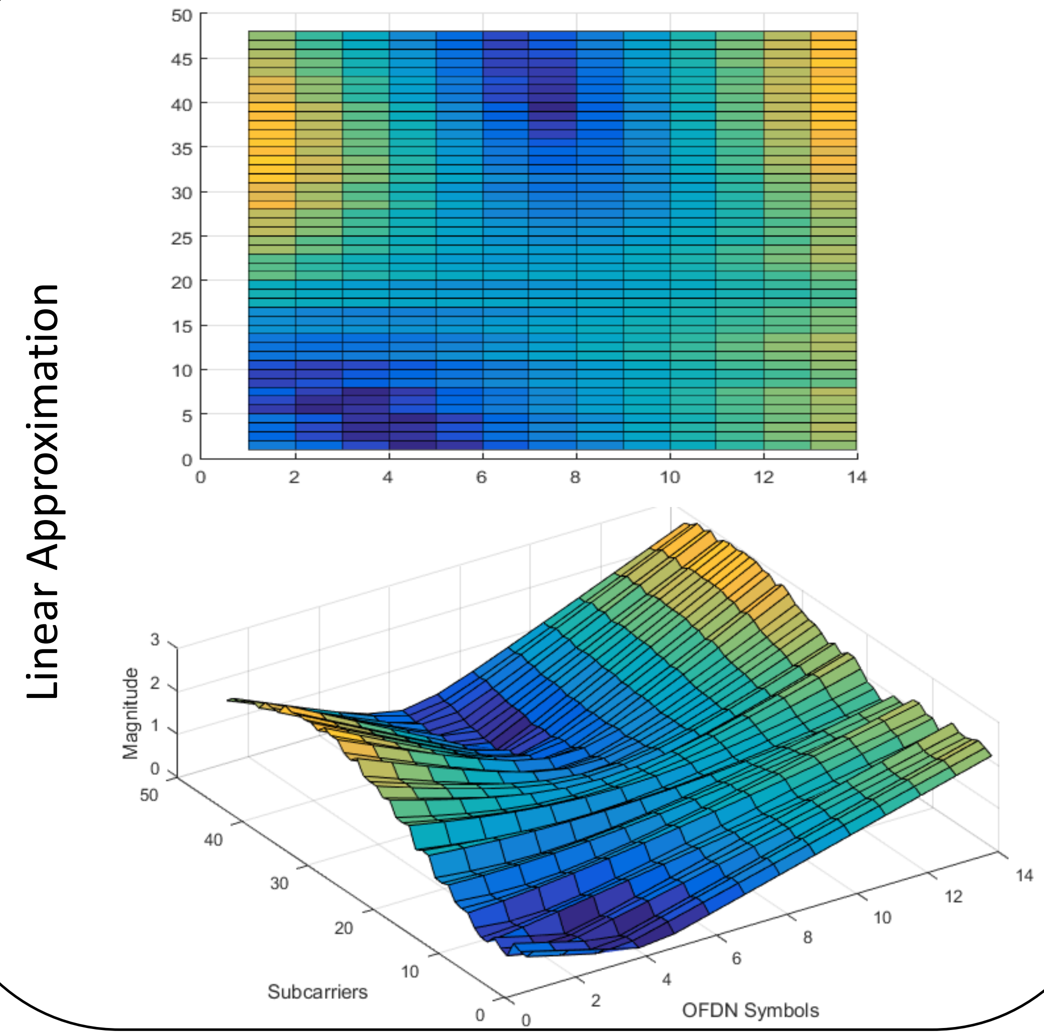
Linear approximation results

Linear approximation

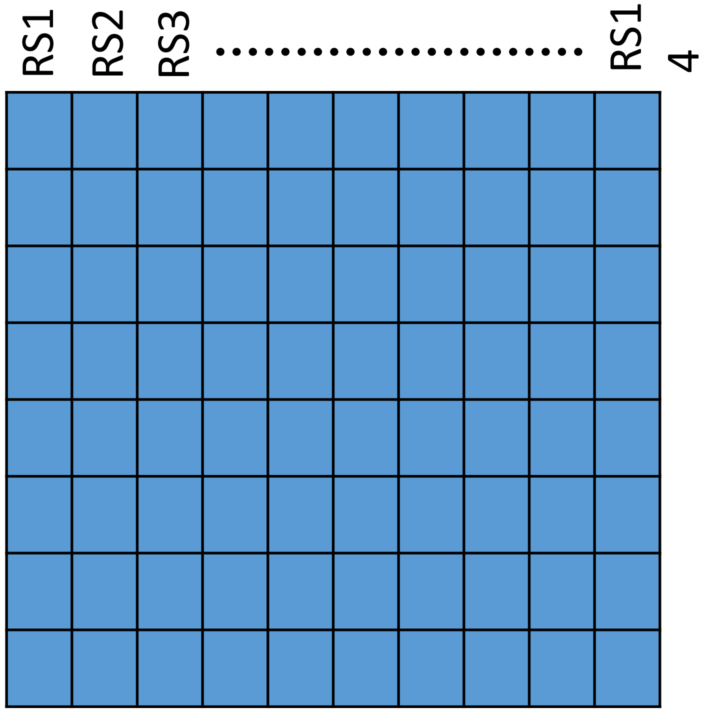
$$CE_{x_k l} = \frac{CE_{x_2 l} - CE_{x_1 l}}{x_2 - x_1}(x_k - x_1) + CE_{x_1 l}$$

Channel estimation is performed by using RSs



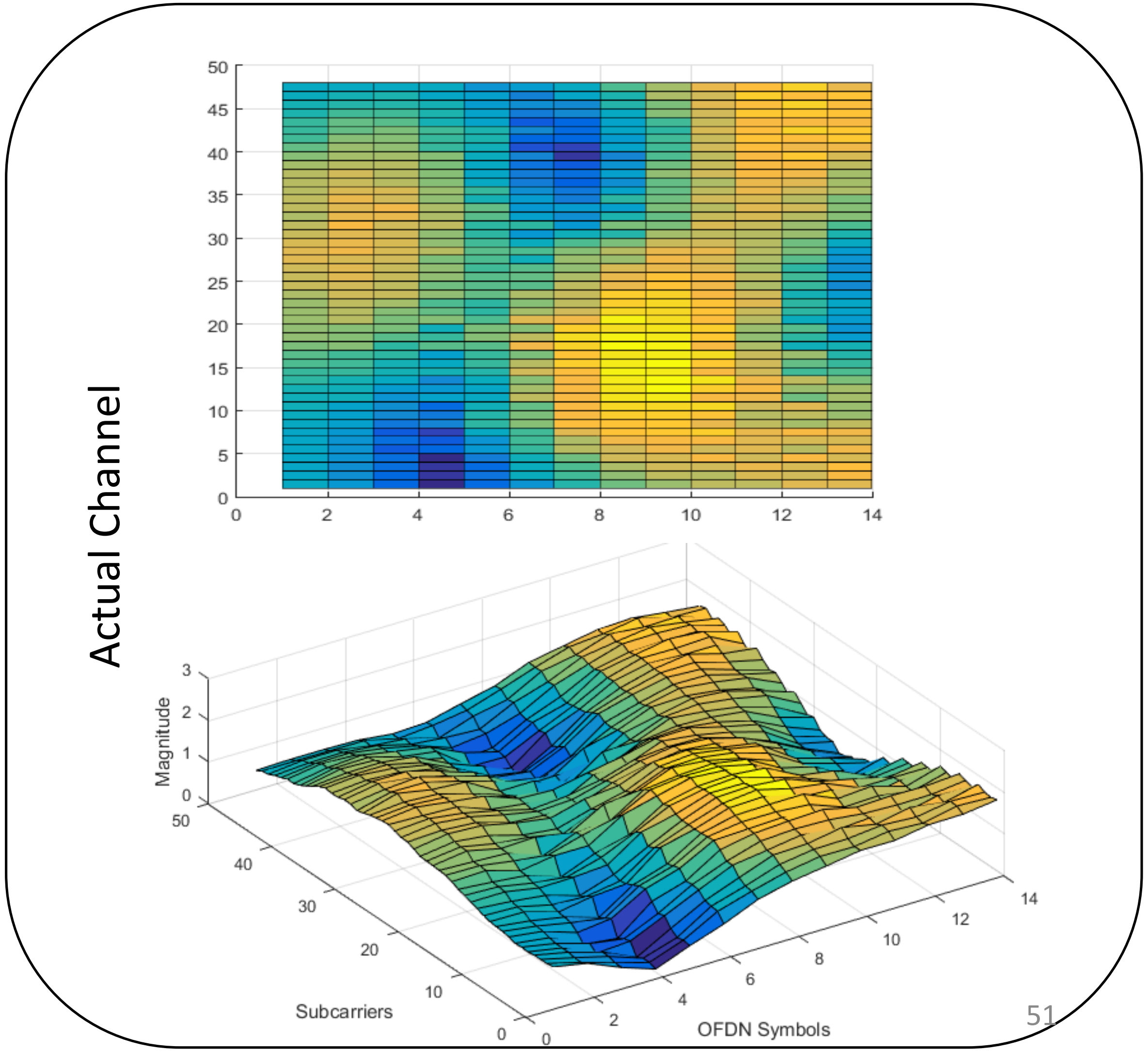


Calculation of actual channel



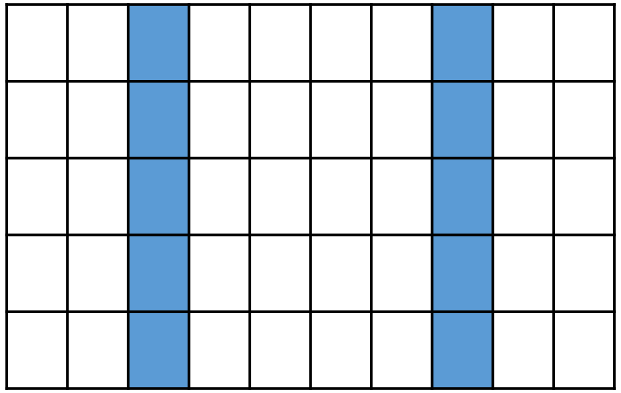
$$CE_{kl} = \frac{RS'_{kl}}{RS_{kl}}$$

Whole resource block is fill by reference symbols



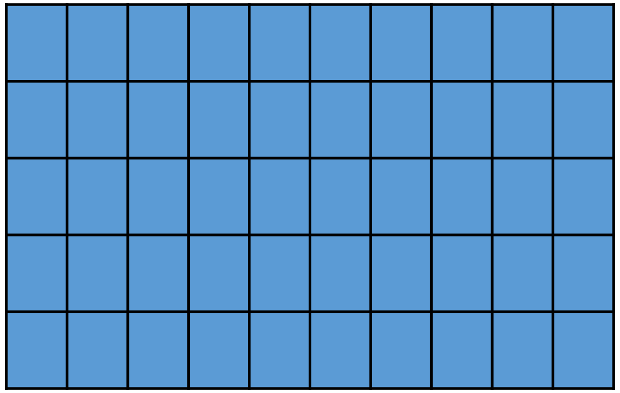
Comparison of Estimated Channel and Actual Channel

Two RSs among Symbols

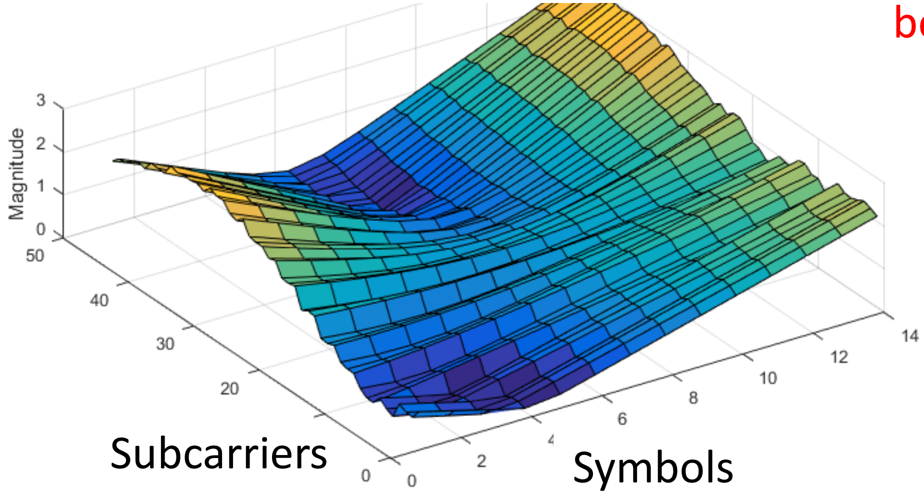


Multipath Channel is complicated object in wireless communication area, which must be accurately estimated for further correct data receiving (ref. page 10)

All Symbols are RS

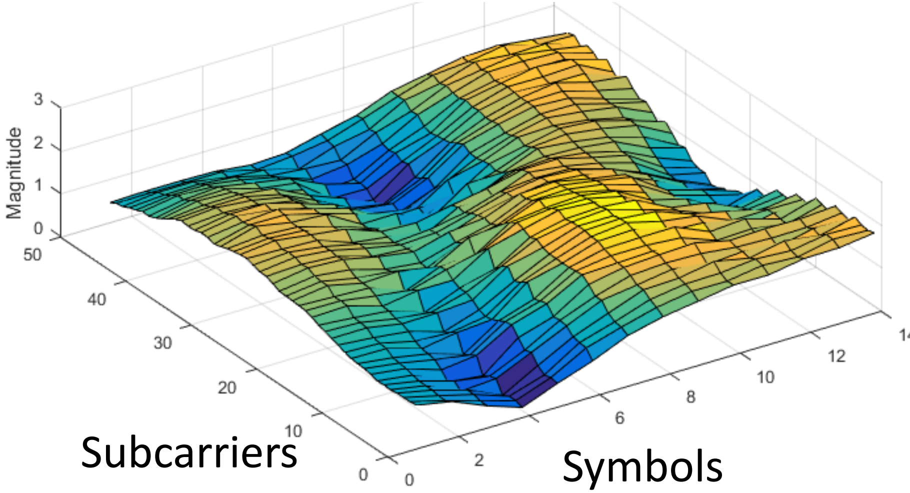


Not accurate estimation



There is trade off between accuracy of CE and the amount of transmitted data

Accurate estimation

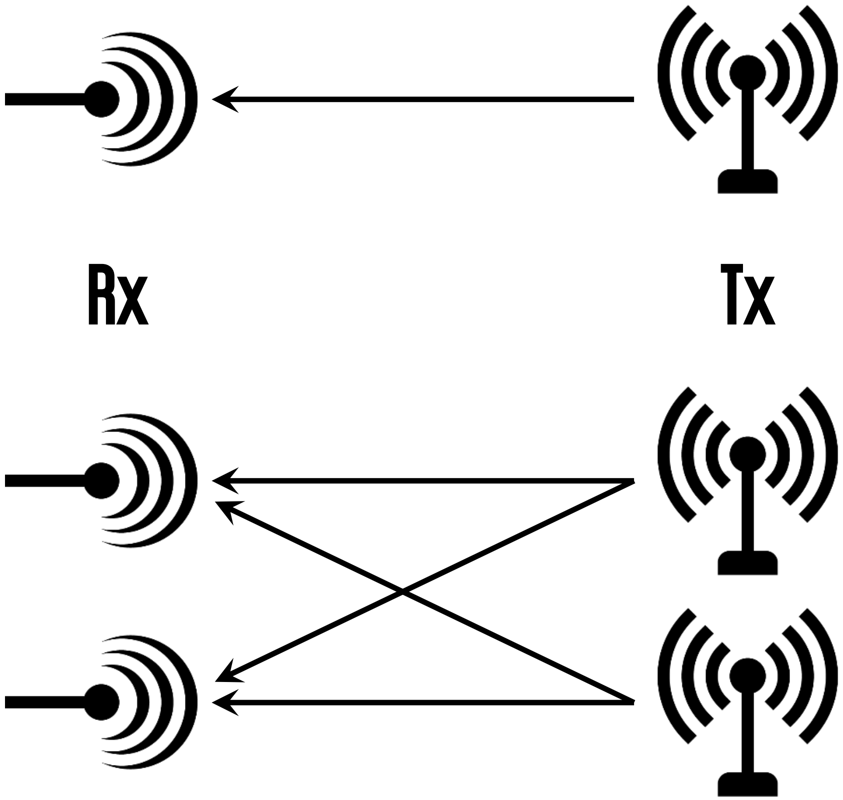


Can we eliminate CE
or
decrease its complexity?

Outline

- History of mobile communication
- Physical aspects of radio signals
- Introduction to LTE/4G
- **Massive MIMO approach**
- What we do

Massive MIMO and big antenna arrays?



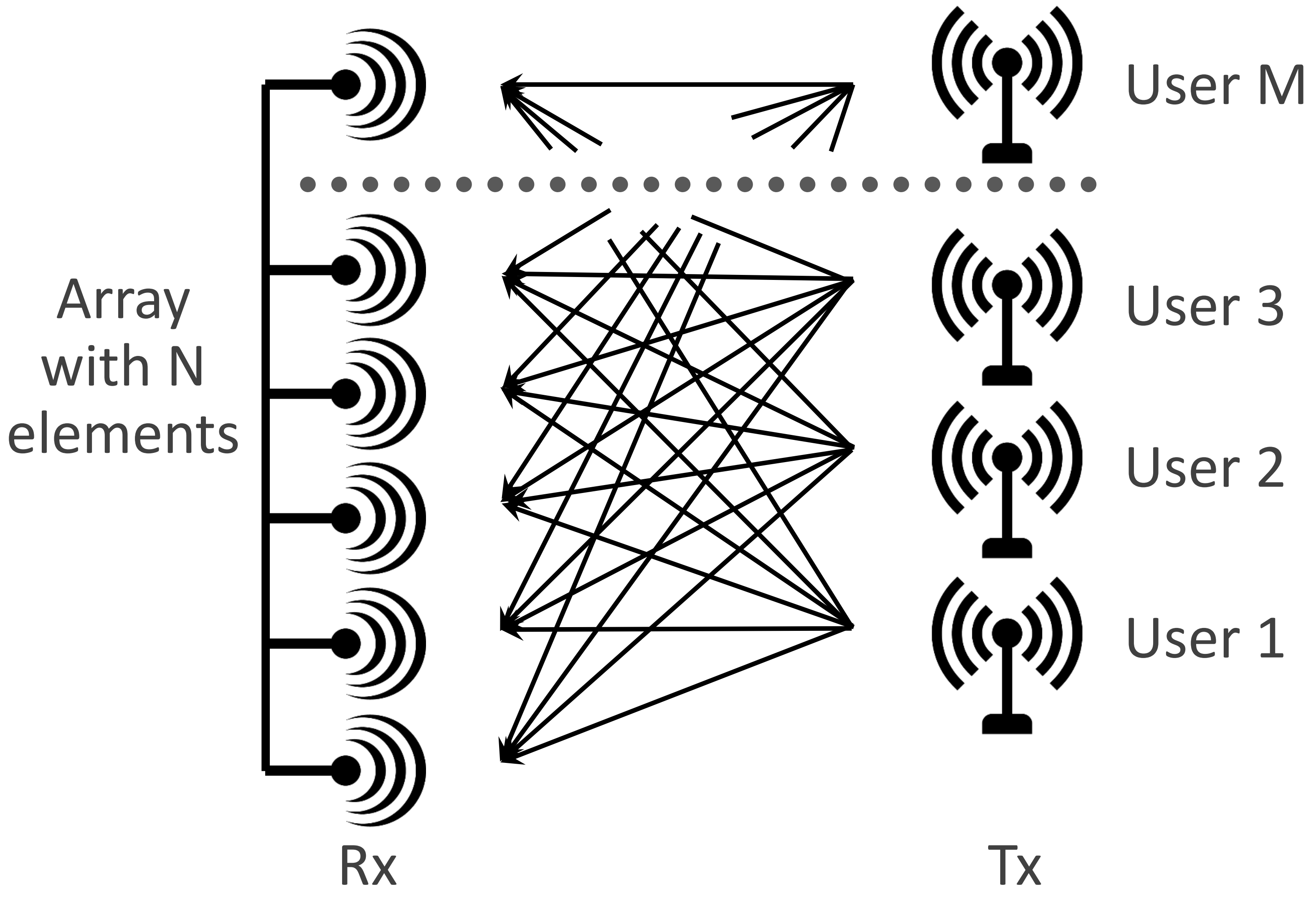
SISO – Single Input Single Output

MIMO – Multiple Input Multiple Output

2x2 MIMO

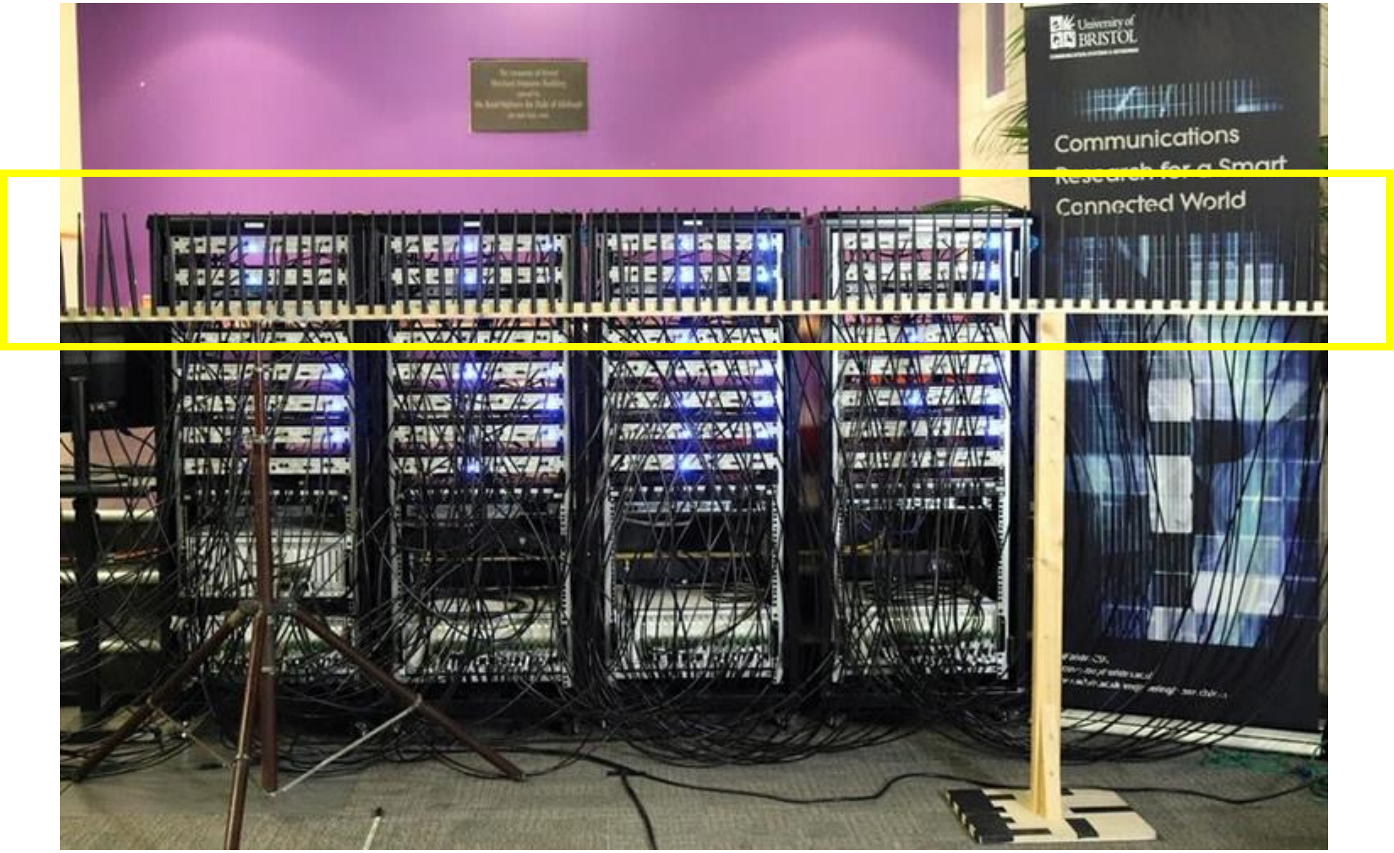
4x4 MIMO 8x2 MIMO 8x8 MIMO

What is massive MIMO and big antenna arrays?

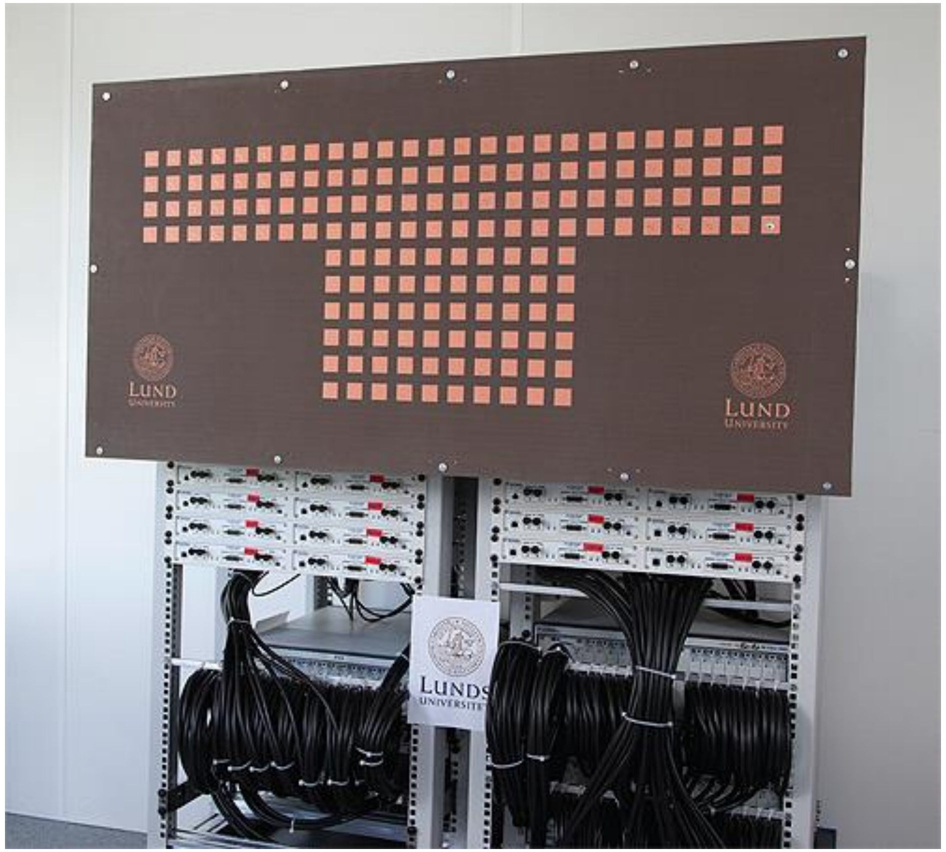


Massive MIMO when the system has a really big amount of Users and a big antenna array.

Existing massive MIMO prototypes

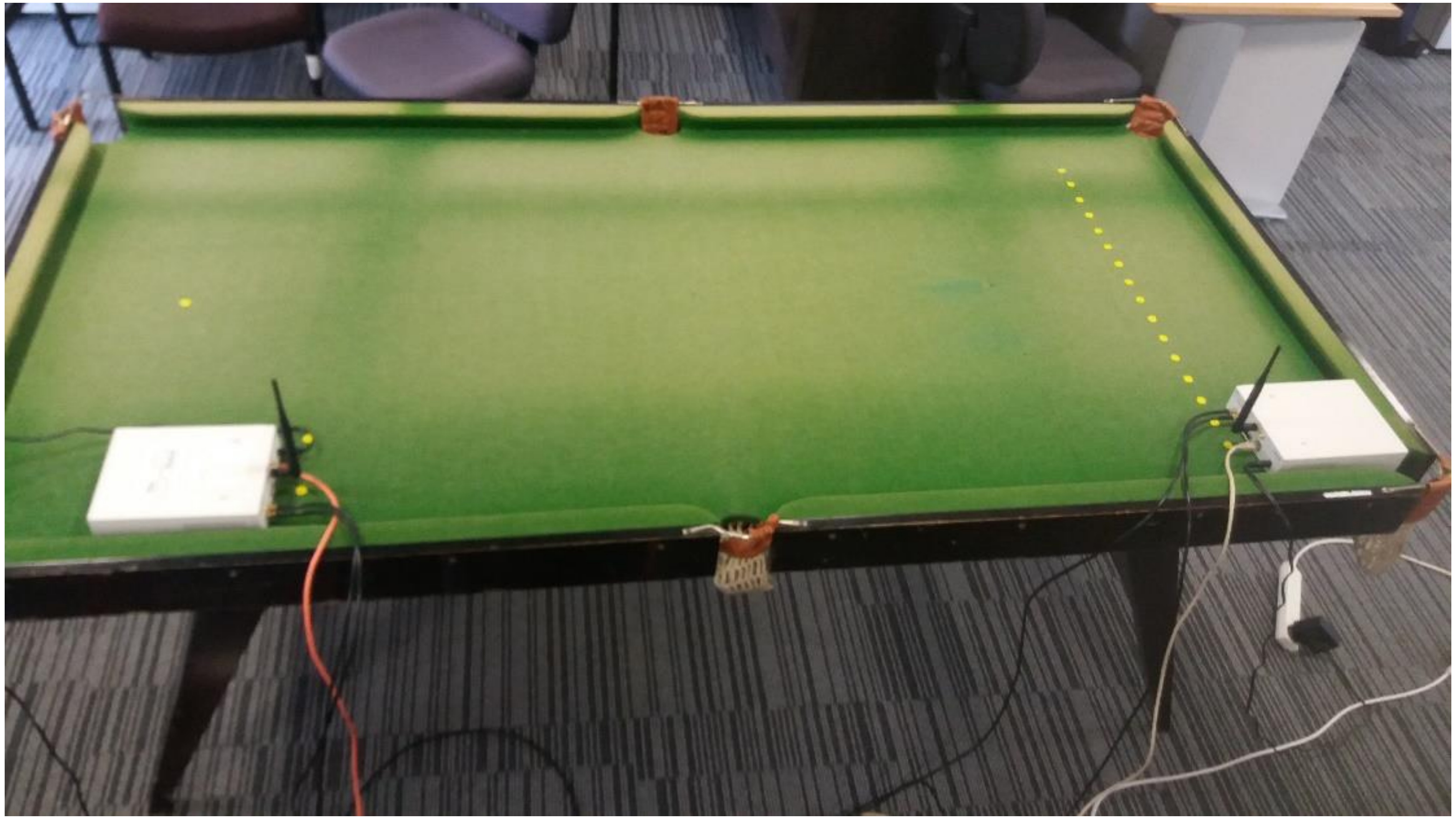


University of Bristol (England)



Lund University (Sweden)

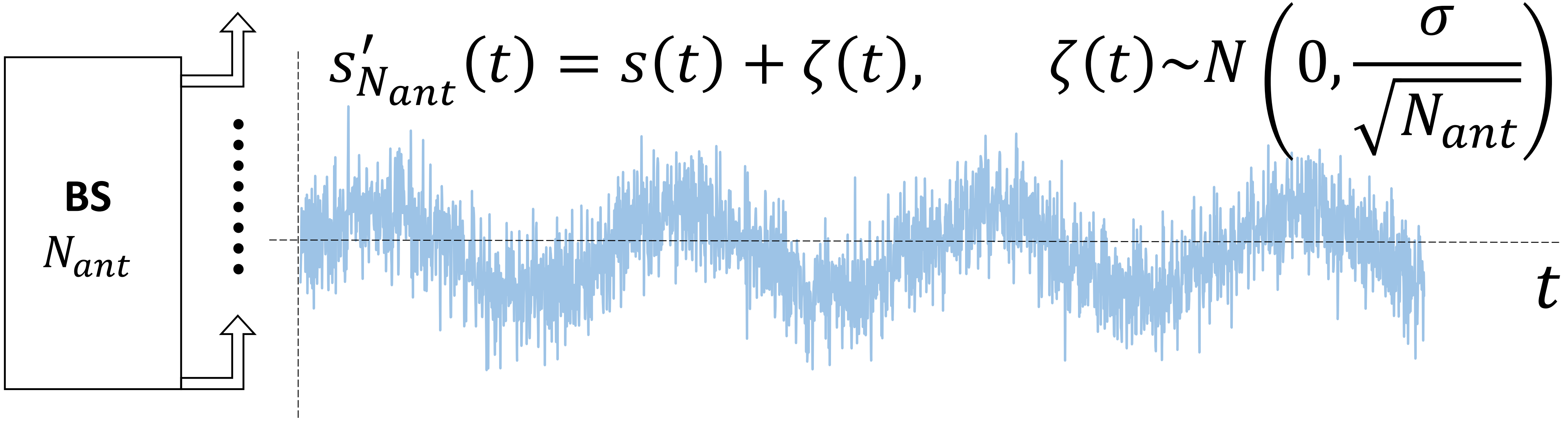
Massive MIMO prototype in Otago University



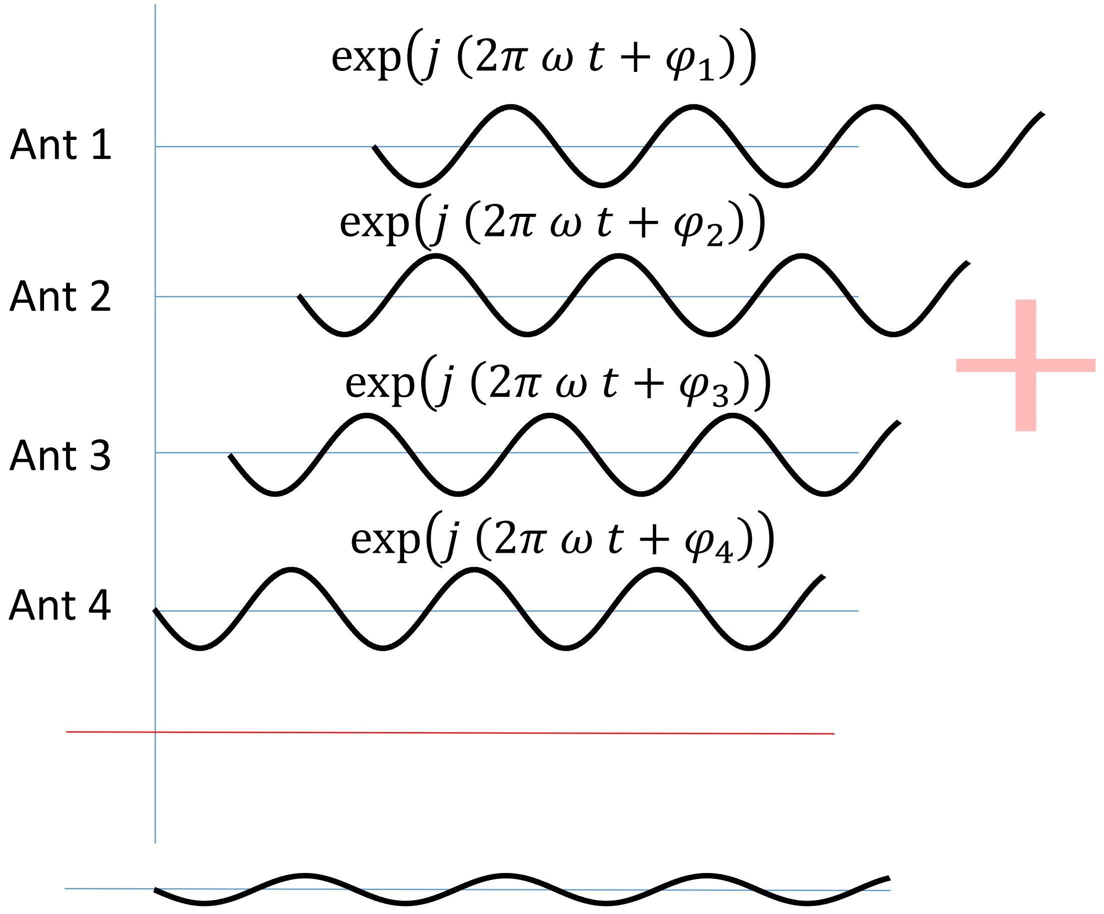
University of Otago (New Zealand)

Benefits of Massive MIMO

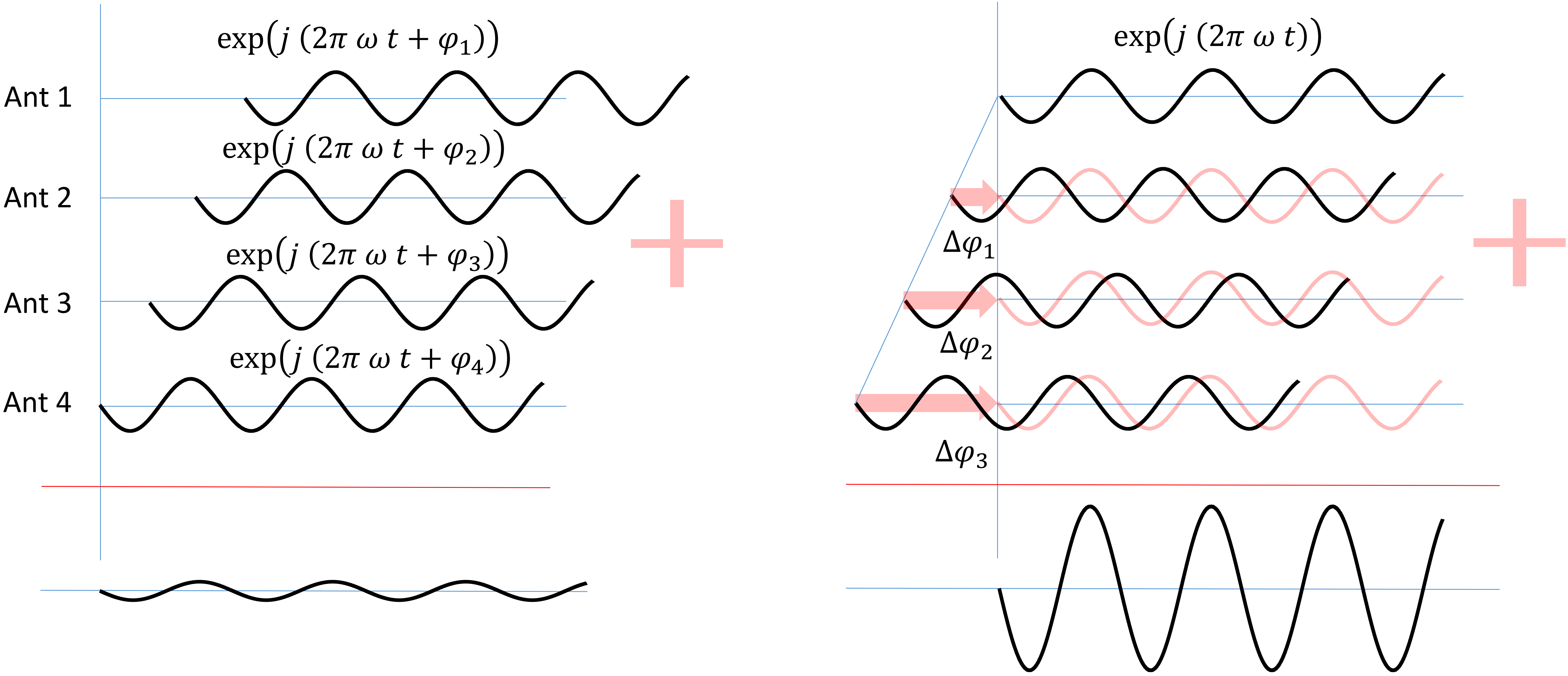
$$s'_{N_{ant}}(t) = s(t) + \zeta(t), \qquad \zeta(t) \sim N\left(0, \frac{\sigma}{\sqrt{N_{ant}}}\right)$$



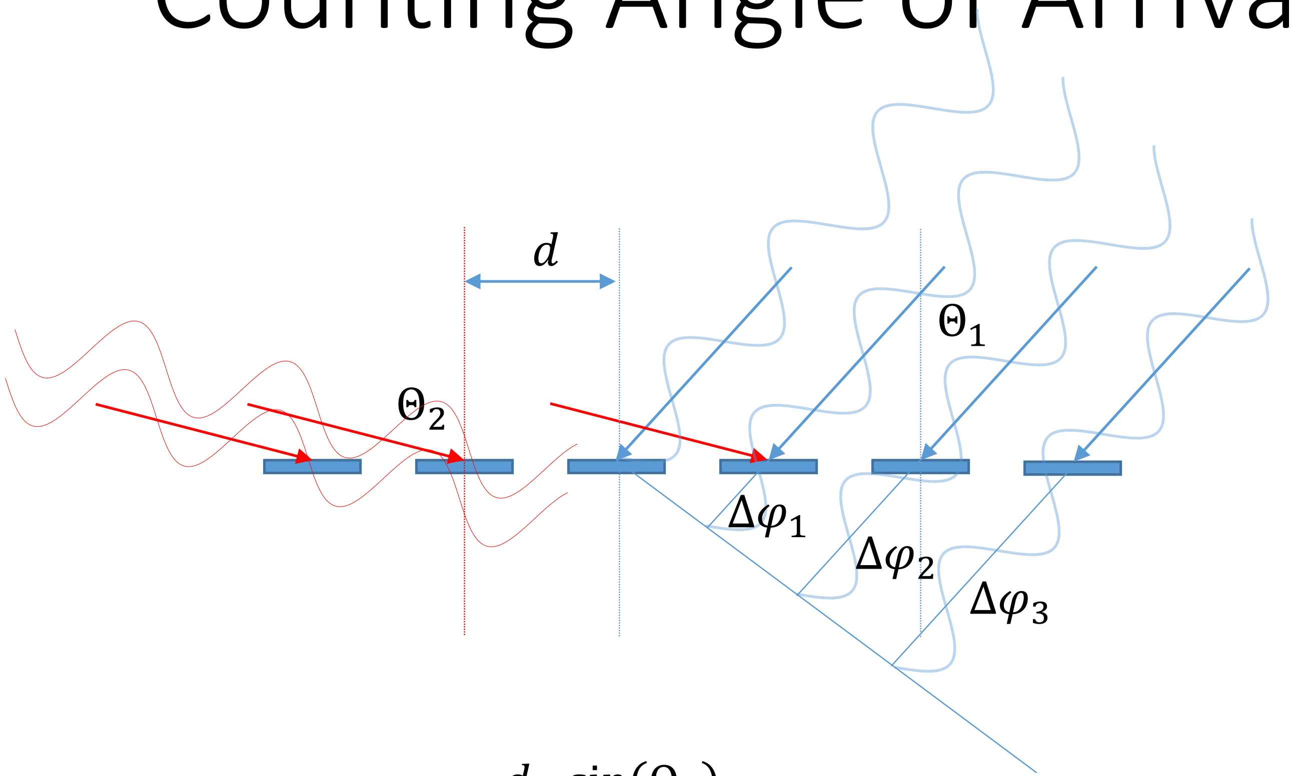
Coherent reception by all antennas



Coherent reception by all antennas



Counting Angle of Arrival



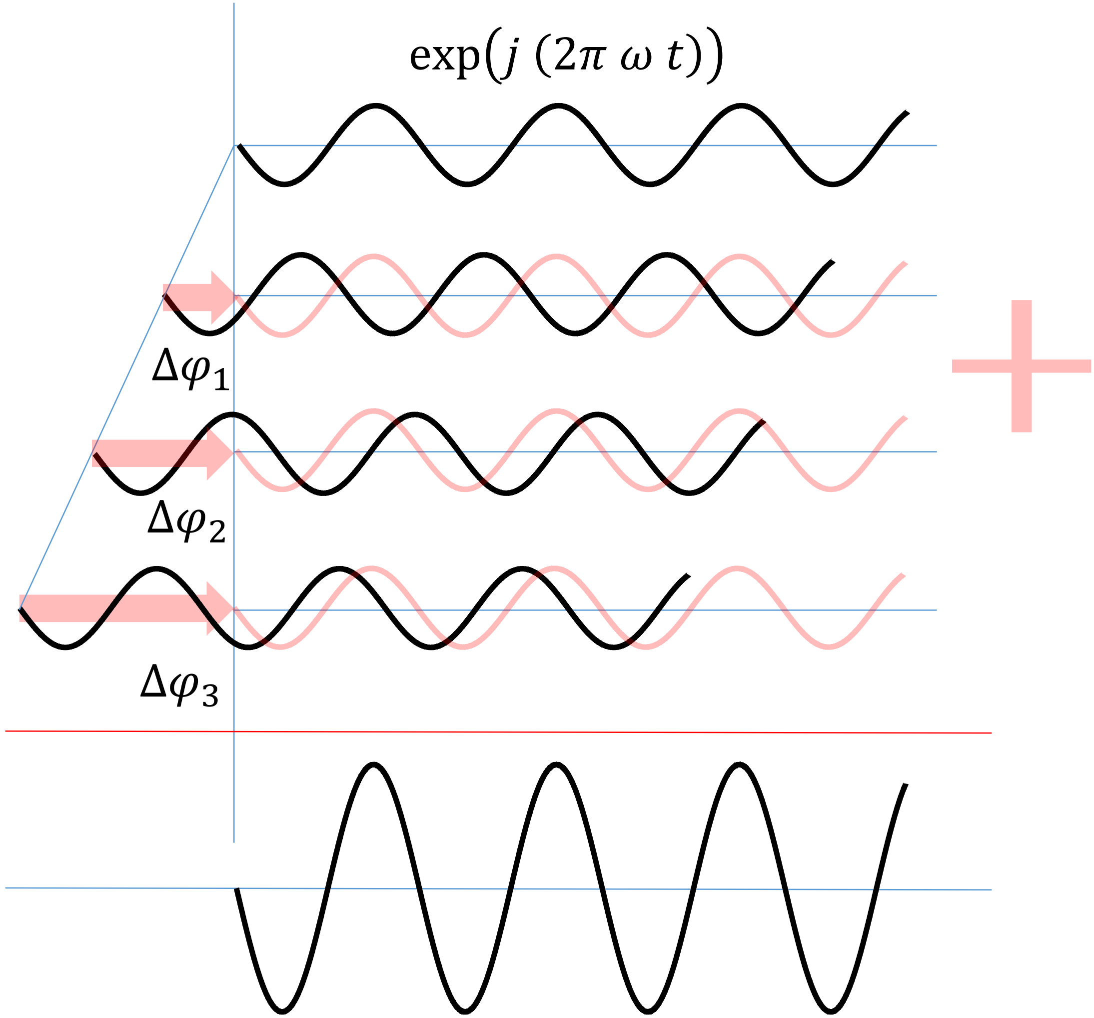
$$\Delta t_1 = \frac{d \cdot \sin(\Theta_1)}{c}$$

$$\Delta\varphi_1 = \Delta t_1 \cdot \omega$$

$$\Delta\varphi_2 = 2\,\Delta\varphi_1$$

$$\vdots$$

$$\Delta\varphi_N = (N-1)\,\Delta\varphi_1$$



Outline

- History of mobile communication
- Physical aspects of radio signals
- Introduction to LTE/4G
- Massive MIMO approach
- **What we do**

What we do

We increase throughput and quality of connection

What we do

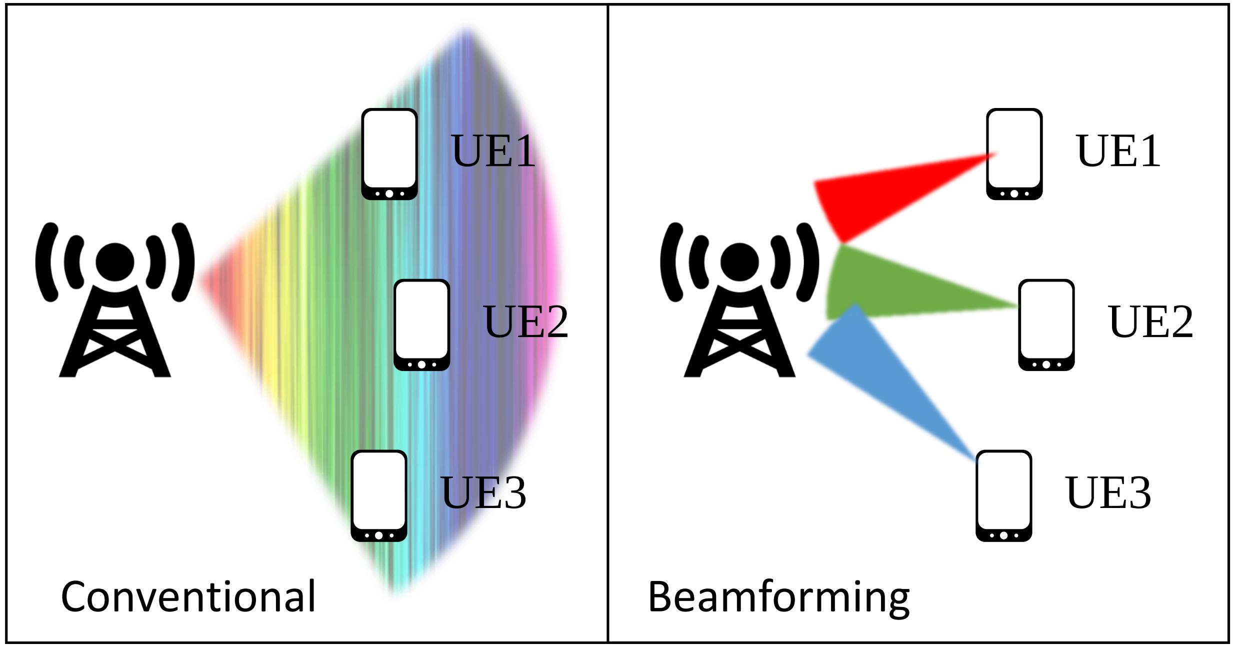
We increase throughput and quality of connection

→ Beamforming

What we do

We increase throughput and quality of connection

Beamforming



Advantages:

1. Increase the signal's power
2. Reduce users interference
3. Radio resource reuse

What we do

We increase throughput and quality of connection

→ Beamforming

→ Localization

What we do

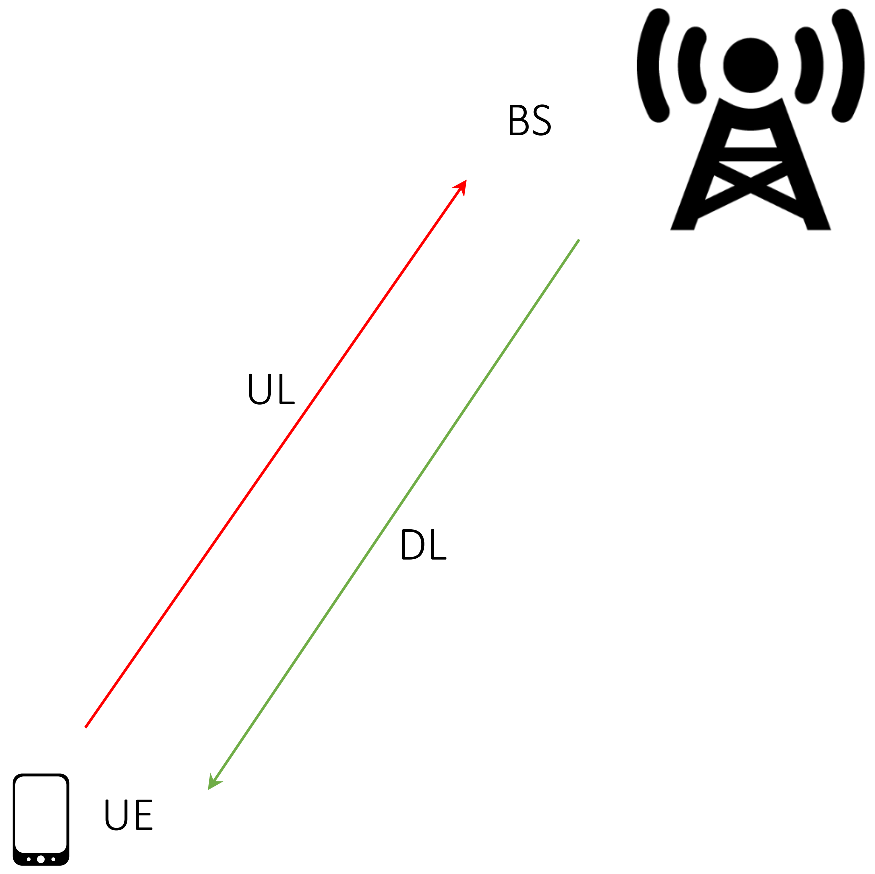
We increase throughput and quality of connection

Beamforming

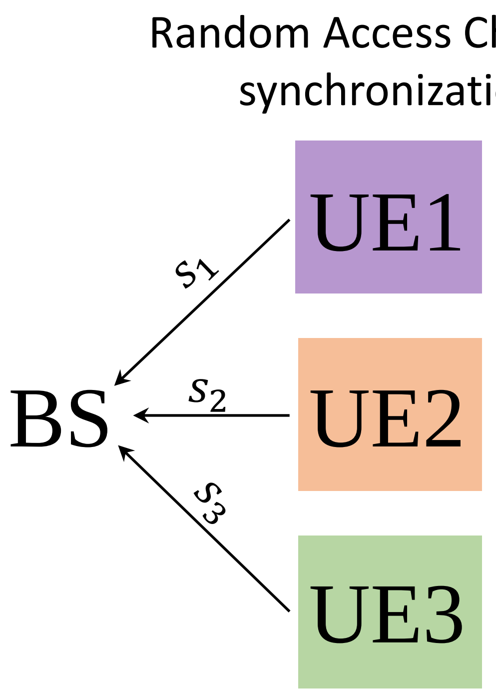
Localization

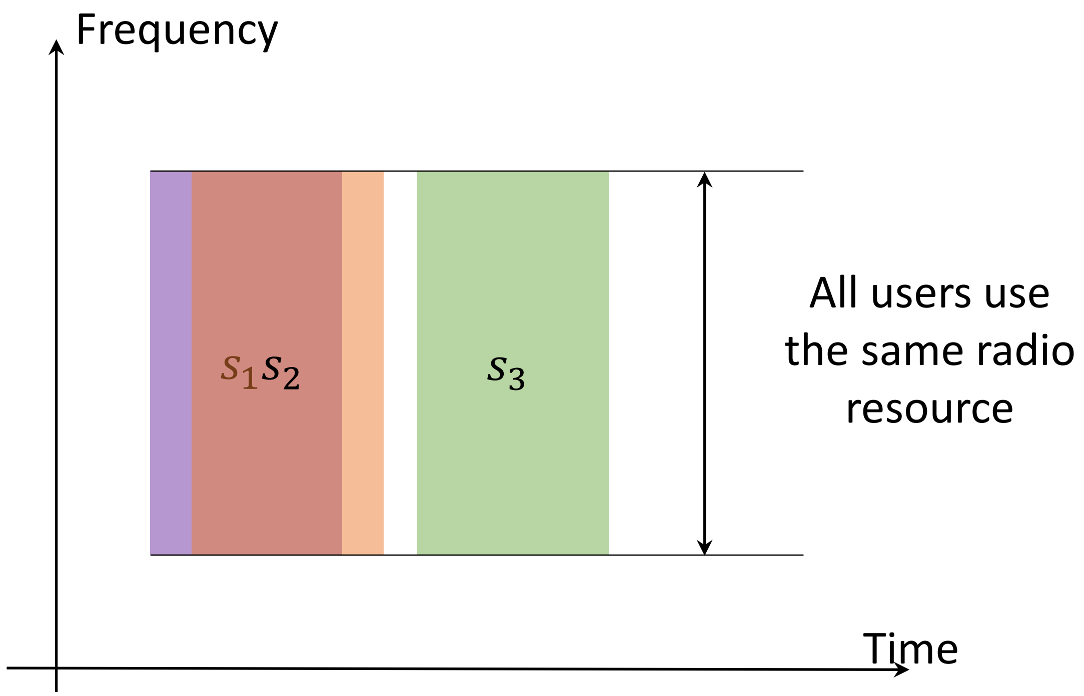
It is challenging task in radio spectrum,
while obvious in visible light spectrum

Theory behind Users localization



Connection to a network



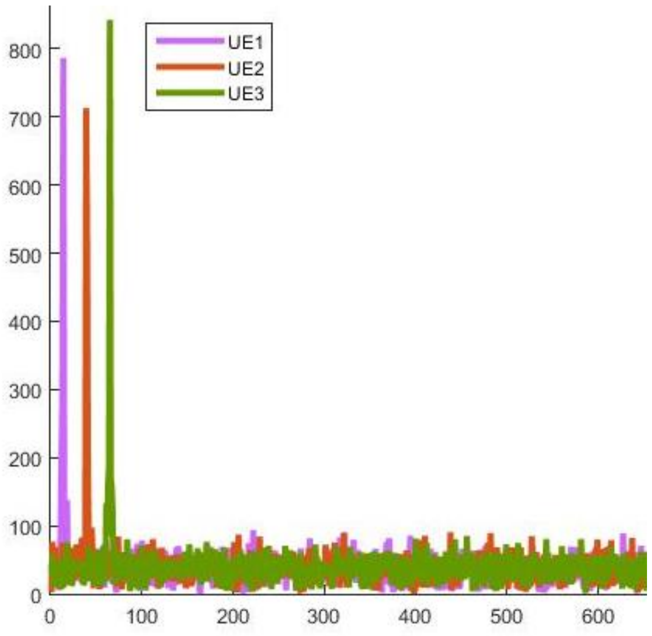


We want to localize users during the connection setup phase as this is going to be used for beam generation.

$$s_{BS} = s_1 + s_2 + s_3 + noise$$

Distinguishing of the users

The BS perception



Absolute values of the convolutions

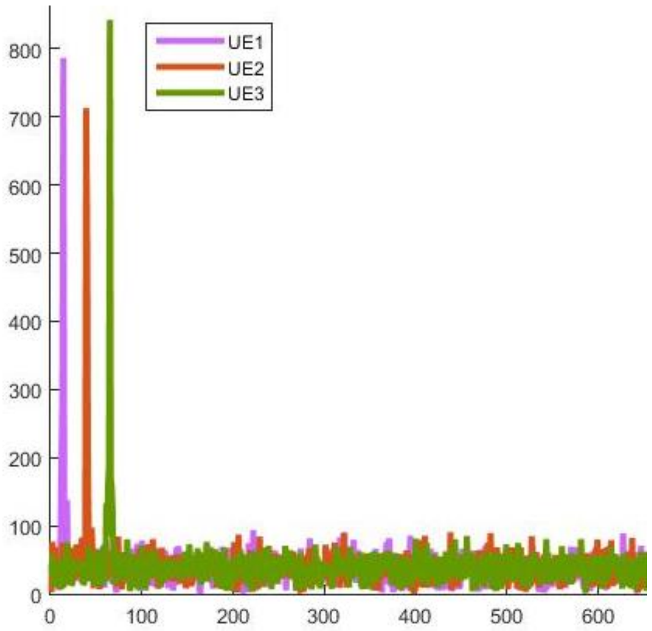
$$s_1 * s_{BS} = s_1 * s_1 + 0 + 0 + r_1$$

$$s_2 * s_{BS} = 0 + s_2 * s_2 + 0 + r_2$$

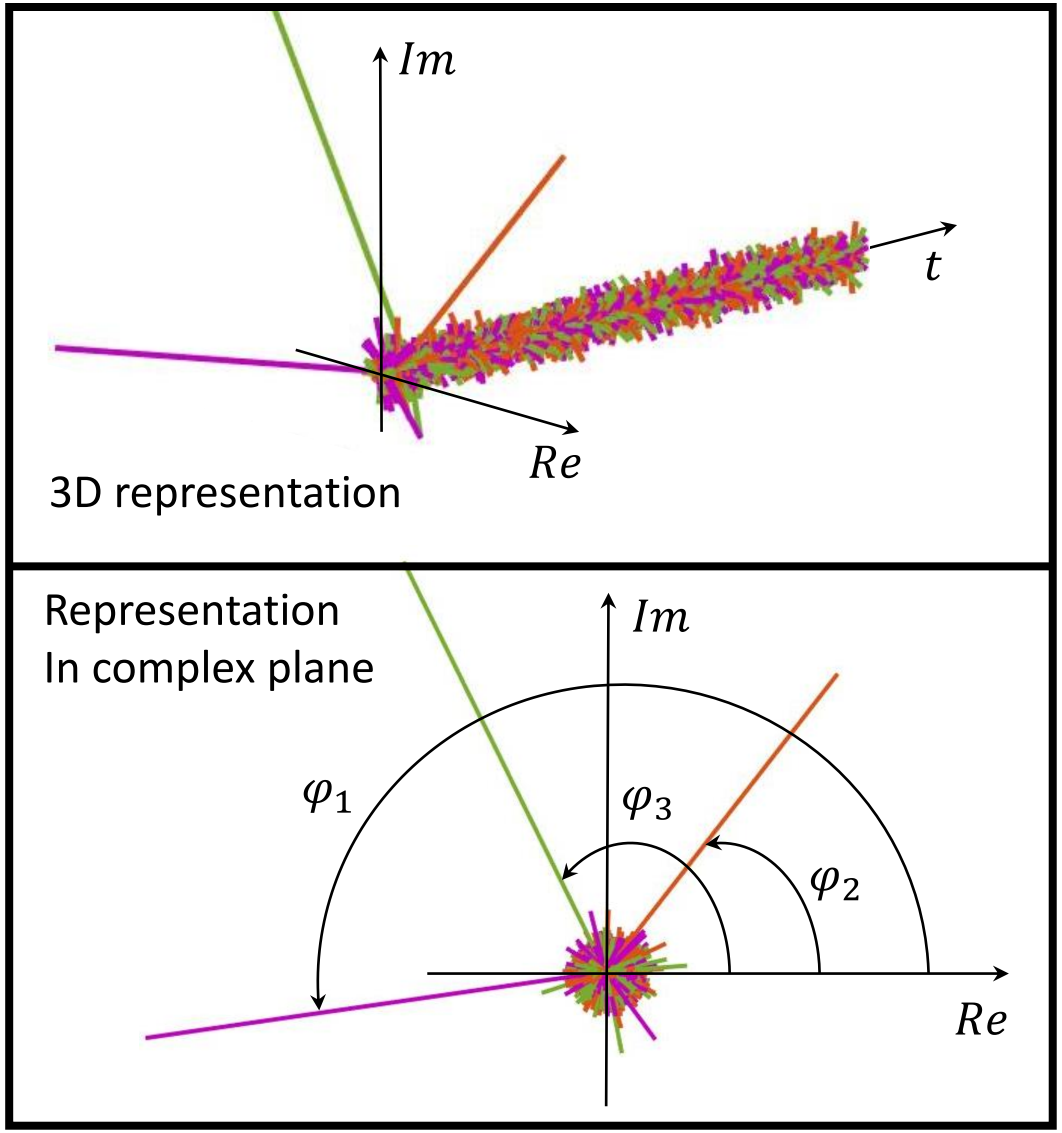
$$s_3 * s_{BS} = 0 + 0 + s_3 * s_3 + r_3$$

Convolution in the complex plane

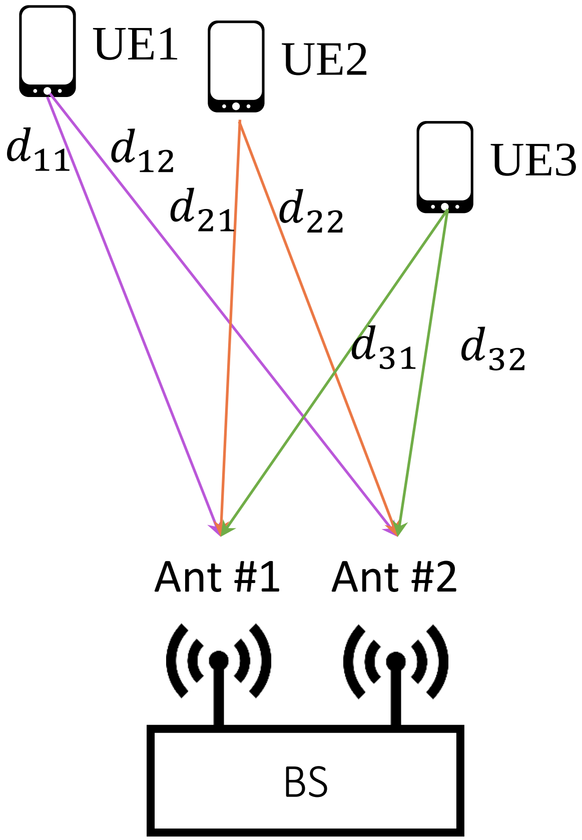
The BS perception



Absolute values of the convolutions

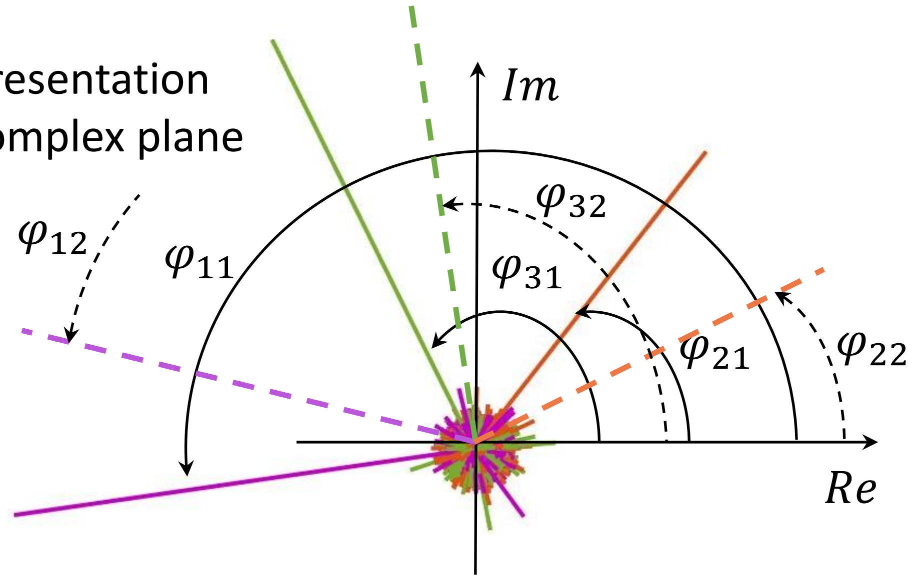


Convolutions’ spike for neighboring antennas



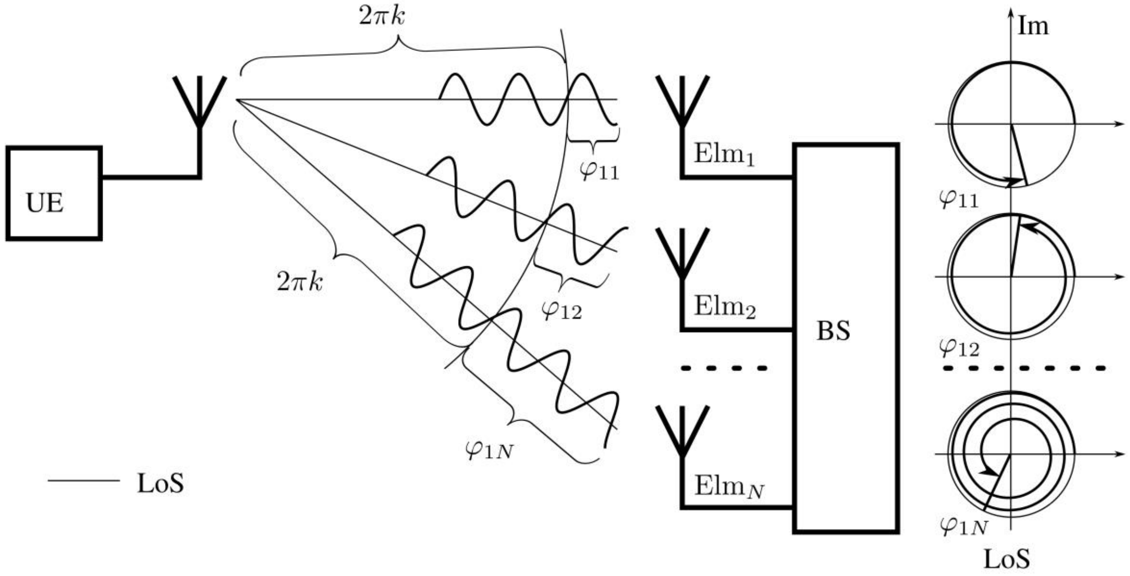
The distance between antennas less than the half of wavelength $\lambda/2$

Representation In complex plane

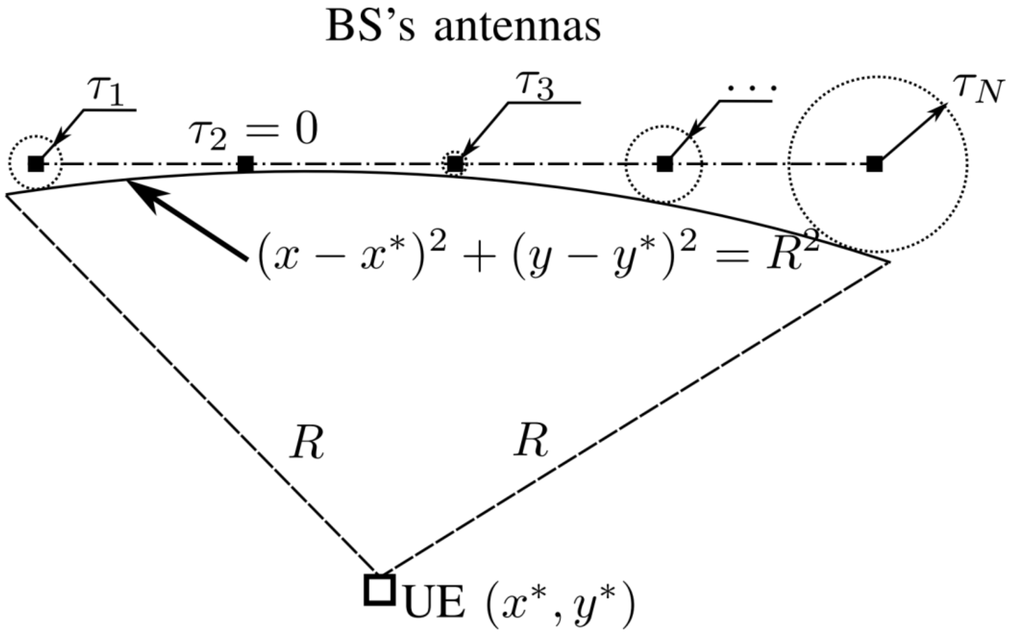


$$\varphi_{ij} = f(\omega, d_{ij})$$

Implementation of the idea

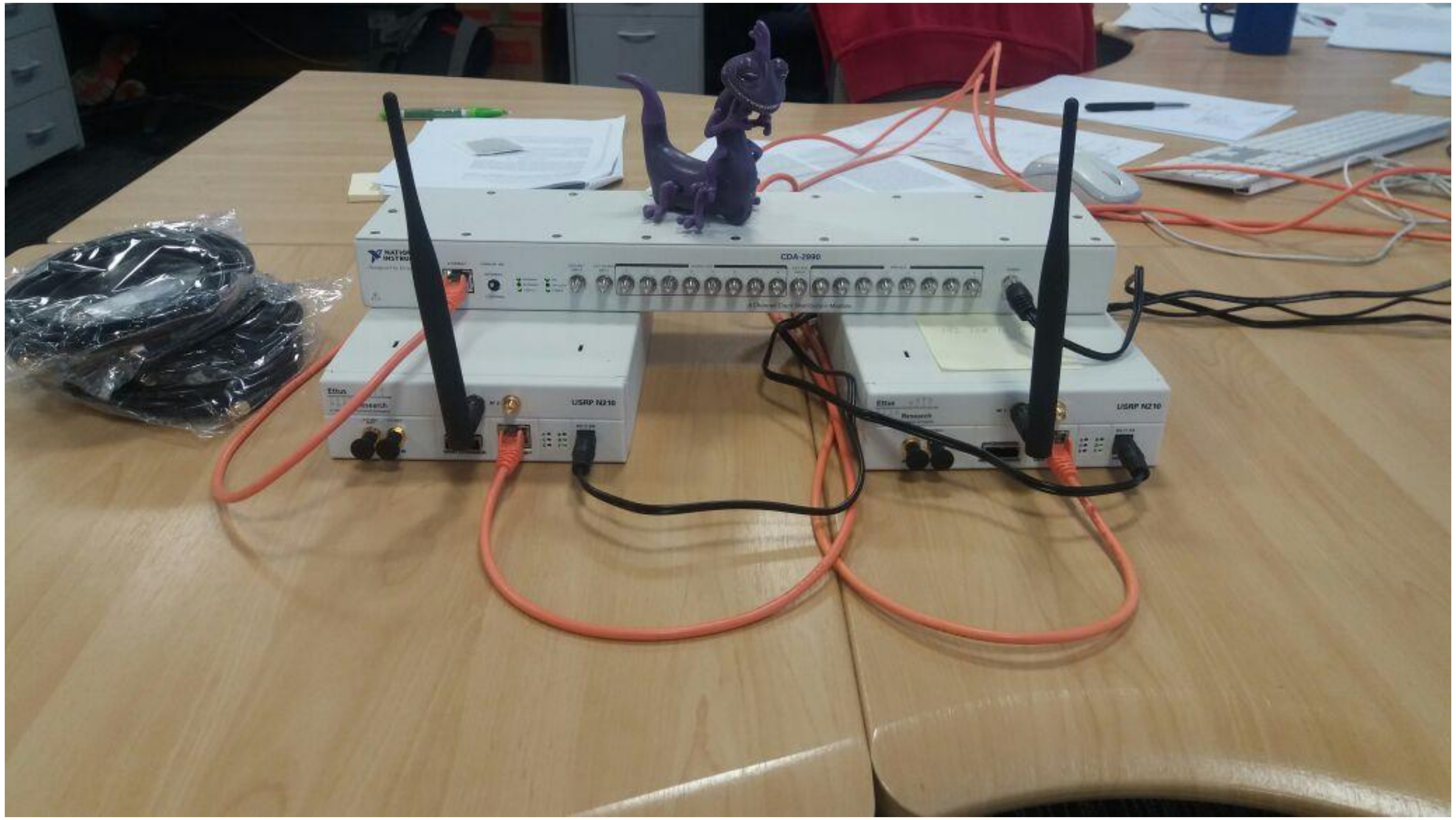


Phase measurements



User localization

10 kNZD experiment hardware



Two USRPs N210, one Octoclock, two antennas and 2 SMA cables

Having only one antenna,

how to increase the number of antenna

elements in the receiving side?

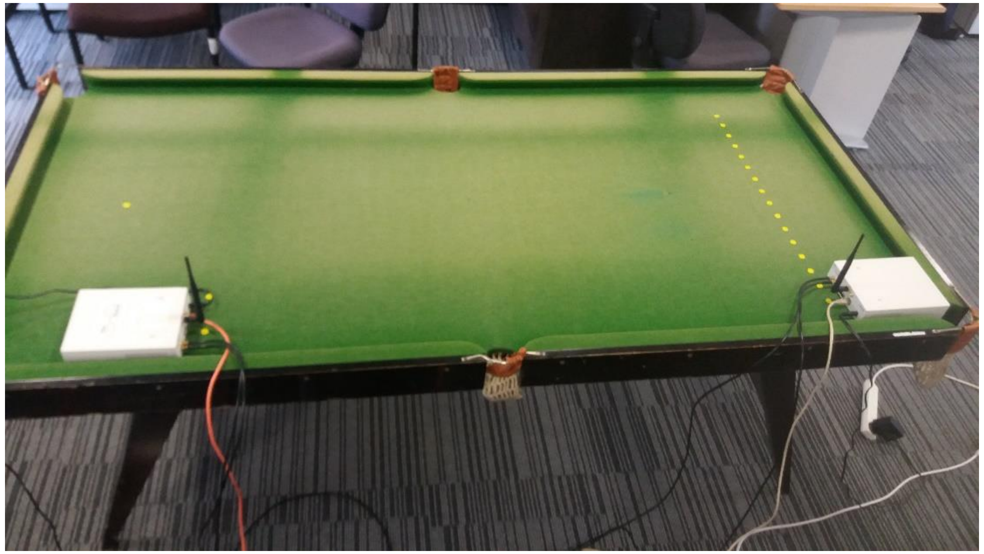
Having only one antenna,

how to increase the number of antenna elements in the receiving side?

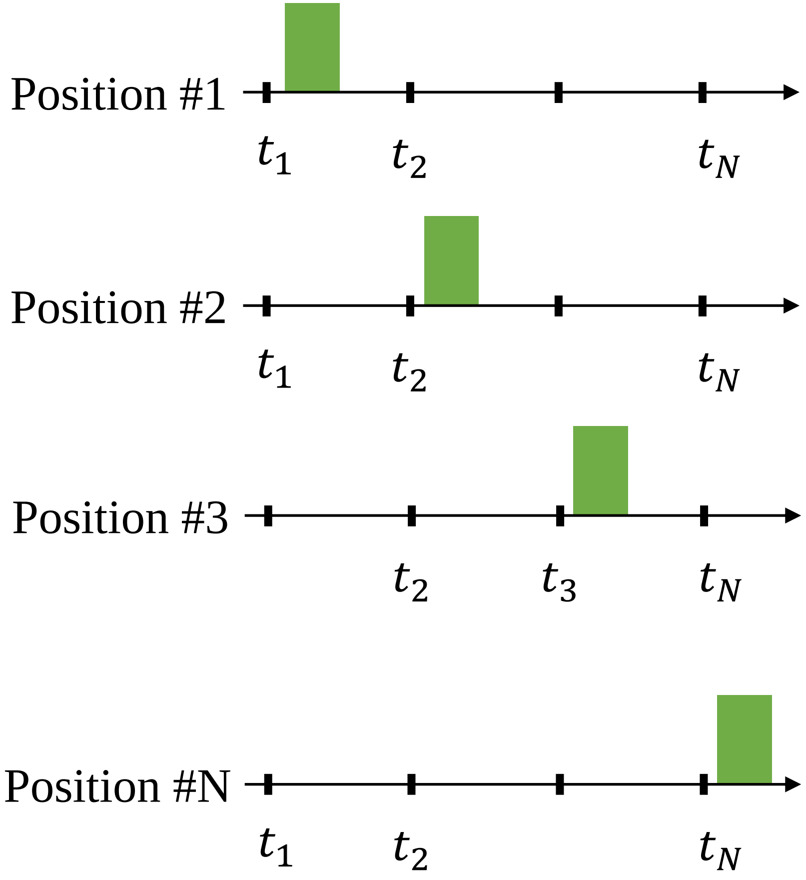
Realize timing is the key (BMW)

Realize timing is the key (BMW)

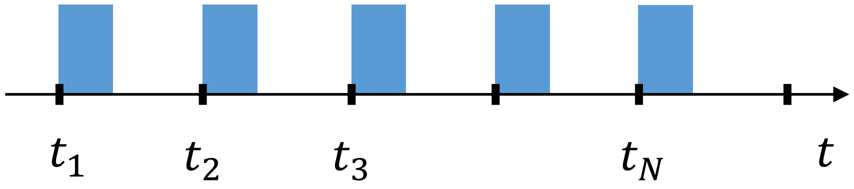
Time alignment



Receiver is recording at exact time

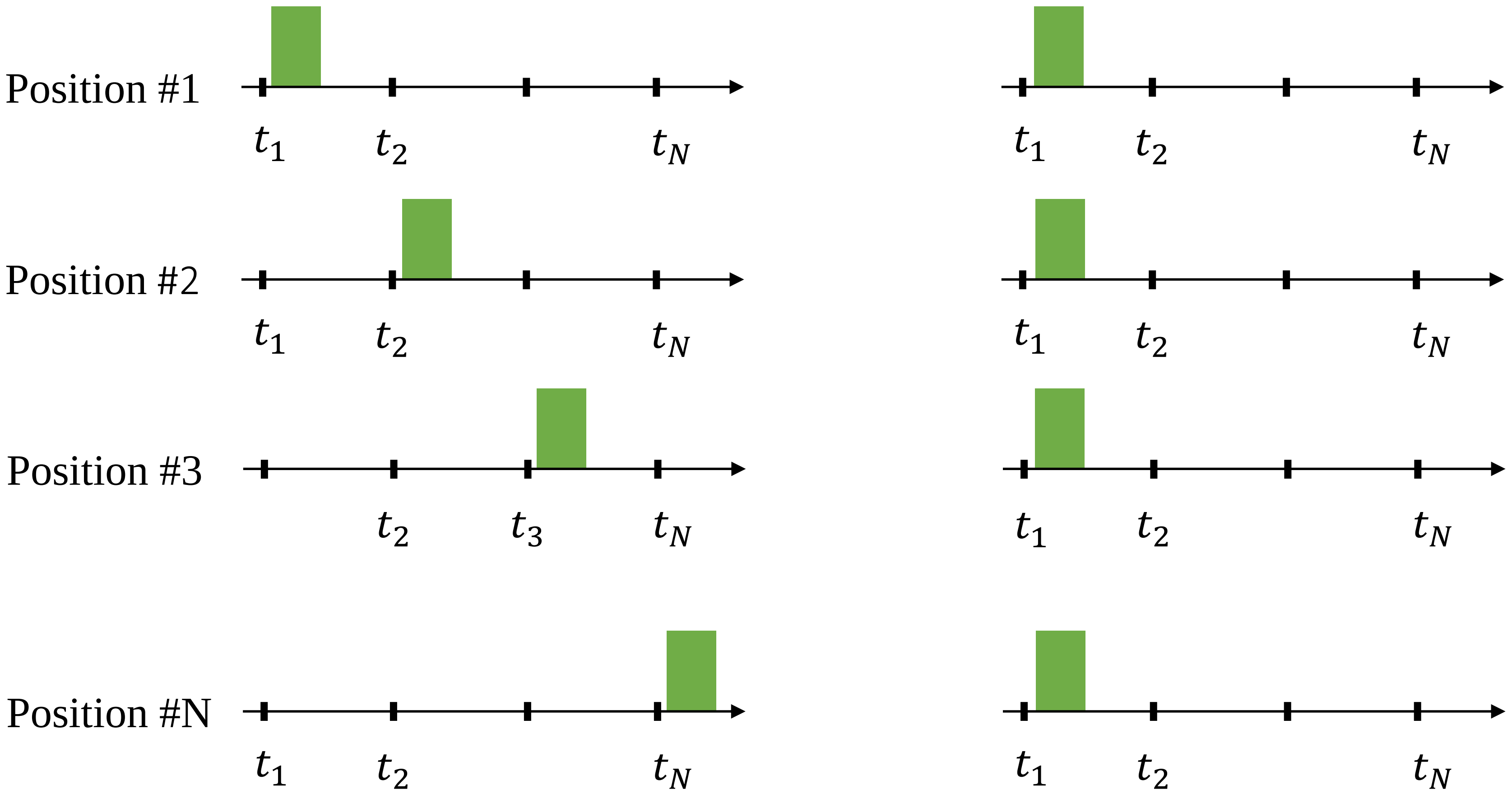


Transmitter is periodically sending a signal



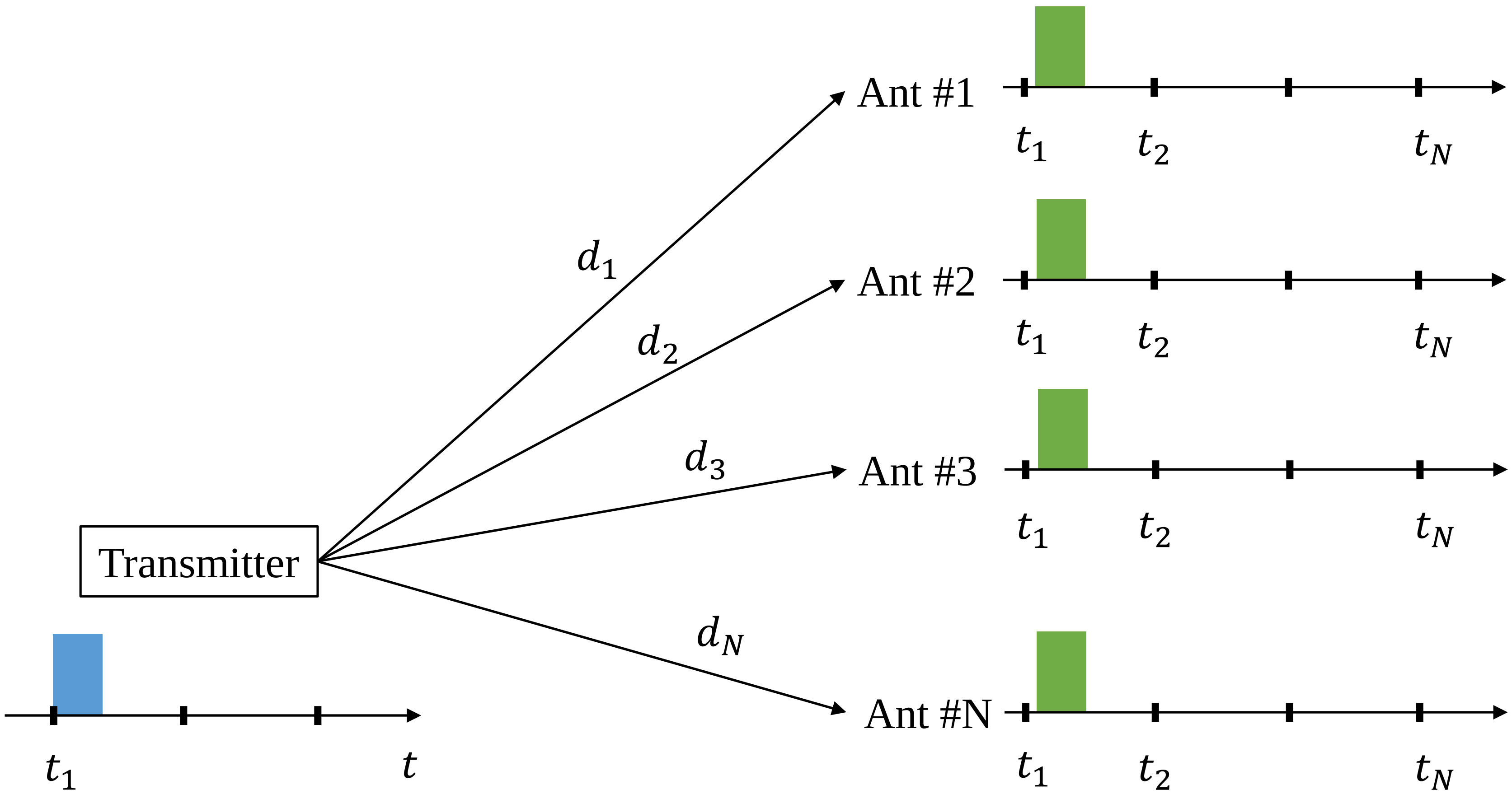
Time alignment

The precise knowledge of time allows us to align the received signals to the start point

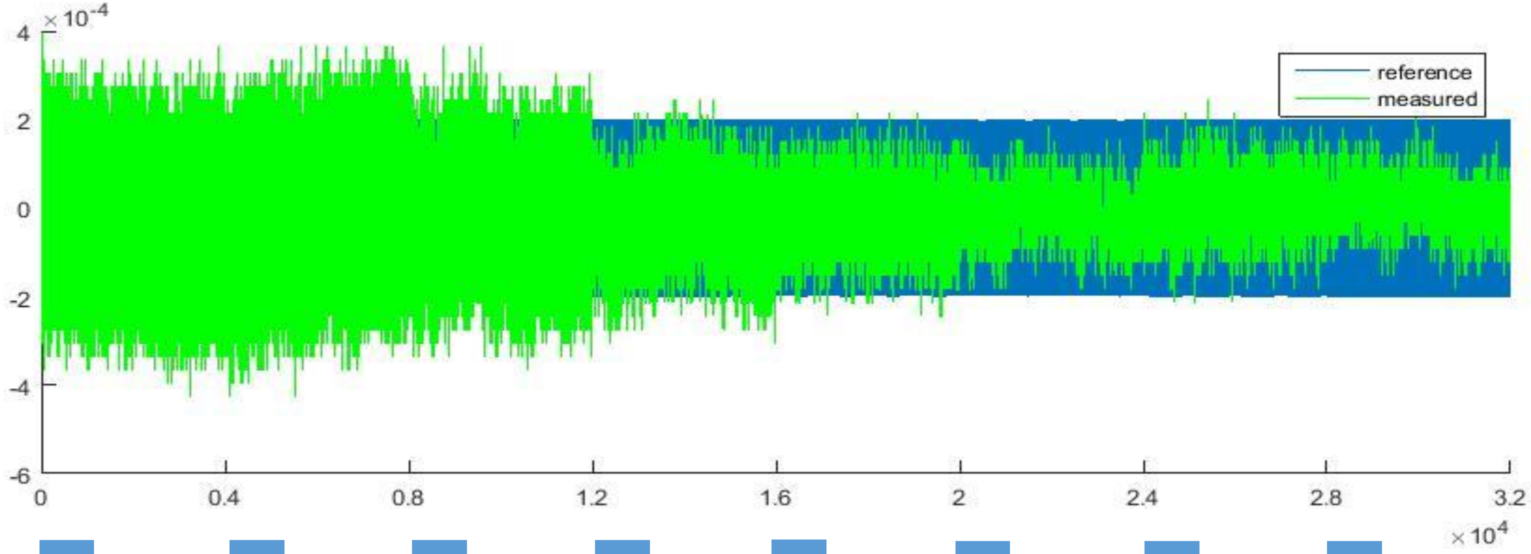


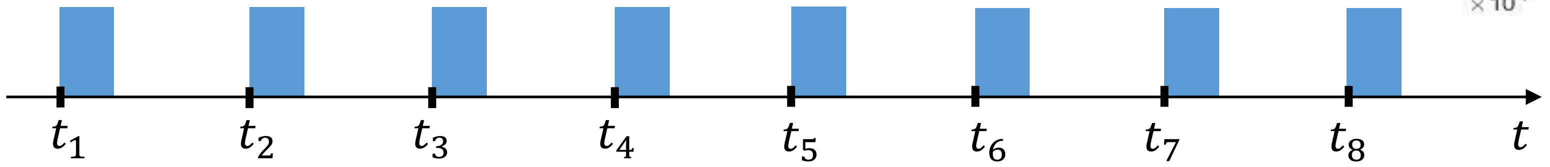
Time alignment

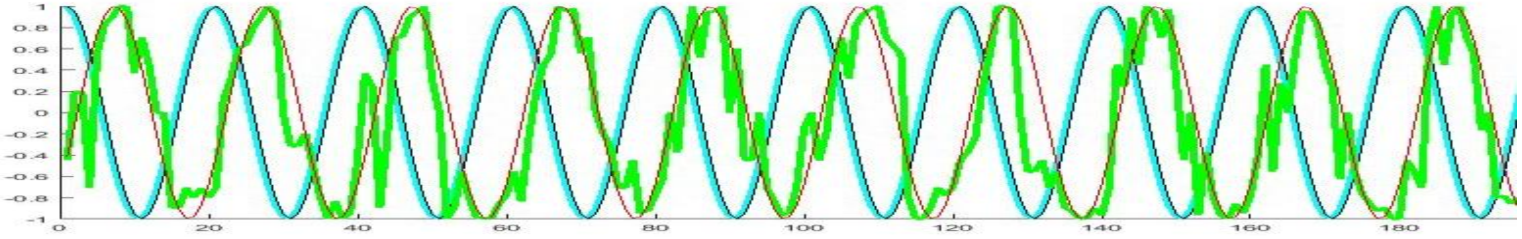
The precise knowledge of time allows us to align the received signals to the start point



Real experiments using 1 antenna







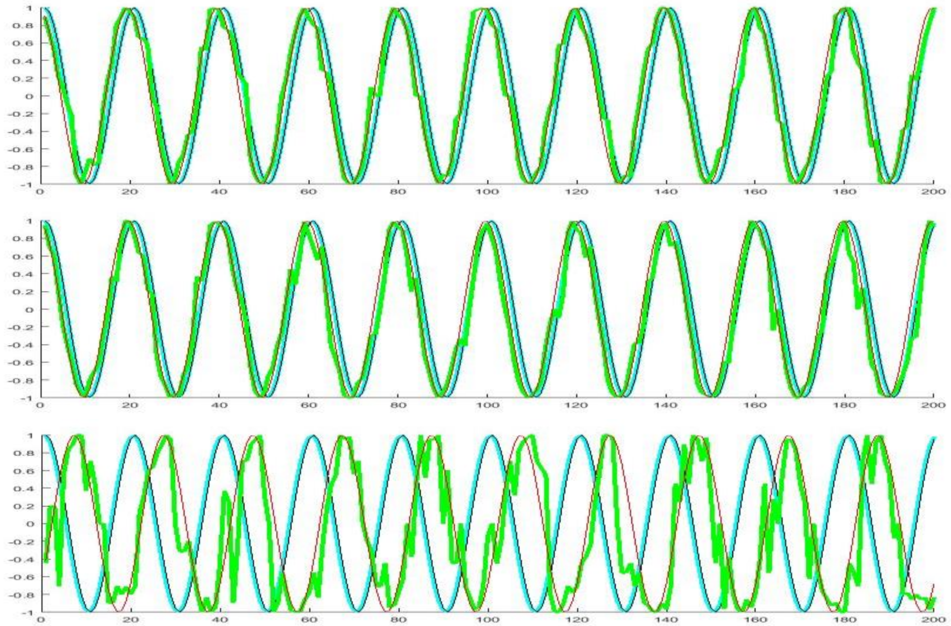
Digital cosine function, which is sent at the exact moments

Real experiments using 1 antenna

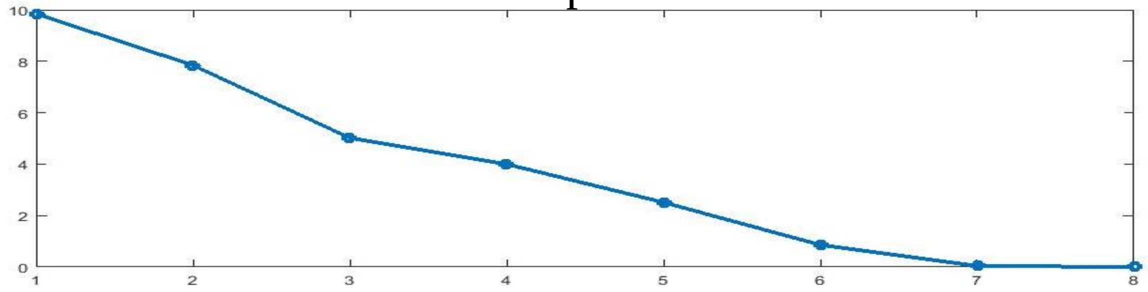
Ant #1

Ant #2

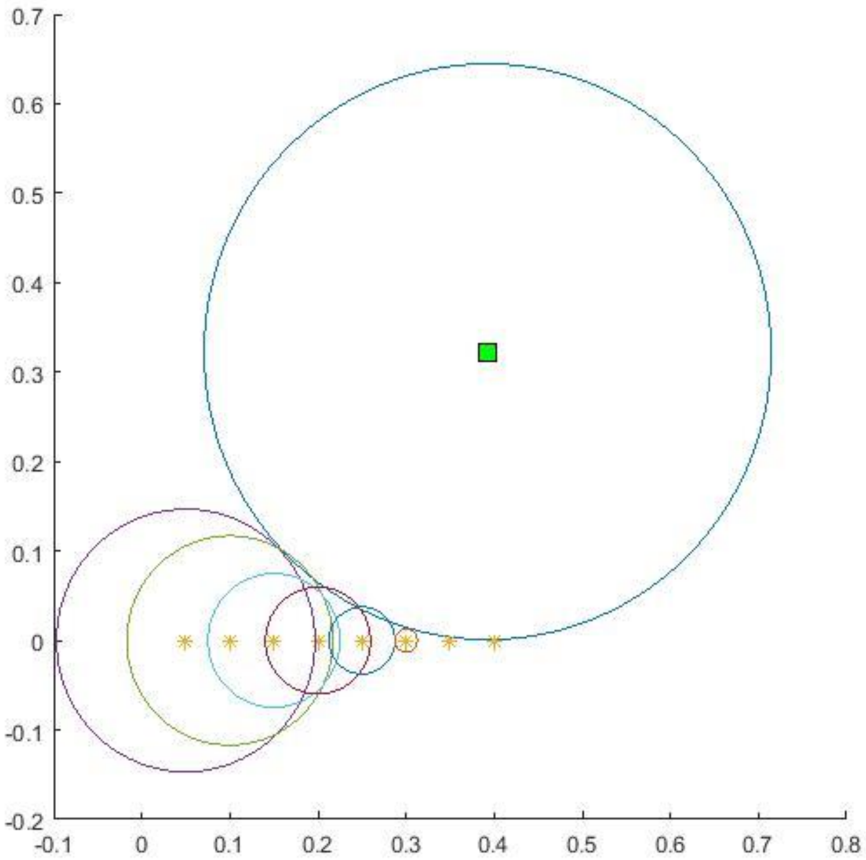
Ant #3

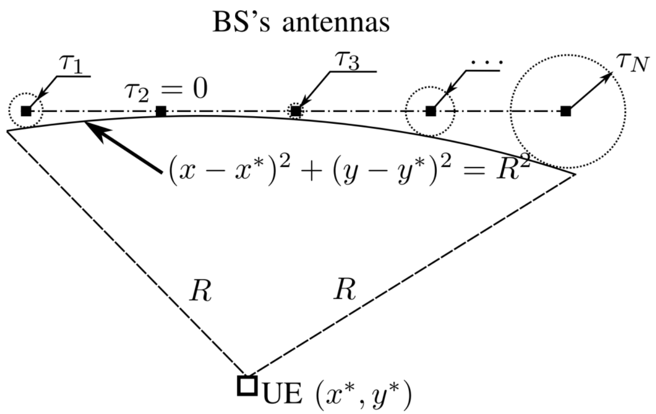


Calculated phase shifts



Localization in a real environments

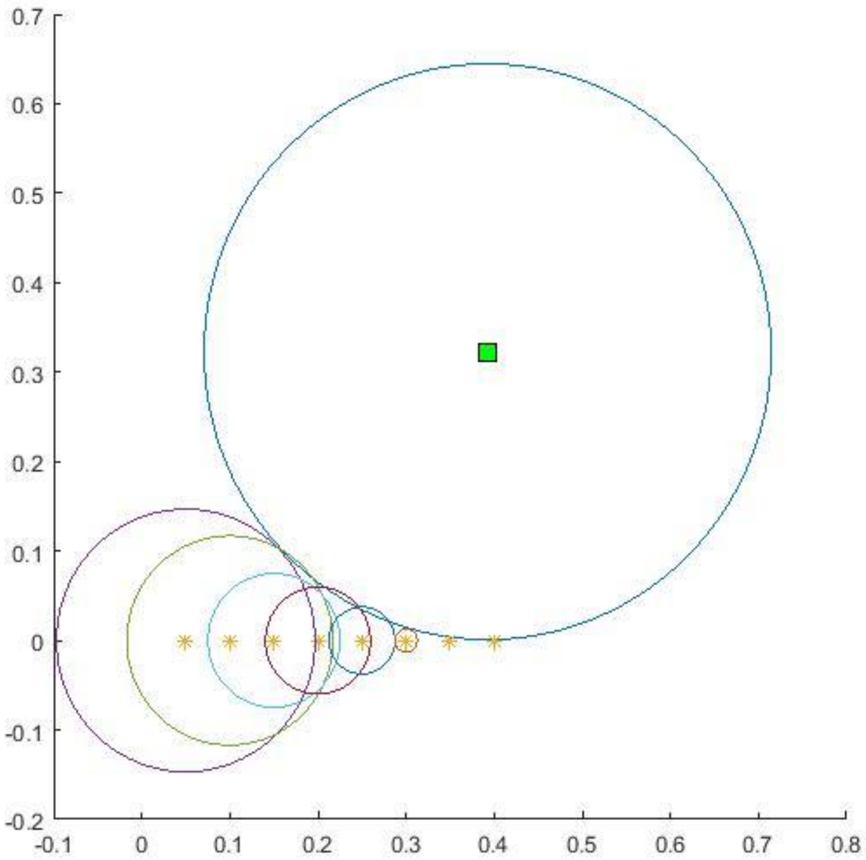




The same algorithm as for simulation.

For single user mode,
the accuracy around 7 cm without calibration and implementing advanced signal processing algorithms.

Localization in a real environments



Thank you