Achievable bandwidth of Reconfigurable Intelligent Surfaces (RIS) concepts towards 6G communications

Werner Mohr

Consultant

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Outline

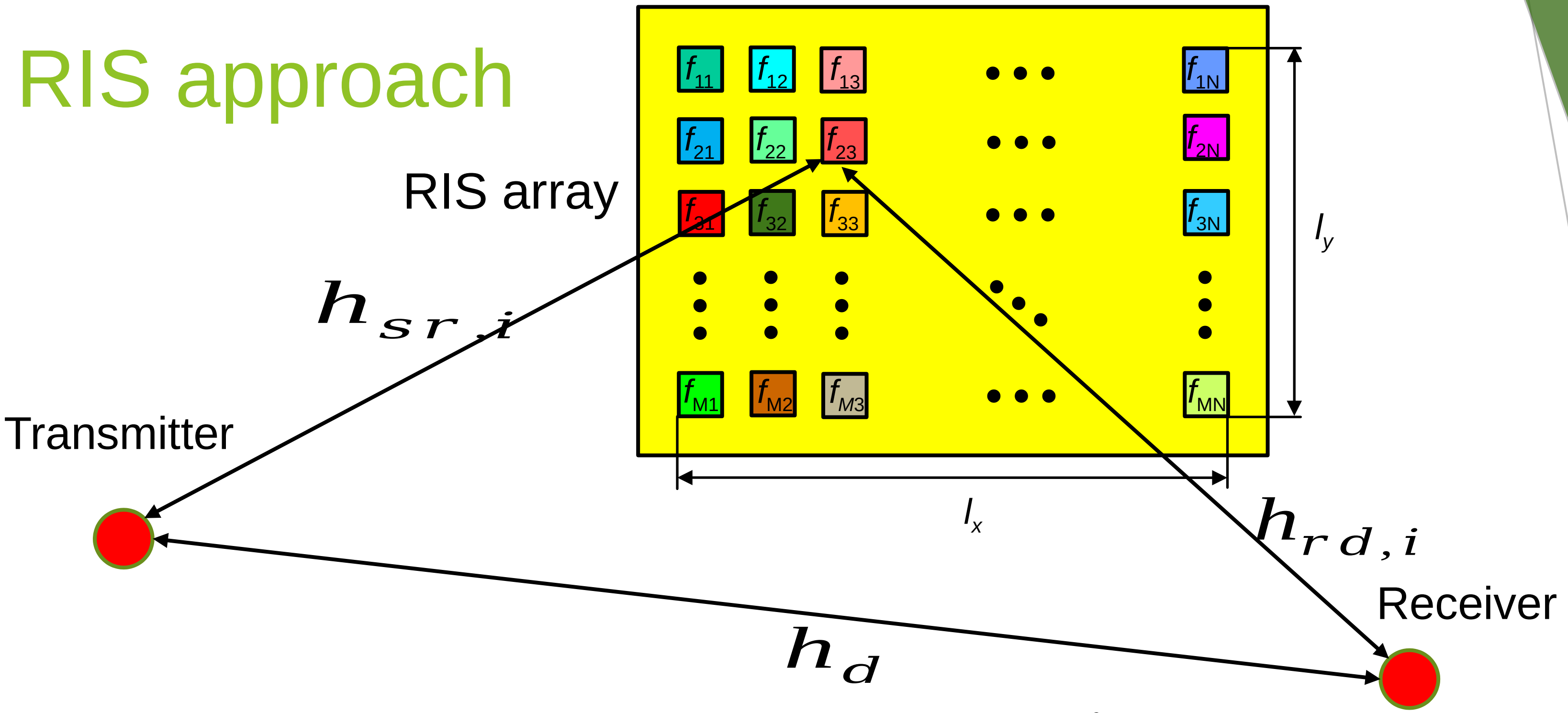
- Introduction and objectives of RIS systems
- Multipath propagation channel
- System- and signal-theoretical conditions for an ideal frequency-independent RIS system
- Delays and phase shifts in realistic multipath propagation channels
- Optimum RIS settings
- Estimated channel capacity
- Impact of displacements of the mobile station
- Approach to increase achievable bandwidth of radio channel transfer function
- Conceptual implementation and operational aspects
- Conclusion

Introduction and objectives of RIS systems

- In 5G and 6G systems frequency bands above 20 GHz and in 6G up to the sub-Terahertz domain are considered
- Such systems are using wide carrier bandwidth in the order of several hundred MHz to several GHz
- Radio channel has significant impact on system performance and is characterized by
  - distant dependent pathloss
  - multipath propagation
  - shadowing
  - atmospheric, rain and foliage attenuation

  which results in a statistical description of the channel
- New concepts like Reconfigurable Intelligent Surfaces (RIS)
  - intends to influence the radio channel environment
  - that at the receiver the different multipath components are super imposed constructively and
  - thereby the channel capacity is increased compared to standard SISO transmission
- **Main objective of this paper: Which bandwidth can be achieved by RIS systems?**

Basic RIS approach



- Standard SISO: reflected waves at surfaces >> wavelength λ are plane waves

$$PL_{reflected} \propto \frac{1}{\left(d_{sr}+d_{rd}\right)^n}$$

- In RIS systems scattering at small RIS elements < wavelength λ result scattered spherical waves (bistatic Radar equation)

$$PL_{reflected} \propto \frac{1}{\left(d_{sr}\cdot d_{rd}\right)^n}$$

- Multipath propagation channel

$$h_{mp}(t)=h_d\cdot\delta(t)+\sum_{i=1}^{I} h_{r,i}\cdot\delta(t-\tau_i)$$

$$\tau_i=\tau_{sr,i}+\tau_{rd,i}$$

Basic RIS approach
Received power and channel capacity

- Standard SISO transmission, summing up power contributions of different paths

$$P_{r,SISO}=P_t\cdot G_t(\varphi,\theta)\cdot G_r(\varphi,\theta)\cdot\left(|h_d|^2+\sum_{i=1}^{I}|h_{r,i}|^2\right)$$

$$C_{SISO}=B_{SISO}\cdot\log_2\left(1+\frac{P_{r,SISO}}{N}\right)=¿\,B_{SISO}\cdot\log_2\left(1+\frac{P_t\cdot G_t(\varphi,\theta)\cdot G_r(\varphi,\theta)\cdot\left(|h_d|^2+\sum_{i=1}^{I}|h_{r,i}|^2\right)}{N}\right)¿$$

- RIS transmission, summing up amplitude contributions of different paths

$$P_{r,RIS}=P_t\cdot G_t(\varphi,\theta)\cdot G_r(\varphi,\theta)\cdot\left(|h_{sd}|+\sum_{i=1}^{I}|h_{r,i}|\right)^2$$

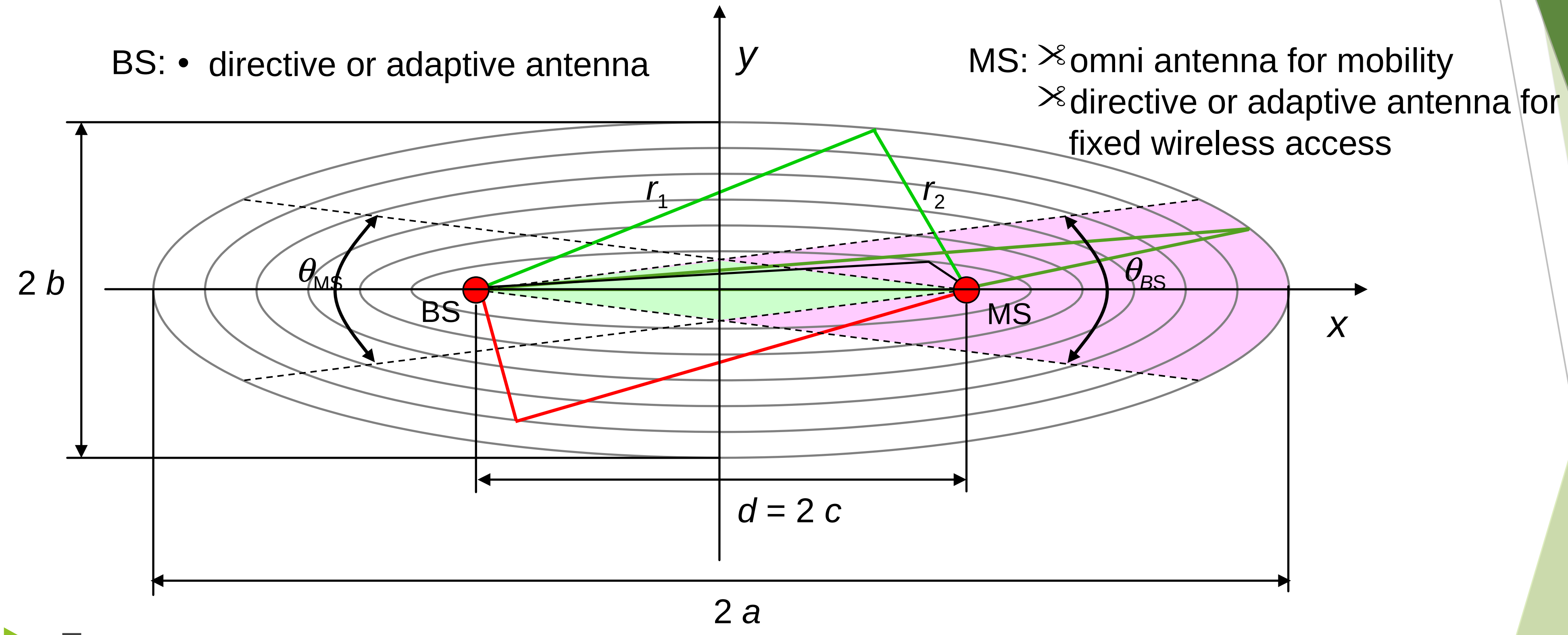
$$C_{RIS}=B_{RIS}\cdot\log_2\left(1+\frac{P_{r,RIS}}{N}\right)=¿\,B_{RIS}\cdot\log_2\left(1+\frac{P_t\cdot G_t(\varphi,\theta)\cdot G_r(\varphi,\theta)\cdot\left(|h_{sd}|+\sum_{i=1}^{I}|h_{r,i}|\right)^2}{N}\right)¿$$

- Inequality holds

$$|h_{sd}|^2+\sum_{i=1}^{I}|h_{r,i}|^2\leq\left(|h_{sd}|+\sum_{i=1}^{I}|h_{r,i}|\right)^2$$

Multipath propagation channel

- Path difference Δd_{max} or delay difference $\Delta\tau_{max}$ with 3 dB beamwidth of base station and of mobile station antenna normalized to the distance d

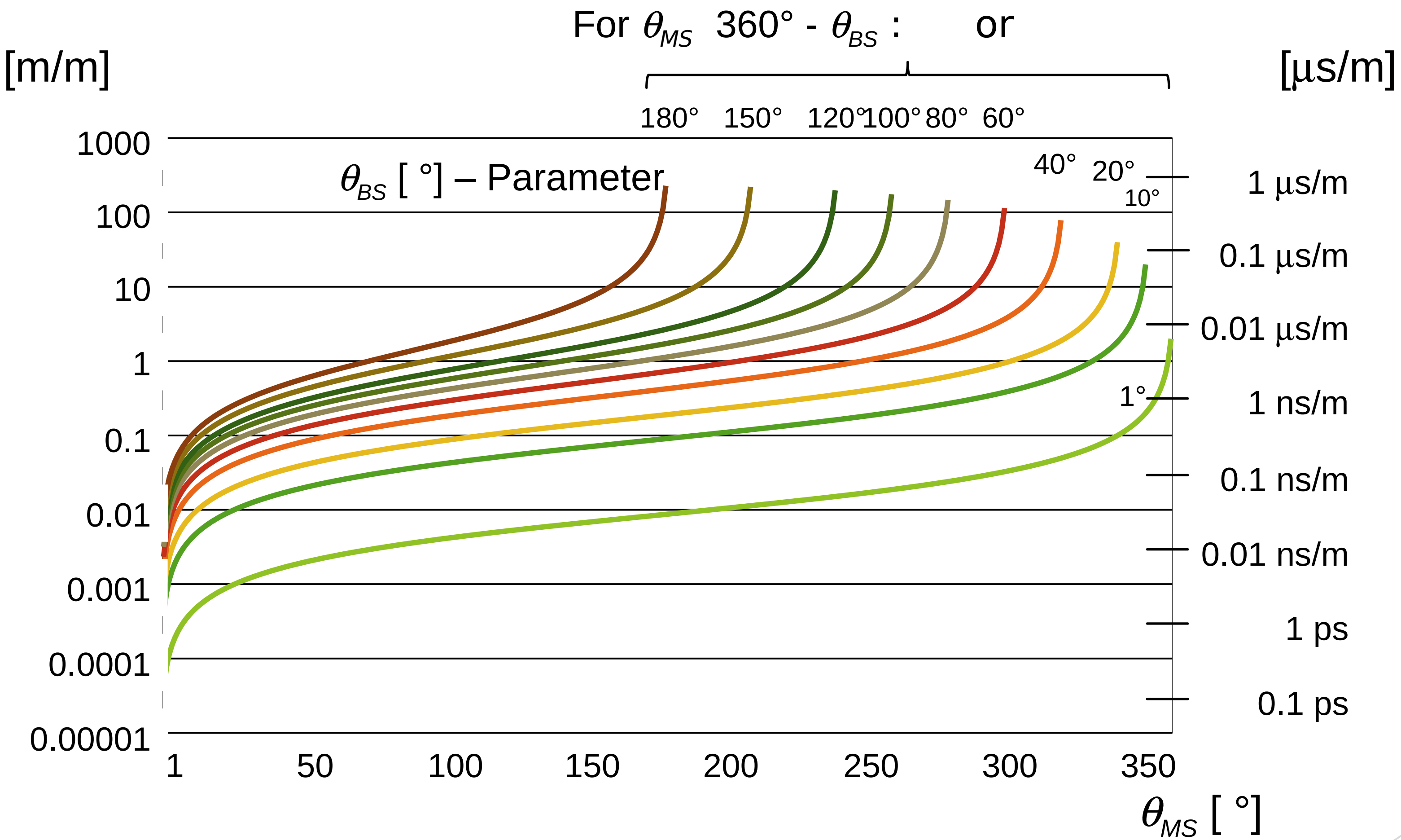


- For

$$\frac{\Delta d_{max}}{d}=\frac{\Delta\tau_{max}\cdot c_0}{d}=\frac{\tan\left(\frac{\theta_{MS}}{2}\right)}{\cos\left(\frac{\theta_{BS}}{2}\right)\cdot\left[\tan\left(\frac{\theta_{BS}}{2}\right)+\tan\left(\frac{\theta_{MS}}{2}\right)\right]}+\frac{\tan\left(\frac{\theta_{BS}}{2}\right)}{\cos\left(\frac{\theta_{MS}}{2}\right)\cdot\left[\tan\left(\frac{\theta_{BS}}{2}\right)+\tan\left(\frac{\theta_{MS}}{2}\right)\right]}-1$$

- For theoretically and

Multipath propagation channel
Maximum path length or delay difference



- In practical situations – especially in bigger halls and outdoor scenarios – long delays in the order of 1 µs corresponding to 300 m in free space possible

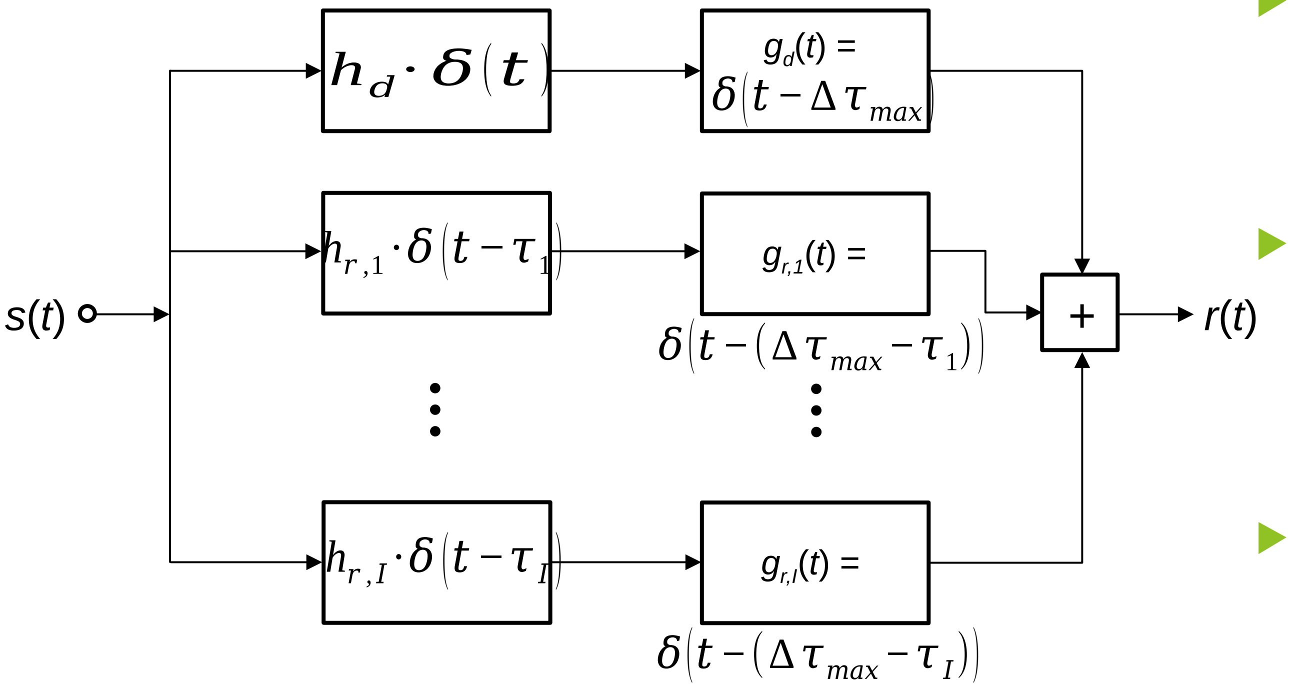
System- and signal-theoretical conditions for an ideal frequency-independent RIS system

- Frequency independent radio channel transfer function requires single path model

$$h_{mp\,RIS}(t) = h_{sum} \cdot \delta(t - \Delta\tau_{max})$$

- Possible, if all resolvable paths are delayed to maximum path delay

$$h_{mp,RIS}(t) = h_d \cdot \delta(t - \Delta\tau_{max}) + \sum_{i=1}^{I} h_{r,i} \cdot \delta(t - \tau_i - \Delta\tau_i) = \left\{ h_{sd} + \sum_{i=1}^{I} h_{r,i} \right\} \cdot \delta(t - \Delta\tau_{max}) = h_{sum} \cdot \delta(t - \Delta\tau_{max})$$



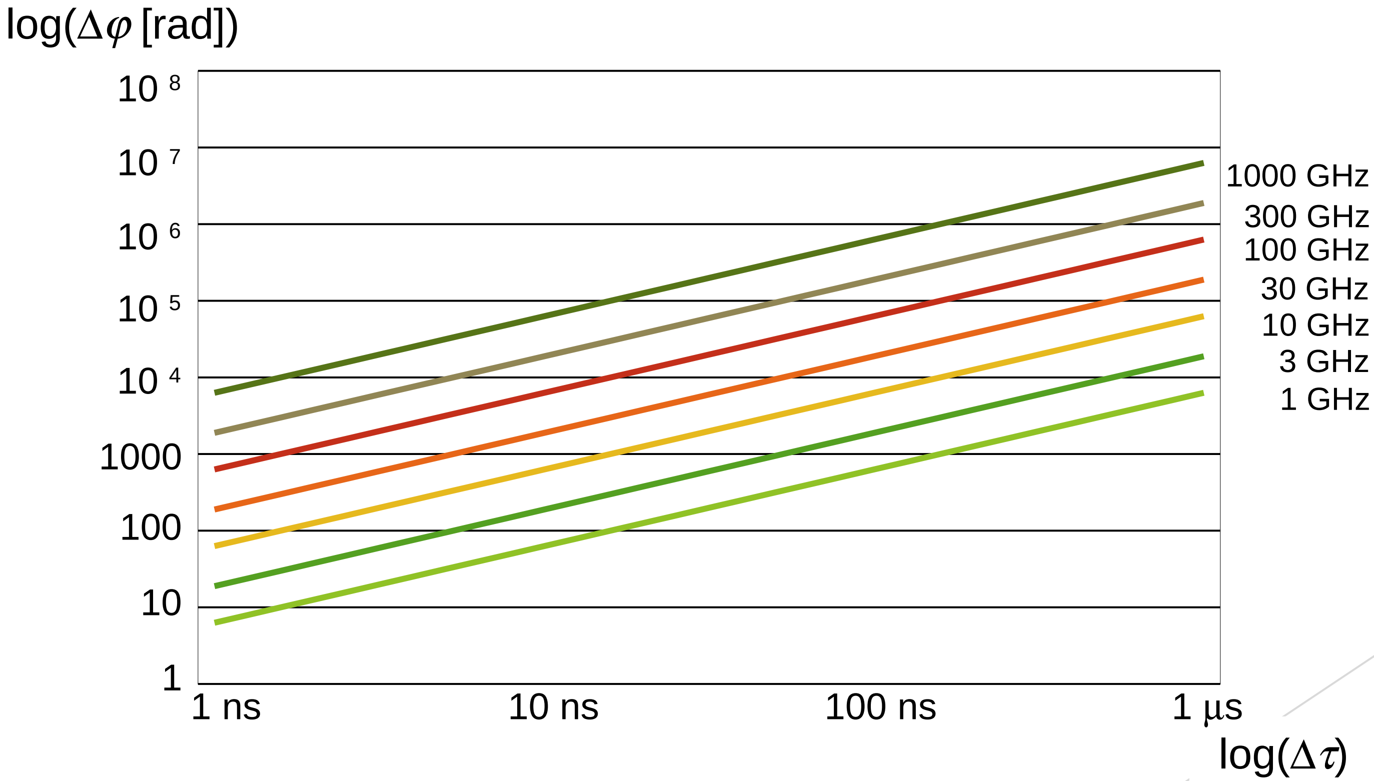
- Delay equalization for Rayleigh channels
  - All paths are affected by reflection and could be influenced by RIS elements
  - Single path impulse response theoretically feasible
- Delay equalization for Rice channels
  - Except direct path all paths are affected by reflection and could be influenced by RIS elements
  - Two-path impulse response theoretically feasible, which is frequency dependent
- In practice not feasible due to very long required delay lines (several m to several 100 m)

Delays and phase shifts in realistic multipath propagation channels

- Path Δd and delay differences $\Delta\tau$ are transformed in phase differences Δ with respect to first path at given carrier frequency f

$$\Delta\varphi = 2\cdot\pi\cdot\frac{\Delta d}{\lambda} = 2\cdot\pi\cdot\frac{\Delta d}{c_0}\cdot f = 2\cdot\pi\cdot\Delta\tau\cdot f \qquad \Delta d = c_0\cdot\Delta\tau$$

- Practical path delays are transformed in huge phase shifts



Optimum RIS settings

- Radio channel transfer function $H_{mp}(\omega)$ around ω_0 is Fourier transform of multipath channel impulse response $h_{mp}(t)$

$$H_{mp}(\omega)=\int_{-\infty}^{\infty} h_{mp}(t)\cdot e^{-j\omega t}dt=\int_{-\infty}^{\infty}\left(h_d\cdot\delta(t)+\sum_{i=1}^{I}h_{r,i}\cdot\delta(t-\tau_i)\right)\cdot e^{-j\omega t}dt=h_d+\sum_{i=1}^{I}h_{r,i}\cdot e^{-j\omega\tau_i}$$

- Maximum of received amplitude requires that all multipath components show the same phase at carrier frequency ω_0

$$\Re\left(H_{mp}(\omega_0)\right)=h_d+\sum_{i=1}^{I}h_{r,i}\cdot\cos(\omega_0\tau_i)=max \quad \Im\left(H_{mp}(\omega_0)\right)=\sum_{i=1}^{I}h_{r,i}\cdot\sin(\omega_0\tau_i)=0$$

- This is fulfilled for adjusted tap delays τ_i and phase shifts

$$\text{for} \quad i=1,2,3\ldots I$$

$$\Delta\varphi_i'=2\cdot\pi\cdot\frac{\Delta d_i'}{\lambda}=2\cdot\pi\cdot f_0\cdot\tau_i'=2i\cdot\pi$$

- Tap delays of RIS affected impulse response h_{mp}'(t) are adjusted to the raster

$$\tau_i'=\frac{i}{f_0}\quad\Delta\tau_{max}'=\frac{I}{f_0}$$ or reduced resolution for B_{system} $$\tau_k'=\frac{k}{B_{system}}\quad\Delta\tau_{max}'=\frac{K}{B_{system}}$$

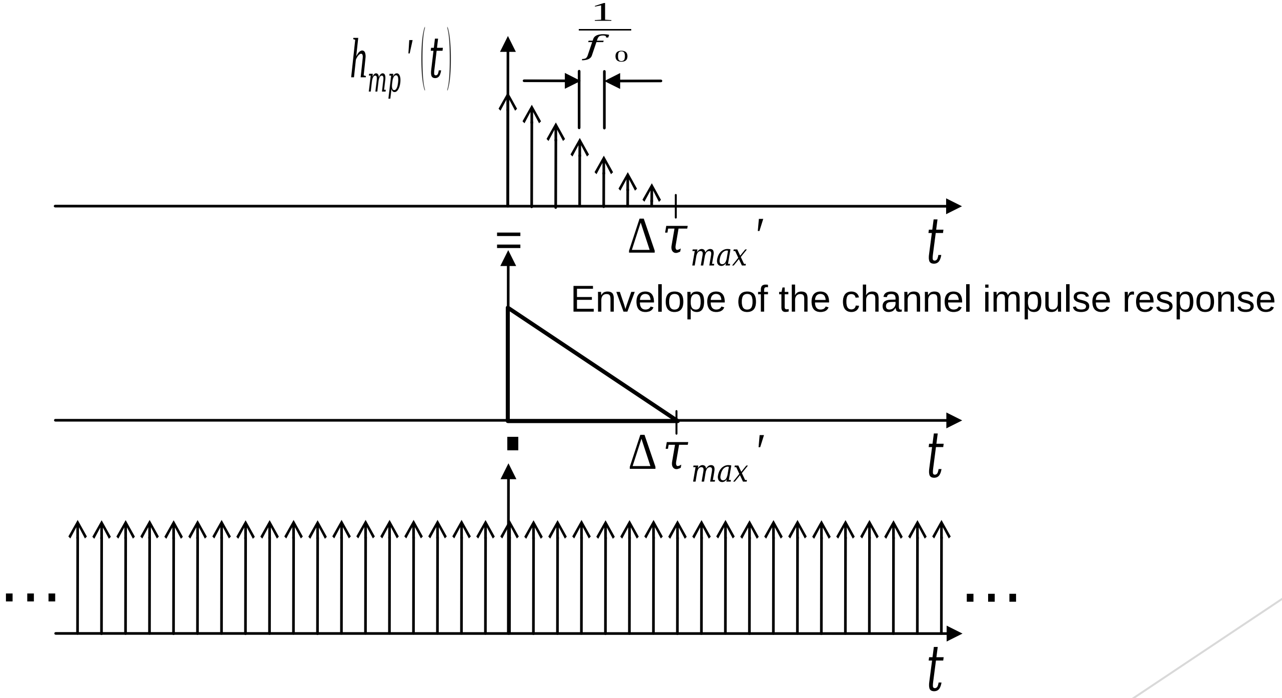
$$K=\int\left\{I\cdot\frac{B_{system}}{f_0}\right\}$$

Optimum RIS settings
Channel transfer function

- Channel transfer function $H'_{mp}(\omega)$ for optimal RIS settings of impulse response $h_{mp}'(t)$

$$h_{mp}'(t) = h_{mp}(t) \cdot \sum_{i=-\infty}^{\infty} \delta\left(t - i \cdot \frac{1}{f_0}\right)$$

$$H'_{mp}(\omega) = \mathcal{F}\left(h_{mp}(t)\right) * \mathcal{F}\left(\sum_{i=-\infty}^{\infty} \delta\left(t - i \cdot \frac{1}{f_0}\right)\right) = \mathcal{F}\left(h_{mp}(t)\right) * \sum_{i=-\infty}^{\infty} \delta(\omega - i \cdot \omega_0)$$



Optimum RIS settings – Examples

- Rectangular impulse response

$$h_{mp}(t)=\begin{cases} h_d & \text{¿}\, 0 \le t \le \Delta\tau_{max} \\ \text{¿}\, 0 & \text{¿}\, t<0 \wedge t>\Delta\tau_{max} \end{cases}$$

- Triangular impulse response

$$h_{mp}(t)=\begin{cases} h_d\cdot\left(1-\dfrac{t}{\Delta\tau_{max}}\right) & \text{¿}\, 0\le t\le\Delta\tau_{max} \\ \text{¿}\, 0 & \text{¿}\, t<0 \; and \; t>\Delta\tau_{max} \end{cases}$$

$$H'_{mp}(\omega)=h_d\cdot e^{-j\omega\cdot\frac{\Delta\tau_{max}}{2}}\cdot\text{¿}$$

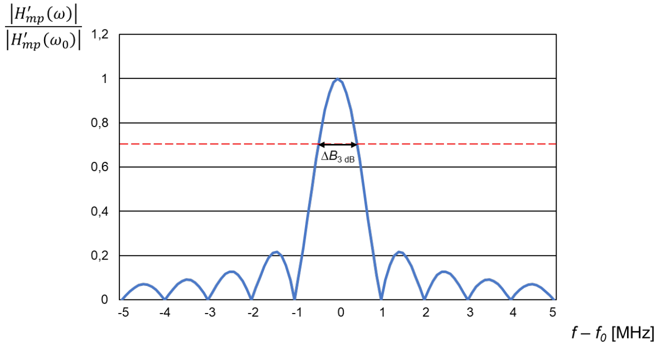
$$+j\frac{\cos\left(\omega\frac{\Delta\tau_{max}}{2}\right)}{\omega}-j\frac{\sin\left(\omega\frac{\Delta\tau_{max}}{2}\right)}{\frac{\Delta\tau_{max}}{2}\cdot\omega^2}\Bigg) * \sum_{k=-\infty}^{\infty}\delta(\omega-k\cdot\omega_0)$$

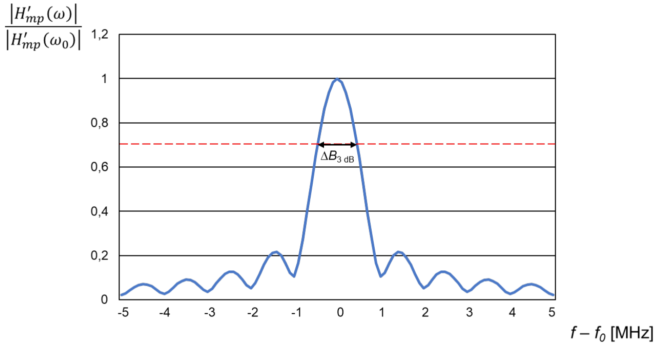
- Exponential impulse response

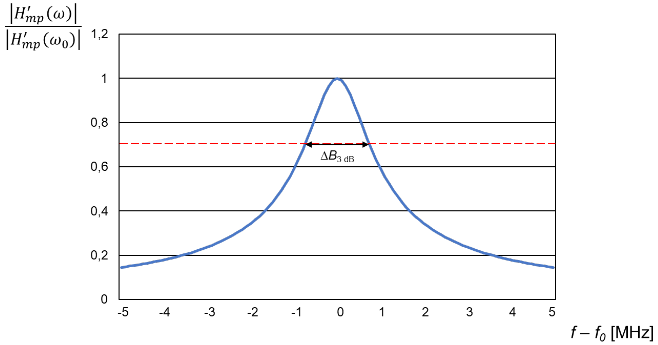
$$h_{mp}(t)=\begin{cases} h_d\cdot e^{-a\cdot t} & \text{¿}\, t\ge 0 \\ \text{¿}\, 0 & \text{¿}\, t<0 \end{cases}$$

$$a=-\frac{\ln 0.01}{\Delta\tau_{max}}$$

$$H'_{mp}(\omega)=h_d\cdot\frac{(a-j\omega)}{a^2+\omega^2}$$







- $\Delta\tau_{max}$ = 1 µs
- $\Delta\tau_{max}$ = 1 µs
- $\Delta\tau_{max}$ = 1 µs

Estimated channel capacity, SISO versus RIS

- With slide 5 the ratio of receive power and channel capacity is given as

$$\frac{P_{r,RIS,narrowband}}{P_{r,SISO,wideband}}=\frac{P_t\cdot G_t(\varphi,\theta)\cdot G_r(\varphi,\theta)\cdot\left(|h_d|+\sum_{i=1}^{I}|h_{r,i}|\right)^2}{P_t\cdot G_t(\varphi,\theta)\cdot G_r(\varphi,\theta)\cdot\left(|h_d|^2+\sum_{i=1}^{I}|h_{r,i}|^2\right)}=\frac{\left(|h_d|+\sum_{i=1}^{I}|h_{r,i}|\right)^2}{\left(|h_d|^2+\sum_{i=1}^{I}|h_{r,i}|^2\right)}$$

- Assumption: all paths have the same amplitude with *I* resolvable paths plus a direct path

and

- Results in power ratio, which increases with *L* of *I*, respectively

$$\frac{P_{r,RIS,narrowband}}{P_{r,SISO,wideband}}=\frac{\left(|\underline{h}_{sd}|+\sum_{i=1}^{I}|\underline{h}_{r,i}|\right)^2}{|\underline{h}_{sd}|^2+\sum_{i=1}^{I}|\underline{h}_{r,i}|^2}=\frac{(L\cdot|\underline{h}|)^2}{L\cdot|\underline{h}|^2}=L\,\hat{\text{¿}}\,10\cdot\log L$$

- It can be shown that the following bandwidth relation holds

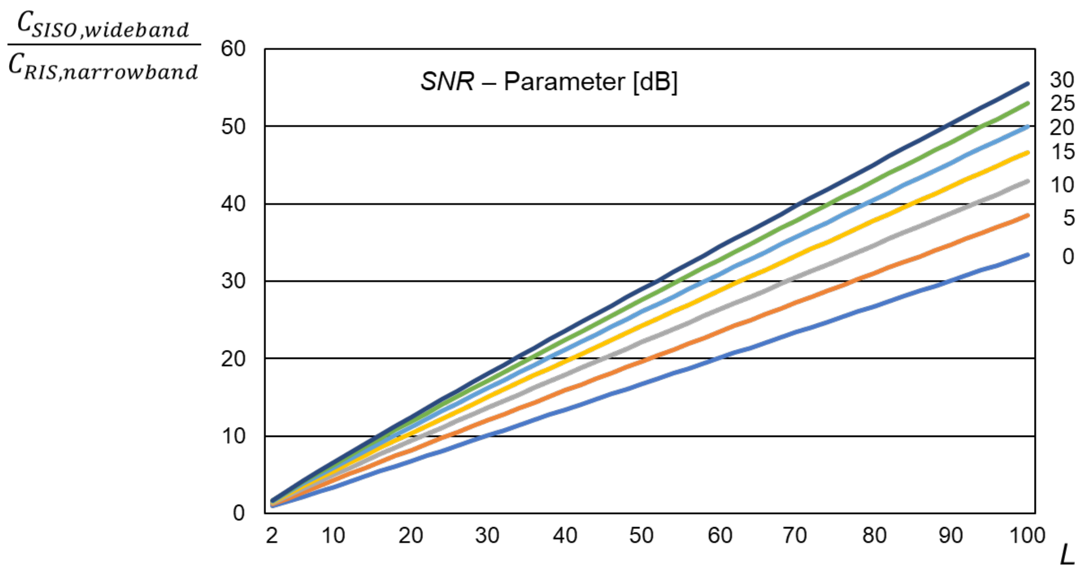
$$L=B_{system}\cdot\Delta\tau_{max}=B_{system,SISO}\cdot\Delta\tau_{max}$$

- Results in ratio of channel capacity ($B_{system,SISO}$ >> coherence bandwidth, fading process is ergodic)

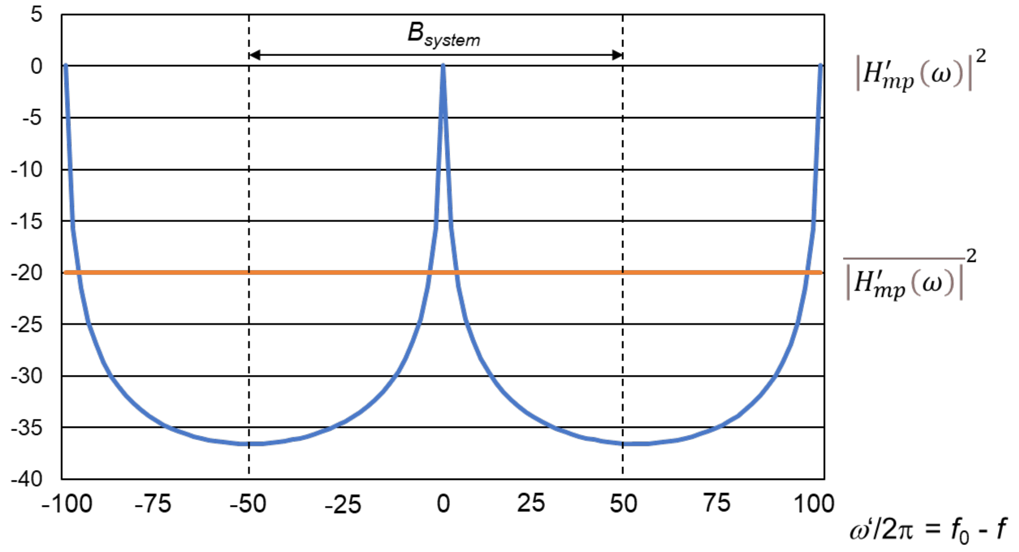
$$\frac{C_{SISO,wideband}}{C_{RIS,narrowband}}=\frac{B_{system,SISO}\cdot\log_2\left(1+\frac{P_t\cdot G_t(\varphi,\theta)\cdot G_r(\varphi,\theta)\cdot|\underline{h}|^2\cdot L}{N_0\cdot B_{system,SISO}}\right)}{\frac{B_{system,SISO}}{L}\cdot\log_2\left(1+\frac{P_t\cdot G_t(\varphi,\theta)\cdot G_r(\varphi,\theta)\cdot|\underline{h}|^2\cdot L^3}{N_0\cdot B_{system,SISO}}\right)}=\frac{L\cdot\log_2(1+SNR\cdot L)}{\log_2(1+SNR\cdot L^3)}$$

Estimated channel capacity, SISO versus RIS

- Channel capacity $C_{RIS,narrowband}$ is smaller than $C_{SISO,wideband}$



Gain of $C_{SISO,wideband}$ compared to $C_{RIS,narrowband}$ is increasing with *SNR* and number *L* of resolvable paths

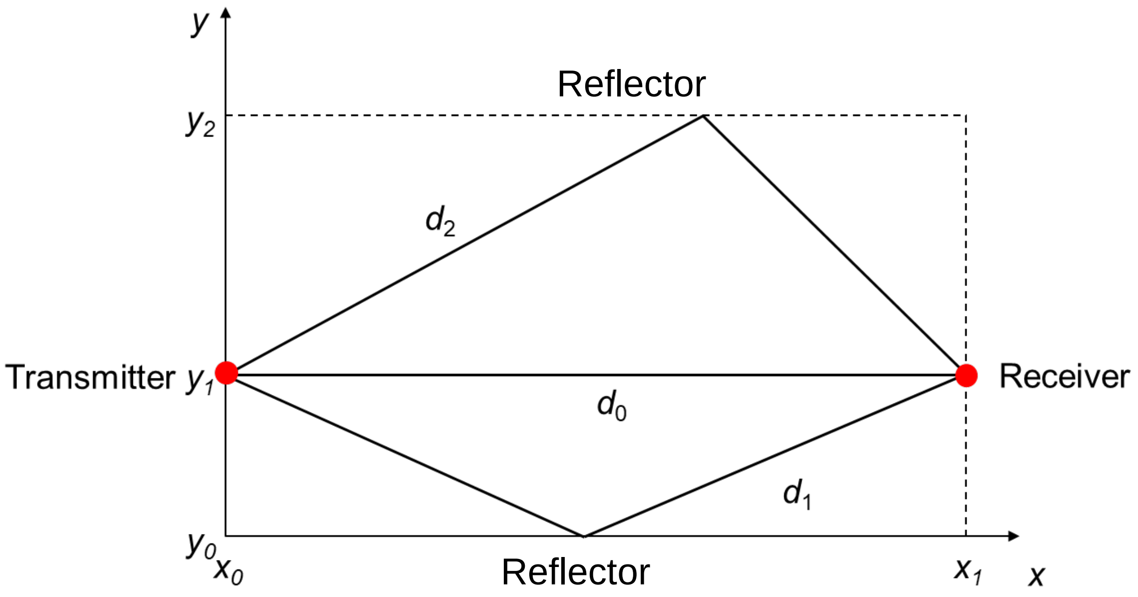


Normalized RIS transfer function for optimal RIS settings compared to average transfer function for parameters: f_0 = 10 GHz, B_{system} = 100 MHz, l = 99, 100, 101, $\Delta\tau_{max}$ = 1 µs

- The reduced RIS bandwidth $B_{system\ RIS} = B_{system,SISO}/L$
  - is reducing the channel capacity $C_{RIS,narrowband}$ linearly in front of the logarithm and
  - is increasing $C_{RIS,narrowband}$ logarithmically,
  - which results in an overall reduction compared to $C_{SISO,wideband}$

Impact of displacements of the mobile station

- Propagation scenario, example



Path lengths

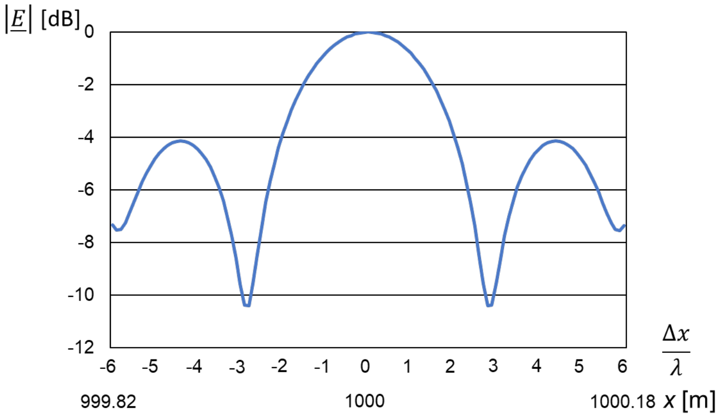
Delays in impulse response

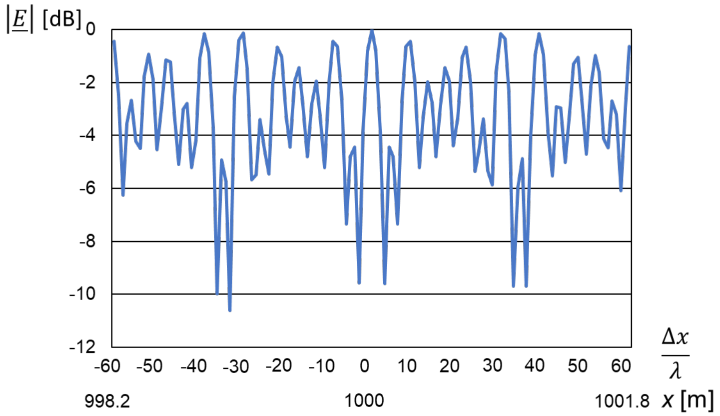
Associated path lengths and receiver coordinates at optimal RIS settings

Phase differences at 10 GHz

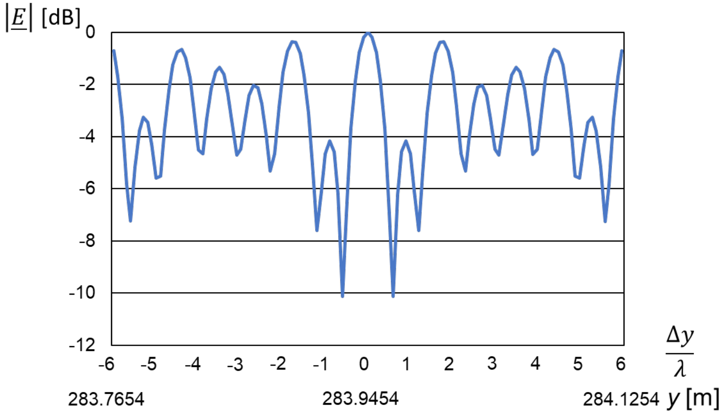
Impact of displacements of the mobile station

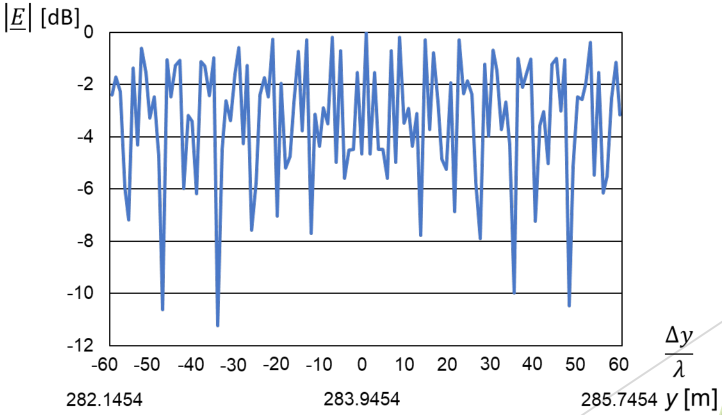
- Displacement along *x*-axis





- Displacement along *y*-axis

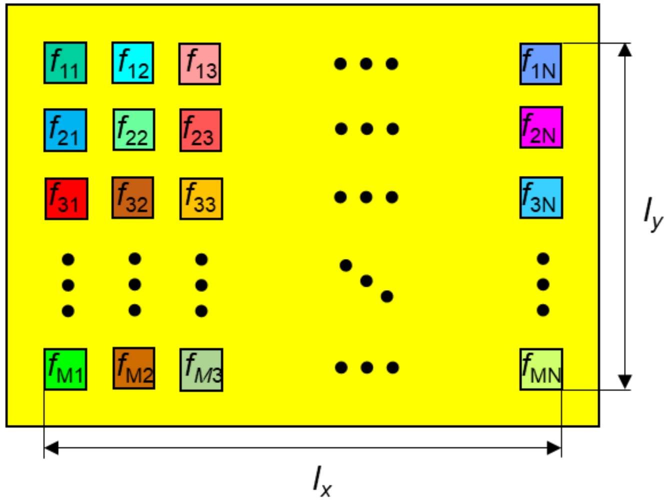




Displacement by 0.36 m or 12 λ (upper figure) and by 3.6 m or 120 λ (lower figure)

Approach to increase achievable bandwidth of radio channel transfer function – Approach

- 5G and 6G systems require system bandwidth in the order of several hundred up to several GHz
- Bandwidth increase by a RIS array, where different RIS array elements are optimized for different center frequencies



- With

$$\Delta B_{3\,dB} = B_{system,RIS} \approx \frac{1}{\Delta \tau_{max}} \qquad \text{for} \quad L >> 1$$

$$L = \int \left\{ \frac{B_{system}}{B_{system,RIS}} \right\} + 1 = \int \left\{ \frac{B_{system}}{\Delta B_{3\,dB}} \right\} + 1 = \int \left\{ B_{system} \cdot \Delta \tau_{max} \right\} + 1$$

RIS elements per array or different transfer functions are required

Approach to increase achievable bandwidth of radio channel transfer function – Approach

- Optimization of different sets for different center frequencies by appropriate tap spacing

$$\tau_{i+\int\left\{\frac{f_0+l\cdot\Delta B_{3dB}}{B_{system}}\right\}}-\tau_i=\Delta\tau_l=\frac{1}{B_{system}}$$

- Around the carrier frequency ω_0 the broadband transfer function follows

$$H'_{bb}(\omega)=\sum_{-L/2}^{L/2}\mathcal{F}\left(h_{mp}(t)\right)*\delta\left(\omega-\omega_0-l\cdot 2\pi\cdot\Delta B_{3dB}\right)$$

- is described by the sum of frequency shifted Fourier transforms of the impulse response

$$\mathcal{F}\left(h_{mp}(t)\right)=H_{mp}(\omega)$$

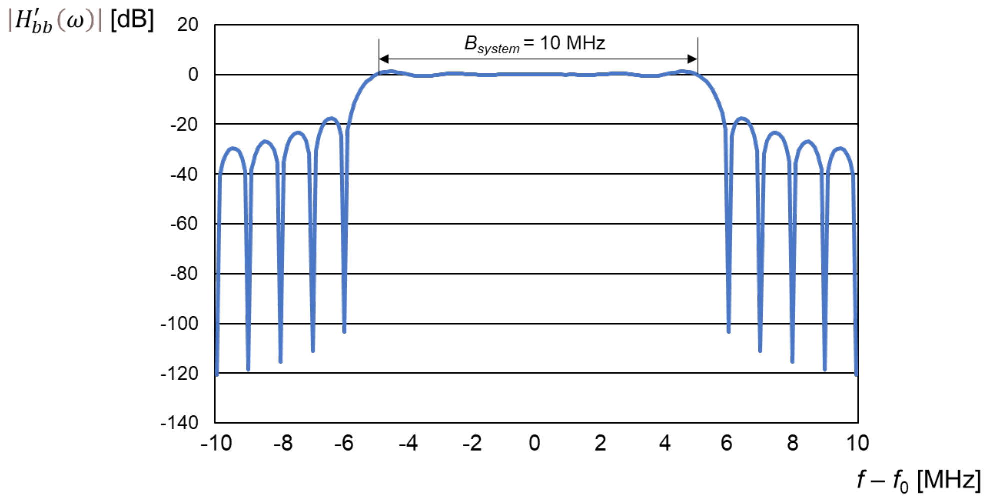
$$H'_{bb}(\omega)=\sum_{-L/2}^{L/2}H_{mp}\left(\omega-\omega_0-l\cdot 2\pi\cdot\Delta B_{3dB}\right)$$

$$\left|H'_{bb}(\omega)\right|=\sqrt{\left[\sum_{-L/2}^{L/2}\Re\left\{H_{mp}\left(\omega-\omega_0-l\cdot 2\pi\cdot\Delta B_{3dB}\right)\right\}\right]^2+\left[\sum_{-L/2}^{L/2}\Im\left\{H_{mp}\left(\omega-\omega_0-l\cdot 2\pi\cdot\Delta B_{3dB}\right)\right\}\right]^2}$$

Approach to increase achievable bandwidth of radio channel transfer function – Examples

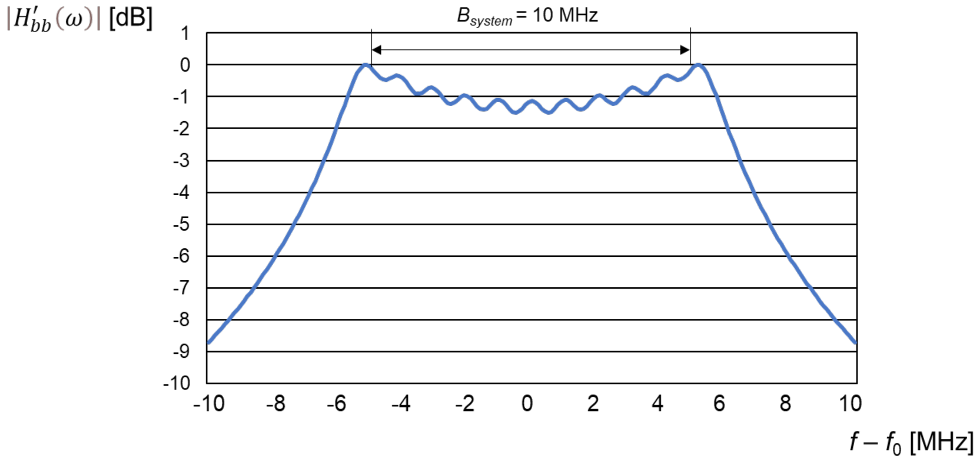
- Rectangular impulse response

$$H_{bb}^{'}(\omega)=\sum_{-L/2}^{L/2} h_{sd}\cdot 2\cdot\frac{\sin\left(\left(\omega-\omega_0-l\cdot 2\pi\cdot\Delta B_{3dB}\right)\cdot\frac{\Delta\tau_{max}}{2}\right)}{\left(\omega-\omega_0-l\cdot 2\pi\cdot\Delta B_{3dB}\right)}\cdot\cos\left(\left(\omega-\omega_0-l\cdot 2\pi\cdot\Delta B_{3dB}\right)\cdot\frac{\Delta\tau_{max}}{2}\right)-j\sum_{-L/2}^{L/2} h_{sd}\cdot 2\cdot\frac{\sin\left(\left(\omega-\omega_0-l\cdot 2\pi\cdot\Delta B_{3dB}\right)\cdot\frac{\Delta\tau_{max}}{2}\right)}{\left(\omega-\omega_0-l\cdot 2\pi\cdot\Delta B_{3dB}\right)}\cdot\sin\left(\left(\omega-\omega_0-l\cdot 2\pi\cdot\Delta B_{3dB}\right)\cdot\frac{\Delta\tau_{max}}{2}\right)$$



- Exponential impulse response

$$H_{bb}^{'}=\sum_{-L/2}^{L/2} h_{sd}\cdot\frac{a}{a^2+\left(\omega-\omega_0-l\cdot 2\pi\cdot\Delta B_{3dB}\right)^2}-j\sum_{-L/2}^{L/2} h_{sd}\cdot\frac{\omega-\omega_0-l\cdot 2\pi\cdot\Delta B_{3dB}}{a^2+\left(\omega-\omega_0-l\cdot 2\pi\cdot\Delta B_{3dB}\right)^2}$$



Parameters: B_{system} = 10 MHz, $B_{system,RIS}$ 1 MHz, $\Delta\tau_{max}$ = 1 µs, L at least 10

Approach to increase achievable bandwidth of radio channel transfer function – Channel capacity

- Standard SISO and RIS have the same bandwidth $B_{system,SISO} = B_{system,RIS}$
- Optimistic assumption: the received path amplitudes for SISO and RIS are the same
- All resolvable paths have the same amplitude h (rectangular envelope of impulse response)

$$C_{SISO,wideband} = B_{system,SISO} \cdot \log_2\left(1 + \frac{P_t \cdot G_t(\varphi,\theta) \cdot G_r(\varphi,\theta) \cdot L \cdot |h|^2}{N_0 \cdot B_{system,SISO}}\right)$$

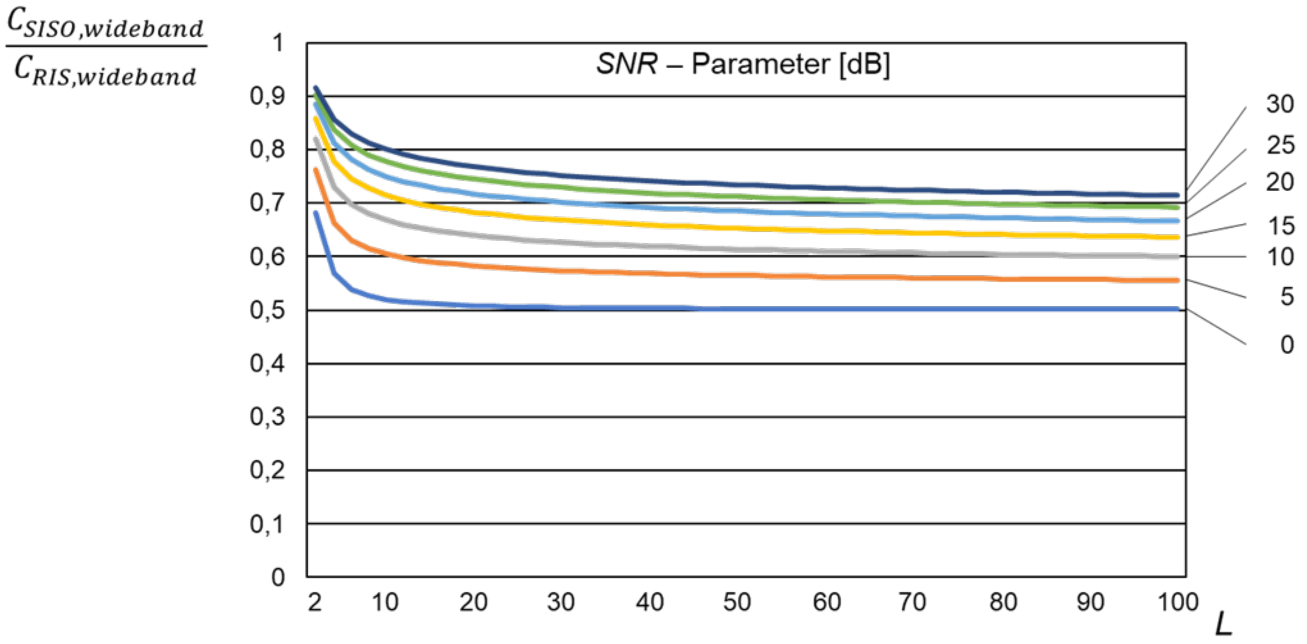
$$C_{RIS,wideband} = B_{system,RIS} \cdot \log_2\left(1 + \frac{P_t \cdot G_t(\varphi,\theta) \cdot G_r(\varphi,\theta) \cdot (L \cdot |h|)^2}{N_0 \cdot B_{system,RIS}}\right)$$

- Ratio of channel capacity with *SNR*

$$SNR = \frac{P_t \cdot G_t(\varphi,\theta) \cdot G_r(\varphi,\theta) \cdot |h|^2}{N_0 \cdot B_{system,SISO}}$$

$$\frac{C_{SISO,wideband}}{C_{RIS,wideband}} = \frac{\log_2(1 + SNR \cdot L)}{\log_2(1 + SNR \cdot L^2)}$$

Approach to increase achievable bandwidth of radio channel transfer function – Channel capacity



- Gain in channel capacity of RIS compared to SISO system is rather limited:

$$0.5 \leq \frac{C_{SISO,wideband}}{C_{RIS,wideband}} \leq 1$$

- Gain disappears,
  - when scattering (spherical waves) at RIS elements considered
  - compared to reflection at bigger areas (plane waves) in standard SISO case

- Limiting values
  - For L = 1 both systems provide same channel capacity
  - $$\frac{C_{SISO,wideband}}{C_{RIS,wideband}} = \lim_{L \to \infty \wedge SNR=1} \frac{\log_2(1+SNR \cdot L)}{\log_2(1+SNR \cdot L^2)} = \frac{\log_2(L)}{\log_2(L)+\log_2(L)} = 0.5$$
  - $$\frac{C_{SIS=,wideband}}{C_{RIS,wideband}} = \lim_{SNR \to \infty} \frac{\log_2(1+SNR \cdot L)}{\log_2(1+SNR \cdot L^2)} = \frac{\log_2(SNR)+\log_2(L)}{\log_2(SNR)+\log_2(L)+\log_2(L)} = 1$$

Implementation and operational aspects

- Conceptual implementation aspects
  - At receiver channel estimation necessary for all significant resolvable paths
  - Channel estimation sent to different RIS arrays and/or for centralized calculation of optimal RIS settings to base station
  - Most probably, centralized calculation of RIS settings required for simultaneous adjustment of all RIS elements and different center frequencies for sub-transfer functions to support requested system bandwidth
  - Settings communicated from base station to all RIS arrays either via an additional radio link or fixed lines
  - Fast adaptation of RIS setting in case of mobility
  - Different users at different locations require different RIS elements
  - Therefore, RIS array size depends on system bandwidth, length of channel impulse response and number of simultaneous users
  - Different RIS arrays need to be deployed in radio environment, where main reflection areas occur, e.g., at buildings
  - Due to limited physical RIS size not feasible that each RIS element can adjust path delay especially for longer impulse responses, only phase shift of each path can be adjusted
  - Wideband systems like 5G or 6G require huge number of sub-transfer functions

- Operational aspects
  - RIS system requires deployment of additional equipment on top of base station sites
    - RIS arrays
    - including centralized evaluation of channel estimation
    - calculation of optimal RIS settings and
    - signaling of RIS settings to RIS arrays
  - Such additional equipment requires
    - site acquisition for RIS arrays in addition to often difficult site acquisition of base station antenna sites
    - power supply for RIS arrays for controlling electronics
    - potentially fixed lines from central RIS optimization in base station to different RIS arrays
    - negotiations and agreements with building owners to deploy and operate RIS arrays
    - additional maintenance of RIS arrays on top of other networking elements

Conclusion

- Reconfigurable Intelligent Surfaces (RIS) investigated to increase the channel capacity
- Multipath propagation results in impulse responses of different delayed paths, which show in practice large delays and are transformed in frequency dependent phase shift
- RIS systems adjust phase shifts of different resolvable paths that all paths are super imposed constructively at carrier frequency
- Frequency independent RIS system requires single path channel; however, not applicable for radio channels with direct component and would require unrealistic long delay lines
- However, in practice all path phase shifts adjusted to modulo 2π instead of same delay
- This superposition is very sensitive with respect to the frequency and displacement of users and only available in very narrow bandwidth
- Achievable 3 dB bandwidth corresponds approximately to inverse of length $\Delta\tau_{max}$ of channel impulse response, which is much smaller than needed for 5G and 6G systems
- Narrowband RIS system provides lower channel capacity than a standard SISO system
- Spatial filter bank with RIS elements, which are optimized for different frequencies, can provide a wideband RIS system
- However, for same received path amplitudes only small RIS gain feasible, which disappears when considering different reflection and scattering behavior for standard SISO and RIS system