Multidimensional Channel Measurement Techniques

June 6, 2008
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Outline

1. Introduction
2. Basic channel measurement techniques
3. Multidimensional measurements
4. UWB and mm-wave measurements
5. References

1. Introduction

TKK

Introduction 1

- **Exact calculation of the field is practically impossible**
  - Electromagnetic modelling of the normally unknown small features of the environment requires randomness (diffuse scattering) to be added
  - Computer resources are limited
- **Pathloss prediction can be done well by ray tracing (etc.) especially in outdoor environments**
- **Delay dispersion is more difficult to calculate**
  - Diffuse components may improve the result
- **Directional calculation including polarization, accuracy of MIMO capacity ...**

  ⇒ measurements are needed to develop models for radio link and system simulation

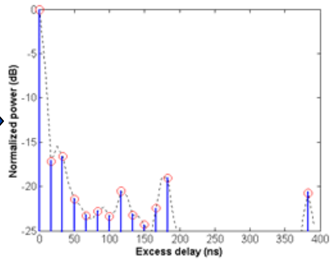
  ⇒ measurements are needed in antenna development, especially for MIMO

  ⇒ measurements give information about the propagation physics, e.g. significance of scattering and diffraction

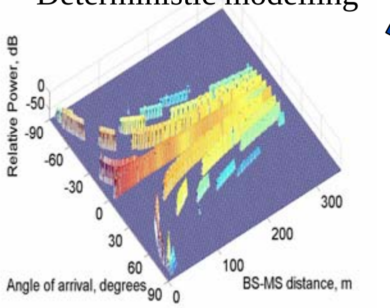
Propagation channel research process

Propagation measurements and directional analysis

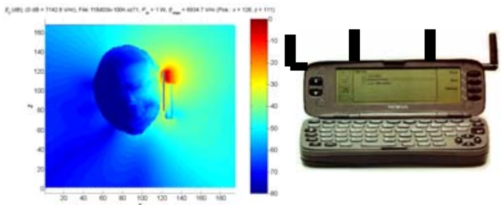
Parametric modelling



Deterministic modelling



Antenna design and evaluation



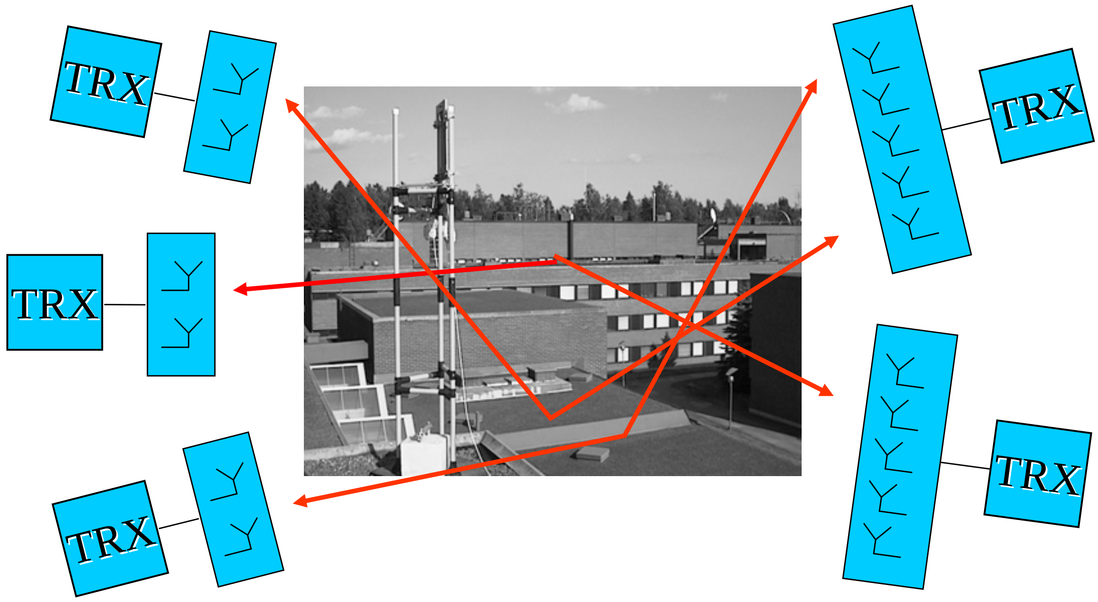
Radio interface research
- link capacity
- MIMO algorithms
- etc.

Radio system research
- interference
- multiuser MIMO
- etc.

Introduction 2

- **Propagation data is needed mainly for two purposes:**
  1. Propagation research
  2. System analysis: prediction of performance, selection of system options
     - Radio interface or parts of it like the antenna system
     - Network planning and optimization
     - Development of propagation models
- **In system analysis, the number of channel parameters should be limited to minimum, because the amount of data or complexity of models forms a problem for the efficiency of the analysis**
  - (Complex) gain
  - Broadband systems: delay of frequency domain data according to the system bandwidth requirements
  - Multi-antenna systems: (double-)directional data
  - Dual-polarized systems: polarimetric data
- **System scenarios and define the measurement environments and configurations:**
  - Indoor, outdoor-indoor, outdoor micro- and macrocellular, urban, rural, etc.

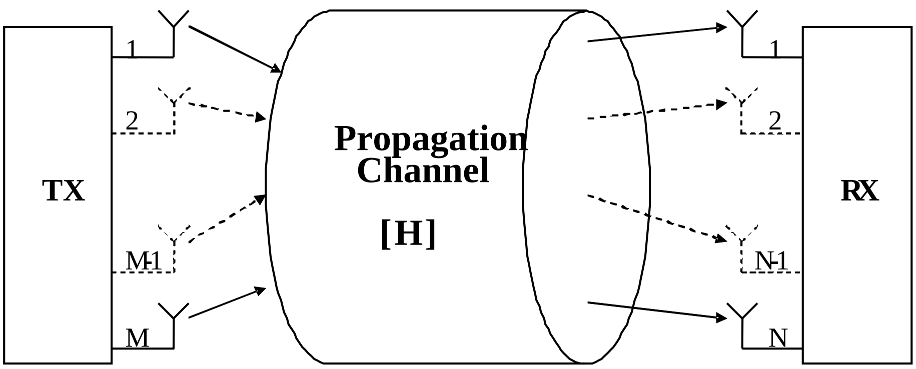
Multiuser MIMO mobile system



Mobile terminals

Base stations
Access points

MIMO antenna system



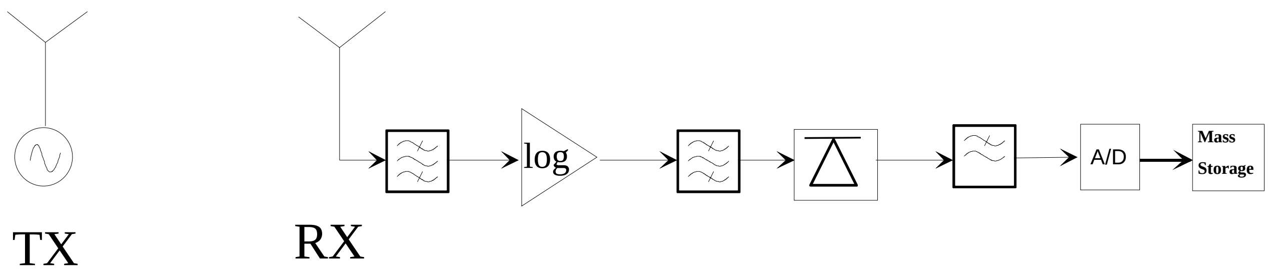
$$\mathbf{H} = \begin{bmatrix} \boldsymbol{h}_{11} & \boldsymbol{h}_{12} & \dots & \boldsymbol{h}_{1N} \\ \boldsymbol{h}_{21} & \boldsymbol{h}_{11} & \dots & \boldsymbol{h}_{2N} \\ \dots & \dots & \dots & \\ \boldsymbol{h}_{M1} & \boldsymbol{h}_{M1} & \dots & \boldsymbol{h}_{MN} \end{bmatrix}$$

$$\boldsymbol{C} = \log_2\left[\det\left(\mathbf{I} + \frac{\rho}{\boldsymbol{M}}\mathbf{HH}^*\right)\right] = \sum_{\min(\boldsymbol{M},\boldsymbol{N})} \log_2\left[1 + \lambda_i \frac{\rho}{\boldsymbol{M}}\right]$$

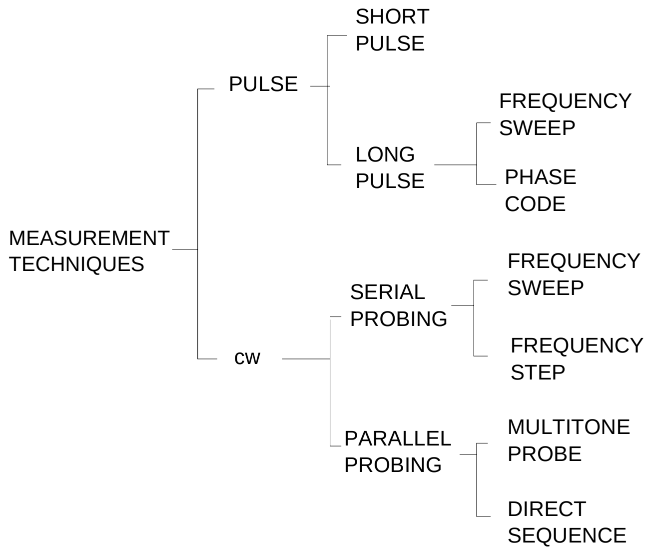
2. Basic channel measurement techniques

Measurement techniques: narrowband measurements

- Sine wave transmitter
- Envelope detector
- Envelope includes the large scale and small scale fading
- Phase measurement requires I and Q demodulation of the signal

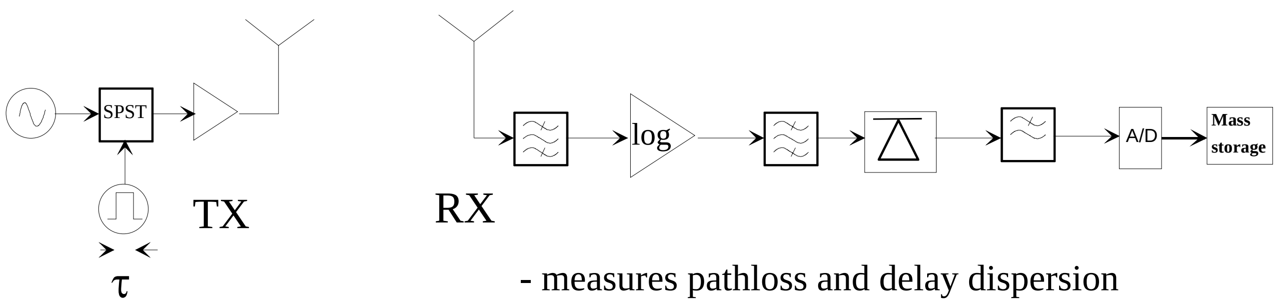


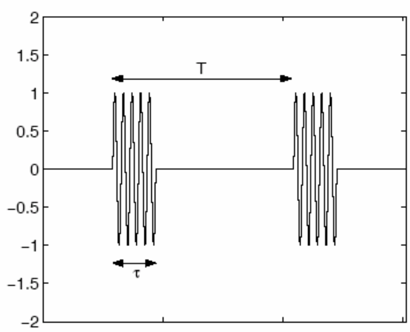
Wideband measurement techniques



- wideband channel: frequency selective fading, $B_{channel} > B_c$
- correlation bandwidth $B_c \sim 1/(2*\pi*\sigma_\tau)$, σ_τ is the rms delay spread
- ’time domain’ and ’frequency domain’ methods are equal, results can be Fourier transformed to any domain

Short pulse method





- measures pathloss and delay dispersion of the radio channel
- delay resolution ~ τ
- I and Q demodulation of the signal is required for the phase information
- power spectrum sinc-shaped

$$S_p(f) = \left(\frac{\tau}{2}\right)^2 \cdot \sin c^2((f - f_{car})\tau)$$

Continuous wave methods

- Energy is transmitted continuously, so less peak power is required in the transmitter
- The delays are found by correlating the received signal with the transmitted waveform
- The waveforms can be
  - frequency sweep
  - frequency step (network analyzer)
  - Direct sequence (TKK sounder, PROPsound by Elektrobit, Finland)
  - Multitone (RUSK sounder by MEDAV, Germany)
  - Combinations of those above

Network analyzer 1

- Newtwork anlayzer covers easily bandwidths of several GHz ⇒ very high delay resolution can achieved (UWB)
- If sweep time is made is long the noise bandwidth gets narrow, e.g Agilent E8363A
  - Number of points: 1601 (step: 2.18 MHz)
  - Sweep time: 1,479 sec
  - Noise floor = -112dBm
- The time domain impulse response is the Fourier transfom of the frequency response *S(f)*

$$\hat{h}(\tau,t) = F^{-1}\left(\frac{S(f)W(f)}{S_{cal}(f)}\right)$$

- W(f) is the window function
- Scal(f) is response of back-to-back measurement
- The delay range is given by the bandwidth *B* and number of frequency points *N*

$$\tau_{\max} = \frac{N-1}{B}$$

Network analyzer 2

- Too short delay range causes aliasing - long delayed components appear in the beginning of the impulse response
- Impulse response is sinc shaped – different window functions can be used to reduce the sidelobes. This makes the main lobe of the impulse response wider
- Cable is needed between TX and RX
- Doppler range is very limited
- Phase continuity in virtual arrays is a major concern
  - phase stability of the measurement system
  - stability of the environment
- Various measurement campaigns have been reported with network analyzers, generally the number of measurement points is limited

MIMO measurement system based on laboratory equipment

Department 'Tecnologías de la Información y las Comunicaciones', Technical University of Cartagena, Research Group SiCoMo (Sistemas de Comunicaciones Móviles)

- Flexible selection of the center frequency and bandwidth
- Example: MIMO WLAN 2.45 GHz channel measurement

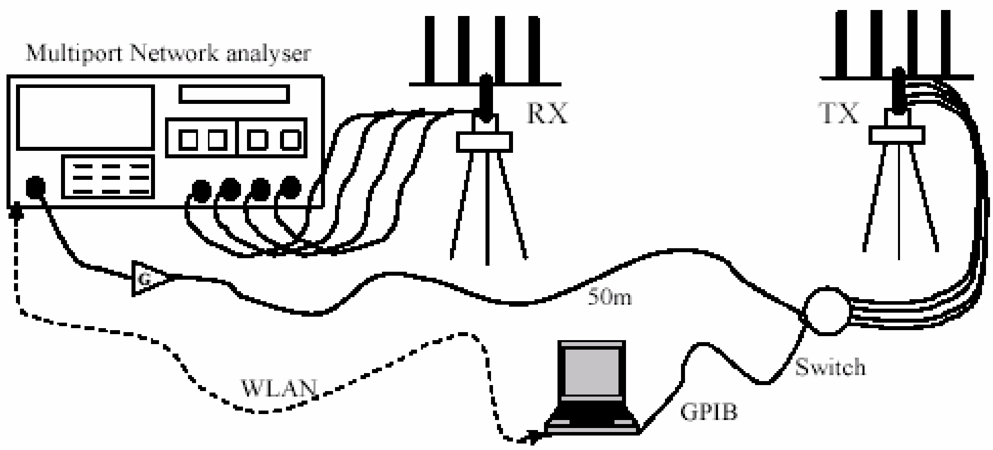


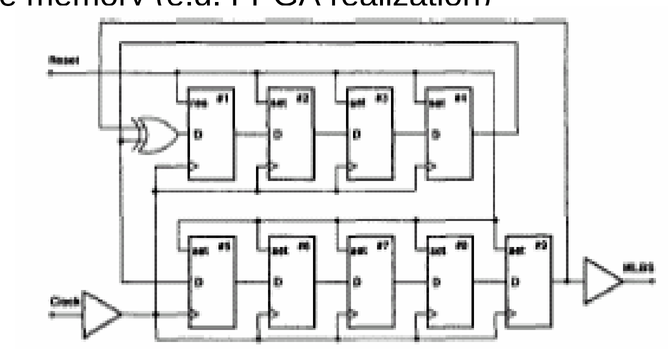
Figure 1: Diagram of the channel sounder based on one multiport network analyzer and a fast switch.

Pseudo-noise coding for the transmitted signal

- Pseudo noise (PN)-coded transmitter
  - length of maximal length sequence in ”chips” (= clock pulse width)

$$L = 2^N - 1$$

- *N* is the number of feedback shift registers
  - generated by
  1. feedback shift register
     -clock rate of 11 GHz has been reported by SiGe HBT technology
  2. directly from the memory (e.g. FPGA realization)



M-sequence waveform properties

- Autocorrelation for sequence *s(t)*

$$R_s(\tau) = \frac{1}{T_s} \int_0^{T_s} s(t)\, s^*(t-\tau)\, dt$$

- Delay resolution ~ T_{chip}
- Delay range LT_{chip}
- Processing gain

$$G_p = 10 \log_{10} L$$

- Dynamic range limited by the autocorrelation of the signal

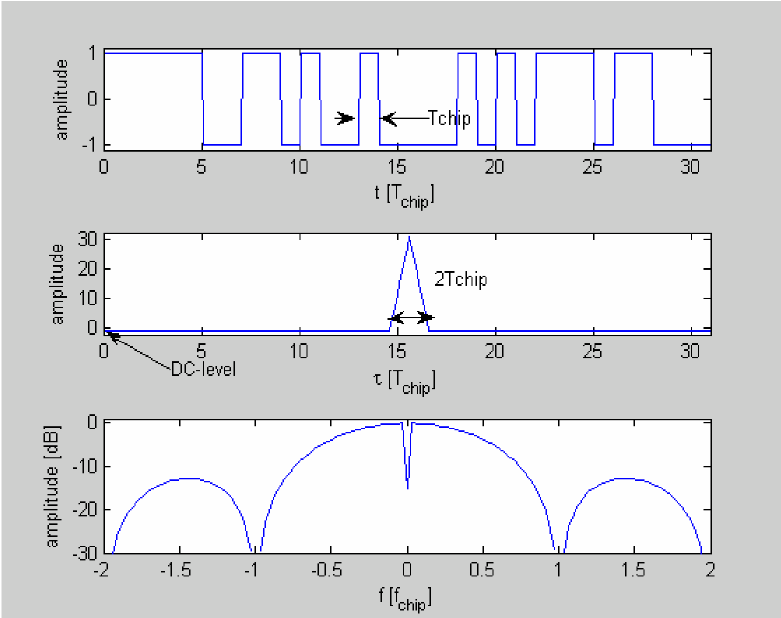
$$D = 20 \log_{10} L$$

M-sequence N = 5, L = 31

- Baseband waveform $s(t)$:
- Autocorrelation:

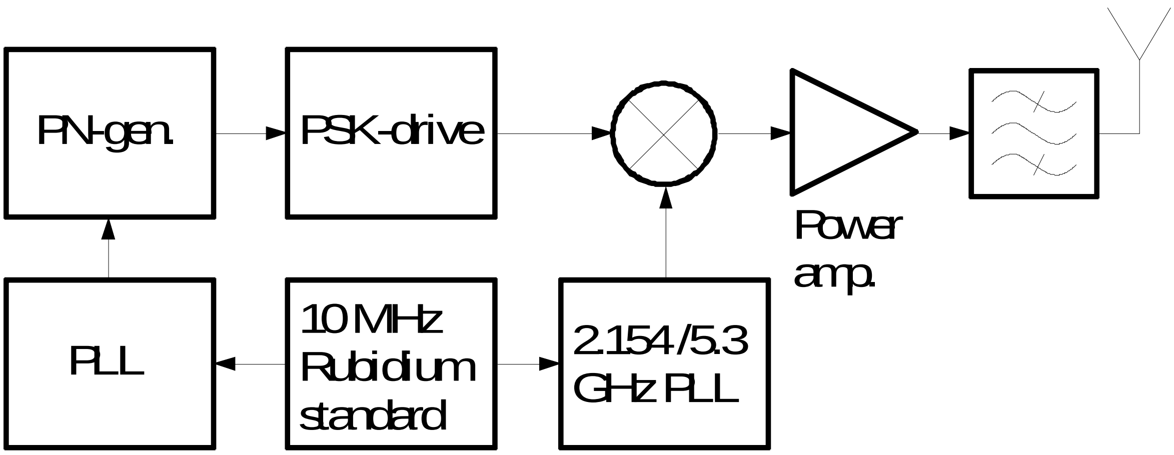
$$R_s(\tau) = \frac{\left[(L+1)\Lambda\left(\frac{\tau}{T_{chip}}\right) - 1\right]}{L}$$

- ”DC-level” outside the main peak = -1
- Power spectrum:

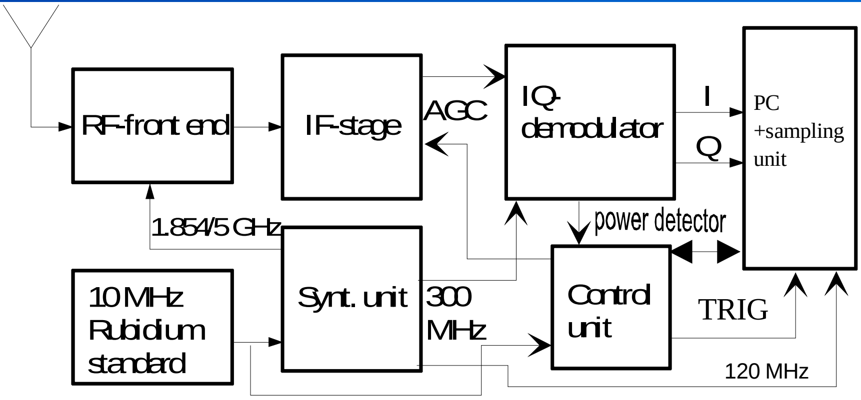


$$S_p(f) = \left[\sum_{\substack{-\infty \\ m\neq 0}}^{\infty} \delta(f - mf_0)\right] \frac{L+1}{L} \mathrm{sinc}^2\left(\frac{f}{f_{chip}}\right) + \frac{1}{L^2}\delta(f), \qquad f_0 = \frac{f_{chip}}{L}$$

Transmitter block diagram (TKK sounder)



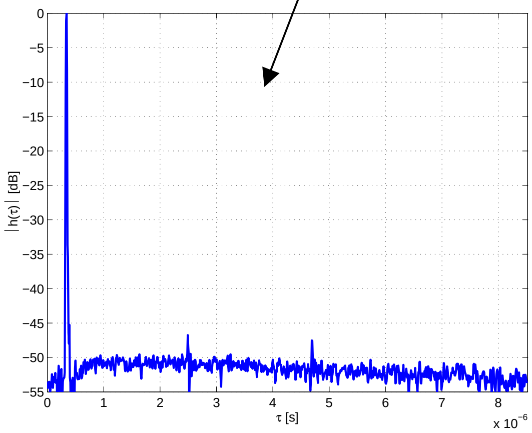
Receiver principle (TKK)

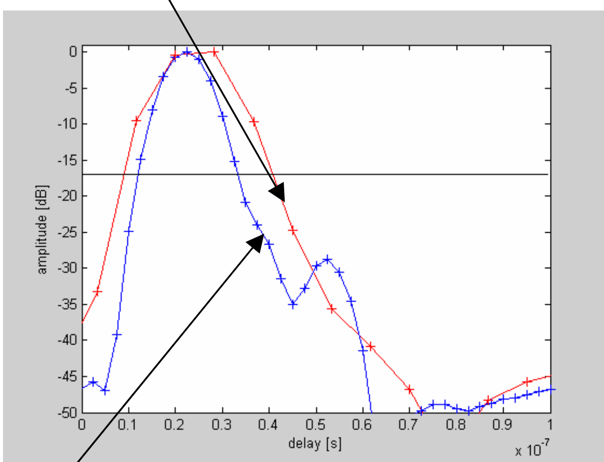


- RF unit filters and downconverts the signal to IF
- IF unit has the major part of the gain and does the Automatic Gain Control (AGC) by detector and digital step attenuators
- Control is done with microcontroller and PC
- IQ-demodulator gives the Inphase (I) and Quadrature (Q) components of signal
- Synthesizer unit generates the needed signals from 10 MHz stable (Rubidium) clock
- Data is collected to hard disks of the sampling unit
- Processing of data is done offline

Back-to back measurements

- 60 MHz chip rate
- 120 MS/s sampling rate





- 100 MHz chip rate
- 400 MS/s sampling rate

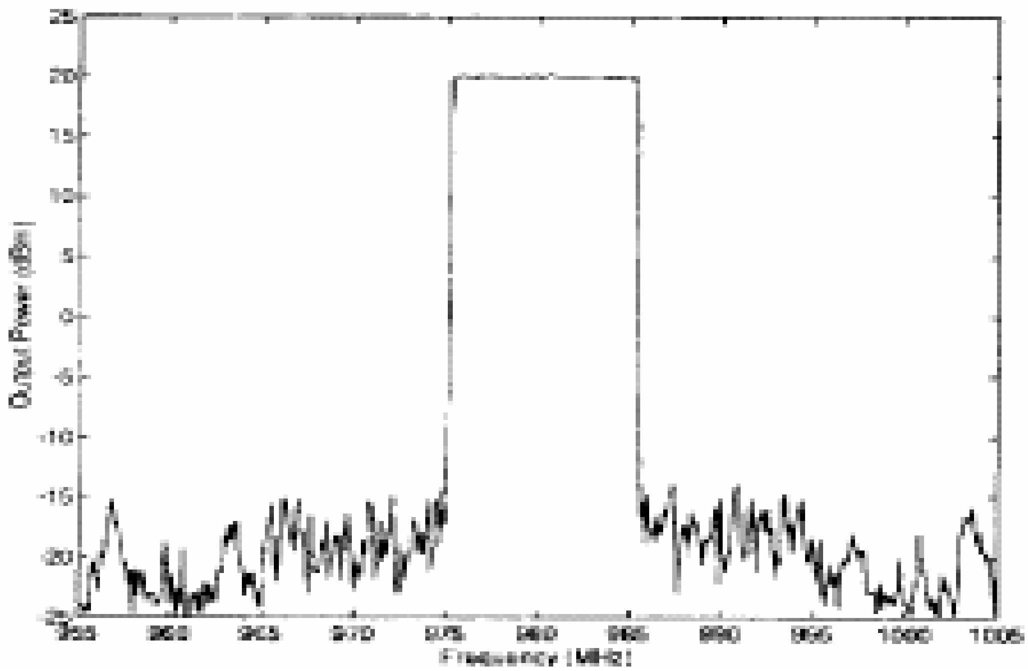
Multitone sounder

- *N* parallel sinusoids are generated. This corresponds to a network analyzer, but here the frequencies are generated simultaneously, and the measurement is equally rapid as with direct sequence sounder
  - Delay range is the same as for a network analyzer:

$$\tau_{\max} = \frac{N-1}{B}$$

- Multitone signal has high crest factor CF (i.e. peak to average ratio). This causes back-off requirement of several dB:s in power amplifier. Two methods can been used to decrease the CF
  - finding optimal phases for sinusoids so that the CF gets lower
  - using nonlinear predistortion
- Advantage over the m-sequence waveform
  - there are no sidelobes in frequency domain⇒less filtering is required in TX
  - spectrum is flat in the whole channel ⇒ efficient use of the available spectrum

Multitone sounder output spectrum

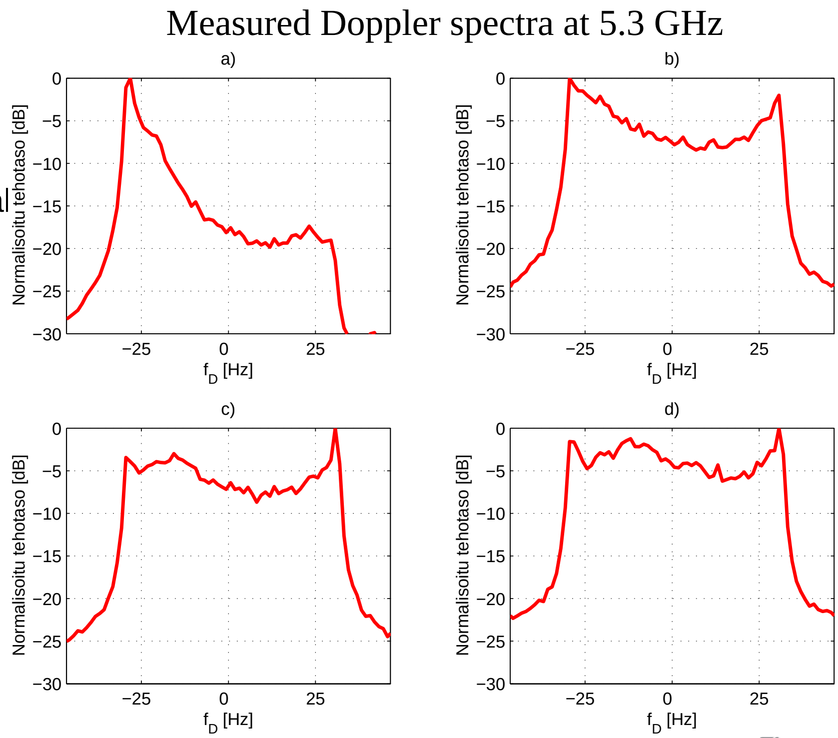


Doppler range of measurements

- maximum Doppler frequency is defined by sampling interval of consecutive channel samples (”snapshots”)

$$f_{D\max} = \frac{1}{2\tau_S}$$

- f_{Dmax} = v/λ gives the maximum mobile speed $v_{max} = \lambda/(2\tau_S)$ in a ‘frozen’ environment (= no moving scatterers)



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3. Multidimensional measurements

TKK

Spatial radio channel: formulation

- time-variant wideband channel

$$h(t,\tau)=\sum_{i=1}^{N} h_i(t)\delta(\tau-\tau_i(t))$$

- propagation channel matrix **H** with antenna gains **F** and **G** and polarization coupling matrix **M** for n_t transmit and n_r receive antennas ("o" refers to elementwise multiplication)

$$\mathbf{F}_y^n=\begin{bmatrix} f_1^n(\theta_t,\phi_t) & f_1^n(\theta_t,\phi_t) & \cdots & f_1^n(\theta_t,\phi_t) \\ f_2^n(\theta_t,\phi_t) & f_2^n(\theta_t,\phi_t) & \cdots & f_2^n(\theta_t,\phi_t) \\ \vdots & \vdots & \ddots & \vdots \\ f_{n_t}^n(\theta_t,\phi_t) & f_{n_t}^n(\theta_t,\phi_t) & \cdots & f_{n_t}^n(\theta_t,\phi_t) \end{bmatrix}$$

$$\mathbf{G}_y^n=\begin{bmatrix} g_1^n(\theta_r,\phi_r) & g_2^n(\theta_r,\phi_r) & \cdots & g_{n_r}^n(\theta_r,\phi_r) \\ g_1^n(\theta_r,\phi_r) & g_2^n(\theta_r,\phi_r) & \cdots & g_{n_r}^n(\theta_r,\phi_r) \\ \vdots & \vdots & \ddots & \vdots \\ g_1^n(\theta_r,\phi_r) & g_2^n(\theta_r,\phi_r) & \cdots & g_{n_r}^n(\theta_r,\phi_r) \end{bmatrix}$$

$$\mathbf{M}_{xx}^n=\begin{bmatrix} h_{1,1}^n(\theta_t,\phi_t,\theta_r,\phi_r) & \cdots & h_{1,n_r}^n(\theta_t,\phi_t,\theta_r,\phi_r) \\ \vdots & \ddots & \vdots \\ h_{n_t,1}^n(\theta_t,\phi_t,\theta_r,\phi_r) & \cdots & h_{n_t,n_r}^n(\theta_t,\phi_t,\theta_r,\phi_r) \end{bmatrix}$$

$$\mathbf{H}=\sum_{n=1}^{N}\left[\mathbf{F}_\phi^n\circ\mathbf{M}_{\phi\phi}^n\circ\mathbf{G}_\phi^n+\mathbf{F}_\phi^n\circ\mathbf{M}_{\phi\theta}^n\circ\mathbf{G}_\theta^n+\mathbf{F}_\theta^n\circ\mathbf{M}_{\theta\phi}^n\circ\mathbf{G}_\phi^n+\mathbf{F}_\theta^n\circ\mathbf{M}_{\theta\theta}^n\circ\mathbf{G}_\theta^n\right]$$

Multidimensional radio channel sounding

- **Double directional sounding**
  - The goal is joint estimation of the wave vectors <u>including the polarization</u> in both transmitter and receiver end of the link
  - This requires measurement of the field in several points
  - Possible methods
    - rotating a directive dual-polarized antenna
    - virtual dual-polarized arrays
    - real dual-polarized antenna arrays
      - multiplexed in time
      - parallel transmitters and receivers
        - different code or frequency shift in each transmitter antenna
      - combinations of different methods
- **MIMO (Multiple Input Multiple Output) measurements**
  - Field solution may not be needed in either or both end of the channel, only the Shannon capacity may be of interest
- **SIMO (Single Input Multiple Output) or MISO (Multiple Input Single Output) measurements**
  - Only other end of the channel is of interest

Rotating the antenna

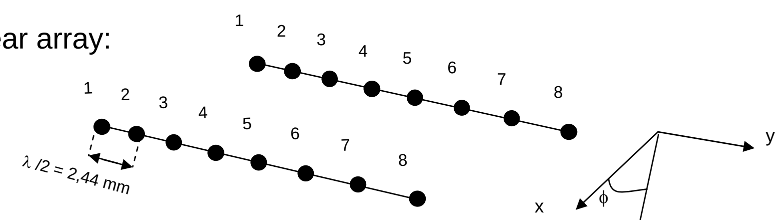
- **This requires a 'frozen' environment**
  - measurement of polarization matrix requires several channels
- **3-D rotation in both ends of the channel is too slow**

H. Hoff, P. Eggers, I. Kovacs, "Directional indoor ultra wideband propagation mechanisms" IEEE 58th Vehicular Technology Conference Fall. 2003, 6-9 Oct. 2003 Page(s):188 – 192.

Virtual antenna arrays

- **transmitter and receiver are moved using matrix shifters or rotators**
- **plane wave approximation is used in both ends**
- **wave vector can be calculated by**
  - beamforming
  - high resolution algorithms (SAGE,ESPRIT)
- **Full characterization requires mesurement points in three dimensions**
- **Polarization needs 2·2 channels**
- **stability of environment**
  - measurements often made late in the evening

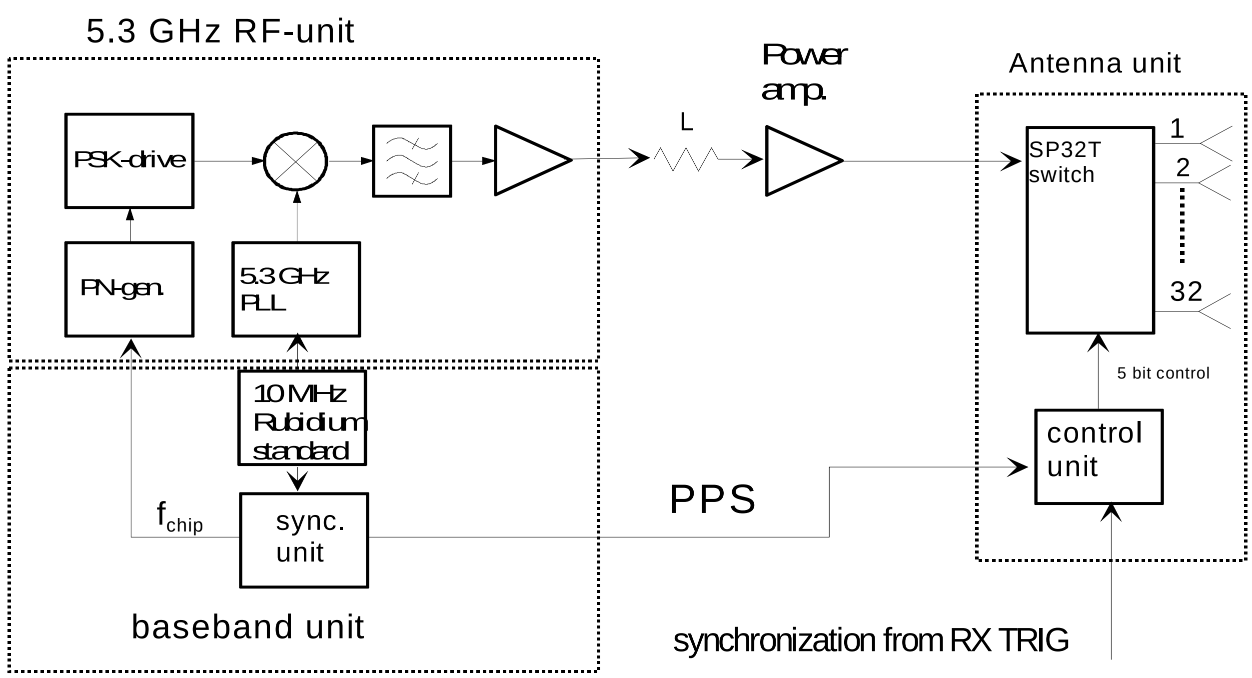
- 60 GHz virtual linear array:



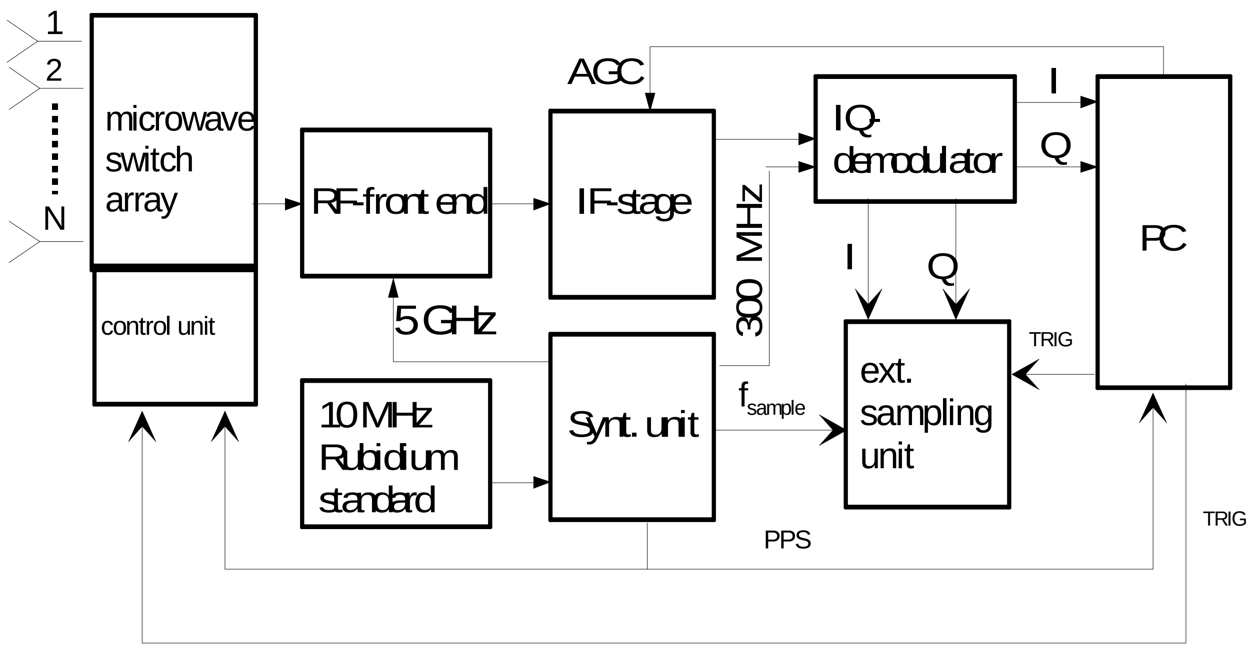
MIMO measurement system based on switched antenna arrays

- **TKK 5.3 GHz MIMO sounder**
  - 32 x 32 matrices, 16 dual polarized elements can be used in both TX and RX
  - high power SP32T TX switch (5 W output)
  - channel matrix is measured in 8.7 ms
  - 2 x 120 MHz sampling rate, 60 MHz chip rate
  - Measurements possible with about 120 dB propagation loss
  - Range is abut 500 meters in NLOS macrocell

Transmitter of the TKK 5.3 GHz sounder



Receiver of the TKK 5.3 GHz sounder



Properties of the microwave MUX switches

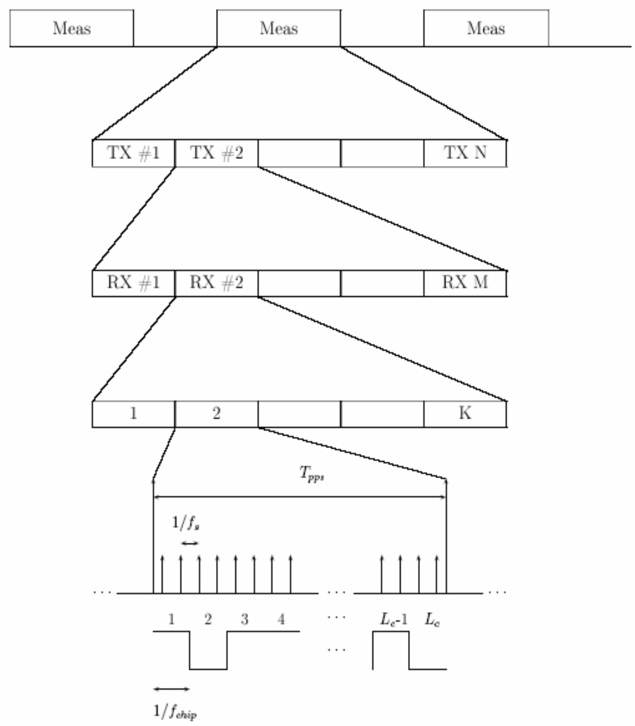
- **Semiconductor or potentially MEMS switches can be used**
  - TX switch requires high power handling capacity
    ⇒ this is achieved with PIN-diode switches

Properties of transmitter and receiver SP32T switches in TKK 5 GHz sounder

	TX	RX
Operating center frequency	5.3 GHz	
Bandwidth	±200 MHz	1 – 18 GHz
VSWR	2:1	2:1
Typical Isolation	40 dB	60 dB
Switching speed	2 µs	200 ns
Type	Absorptive	Absorptive
Max input power	10 W	0.8 W
Typical insertion loss	3.5 dB	4 dB (at 5 GHz)

-TX switch is one of the most expensive components of the measurement system

Synchronization of switches



- Synchronization is typically based on the high-precision clocks of the sounders
- It requires back to back resetting of the system
- Syncronization holds for couple of hours depending on the timing marginal and clock accuracy
- Also wireless MIMO synchronization possible (MEDAV RUSK)
- Switching time is significant and has to be discarded from the data either online or offline

⇒ there must be redundancy in the measurement

Data collection and frame movement limits

- The joint amount of data in I and Q channels (which have separate A/D converters in our sampler) with *N* and *M* dual polarized elements in the arrays is

$$N_{byte} = N \cdot M \cdot 2^2 \cdot L \cdot T_{chip} \cdot N_{ave} \cdot f_{sample}$$

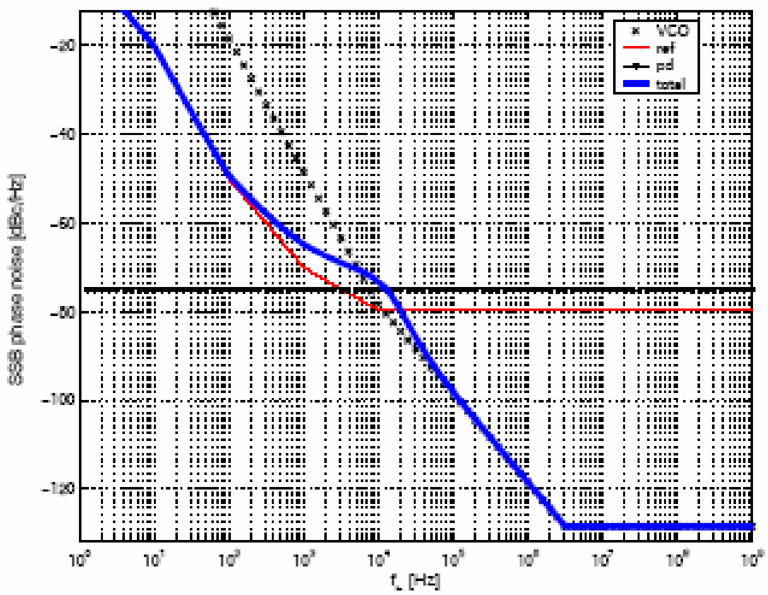
- here N_{ave} is the number of averaged sequencies and f_{sample} the sampling frequency

- For example, in TKK 5 GHz sounder each snapshot size is 2 Mbytes. When samples are taken in 1cm interval, 100 meter dataset size is 20 Gbytes.
- Frame movement: measurement time of 32 x 32 size array is about 8.7 ms. Speed of 0.2 m/s gives peak-to peak phase error of 10 degrees

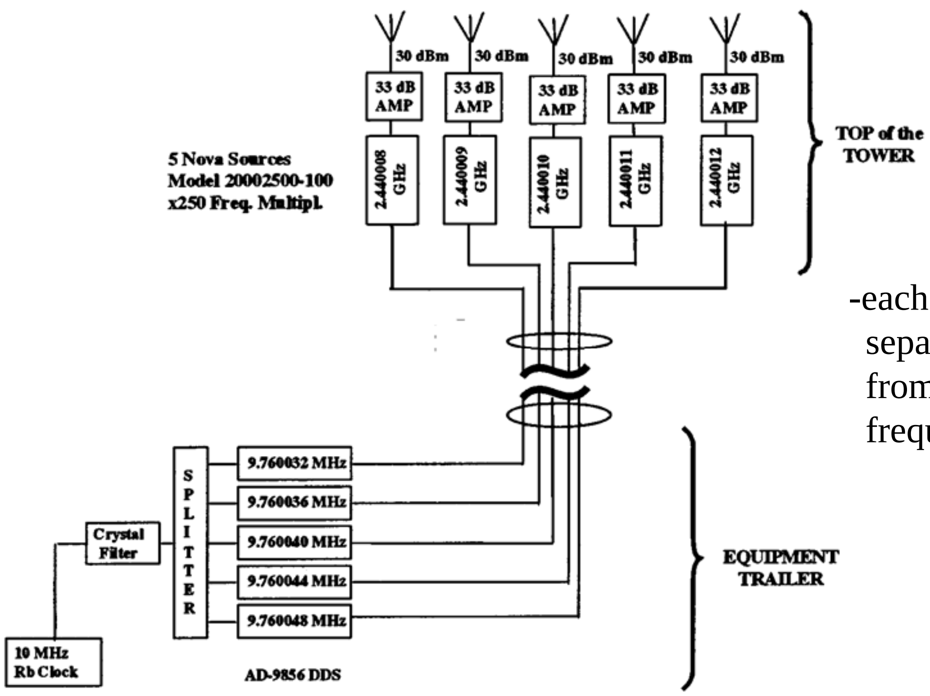
⇒ MIMO measurements are quite tedious

Phase noise of the measurement system limits the

- dynamic range (if excessive)
- Doppler measurement capability
- arrival time estimation
- accuracy of DOA and DOD measurement
- accuracy of MIMO capacity
  - There has been discussion on the effect of phase noise in multiplexed MIMO measurements, but for practical measurement systems and MIMO channels, the error is not significant at reasonable SNR levels

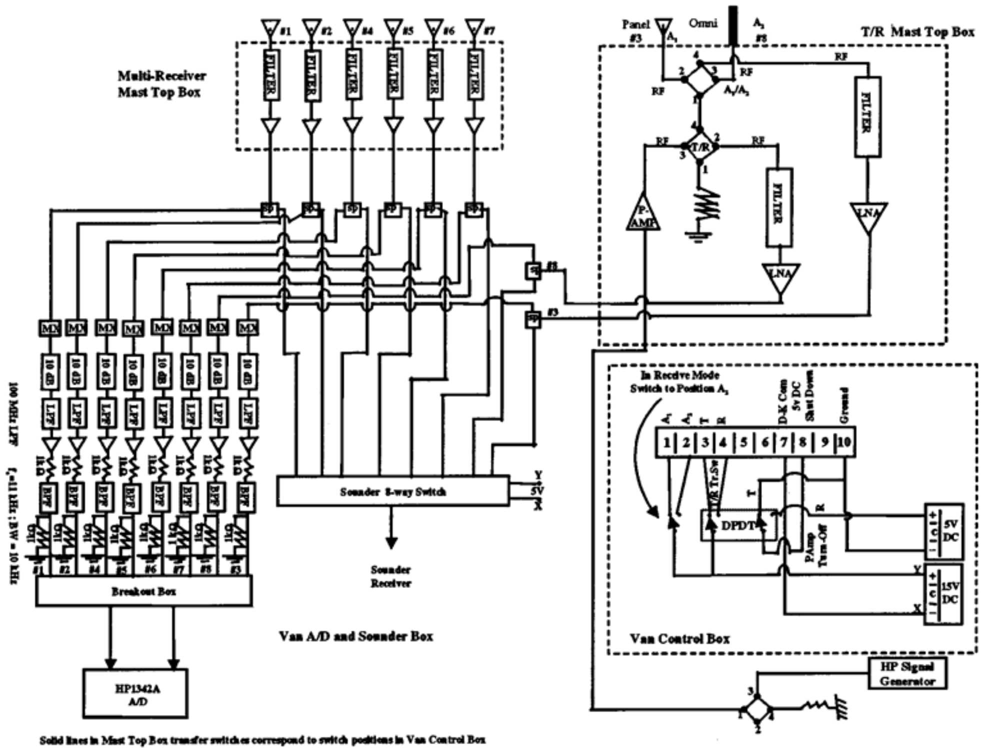


A narrowband MIMO measurement system (TX) by Lucent Technology Bell Labs



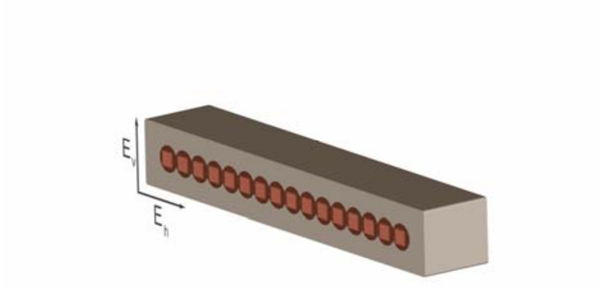
-each TX antenna can be separated in the receiver from the different frequency shift

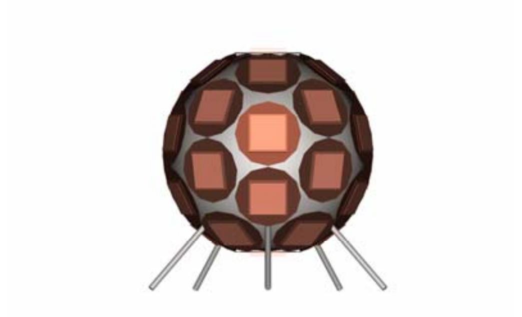
A narrowband MIMO measurement system (RX)



Antenna arrays

- **Linear (ULA = Uniform Linear Array)**
  - ambiguous in θ-plane
  - visibility area limited if distance between elements is more that λ/2
- **Planar arrays**
  - unambiguous in other half plane
- **Circular arrays**
  - unambiguous in other half plane
- **3-D arrays**
  - unambiguous, if enough elements with sufficiently small separation
    - cubical, spherical, semispherical, cylindrar, conical ...



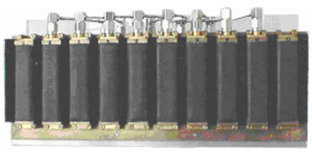


High Resolution Planar Antenna Arrays (Ilmenau Univ. of Technology)

4x8x2 PURA

Dual polarized uniform rectangular Vivaldi array

4x8x2 PURA
Dual polarized uniform rectangular patch array



8x ULA

uniform linear Dipole array

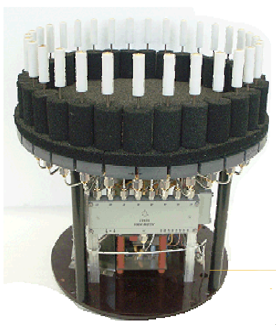
8x8 URA

uniform rectangular patch array

High Resolution Circular Antenna Arrays (Ilmenau Univ. of Technology)

16/32 UCA

uniform circular array



8x CUBA

circular uniform beam array

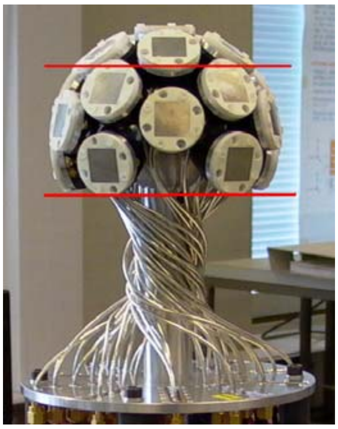
24x2 PUCPA

Dual polarized uniform circular patch array

4x24x2 SPUCPA
Stacked Polarimetric Uniform Circular Patch Array

Semispherical arrays - TKK

- **Spherical arrays**
  - non-slanted elements
  - slanted elements
- **Dual-polarized elements**
- **21 elements, 42 channels**
- **Used channels can be selected by cable connection**

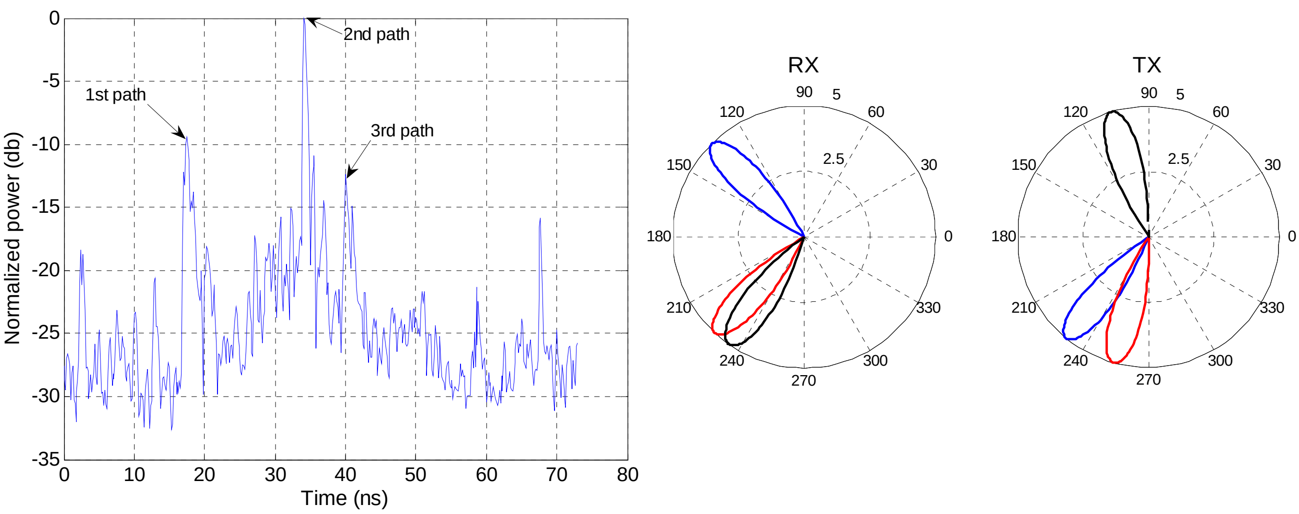


$$\theta = 50^\circ \ldots -30^\circ$$

$$\phi = 0^\circ \ldots 360^\circ$$

Beamforming with arrays

- **Beamforming (Fourier processing) is a simple, robust and fast method to esitmate the directions of departure and arrival with moderate resolution**
- **In wideband data, the paths are first searched in delay domain**
- **Beamforming is used separately for each peak to find the angular spectrum and polarization**



Beamforming algorithm

$$S(\theta,\phi)=\sum_{n=1}^{N}\left[h_n(\theta,\phi)s_n+v_n(\theta,\phi)t_n\right]a_n(\theta,\phi)$$

$$\begin{bmatrix} s_n \\ t_n \end{bmatrix} = e^{jk\mathbf{u}_s(\theta_s,\phi_s)\cdot\mathbf{r}_n}\begin{bmatrix} g^{\phi}(\theta_s,\phi_s)\cdot\mathbf{k}_s \\ g^{\theta}(\theta_s,\phi_s)\cdot\mathbf{k}_s \end{bmatrix}$$

$$a_n = a_{t,n}(\mathbf{u}_r)e^{-jk\mathbf{u}_r\bullet\mathbf{r}_n}$$

- *S* is the array response in angular domain
- Elevation scanning angle θ
- Azimuth scanning angle ϕ
- h_n and v_n determine the polarization of $S(\theta,\phi)$,
- s_n and t_n are the ϕ- and θ- polarized signal components of the field vector k_s
- u_r is the scanning vector and r_n is the position of the element,
- $a_{t,n}$ is the tapering function to reduce the sidelobes

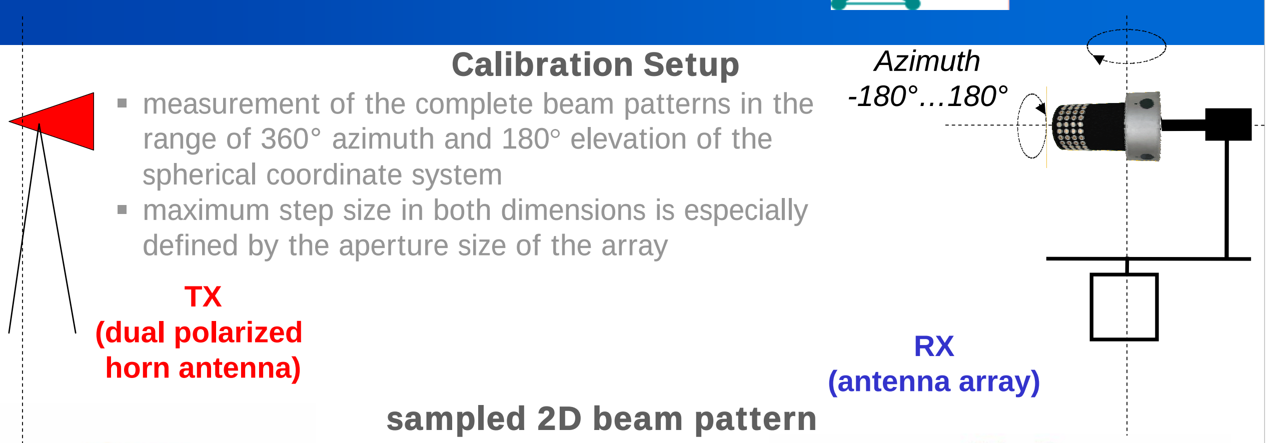
Superresolution

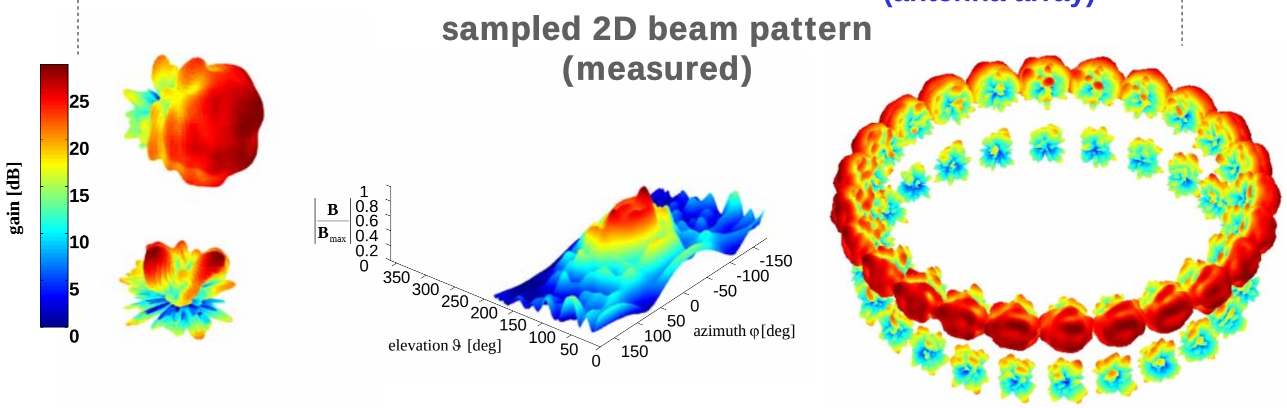
- Analysis with matched filter and beamformer gives complex delay-amplitude and angular-amplitude spectra as output
- Discrete solutions are preferred by users of the data (raw data amount can be hundreds of Gigabytes)
- Resolution can be improved by maximum likelihood estimation
- ESPRIT (Estimation of Signal Parameter Via Rotational Invariance Techniques)
- SAGE (space alternating generalized expectation maximization)
  - needs input parameters like number of paths and maximum number of iterations
  - convergence is not certain in complicated propagation situations
  - uses complex radiation patterns of antennas as input data in estimation
    - calibration of arrays major problem
  - supports joint estimation of DOA and DOD
  - is more sensitive to noise than beamforming

Antenna array calibration

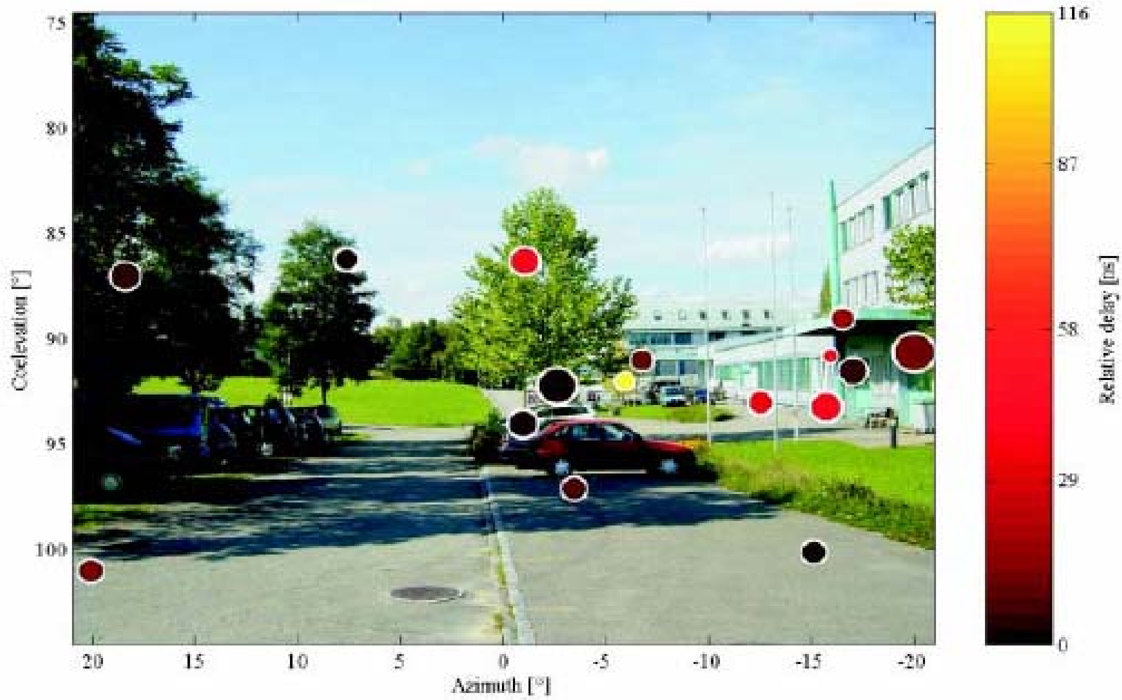
Calibration Setup

- measurement of the complete beam patterns in the range of 360° azimuth and 180° elevation of the spherical coordinate system
- maximum step size in both dimensions is especially defined by the aperture size of the array



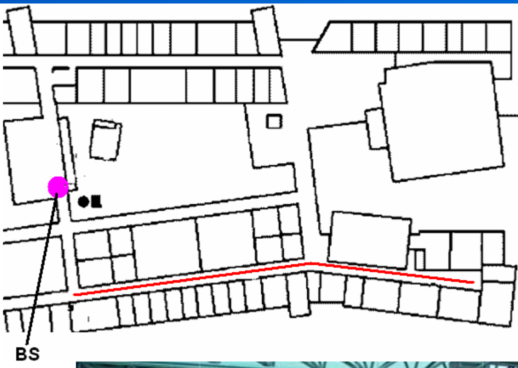


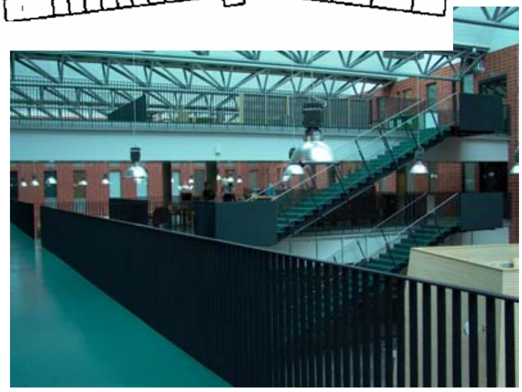
SAGE estimation result (Elektrobit)



- diameter of the dots is relative to magnitude in dB

TKK indoor measurement
Semispherical arrays





Indoor DOA and DOD spectrum with SAGE

- DOA=Direction Of Arrival

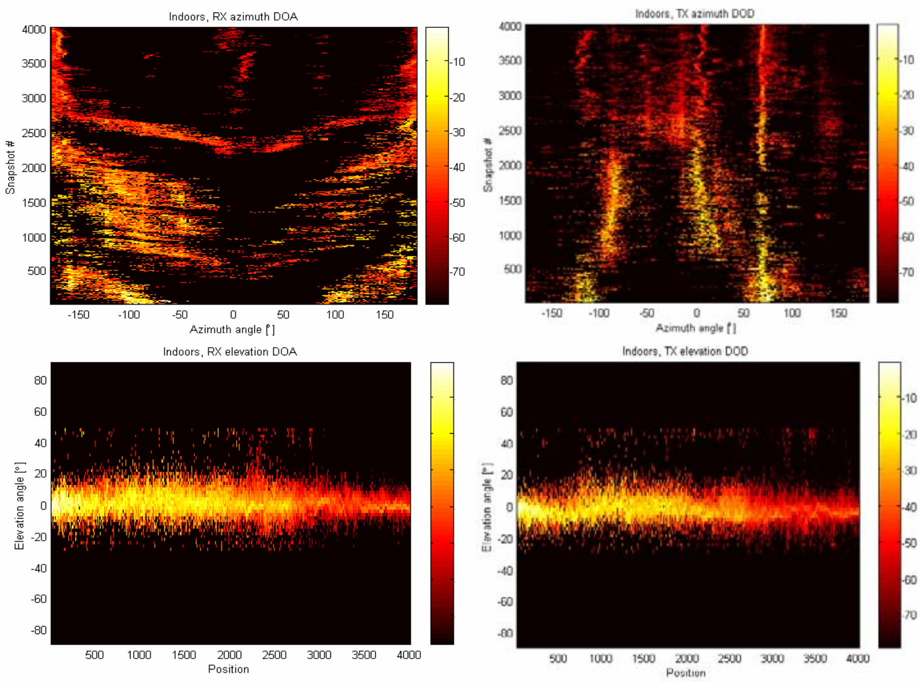
azimuth

- DOD=Direction Of Departure

elevation

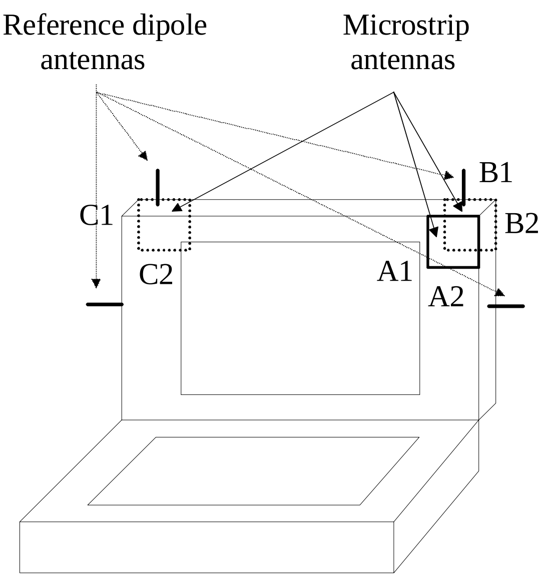
RX DoA

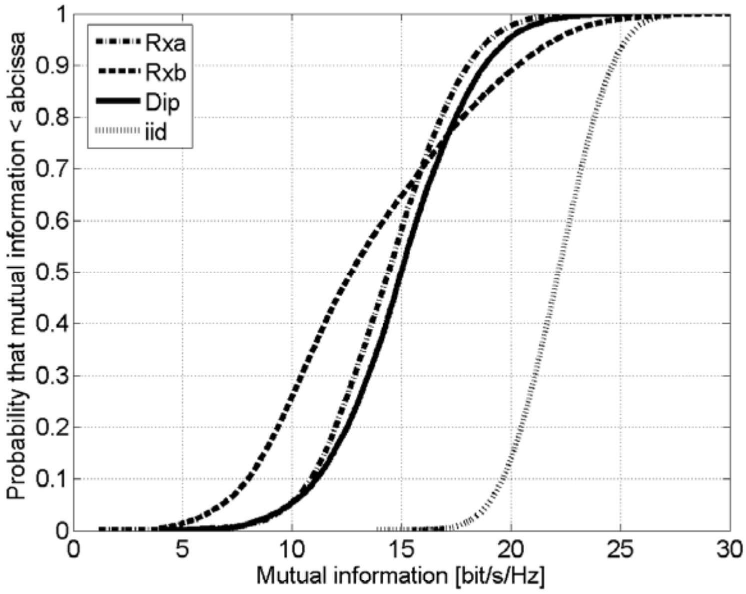
TX DoD



Application example:
5 GHz 4x4 MIMO antenna evaluation with indoor data

- Combination of measured channel and simulated antenna patterns
- Enables rotation of the terminal and inclusion of user effect like shadowing





TKK

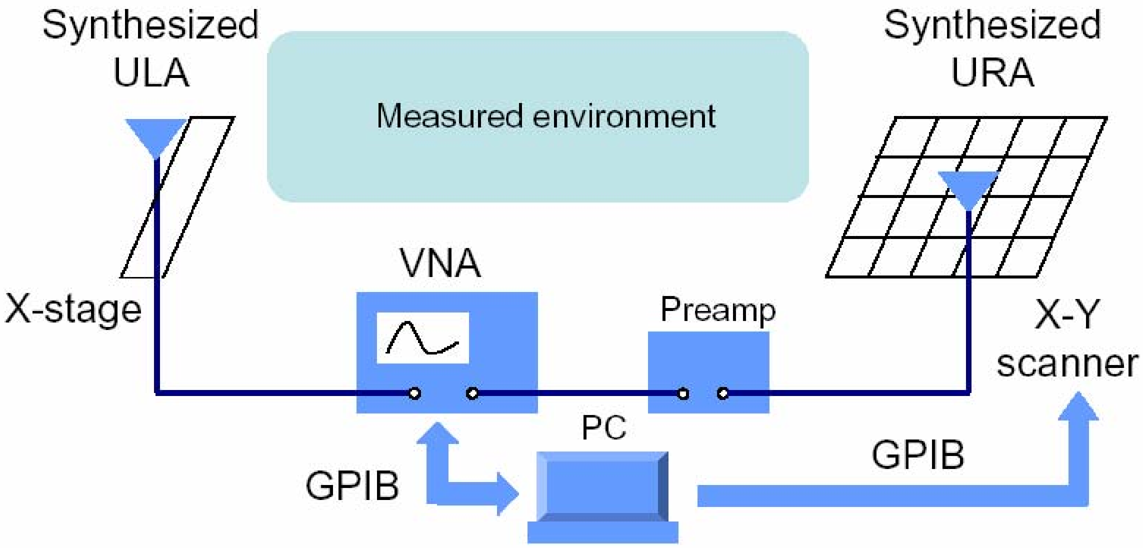
4. UWB and mm-wave measurements

TKK

UWB channel sounding system

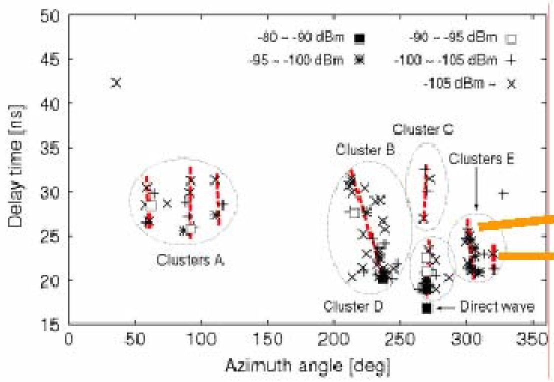
Takada Laboratory
Tokyo Institute of Technology

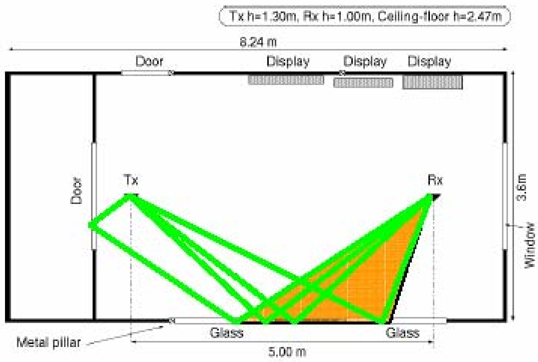
- System configuration
  - Network Analyzer and spatial antenna scanning
  - Automatic measurement by GPIB

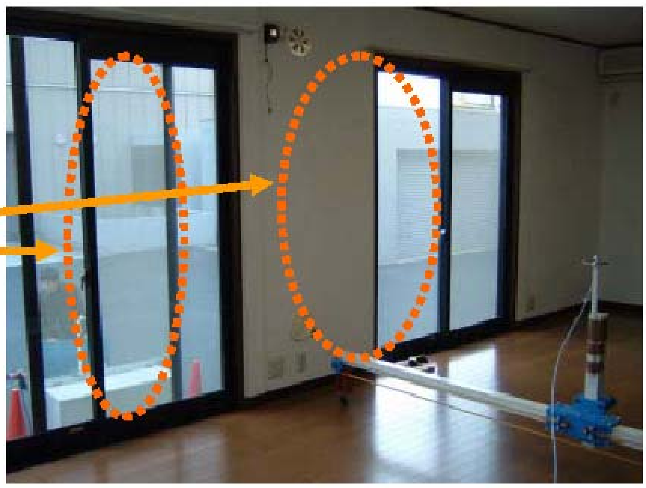


Identification of clusters (5)

Takada Laboratory
Tokyo Institute of Technology







Clusters E

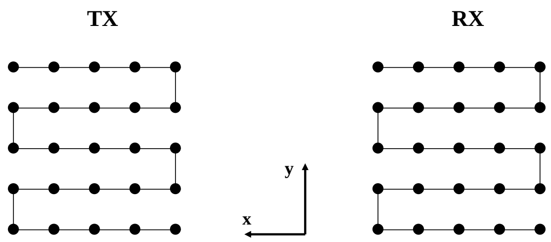
Reflection from the window (including window glass and metal frame)

Dual MIMO sounder measurements

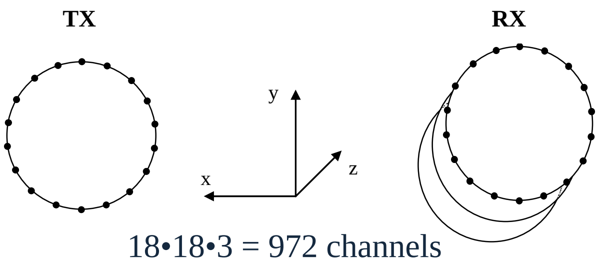
- WILATI project in the joint Nordic Nordite Technology Programme (TEKES & resp. organisations from Sweden and Norway)
- The 5 GHz MIMO sounders of TKK and Lund University were used jointly in the measurements to obtain information on the *interference limited* WLAN channels
- One of the first such experiments ever

60 GHz MIMO measurements with virtual antenna arrays

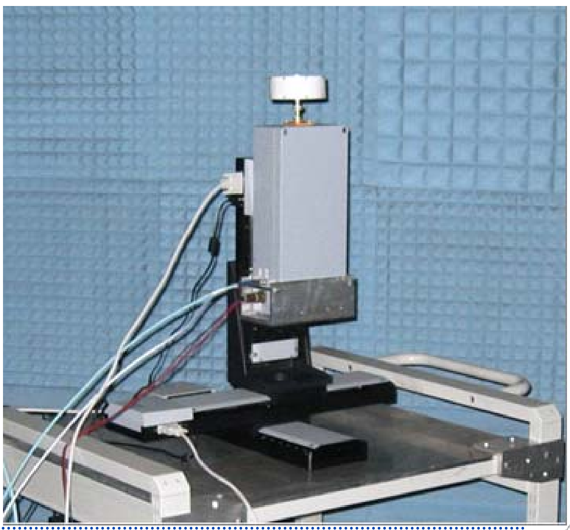
- Advantages compared to the use of switches: no losses, less expensive, antennas with higher gain, easily reconfigurable
- Main problem: long measurement time => high phase stability, static measurements
- 2 identical biconical omnidirectional antennas (+5 dBi)



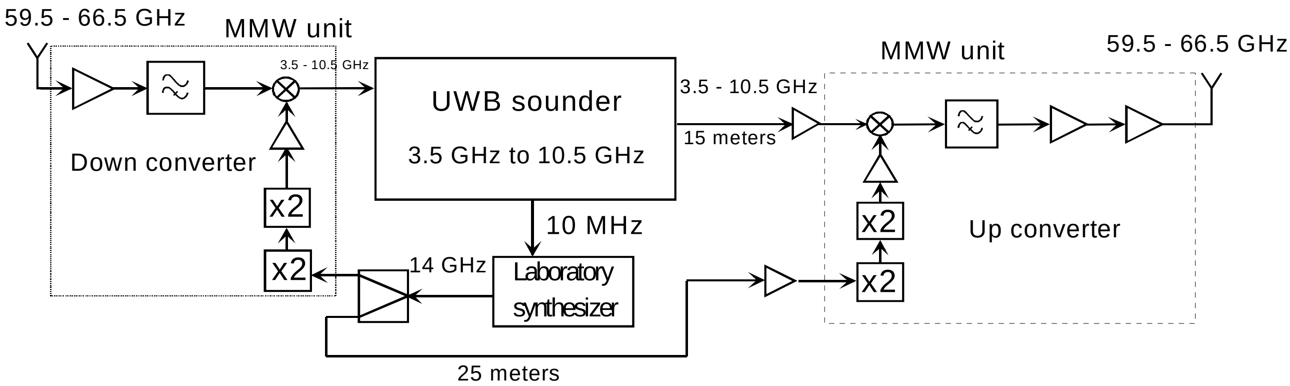
25 •25 = 625 channels



18•18•3 = 972 channels



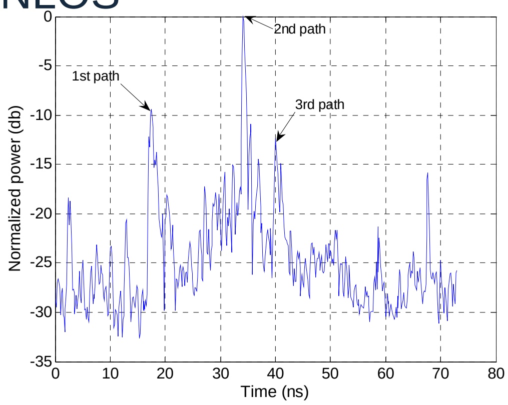
UWB 60 GHz Measurement Setup

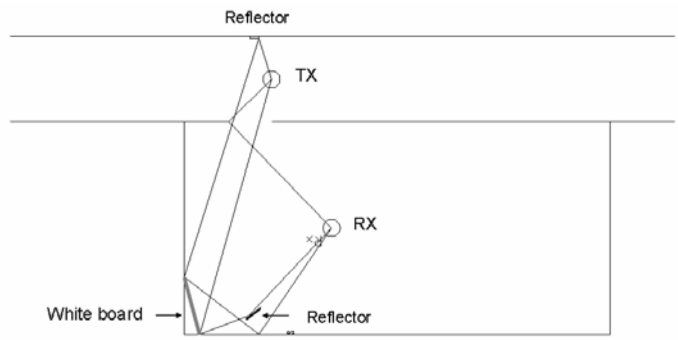


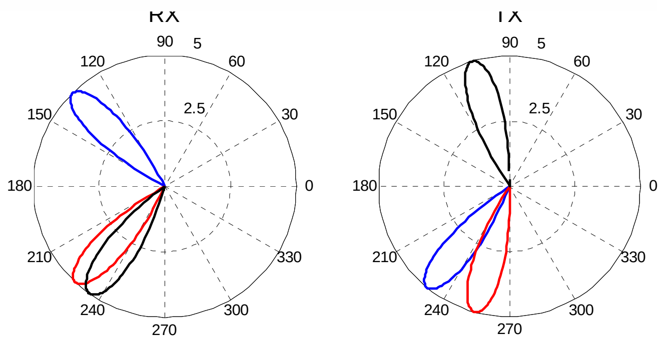
- Combination of 2 sub-systems : Mm-wave MIMO system (TKK) and UWB sounder (TU Ilmenau, Germany)
- 7 GHz nominal signal bandwidth, effective bandwidth of the mm-wave parts about 3 GHz
- Nominal spatial resolution 43 mm, real around 100 mm
- Output power : +17 dBm
- Recently, the UWB sounder has been replaced with a network analyzer
  - Measurement time tens of minutes/"snapshot"

Results for indoor measurements

NLOS







1st path : blue

2nd path : red

3rd path : black

Dynamic range : more than 20 dB in NLOS

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