Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Mobile Channel Characterization in Typical Subway Tunnels at 30 GHz
Date Submitted: 11 September, 2015
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Abstract: Based on extensive ray-tracing simulations, this document presents channel characterization for a receiver moving at the speed of 100 m/s in tunnels with 2 GHz bandwidth between 31.5 GHz and 33.5 GHz. The main channel parameters, such as path loss, Rician K-factor, delay spread, Doppler spread, coherence time, decorrelation distance, XPD and CPR are analyzed for three antenna setups.

Purpose: The Channel characteristics can be helpful for link-level simulation of mobile communications in tunnel environments at 30 GHz

Outline

- Introduction of BJTU and RCS
- Motivation of channel characterization for HRRC
- Deterministic channel modeling approach
  - Ray-tracing simulator
  - Frequency domain simulation
- Channel simulation and characteristics
- Conclusion and future work

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1. Introduction of BJTU

Beijing Jiaotong University (BJTU) is a national key university in China:

1. What does "Jiaotong" mean? -- Internet of Everything
2. Established the Collaborative Innovation Centre for Rail Transit Safety, approved by the Chinese government to enter the "National 2011 Projects".

1. Introduction of RCS

The **State Key Laboratory of Rail Traffic Control and Safety** (RCS) in BJTU is the **only state key laboratory** for rail traffic control and safety.

The basic theory and key technology

- Rail traffic control
- Safety assurance
- Train control
- **Dedicated communication**

1. Introduction of RCS

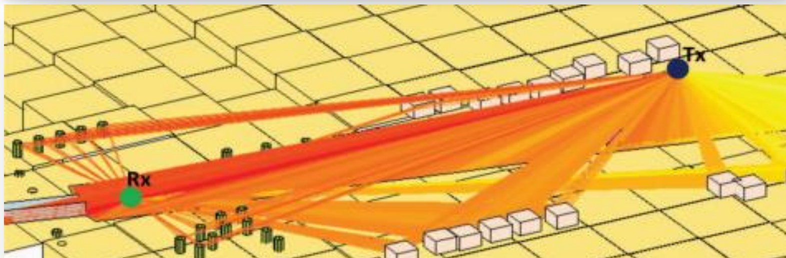
GSM-R and LTE-R Research and Application Network System

- **1st GSM-R and LTE-R research platforms in China**
- **Leading the work of GSM-R and LTE-R technical specifications**

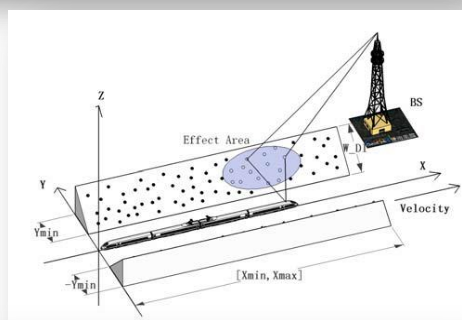
The first GPRS access server interfacing with railway Intranet in China

1. Introduction of RCS

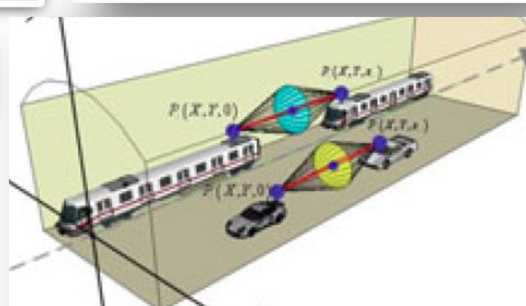
Deterministic modeling



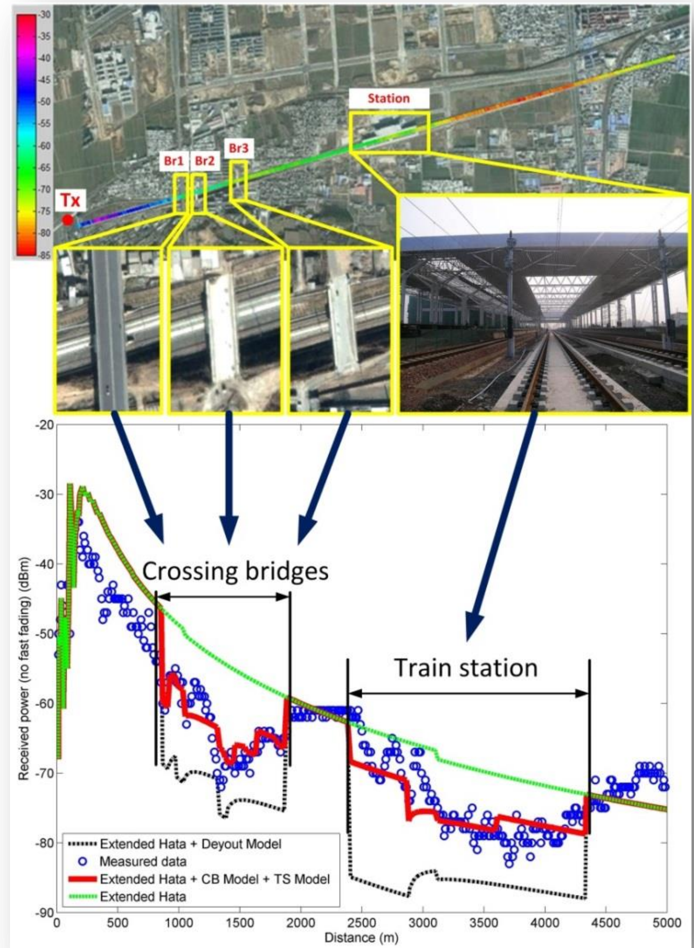
Geometry-based stochastic modeling



Tunnels



Semi-closed obstacles



1. Introduction of RCS

- **Latest selected journal publications:**

- **K. Guan**, et al., "Measurements and Analysis of Large-Scale Fading Characteristics in **Curved Subway Tunnels** at 920 MHz, 2400 MHz, and 5705 MHz," to appear, ***IEEE Transactions on Intelligent Transportation Systems***, 2015.
- **K. Guan**, et al., "Empirical Models for Extra Propagation Loss of **Train Stations** on High-Speed Railway," ***IEEE Transactions on Antennas and Propagation***, vol. 62, no. 3, pp. 1395-1408, 2014.
- **K. Guan**, et al., "Propagation Measurements and Analysis for **Train Stations** of High-Speed Railway at 930 MHz," ***IEEE Transactions on Vehicular Technology***, vol. 63, no. 8, pp. 3499-3516, 2014.
- **K. Guan**, et al., "Propagation Measurements and Modeling of **Crossing Bridges** on High-Speed Railway at 930 MHz," ***IEEE Transactions on Vehicular Technology***, vol. 63, no. 2, pp. 502-517, 2014.
- **K. Guan**, et al. "Measurements of Distributed Antenna Systems at 2.4 GHz in a Realistic **Subway Tunnel** Environment," ***IEEE Transactions on Vehicular Technology***, vol. 61, no.2, pp. 834-837, 2012.
- **K. Guan**, et al., "On the Influence of Scattering from Traffic Signs in **Vehicle-to-X** Communications," to appear, ***IEEE Transactions on Vehicular Technology***, 2015.
- B. Ai, **K. Guan**, et al., "Measurement and Analysis of Extra Propagation Loss of **Tunnel Curve**," to appear, ***IEEE Transactions on Vehicular Technology***, 2015.
- B. Ai, **K. Guan**, et al., "**Future Railway** Services Oriented Mobile Communications Network," to appear, ***IEEE Communication magazine***, 2015.
- **K. Guan**, et al., "Semi-Deterministic Path-Loss Modeling for **Viaduct and Cutting Scenarios** of High-Speed Railway," ***IEEE Antennas and Wireless Propagation Letters***, vol. 12, pp. 789-792, 2013.
- **K. Guan**, et al., "Complete Propagation Modeling in **Tunnels**," ***IEEE Antennas and Wireless Propagation Letters***, vol. 12, pp. 741-744, 2013.

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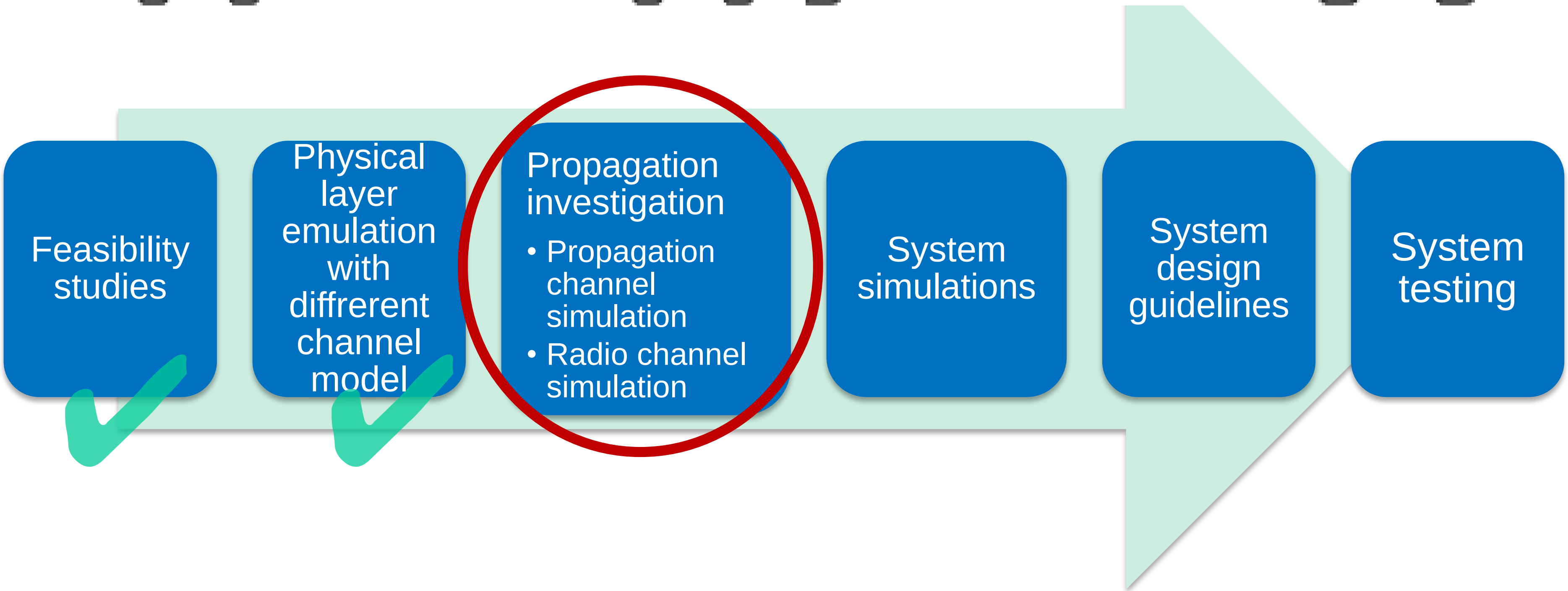
2. Motivation of channel characterization for HRRC

Gbps data rate with high performance should be provided to the user groups inside of the fast-moving vehicles.



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3. Deterministic channel modeling approach

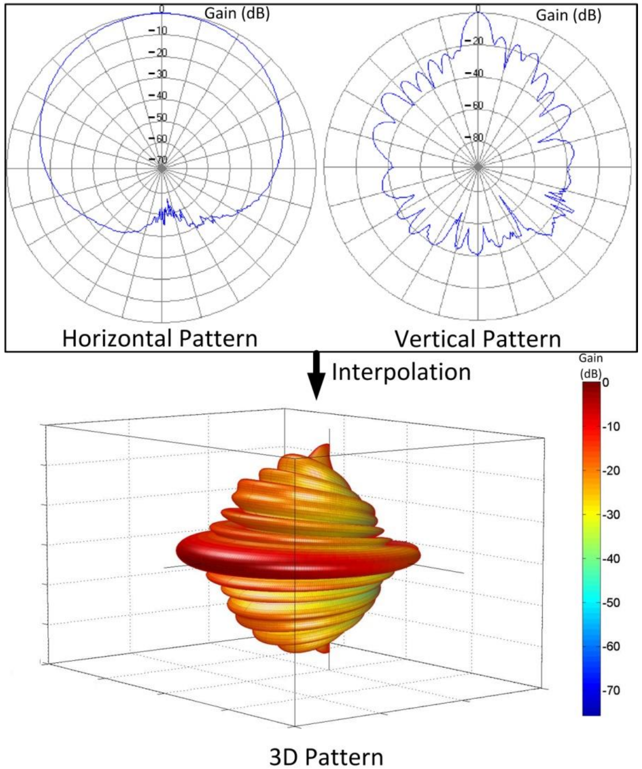
Ray-tracing based channel modeling

Deterministic modeling approach towards real scenarios

3D ray optical channel model:
Transmission, reflection, scattering

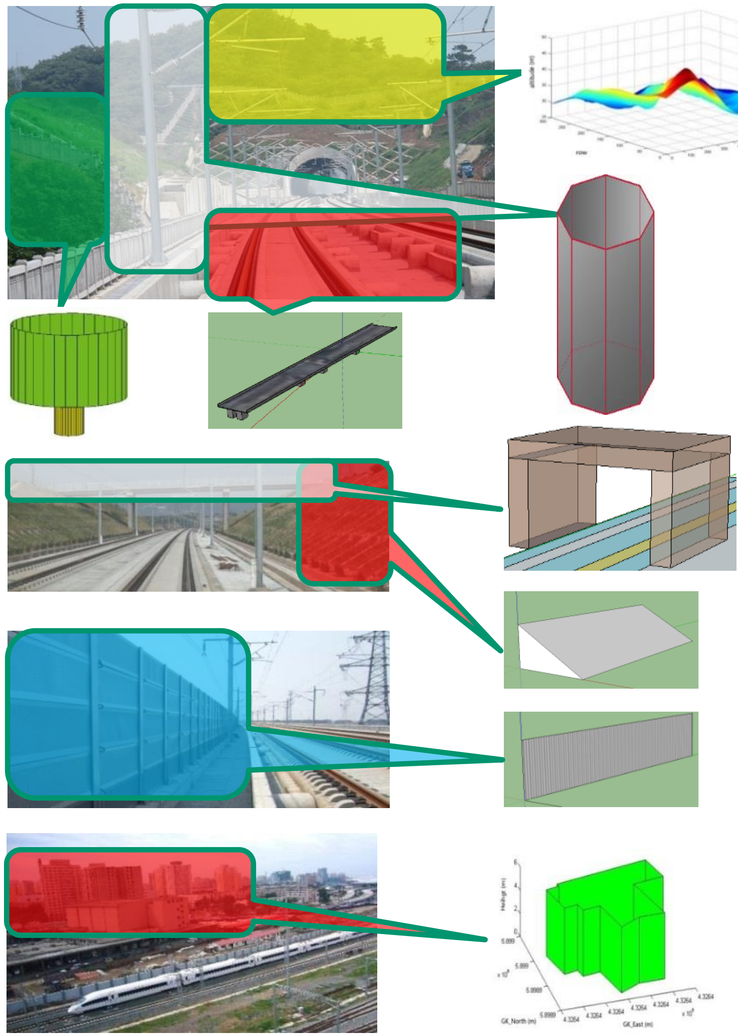
- Antenna modeling
- Ray optical method

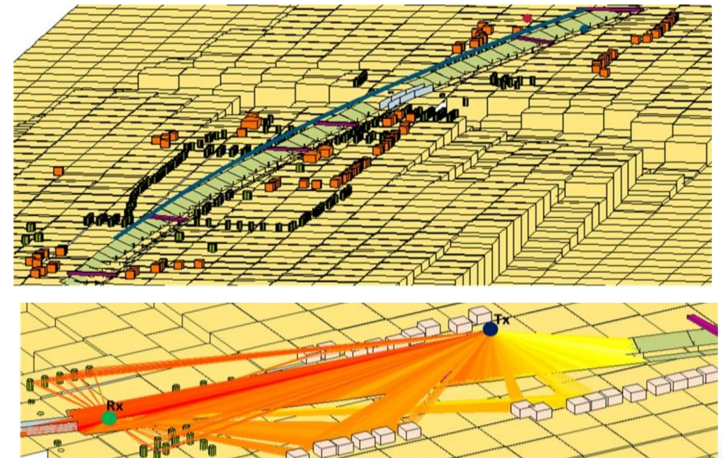
$$h(\tau,t)=\sum_{k=1}^{N(t)} a_k(t)\cdot e^{j(2\pi f\tau_k(t)+\varphi_k(t))}\cdot\delta(\tau-\tau_k(t))$$

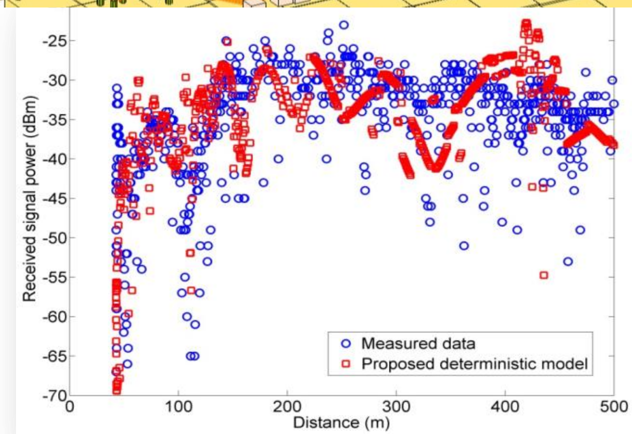


J. Nuckelt, et al., “Deterministic and stochastic channel models implemented in a physical layer simulator for Car-to-X communications,” 2010 Advances in Radio Science, 2010.

3. Deterministic channel modeling approach







K. Guan, Z.D. Zhong, B. Ai, and T. Kuerner, "Deterministic Propagation Modeling for the Realistic High-Speed Railway Environment," IEEE 77th VTC2013-Spring, Dresden, Germany, pp. 1-5, June 2013.

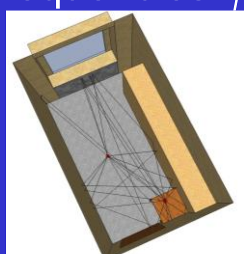
3. Deterministic channel modeling approach

UWB channel: Frequency domain simulation

UWB → Significant frequency dispersion → Single frequency ray tracing insufficient

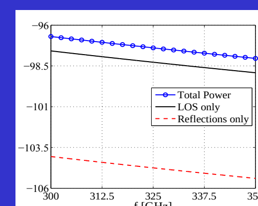
Idea: Channel simulation in frequency domain

Ray tracing at multiple frequencies f_i

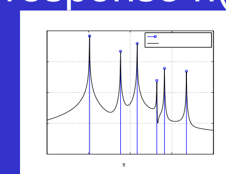


→ Coherent summation of all ray amplitudes for each f_i

→ Channel transfer function *H(f)*



IFFT → Broadband channel impulse response h(t)



$$H(f_i) = \sum_{j=1}^{N_{Rays}} E_j(f_i)$$

Ray amplitudes from ray tracing

$$H(f) = \sum_{i=1}^{N_f} H(f_i)$$

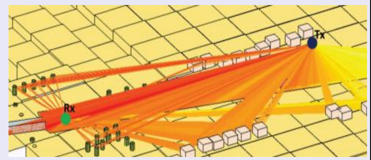
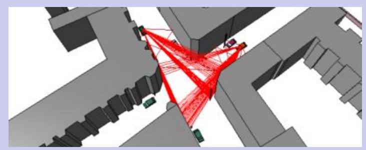
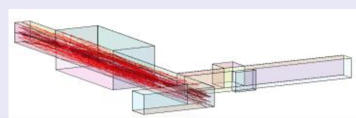
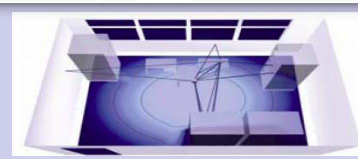
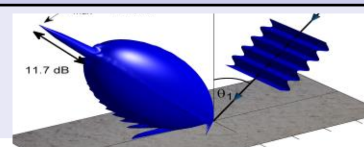
$$N_f \cdot \left(\frac{1}{B}\right) \geq \tau_{\max} \Rightarrow N_f \geq \tau_{\max} \cdot B$$

2 GHz, 177 ns → 266 frequencies

S. Priebe and T. Kürner, "Stochastic Modeling of THz Indoor Radio Channels," IEEE Trans. Wireless Commun., vol.12, no.9, pp. 4445–4455, Sept. 2013.

3. Deterministic channel modeling approach

The ray-tracing simulator has been verified by extensive measurements:

Frequency	System	Scenario	reference
930 MHz	GSM-R	High-speed railway 	K. Guan, et al., "Deterministic Propagation Modeling for the Realistic High-Speed Railway Environment," IEEE VTC2013-Spring, Dresden, Germany, pp. 1-5, June 2013.
5.9 GHz	DSRC	Urban 	T. Abbas, et al., "Simulation and Measurement Based Vehicle-to-Vehicle Channel Characterization: Accuracy and Constraint Analysis," IEEE Trans. on Ant. and Prop., 2015.
15 GHz	5G D2D	Corridor 	Q. Wang, et al., "Ray-Based Analysis of Small-Scale Fading for Indoor Corridor Scenarios at 15 GHz," APEMC 2015
30 GHz, HRRC, Typical subway tunnel			
60 GHz	WLAN	Indoor 	M. Jacob, et al., "Diffraction in MM and Sub-MM Wave Indoor Propagation Channels," IEEE Transactions on Microwave Theory and Techniques, vol.60, no.3, pp.833-844, Mar. 2012.
275 GHz-325 GHz	WLAN WPAN	Indoor 	S. Priebe et al., "Stochastic Modeling of THz Indoor Radio Channels," IEEE Trans. Wireless Commun., vol.12, no.9, pp. 4445–4455, 2013.

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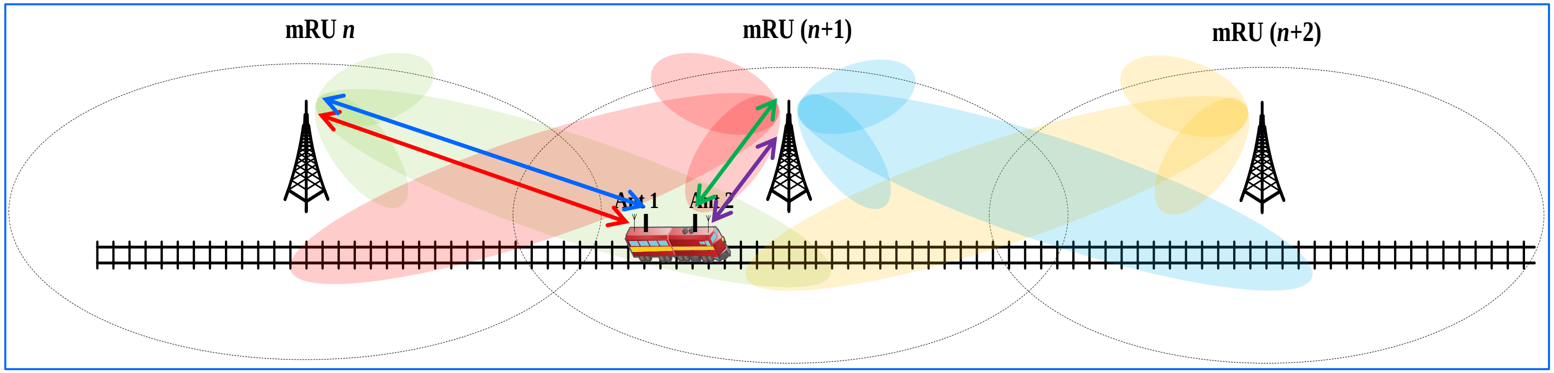
4. Channel simulation and characteristics

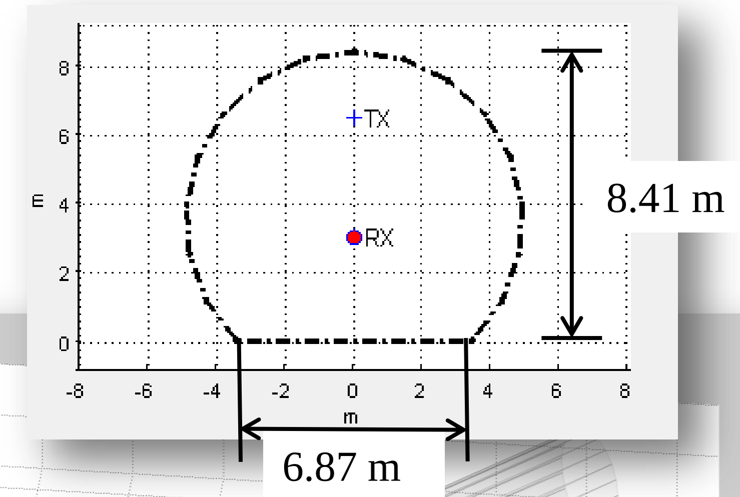
System: Mobile Hotspot Network (MHN)	
Cell Coverage	1 km (mRU interval)
Frequency	31.5~33.5 GHz
Bandwidth	125 MHz x 4
Length of Train	200 m
Antenna Setup	Head ant. + Tail ant.
MIMO Configuration	1x1, 1x2, 2x1, 2x2
Target Maximum Speed	400 ~ 500 km/h
Antenna Type	Patch array antenna (directional ant.) w. 8^{o} beam width (3 dB width)
Antenna Separation	Around 10 cm

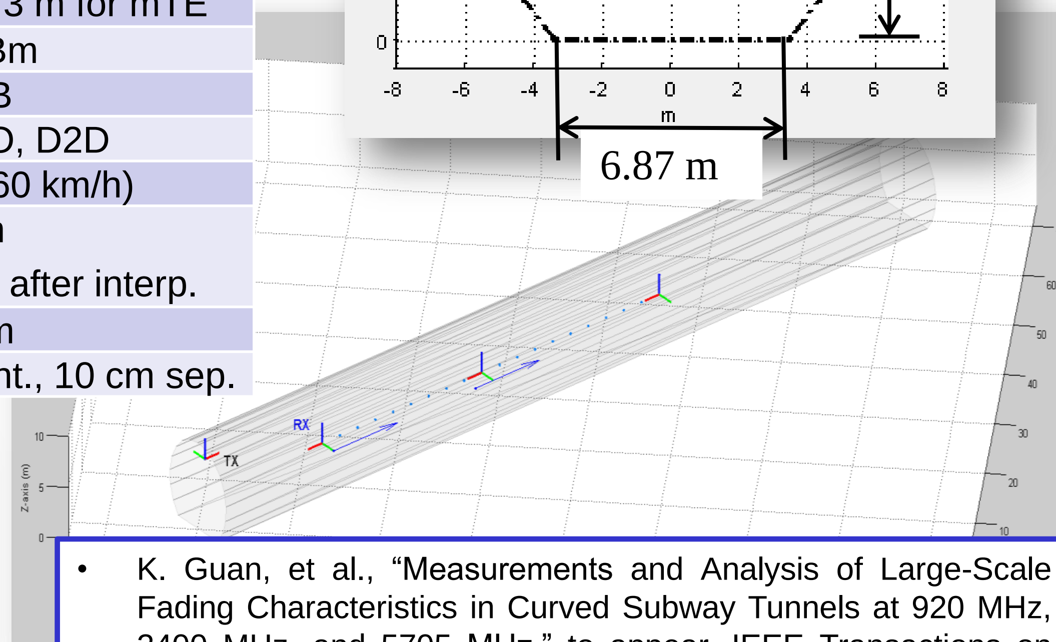
Dae-Soon Cho, et al., "Performance of downlink control channels for Mobile Hotspot Network system," in 2013 International Conference on ICT Convergence (ICTC), pp.909-912, 14-16 Oct. 2013



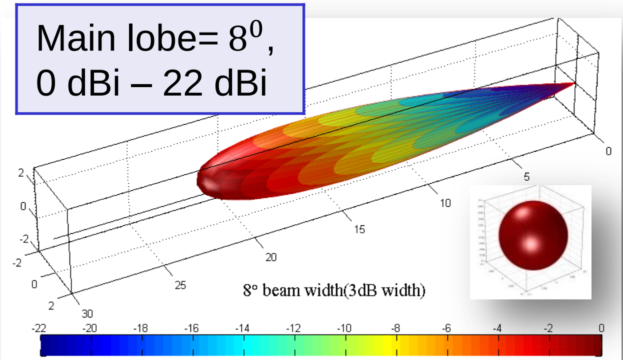
4. Channel simulation and characteristics

Simulation Setup	
Environment	Subway tunnel
Tunnel Type	Arched subway tunnel
Frequency	31.5~33.5 GHz
Bandwidth	125 MHz (Time resolution: 8 ns)
Antenna Height	6.5 m for mRU, 3 m for mTE
Transmission Power	20 dBm
Cable Loss	6 dB
Antenna Setup	O2O, D2O, D2D
Speed	100 m/s (360 km/h)
Sampling Interval	1 m 2 mm (≈0.2λ) after interp.
Distance	1 km
MIMO Antennas	2 Head + 2 Tail ant., 10 cm sep.





Main lobe= 8^0,
0 dBi – 22 dBi



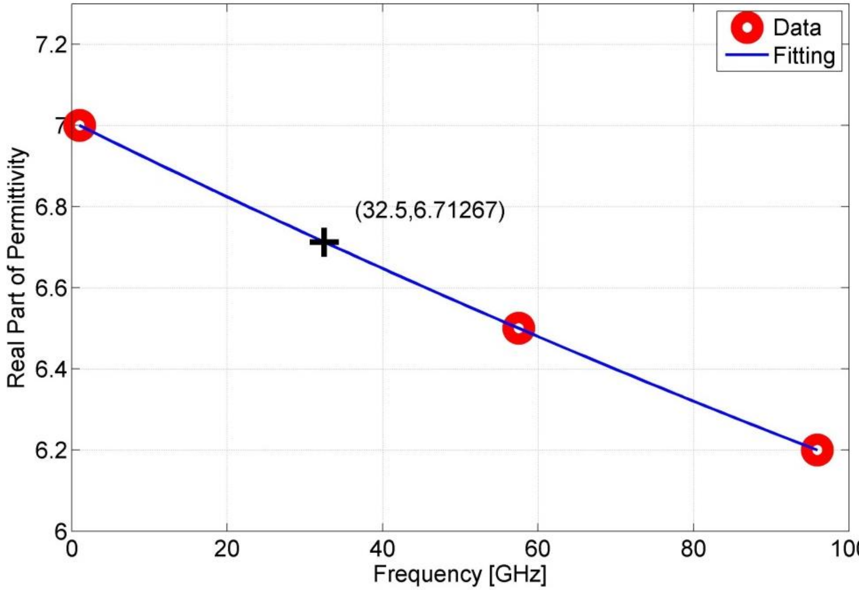
- K. Guan, et al., "Measurements and Analysis of Large-Scale Fading Characteristics in Curved Subway Tunnels at 920 MHz, 2400 MHz, and 5705 MHz," to appear, IEEE Transactions on Intelligent Transportation Systems, 2015.
- M. Schack, Integrated Simulation of Communication Applications in Vehicular Environments, Ph.D. Dissertation

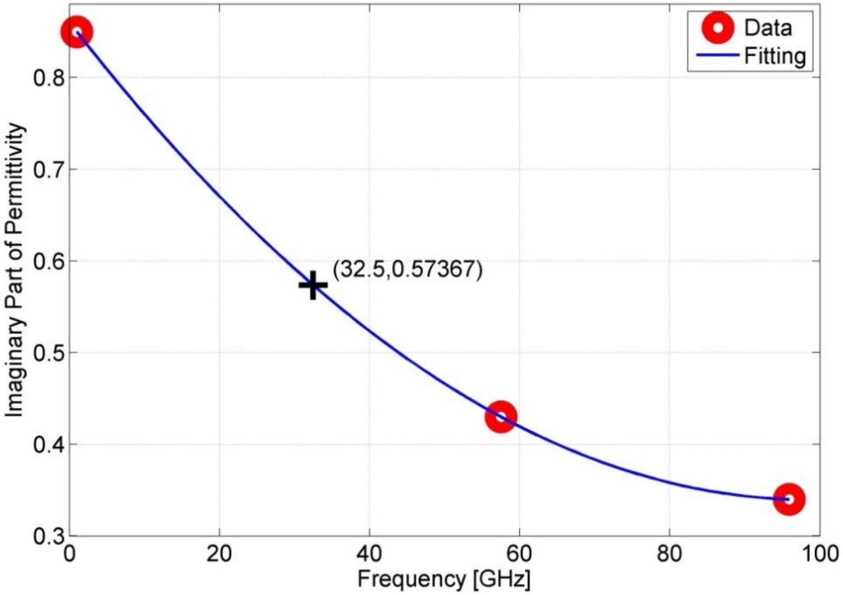
Electromagnetic property

Material	
Tunnel walls	Concrete
Real part of relative permittivity	6.71267
Imaginary part of relative permittivity	0.67367

$$\varepsilon = \varepsilon' - j\varepsilon''$$

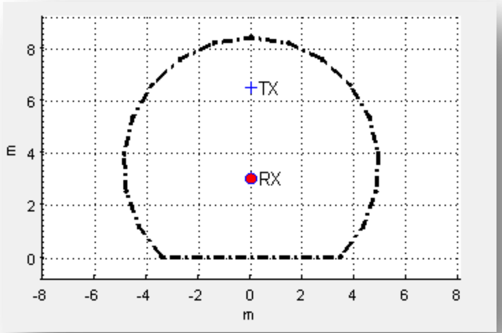
$$\text{Loss tangent} = \arctan\frac{\varepsilon''}{\varepsilon'}$$





Recommendation ITU-R P.1238-7-EM Property

Geometry of tunnel and orders of reflections

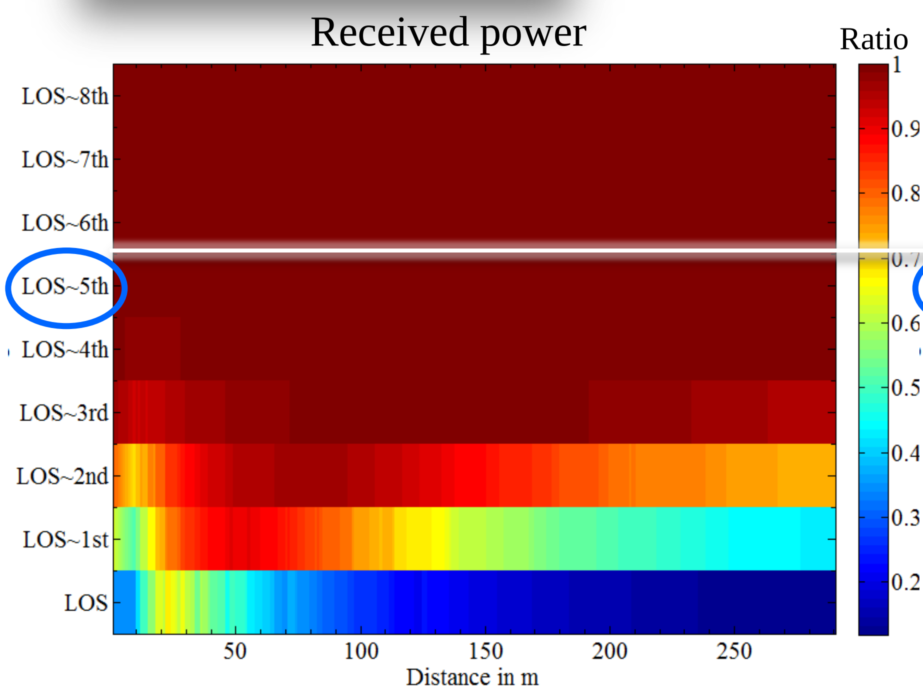


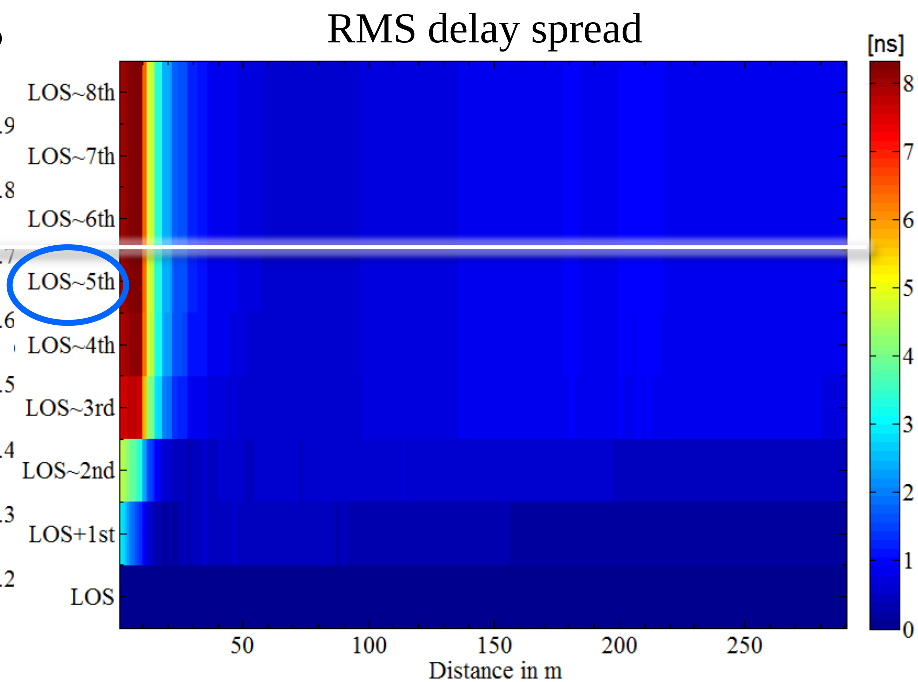
Tunnel – 17 faces

Direct ray + reflected rays

Order of reflections – 5

K. Guan, et al., "Measurements and Analysis of Large-Scale Fading Characteristics in Curved Subway Tunnels at 920 MHz, 2400 MHz, and 5705 MHz," to appear, IEEE Transactions on Intelligent Transportation Systems, 2015.

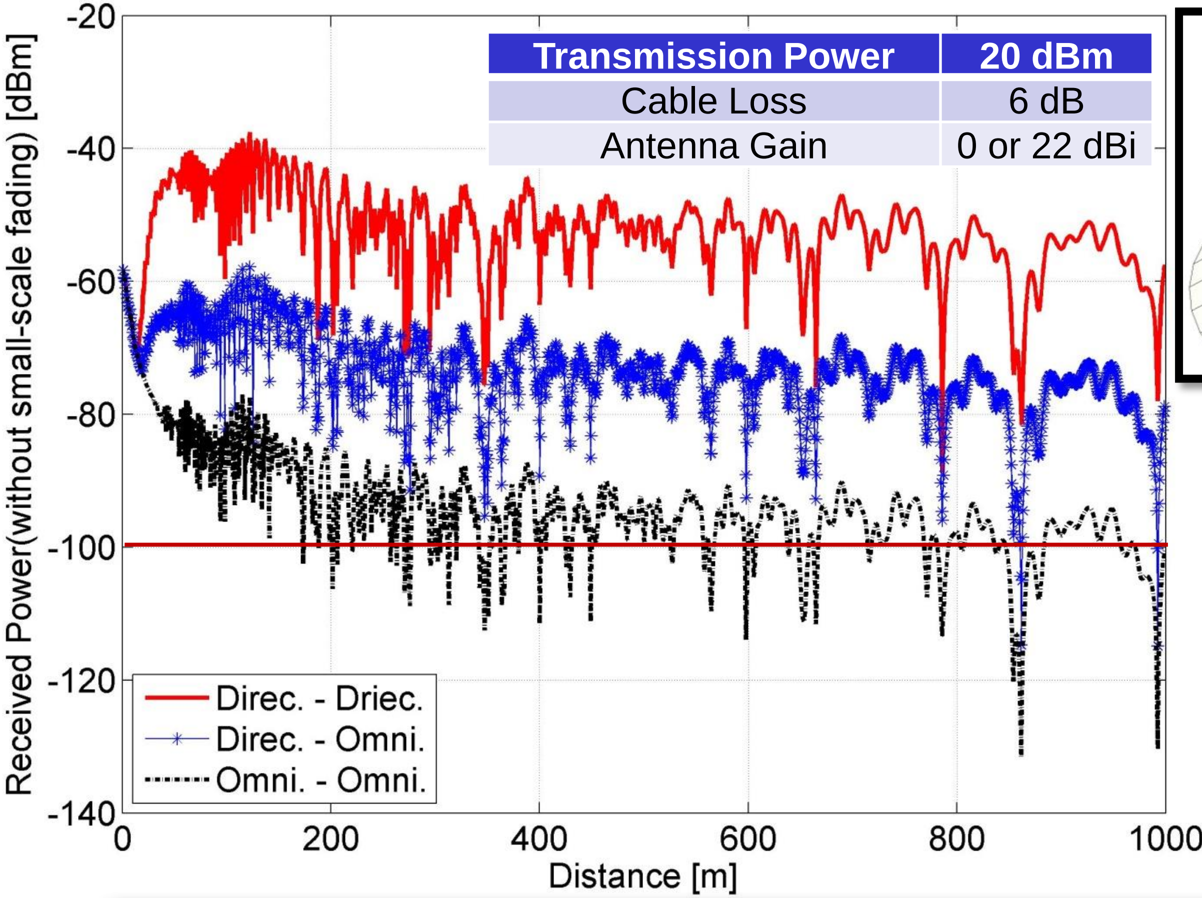




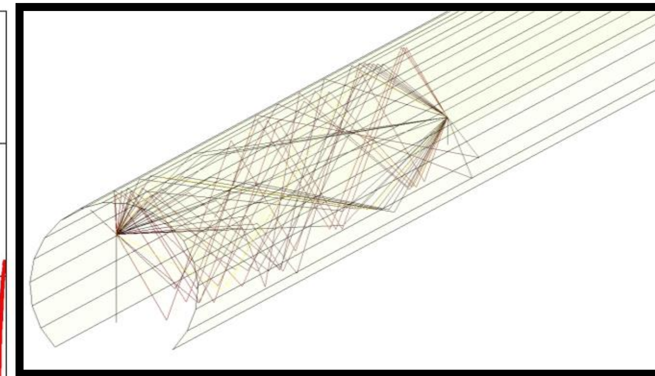
Parameters of channel characteristics

Parameters of channel characteristics	
Loss and fading	Received power
	Rician K-factor
Power delay profile	RMS delay spread
Doppler spectrum	RMS Doppler spread
	Mean Doppler shift
Time-varying property	Coherence time
Correlation of shadow fading	Decorrelation distance
	Cross-correlation coefficient
Polarization	Cross polarization discrimination (XPD)
	Co-polarization power ratio (CPR)

Received power (without small scale fading)



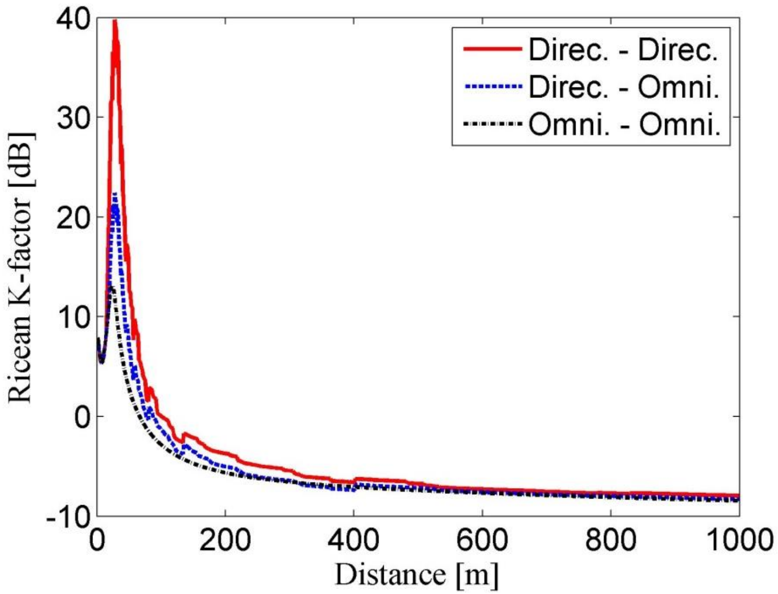
Transmission Power	20 dBm
Cable Loss	6 dB
Antenna Gain	0 or 22 dBi

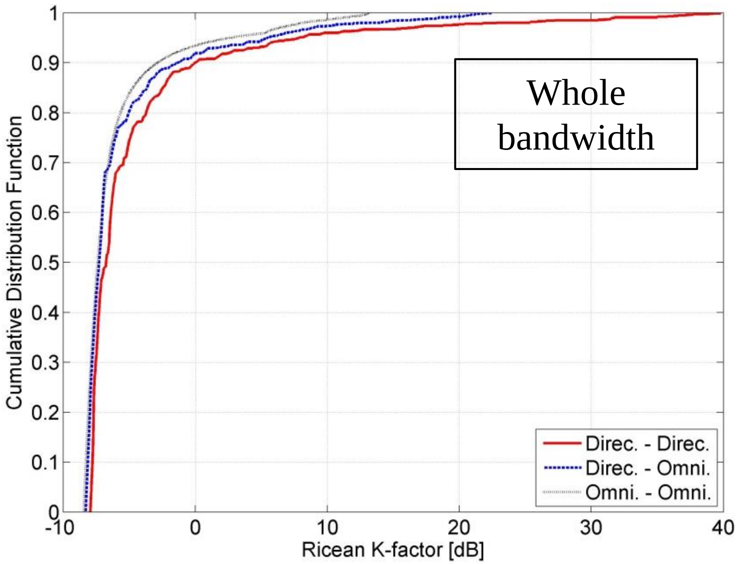


Coverage range [m]	-100 dBm
Direc. – Direc.	1000 +
Direc. – Omni.	1000
Omni. – Omni.	< 300

- **Enough coverage can be realized by usage of directional antenna**
- **At least one directional antenna should be used for enough link length**

Rician K-factor





- Ricean K-factor is defined as the power ratio of LOS components to NLOS components.
- K=0 -- Rayleigh fading; K=∞ -- no fading.

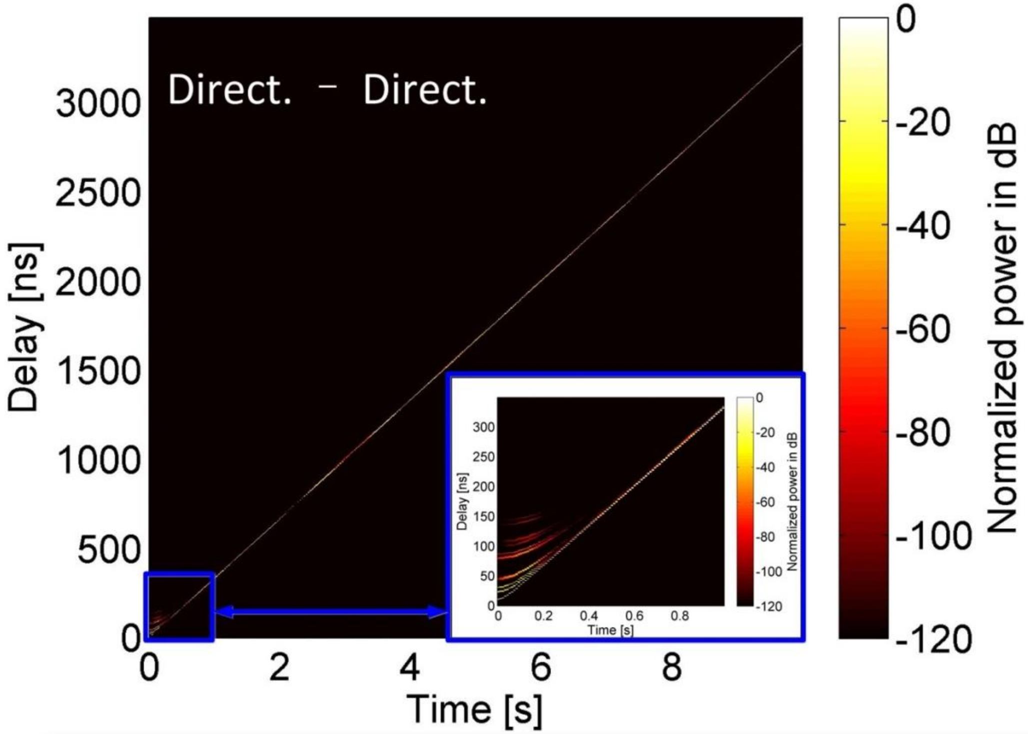
Ricean K-factor [dB]	50%	90%
Direc. – Direc.	-6.750	-0.006
Direc. – Omni.	-7.280	-1.368
Omni. – Omni.	-7.400	-2.844

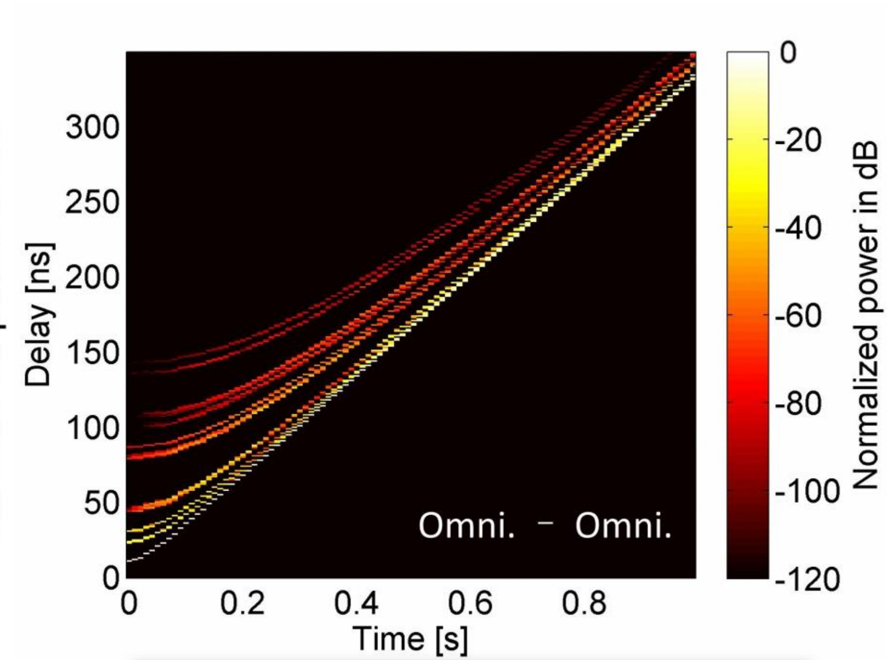
In the first 50 m, channel fading is weak, but after 50 m, channel goes through a serious fading.

Andrea Goldsmith. 2005. Wireless Communications. Cambridge University Press, New York, NY, USA.

Power delay profile

Normalized Power Delay Profile (32.5 GHz)





Very short delay spread due to LOS condition, high frequency and limited space

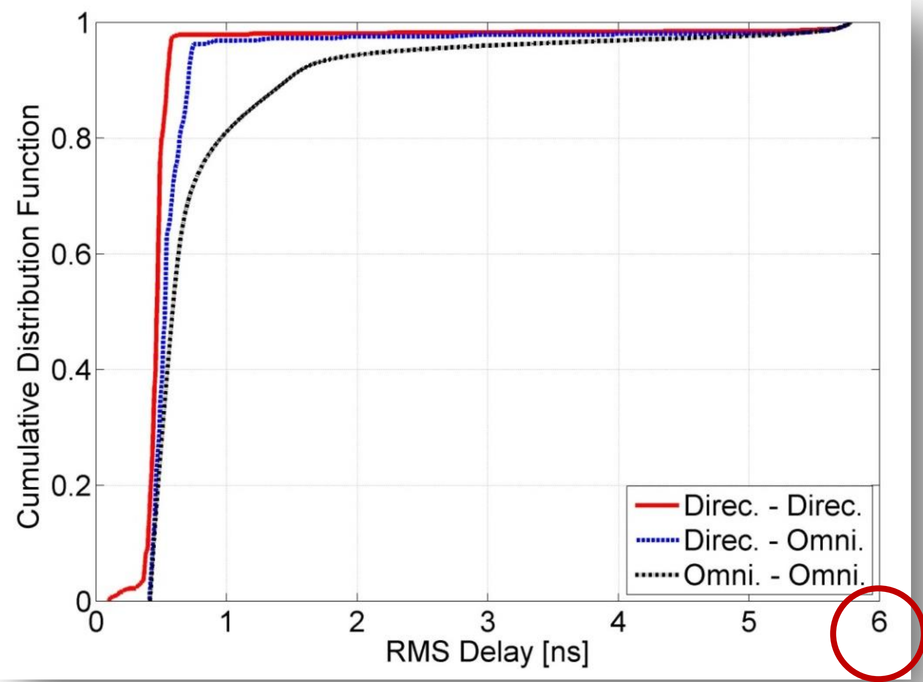
Directional antennas on both Tx and Rx sides reduce the influence of multipath

Root-mean-square (RMS) delay spread

$$\tau_{\rm rms} = \sqrt{\frac{\sum_{r=1}^{N}\tau_r^2 X(r)}{\sum_{r=1}^{N}X(r)} - \left(\frac{\sum_{r=1}^{N}\tau_r X(r)}{\sum_{r=1}^{N}X(r)}\right)^2}$$

$X(r)\ \ (r=1,2,\cdots,N)$ be the r-th sample of the power delay profile (PDP) at a certain time

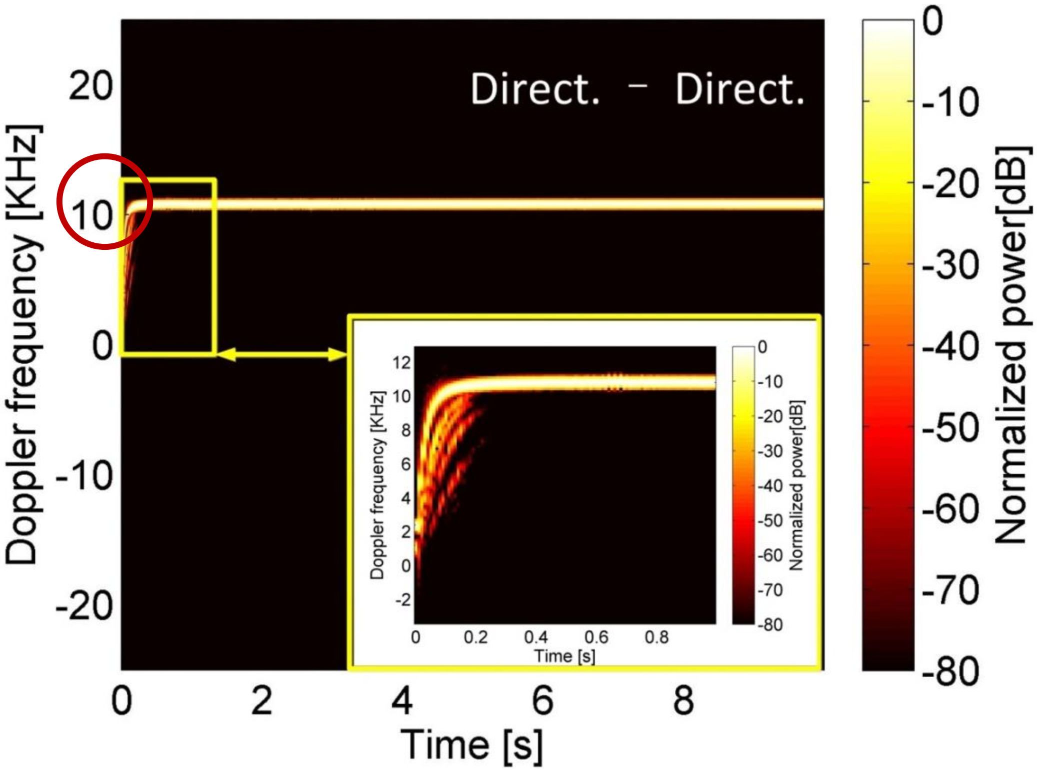
τ_r denote the excess delay of the r-th sample of PDP

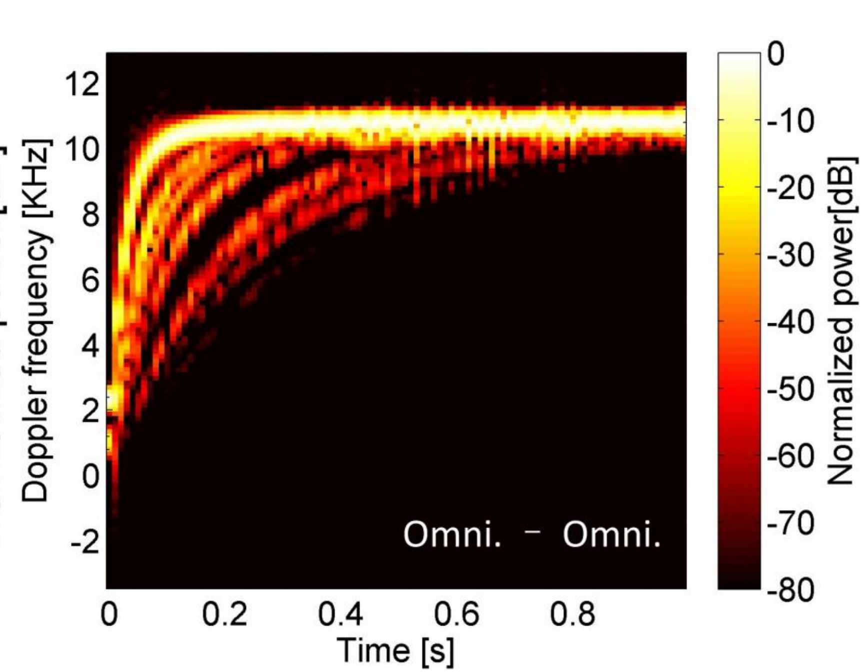


RMS delay spread [ns]	50%	90%
Direc. – Direc.	0.467	0.545
Direc. – Omni.	0.528	0.708
Omni. – Omni.	0.586	1.463

So short time delay spread will not introduce Inter-symbol Interference (ISI) → High symbol rate

Doppler spectrum at 32.5 GHz

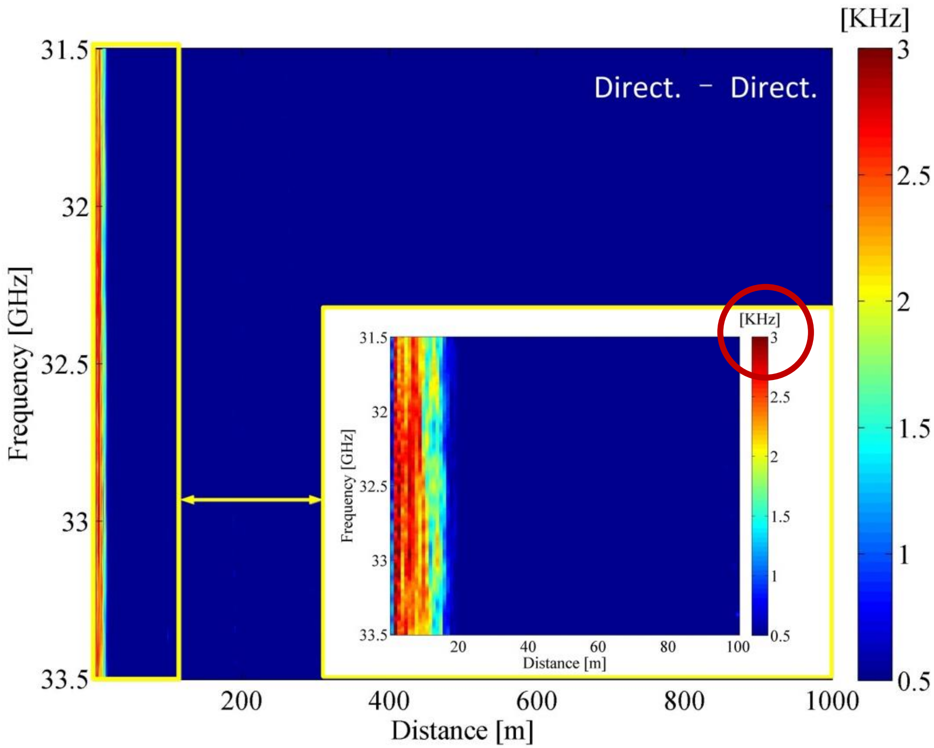


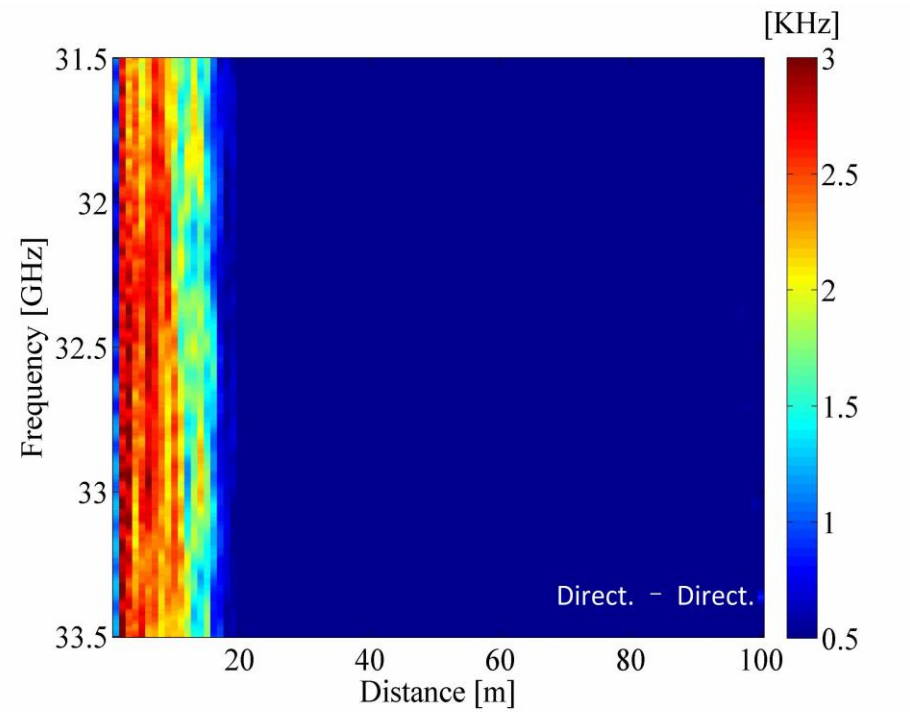


- **Maximum Doppler shift is around 12 kHz**
- **Large Doppler spread happens in the first 100 m**

Directional antennas reduce the RMS Doppler spread

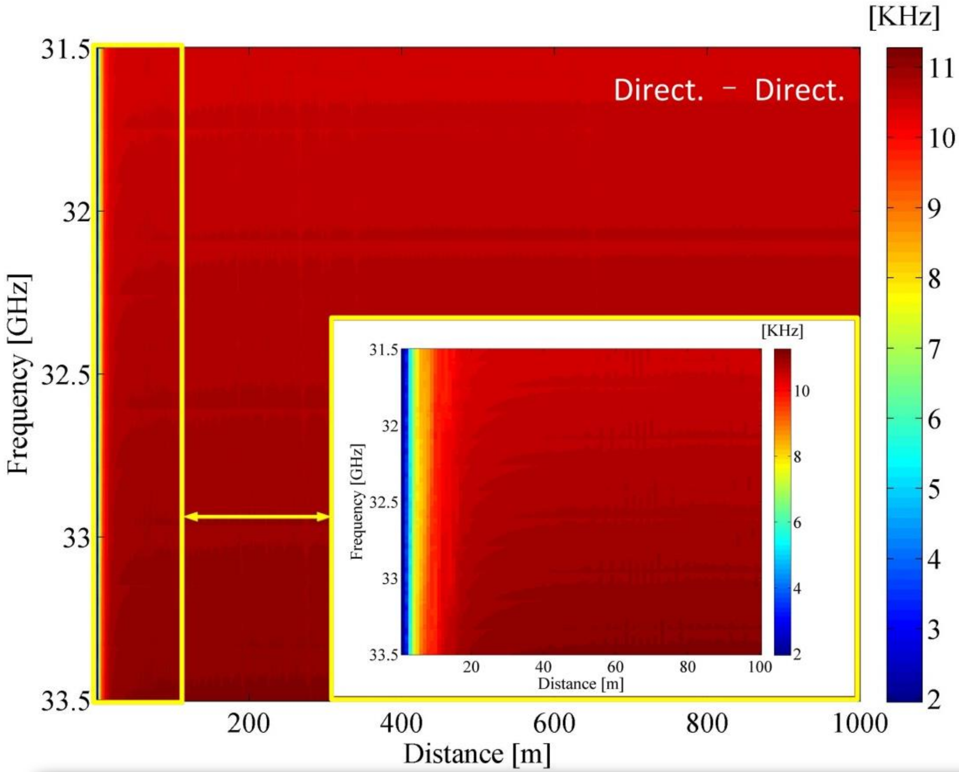
RMS Doppler Spread for the whole 2-GHz bandwidth

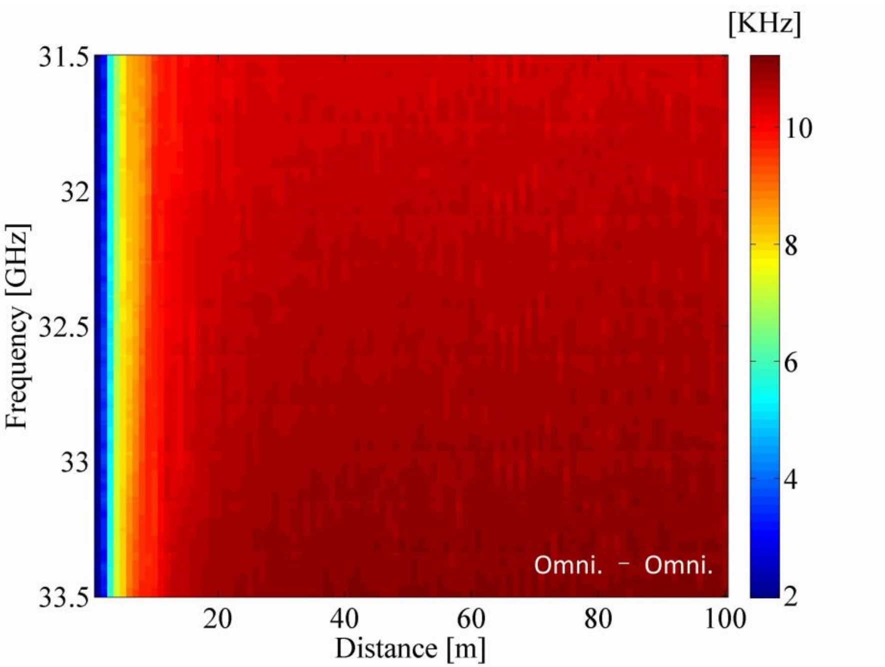




- **In the first 20 m, the RMS Doppler spread increases fast up to 3 kHz, and then decreases to be around 400 Hz**
- **Directional antennas reduce the distance of the signal suffering Doppler spread**

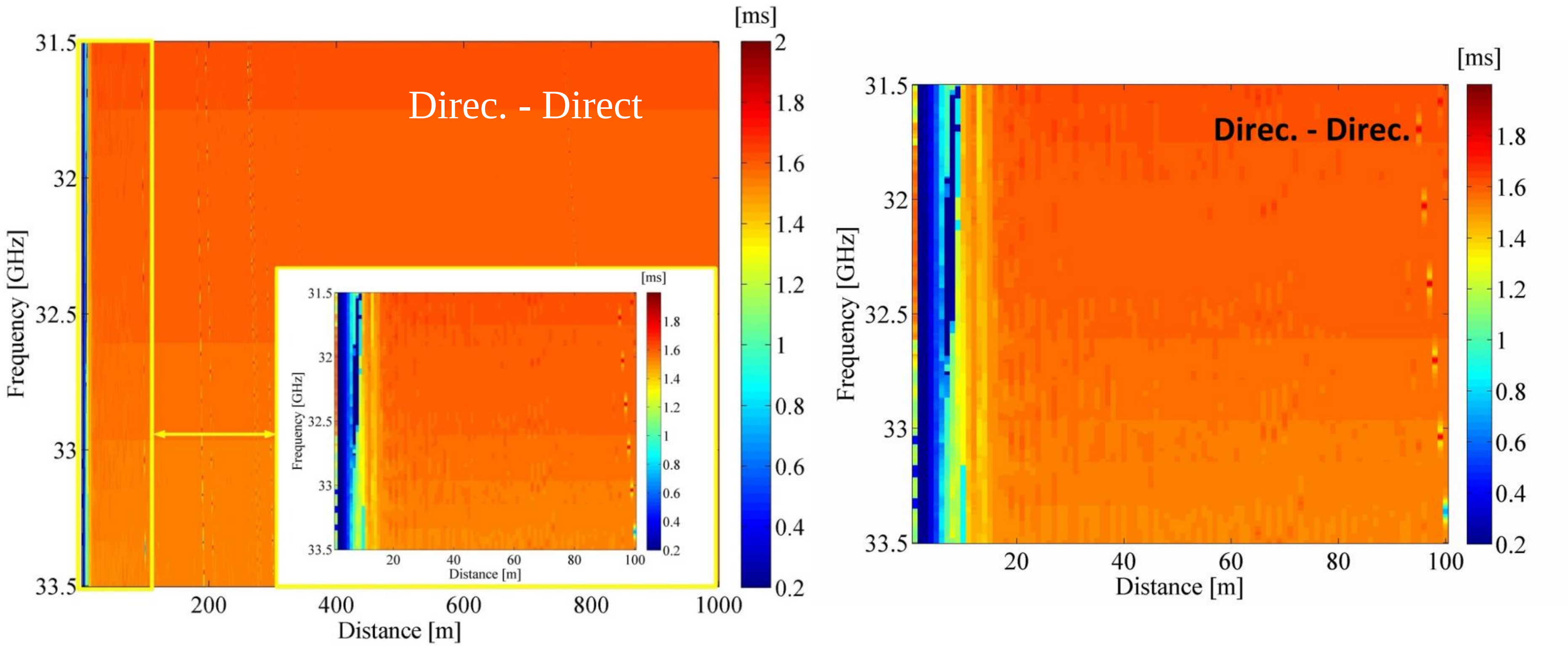
Mean Doppler shift for the whole 2-GHz band





- **Mean Doppler shift increases very fast up to 11 kHz within the first 10 m, then becomes constant**
- **Directional antennas do NOT influence Doppler shift as it comes from the direct path at short distance, and at long distance the reflections are close to direct paths.**

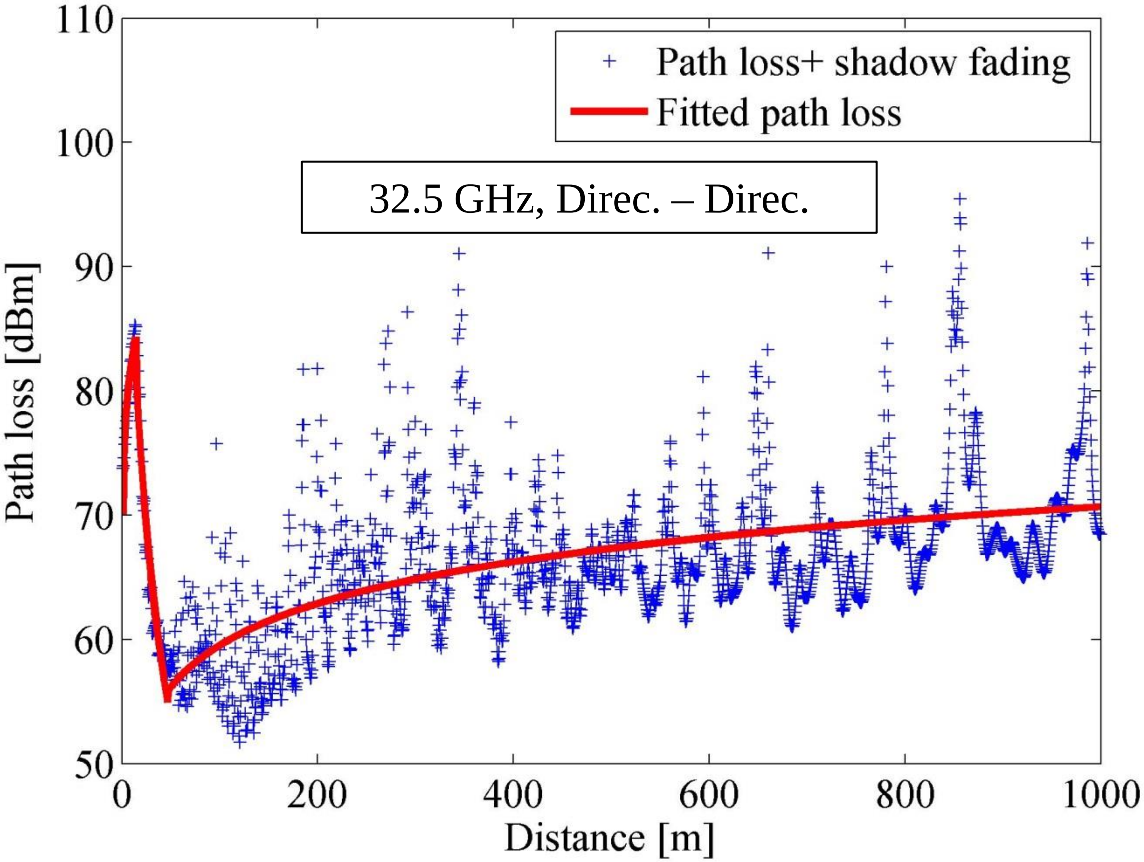
Coherence time



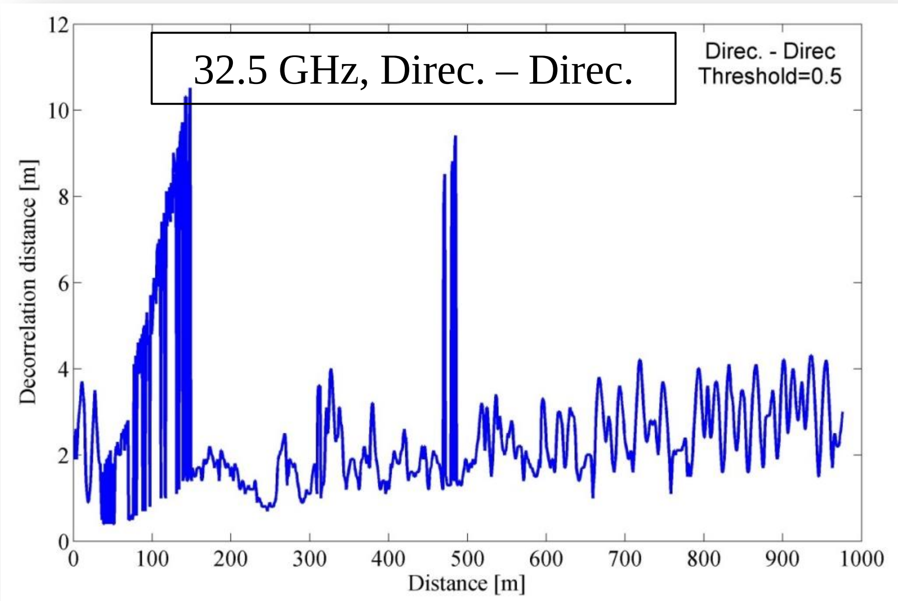
- **Coherence time increases from 0.2 ms to around 1.5 ms within the first 20 m, then becomes constant around 1.5 ms due to several-hundred Hz Doppler spread**
- **Directional antennas constrain the fluctuation of coherence time versus distance**

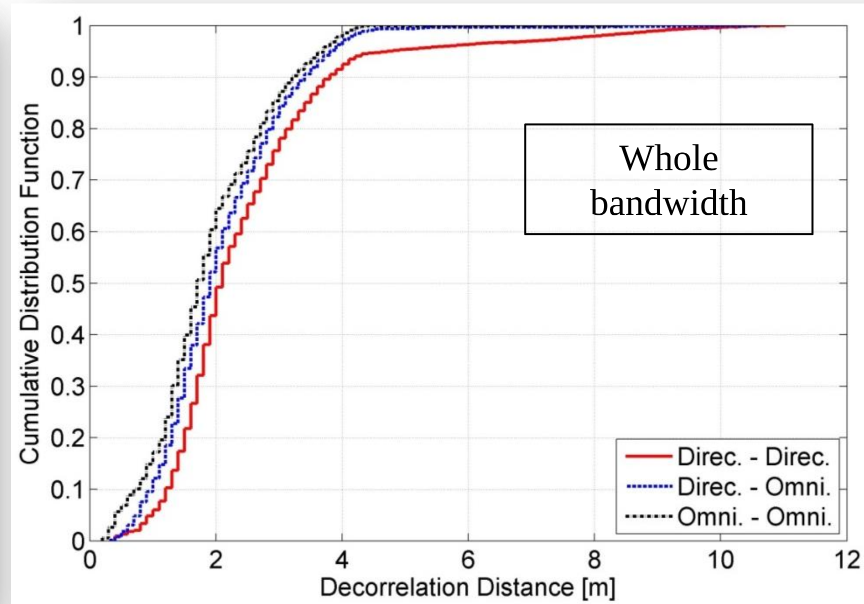
Correlation of shadow fading

$$L(d) = \bar{L}(d_0) + 10n\lg\left(\frac{d}{d_0}\right) + X_\sigma$$



Decorrelation distance with threshold 0.5

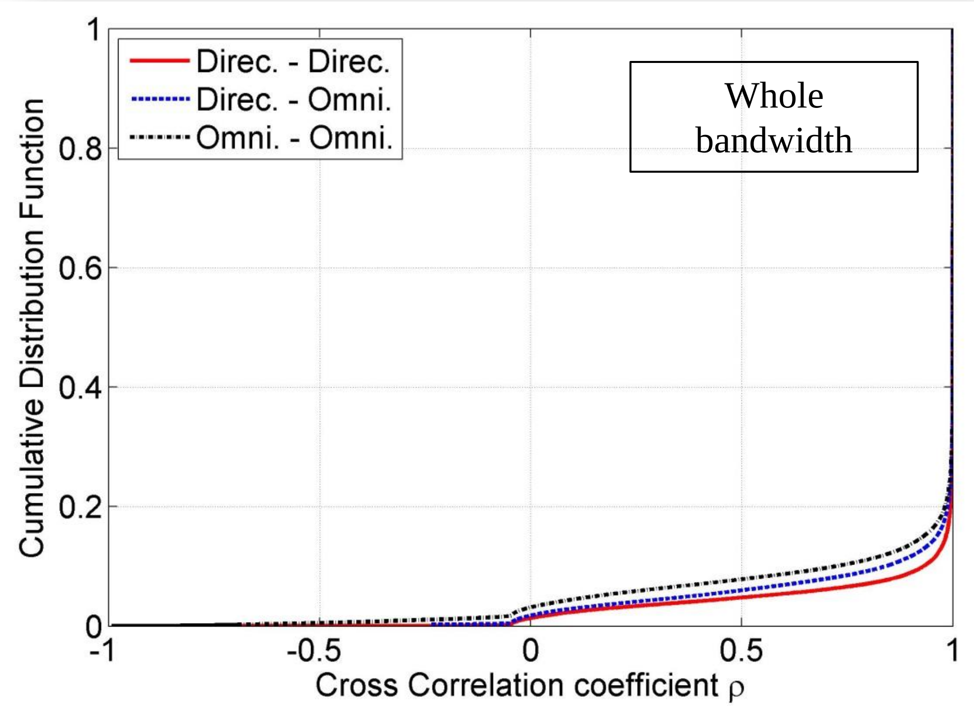




Decorrelation distance [m]	50%
Direc. – Direc.	2.104
Direc. – Omni.	1.904
Omni. – Omni.	1.703

- **Directional antennas increase the decorrelation distance**
- **Mean decorrelation distance is around 2 m, MIMO antennas should separated further to get diversity gain**

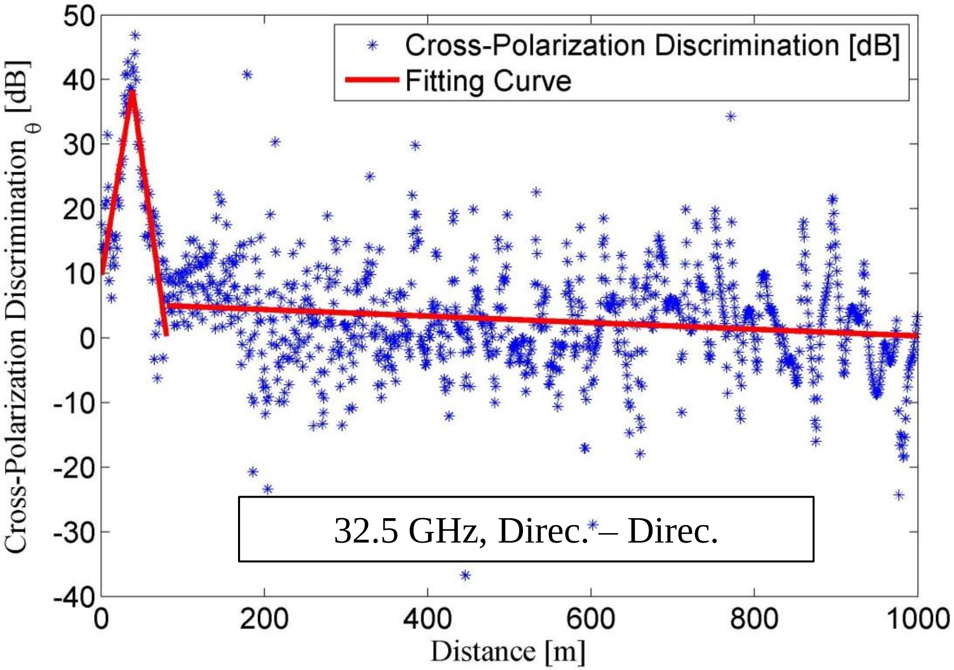
Cross correlation coefficient between two adjacent links

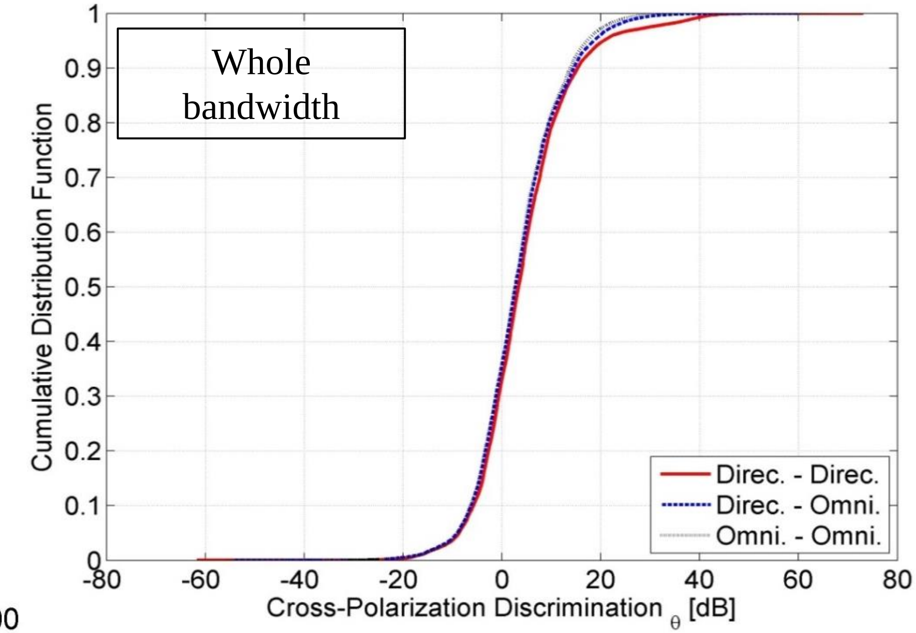


Cross correlation coefficient	>0.5	>0.9
Direc. – Direc.	99.5%	99.1%
Direc. – Omni.	99.4%	98.8%
Omni. – Omni.	99.3%	98.6%

- **Cross correlation coefficient between two adjacent links with 10-cm separation is larger than 0.9 in 99% cases.**
- **Diversity gain can be expected by enlarging the separation between MIMO antennas**

Polarization – XPD_VH





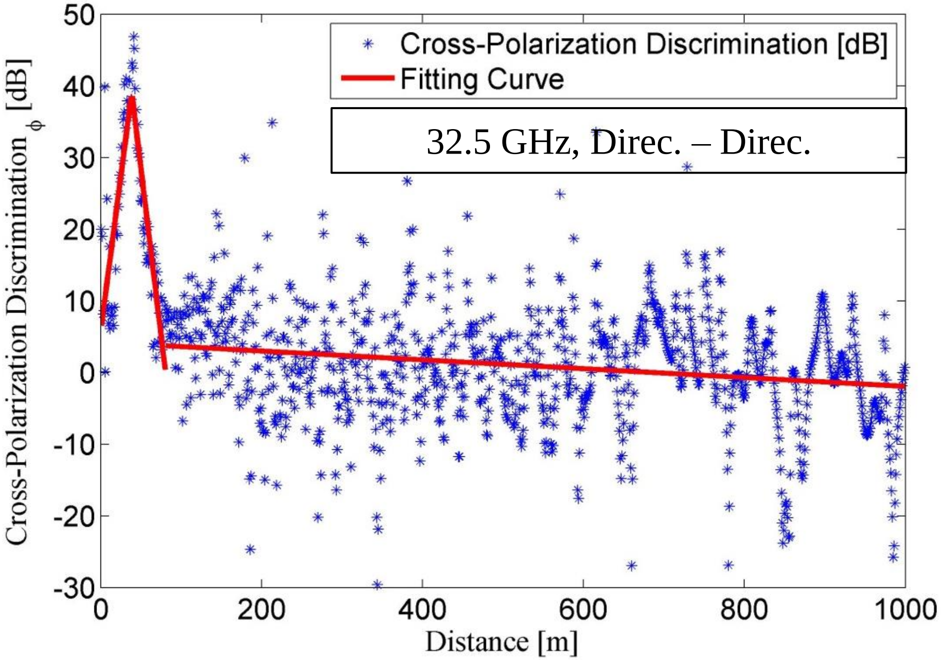
XPDθ[dB]	50%
Direc. – Direc.	3.343
Direc. – Omni.	2.695
Omni. – Omni.	2.644

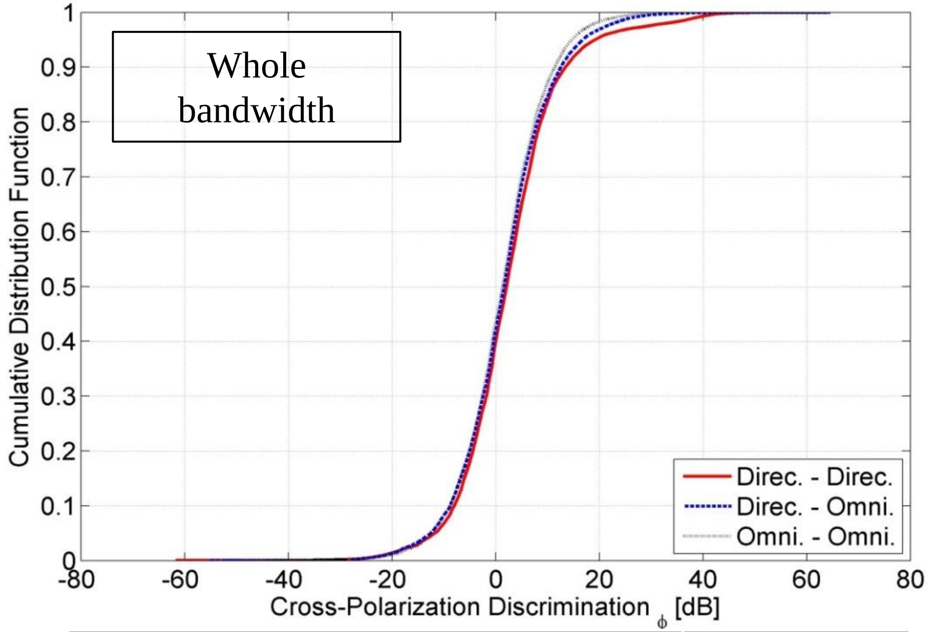
$$XPD_\theta = 20\log_{10}\left(\frac{E_{Co}}{E_{Cross}}\right)$$

XPD_θ refers to the field received in θ co-polarization relative to the field transmitted in θ and received in ϕ polarization

1/3 energy of the vertically polarized wave is depolarized

Polarization – XPD_HV





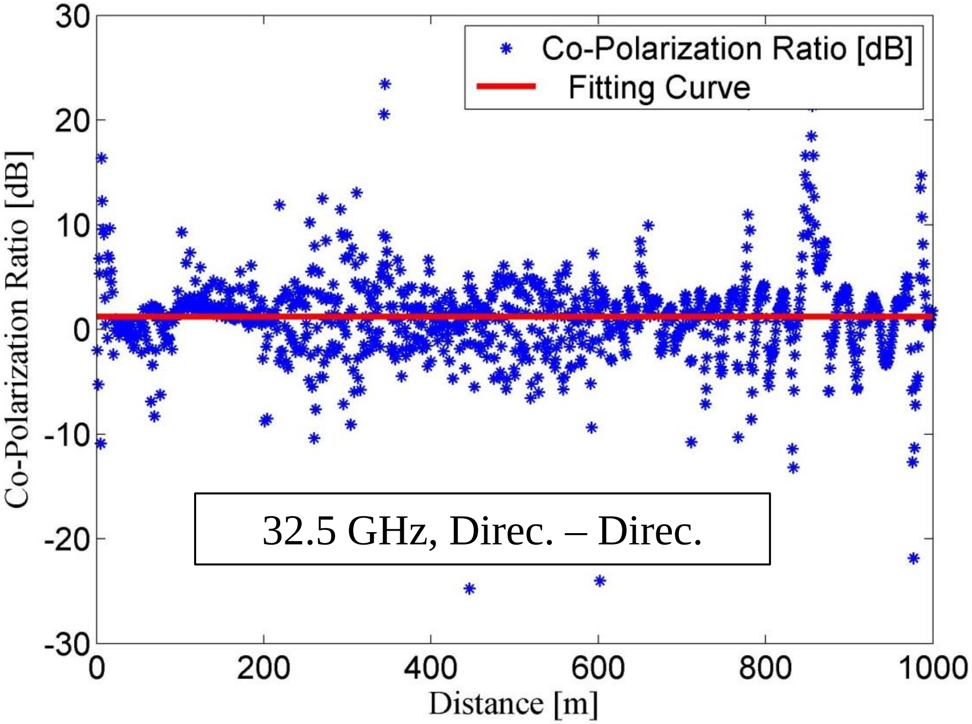
$$XPD_\phi = 20\log_{10}\left(\frac{E_{Co}}{E_{Cross}}\right)$$

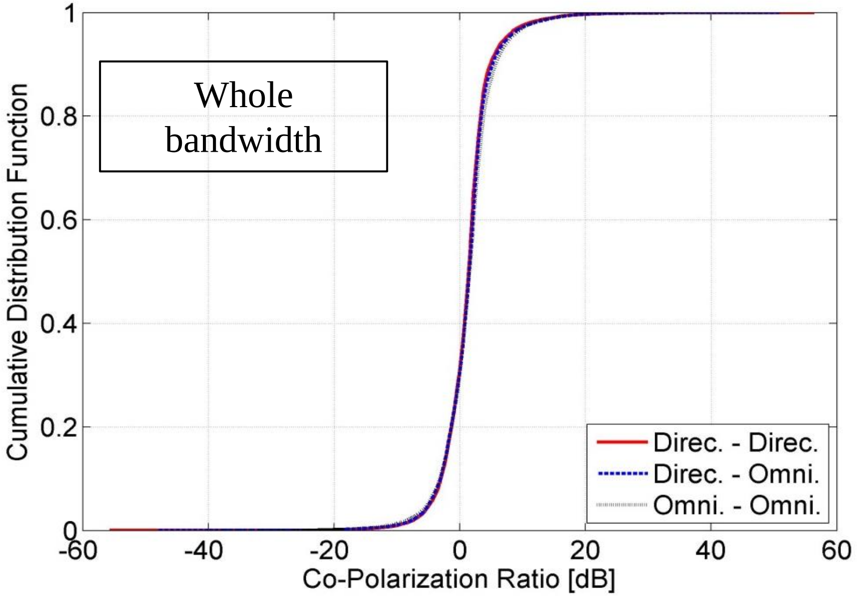
XPD_ϕ refers to the field received in ϕ co-polarization relative to the field transmitted in ϕ and received in θ polarization

$XPD\phi$[dB]	50%
Direc. – Direc.	2.097
Direc. – Omni.	1.639
Omni. – Omni.	1.315

Around half energy of the horizontally polarized wave is depolarized

Polarization – CPR





Co-polarization Ratio [dB]	50%
Direc. – Direc.	1.386
Direc. – Omni.	1.499
Omni. – Omni.	1.561

The CPR, which describes the power ratio between the co-polarized V-channels (h_{VV}) and H-channels (h_{HH}), is defined:

$$\mathrm{CPR}=\frac{\mathrm{E}\left\{|h_{VV}|^2\right\}}{\mathrm{E}\left\{|h_{HH}|^2\right\}}$$

Vertical polarization is slightly better than horizontal polarization

Outline

- Introduction of BJTU and RCS
- Motivation of channel characterization for HRRC
- Deterministic channel modeling approach
  - Ray-tracing simulator
  - Frequency domain simulation
- Channel simulation and characteristics
- **Conclusion and future work**

Conclusion

Conclusion on channel characteristics	
Received power	1-km long coverage is promising by using dual-directional antenna setup
Rician K-factor	Very small and the channel suffers Rayleigh fading
RMS delay spread	Very short, no bother
RMS Doppler spread	Around 3 kHz in the first 20 m, then around 400 Hz for the rest range, which can reduced by direct. antennas
Mean Doppler shift	Increase up to 12 kHz in the first 10 m, then constant
Coherence time	Very short, from 0.2 ms to 1.5 ms
Decorrelation distance	Around 2 m, much larger than 10 cm
Cross-correlation coefficient	Links separated only by 10 cm are highly correlated
XPD	Around half energy is depolarized
CPR	Vertical polarization is slightly better

Future work

- **Future work:**
  - More railway scenarios
  - More communication system setups
  - Stochastic modeling and channel realization

Rail traffic – an efficient and green transport model, playing a more and more significant role for human development!