Wireless Channel Modeling and Wireless Systems Design

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- ➢Wireless Channel Modeling
- ➢Wireless Systems and Techniques
  - ✓Antenna Array Design
  - ✓Cryptographic Key Generation

Short Bio

- Apr 2003 – Jun 2008: PhD Candidate, University of Patras
  - ✓Dissertation: "Statistical Characterization of Multipath Propagation and Received Signal in Time Varying Wireless Channels"

- Dec 2009 – Jul 2016: University of Bedfordshire
  - ✓Research Fellow, Dec 2009 – Aug 2011
  - ✓Lecturer/Senior Lecturer, Sep 2011 – Jul 2016

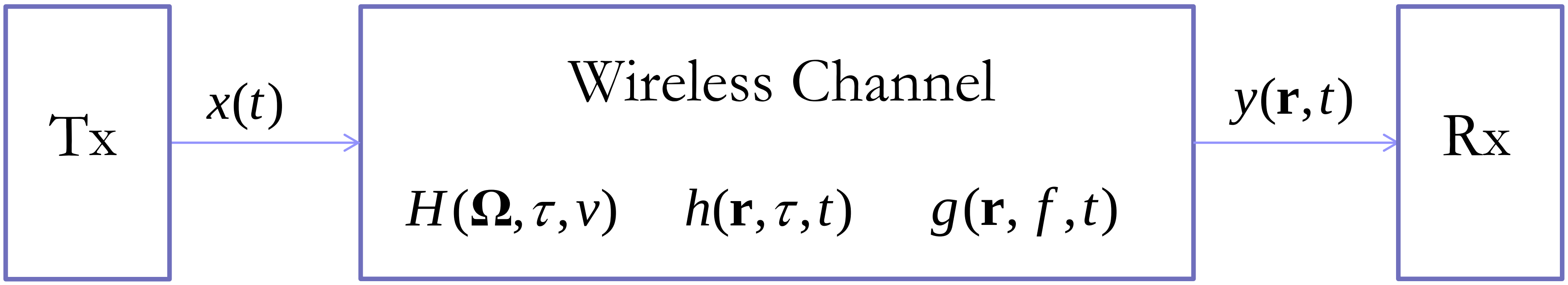
- Aug 2016 – Dec 2021: Lecturer, University of Glasgow

- Jan 2022 – Today: Associate Professor, Edinburgh Napier University

Contents

- Wireless Channel Modeling

Wireless Communication System Model



Tx

$x(t)$

Wireless Channel

$H(\mathbf{\Omega},\tau,v)$ $h(\mathbf{r},\tau,t)$ $g(\mathbf{r},f,t)$

$y(\mathbf{r},t)$

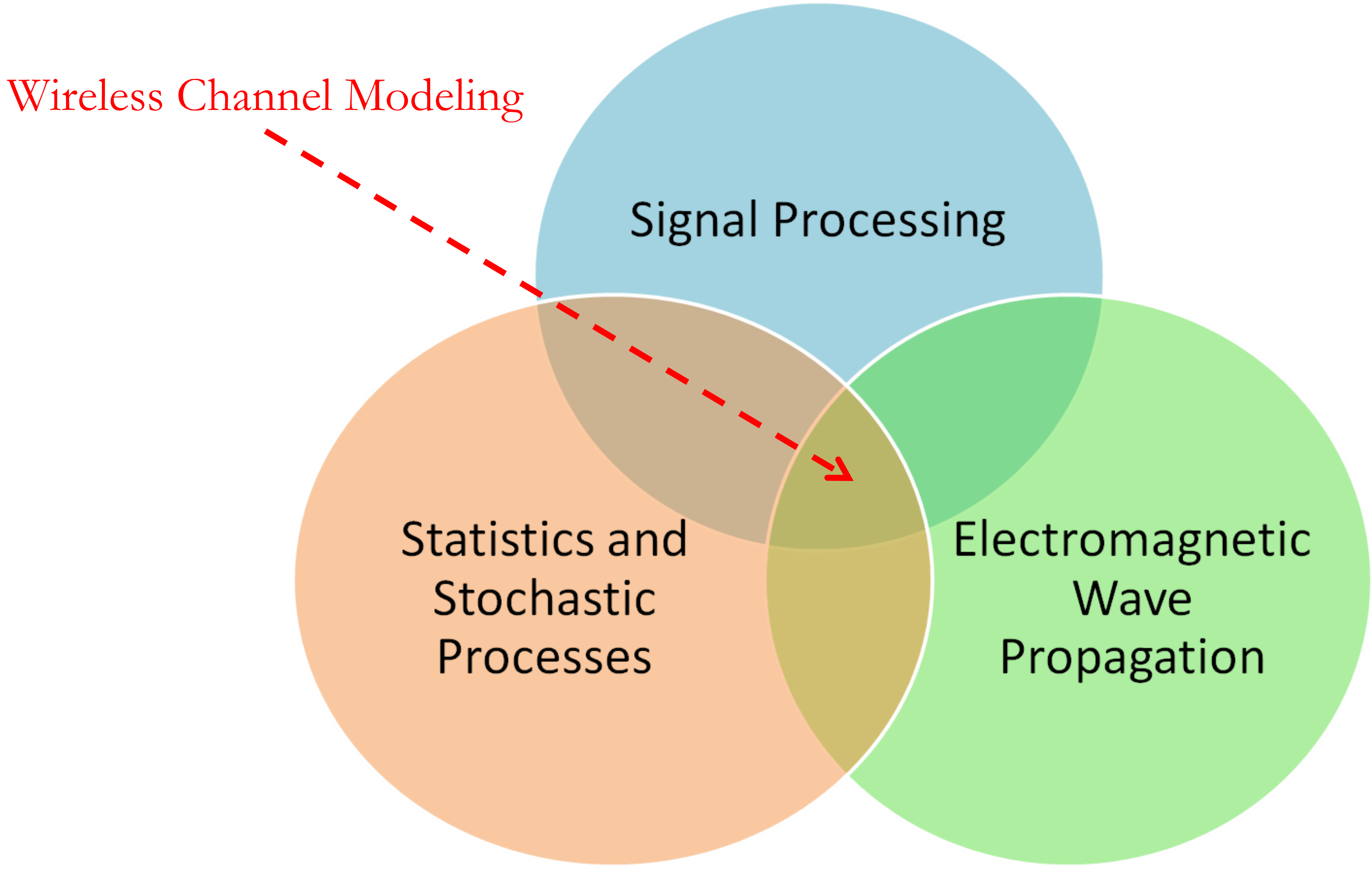
Rx

➢ Wireless Channel Modeling (Small Scale)

Mathematically describe/characterize the (equivalent) wireless channel responses in compliance with the Maxwellian basis of electromagnetic wave propagation.

✓ Absolutely necessary to design reliable/optimum wireless systems and components, i.e., antennas, multiplexers (OFDM, CDMA), diversity combiners!

Research Disciplines



Wireless Channel Modeling

Signal Processing

Statistics and Stochastic Processes

Electromagnetic Wave Propagation

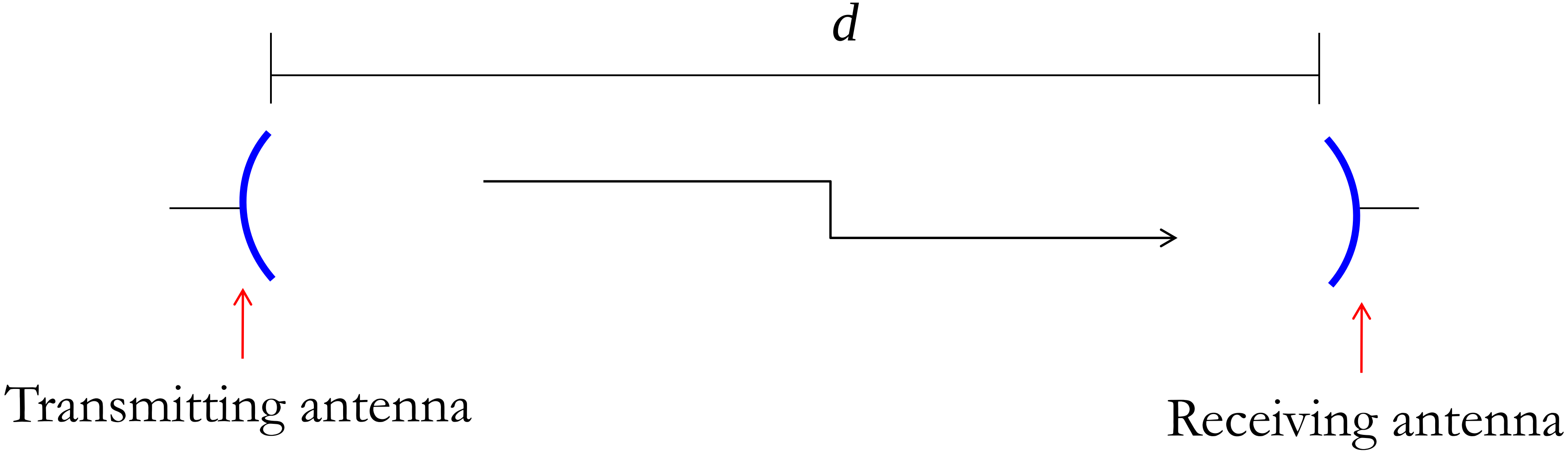
Propagation Mechanisms

- Line-of-sight (LOS)
- Reflection and transmission
- Diffraction
- Scattering
- Waveguiding

A. F. Molisch, “Wireless Communications,” 2nd Edition, Wiley, 2011.

Propagation Mechanisms

Line-of-sight (LOS)



d

Transmitting antenna

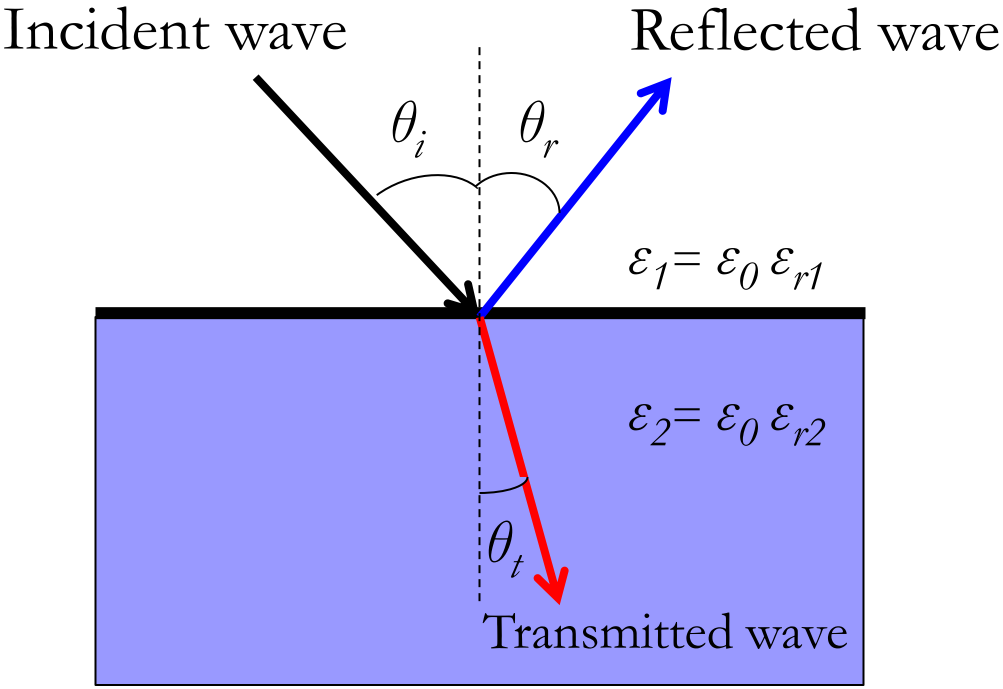
Receiving antenna

✓Friis' formula : $P_r = P_t G_r G_t \left(\frac{\lambda_0}{4\pi d} \right)^2 = \frac{P_t G_r G_t}{L}$

✓Free space loss : $L = \left(\frac{4\pi d}{\lambda_0} \right)^2$

Propagation Mechanisms

Reflection and transmission



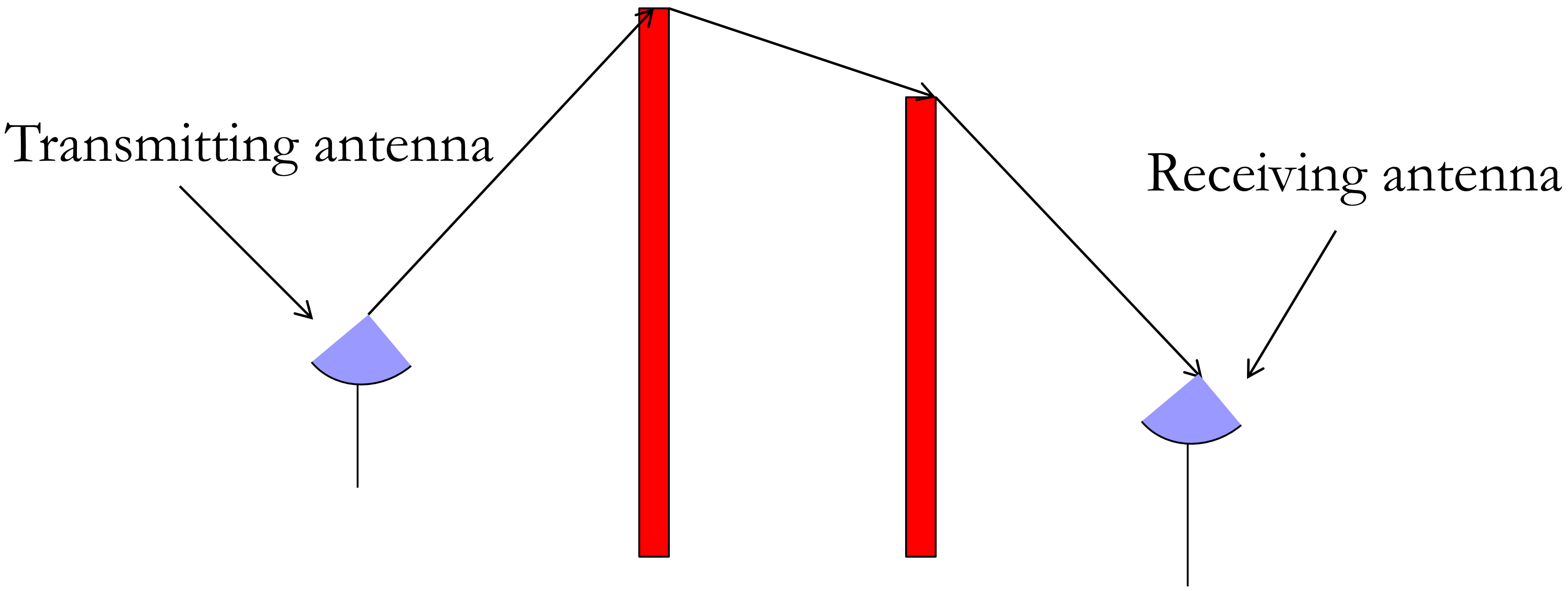
ε_{r1}, ε_{r2} : Relative dielectric constants of materials 1 and 2, respectively

θ_i, θ_r, θ_t : Incidence angle, reflection angle, transmission angle, respectively

✓Snell's law : $\theta_r = \theta_i$ $\quad \dfrac{\sin\theta_t}{\sin\theta_r} = \sqrt{\dfrac{\varepsilon_{r1}}{\varepsilon_{r2}}}$

Propagation Mechanisms

Diffraction



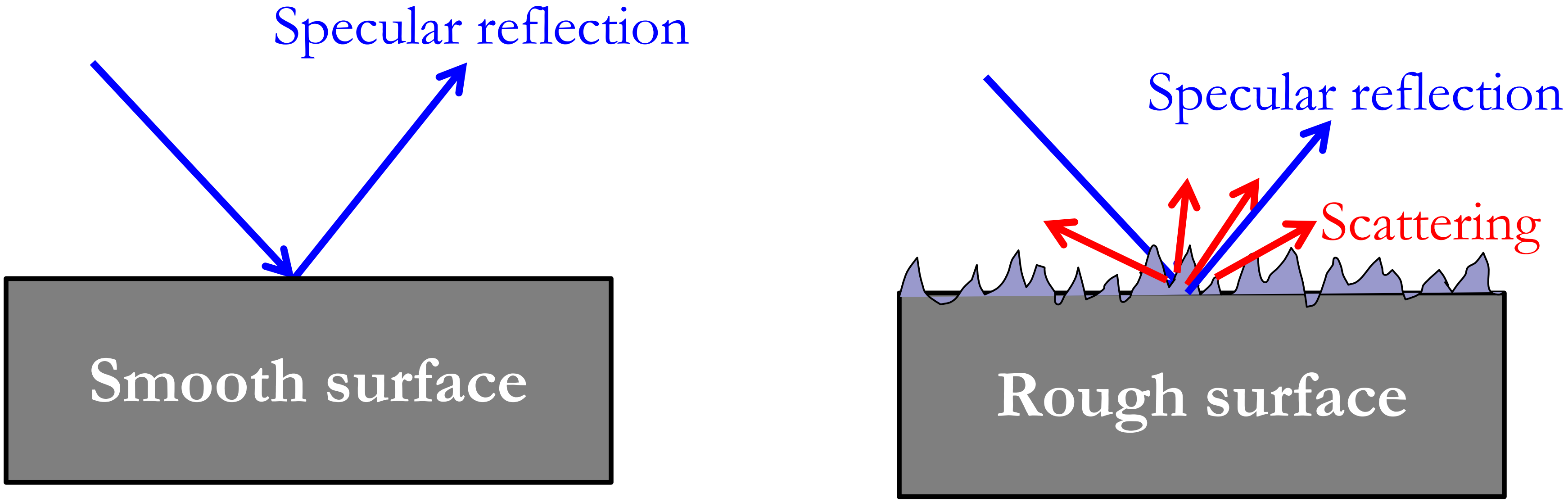
- ✓Wave “bending” during the interaction with sharp edges
- ✓Causes power loss (shadowing), but makes propagation possible behind tall objects

➢Rules-of-thumb

1. Increased power loss with increased frequency (decreased wavelenght)
2. Less evident as wavelength decreases with respect to sharpness size

Propagation Mechanisms

Scattering



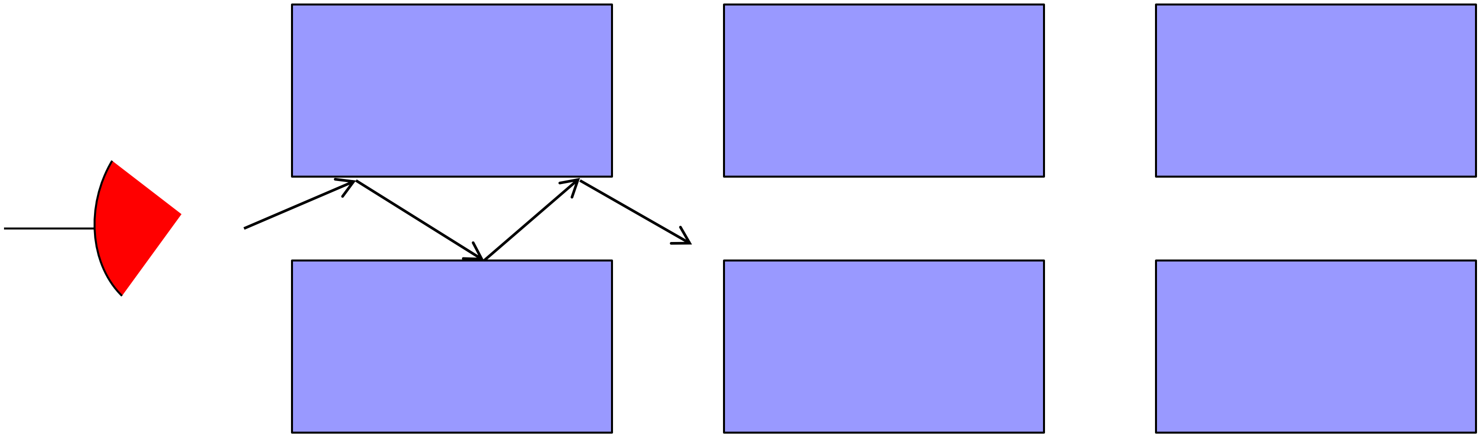
- ✓Results random number of arbitrarily directed diffuse components
- ✓Smoothness and roughness are determined by the wavelength

➢ <u>Rules-of-thumb</u>

1. Roughness dimension should be much larger than the wavelength
2. Increased roughness with decreased wavelength (increased frequency)

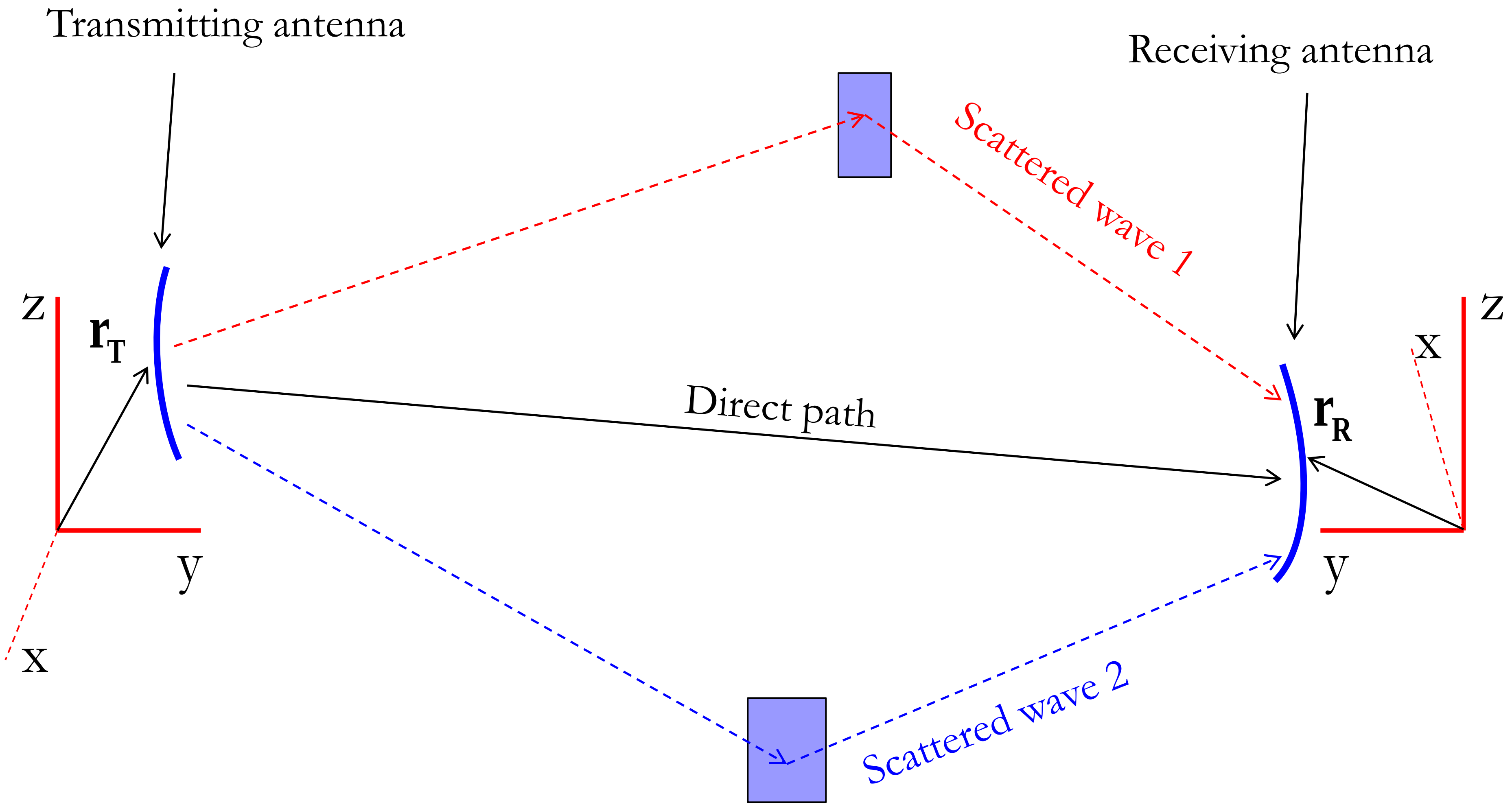
Propagation Mechanisms

Waveguiding



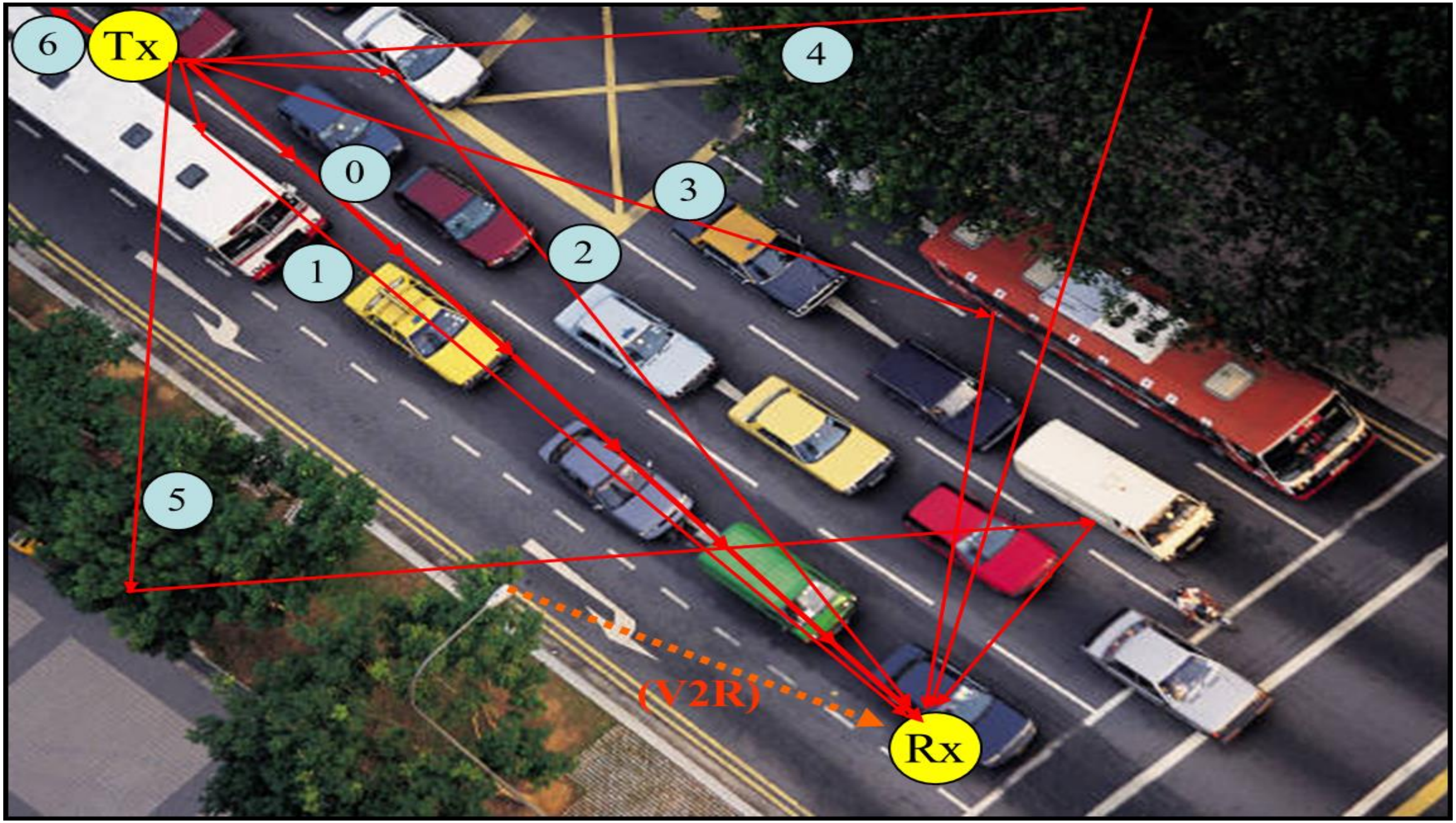
✓Propagation through confined structures, e.g., street canyons, tunnels, corridors

Multipath Propagation



Multipath Propagation

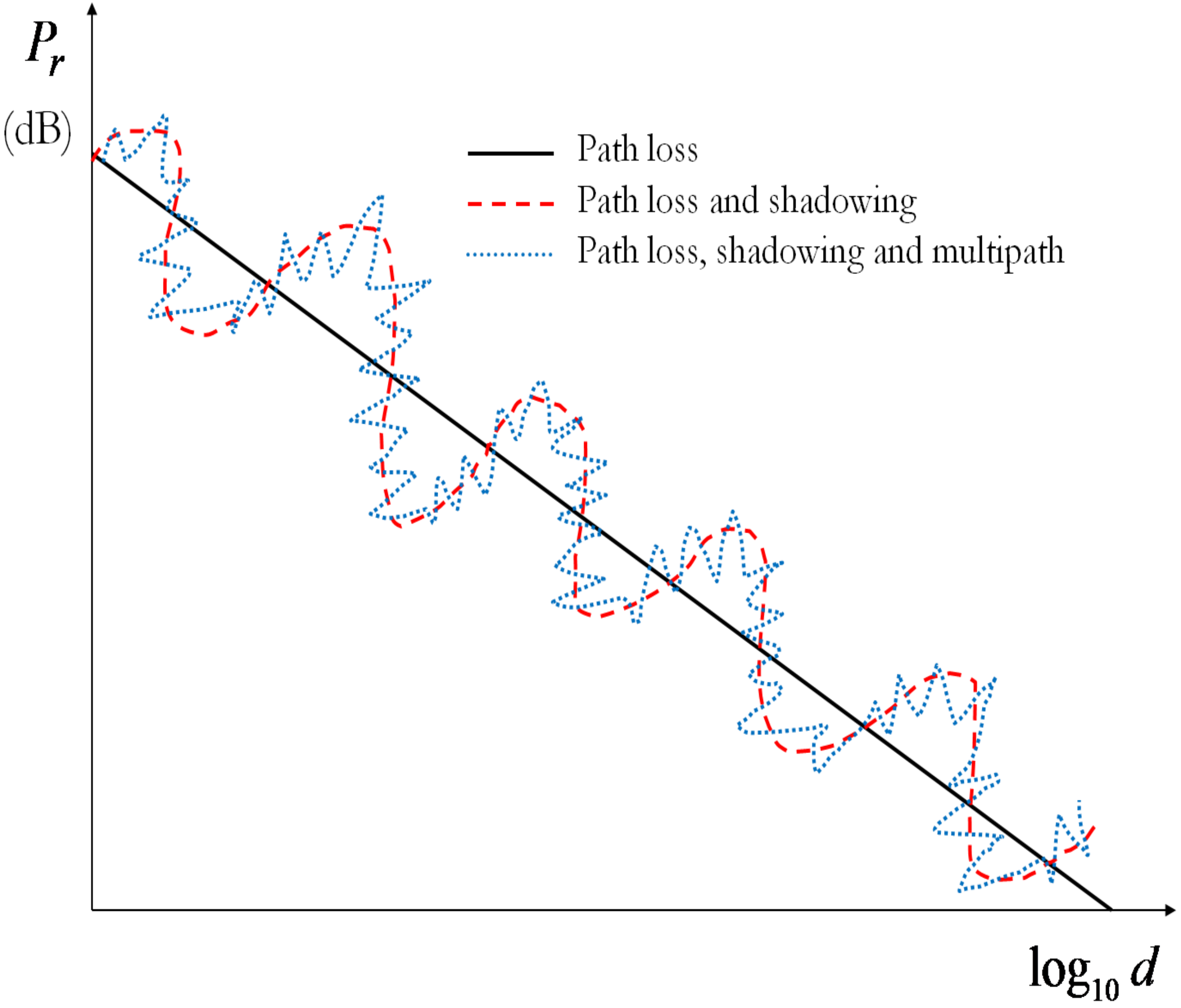
Vehicle-to-Vehicle (V2V) Communication Scenario



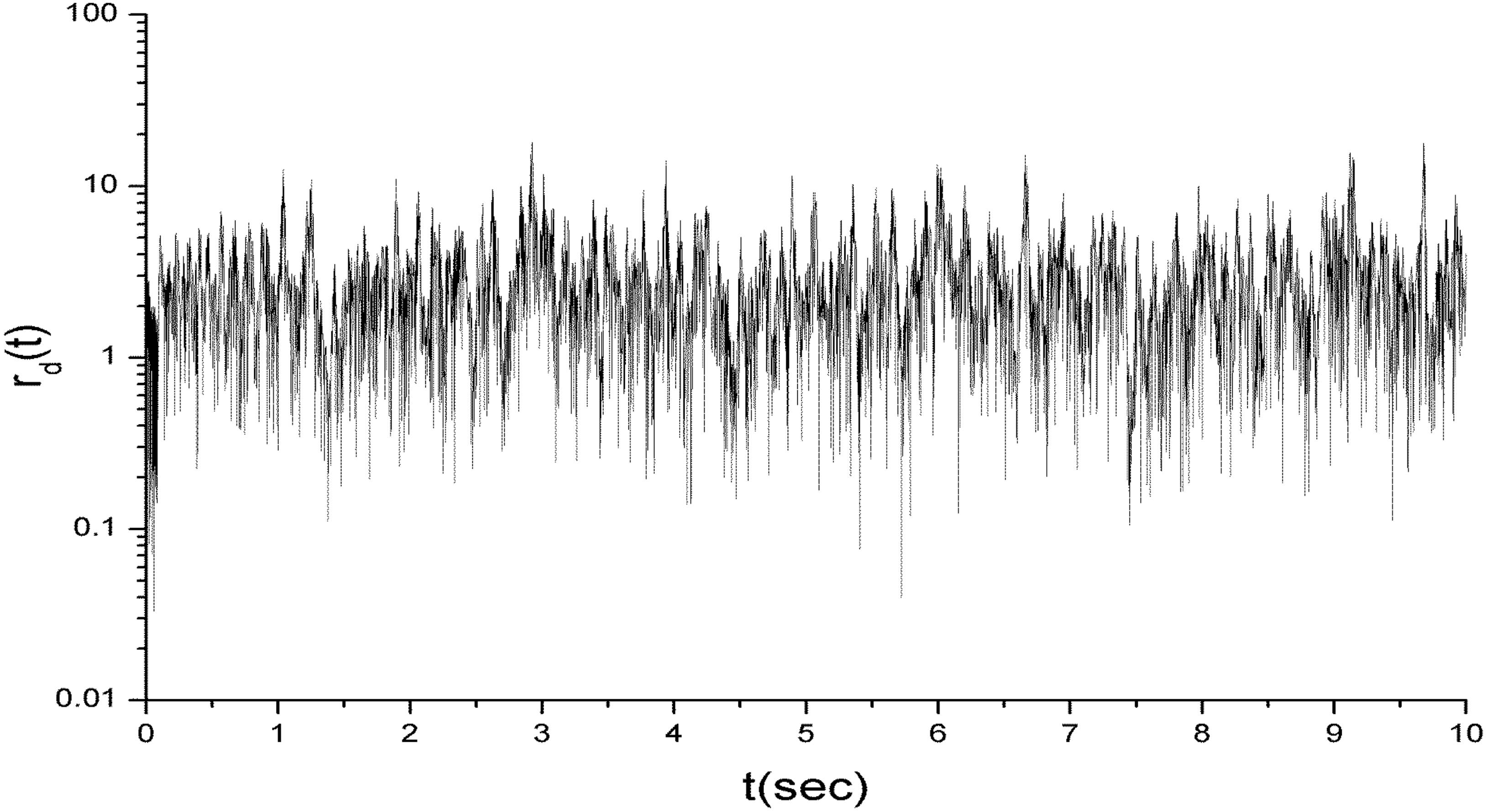
P. Karadimas and D. Matolak, "Generic Stochastic Modeling of Vehicle-to-Vehicle Wireless Channels," Elsevier Vehicular Communications vol. 1, no. 4, pp. 153-167, Oct. 2014.

Path Loss, Shadowing, Multipath

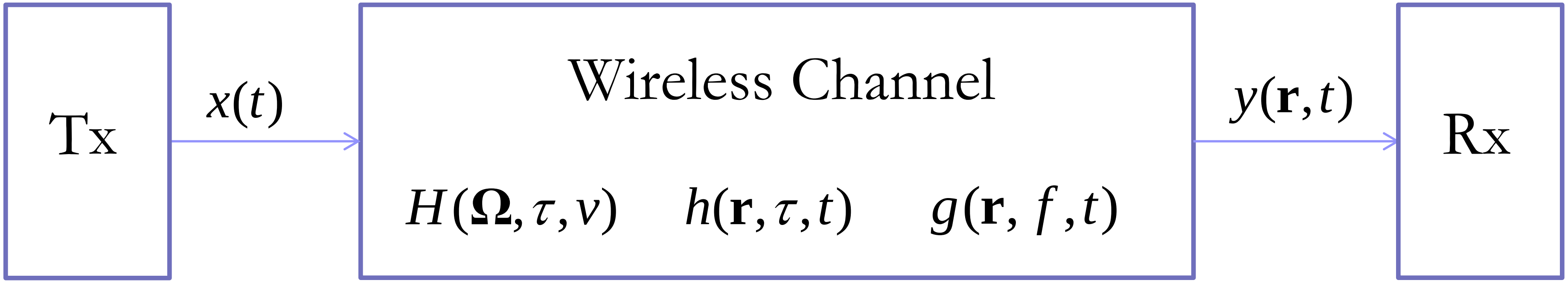
- **Path loss**
  - ✓Power decay due to transmission distance.
- **Shadowing**
  - ✓Power loss and large scale space-time variations due to obstruction by large objects.
- **Multipath propagation**
  - ✓Small scale space-time variations due to multipath components arrival and their interaction.



Baseband Received Fading Signal



Wireless Channel Responses



$$H(\mathbf{\Omega}, \tau, \nu) \xrightarrow{F_\nu^{-1} \quad F_{\mathbf{\Omega}}^{-1}} h(\mathbf{r}, \tau, t) \qquad h(\mathbf{r}, \tau, t) \xrightarrow{F_\tau} g(\mathbf{r}, f, t)$$

$$H(\mathbf{\Omega}, \tau, \nu) \xrightarrow{F_\nu^{-1} \quad F_{\mathbf{\Omega}}^{-1} \quad F_\tau} g(\mathbf{r}, f, t)$$

$H(\mathbf{\Omega}, \tau, \nu)$: directional-delay-Doppler variant channel response

$h(\mathbf{r}, \tau, t)$: space-delay-time variant channel response

$g(\mathbf{r}, f, t)$: space-frequency-time variant channel response

Tx – Rx Baseband Signal Relationships

$$y(\mathbf{r},t)=\iiint \exp[j2\pi(\mathbf{\Omega}\cdot\mathbf{r})/\lambda_0]\exp(j2\pi vt)x(t-\tau)H(\mathbf{\Omega},\tau,v)d\mathbf{\Omega}d\tau dv \quad (1)$$

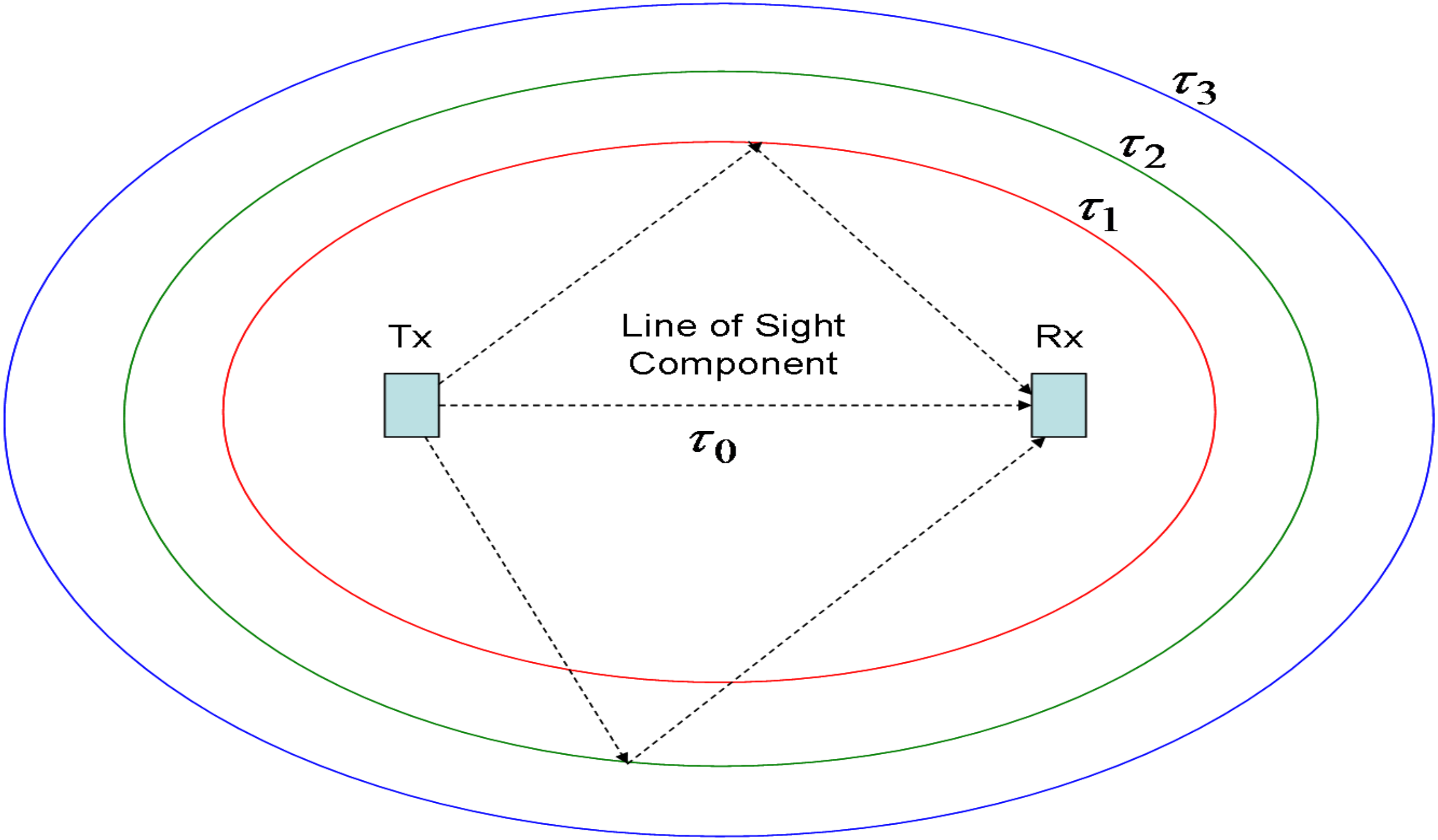
$$y(\mathbf{r},t)=\int h(\mathbf{r},\tau,t)x(t-\tau)d\tau \quad (2)$$

$$y(\mathbf{r},t)=\int g(\mathbf{r},f,t)X(f)\exp(j2\pi ft)df \quad (3) \qquad x(t)\xleftrightarrow{F_t}X(f)$$

$$g(\mathbf{r},f,t)=\sum_{l=1}^{L}a_l\exp[j2\pi(\mathbf{\Omega}_l\cdot\mathbf{r})/\lambda_0]\exp(j2\pi v_l t)\exp(-j2\pi f\tau_l) \quad (4)$$

L: number of multipath components, λ_0: carrier wavelength

Frequency Selective (Wideband) Modeling



J. D Parsons and A. S. Bajwa, "Wideband Characterization of Fading Mobile Radio Channels,"
IEE Proc. vol. 129, no. 2, pp. 95-101, Apr. 1982.

Narrowband Modeling

$$x(t-\tau_l) \approx x(t) \Leftrightarrow \tau_l \approx 0 \quad (5)$$

$$g(\mathbf{r}, f, t) = g(\mathbf{r}, t) = \sum_{l=1}^{L} a_l \exp[j2\pi(\mathbf{\Omega}_l \cdot \mathbf{r})/\lambda_0]\exp(j2\pi v_l t) \quad (6)$$

$$y(\mathbf{r}, t) = g(\mathbf{r}, t)x(t) \quad (7)$$

First – Order Statistical Modeling

$$(6):\ g(\mathbf{r},t)=\sum_{l=1}^{L}|a_l|\exp(j\Phi_l)=A\exp(j\Phi)\quad(7)$$

➢<u>First – Order Statistical Modeling</u>

Probabilistic characterization of the amplitude A, i.e., the received signal envelope, and phase Φ in (7).

✓Modeling should comply with the physical characteristics of the wireless propagation channel, e.g., Rayleigh distribution for A in the case of purely diffusive multipath propagation, Rice distribution in the case of a strong specular/LOS component added to purely diffusive multipath propagation.

Second – Order Statistical Modeling

$$g(\mathbf{r},t)=\sum_{l=1}^{L} a_l \exp[j2\pi(\mathbf{\Omega}_l\cdot\mathbf{r})/\lambda_0]\exp(j2\pi v_l t) \quad (6)$$

$$R(\Delta\mathbf{r},\Delta t)=E[g^*(\mathbf{r},t)g(\mathbf{r}+\Delta\mathbf{r},t+\Delta t)] \quad (8)$$

- ➢<u>Second – Order Statistical Modeling</u>

Mathematical expansion of the expectation formula in (8) and further processing to characterize the space and time variability of the wireless propagation channel.

✓Mathematical analysis should rely on the physical spatial characteristics of the wireless propagation channel, i.e., how multipath power is distributed in the three-dimensional space surrounding the Tx or the Rx.

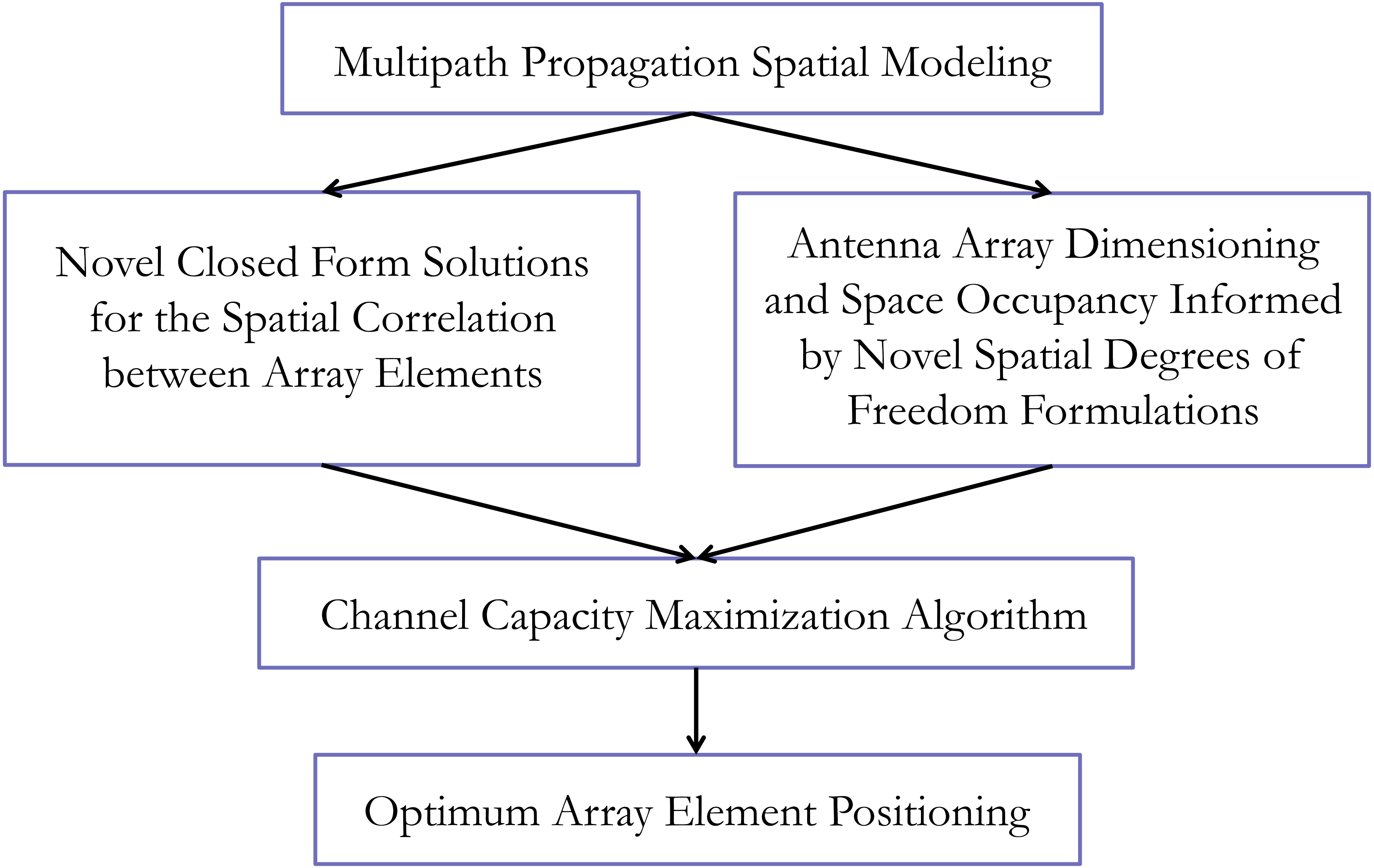
Contents

- ➢Wireless Systems and Techniques
  - ✓Antenna Array Design*
  - ✓Cryptographic Key Generation**

*Y. Huang, P. Karadimas, and A.P. Sohrab, “Spatial Degrees of Freedom for Optimum Antenna Arrays,” IEEE Trans. Wirel. Commun., under review, May 2022.

**M. Bottarelli, P. Karadimas, G. Epiphaniou, D. K. B. Ismail and C. Maple, “Adaptive and Optimum Secret Key Establishment for Secure Vehicular Communications,” IEEE Trans. Veh. Technol., vol. 70, no. 3, pp. 2310-2321, Mar. 2021.

Antenna Array Design – Methodology



Multipath Propagation Spatial Modeling

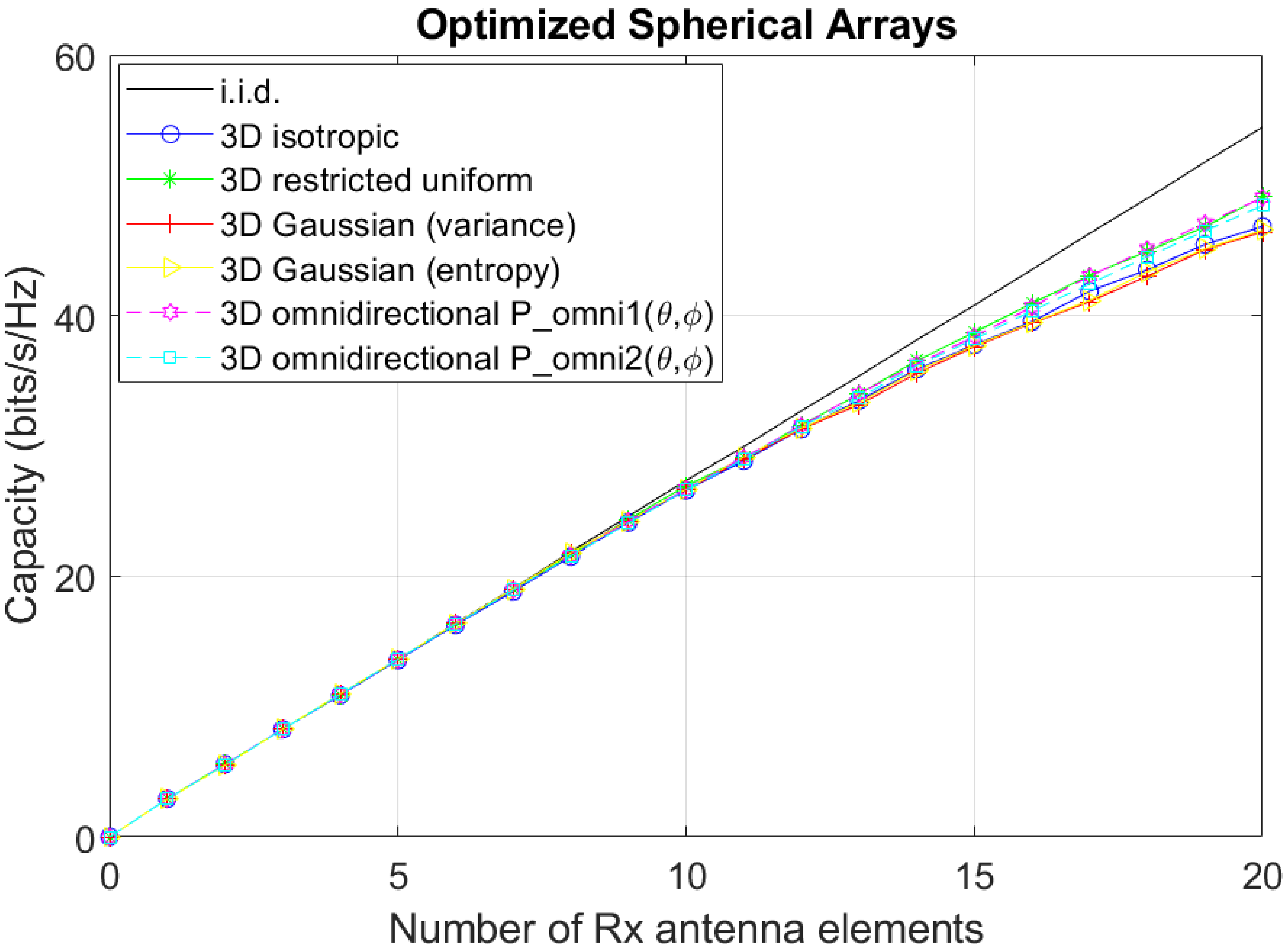
Novel Closed Form Solutions for the Spatial Correlation between Array Elements

Antenna Array Dimensioning and Space Occupancy Informed by Novel Spatial Degrees of Freedom Formulations

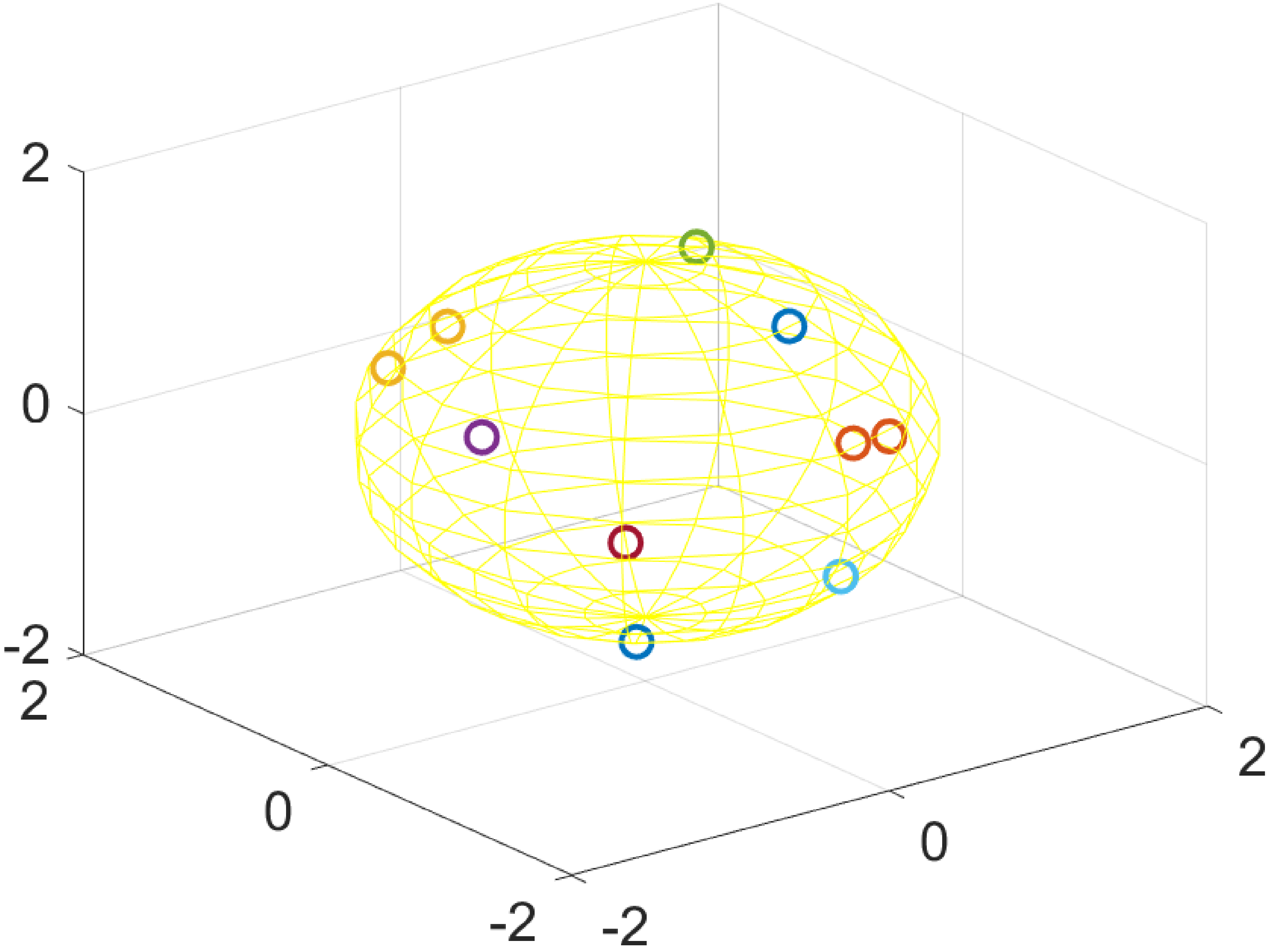
Channel Capacity Maximization Algorithm

Optimum Array Element Positioning

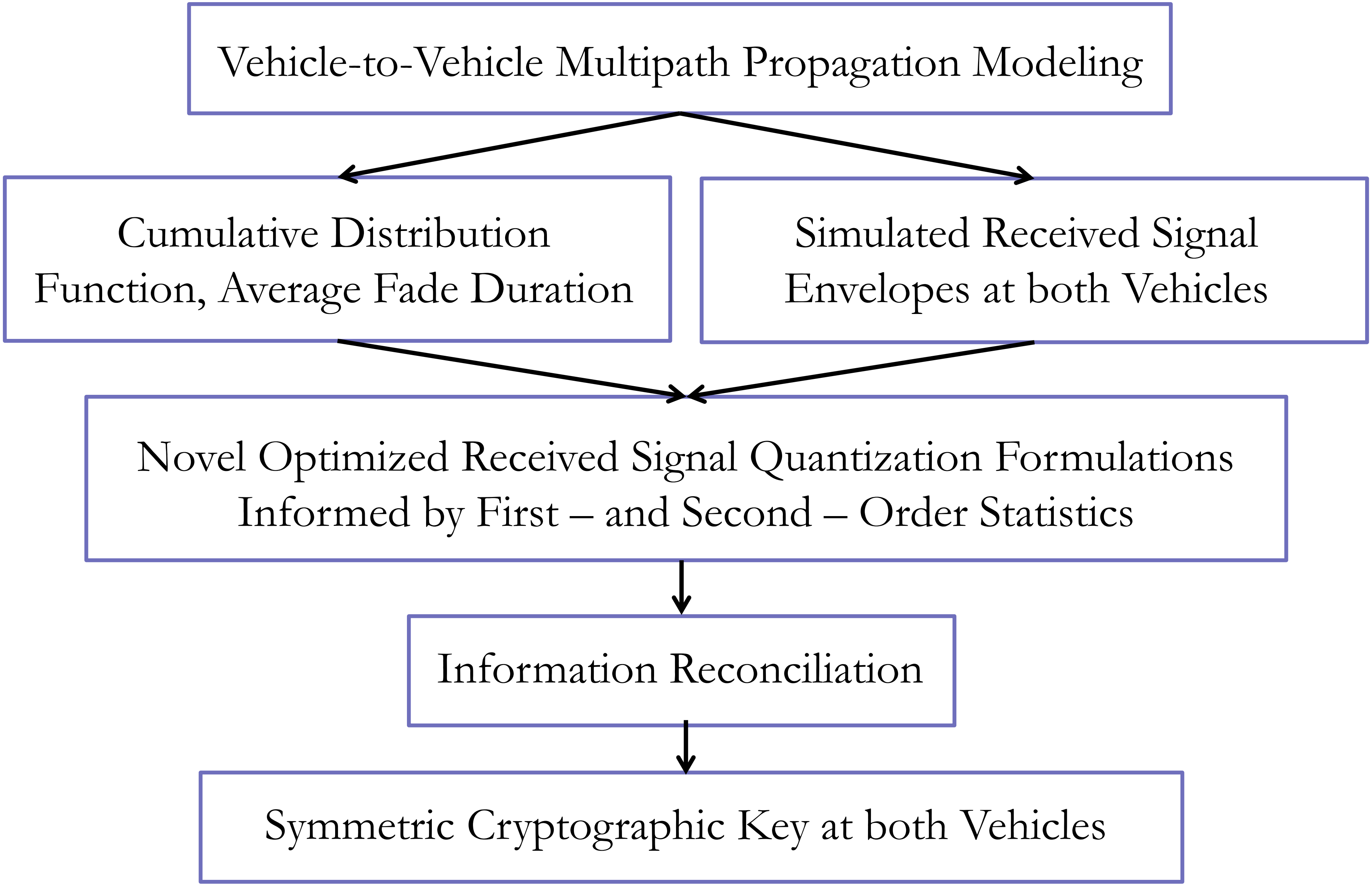
Maximized Channel Capacities



An Optimum Spherical Antenna Array



Cryptographic Key Generation – Methodology



Vehicle-to-Vehicle Multipath Propagation Modeling

Cumulative Distribution Function, Average Fade Duration

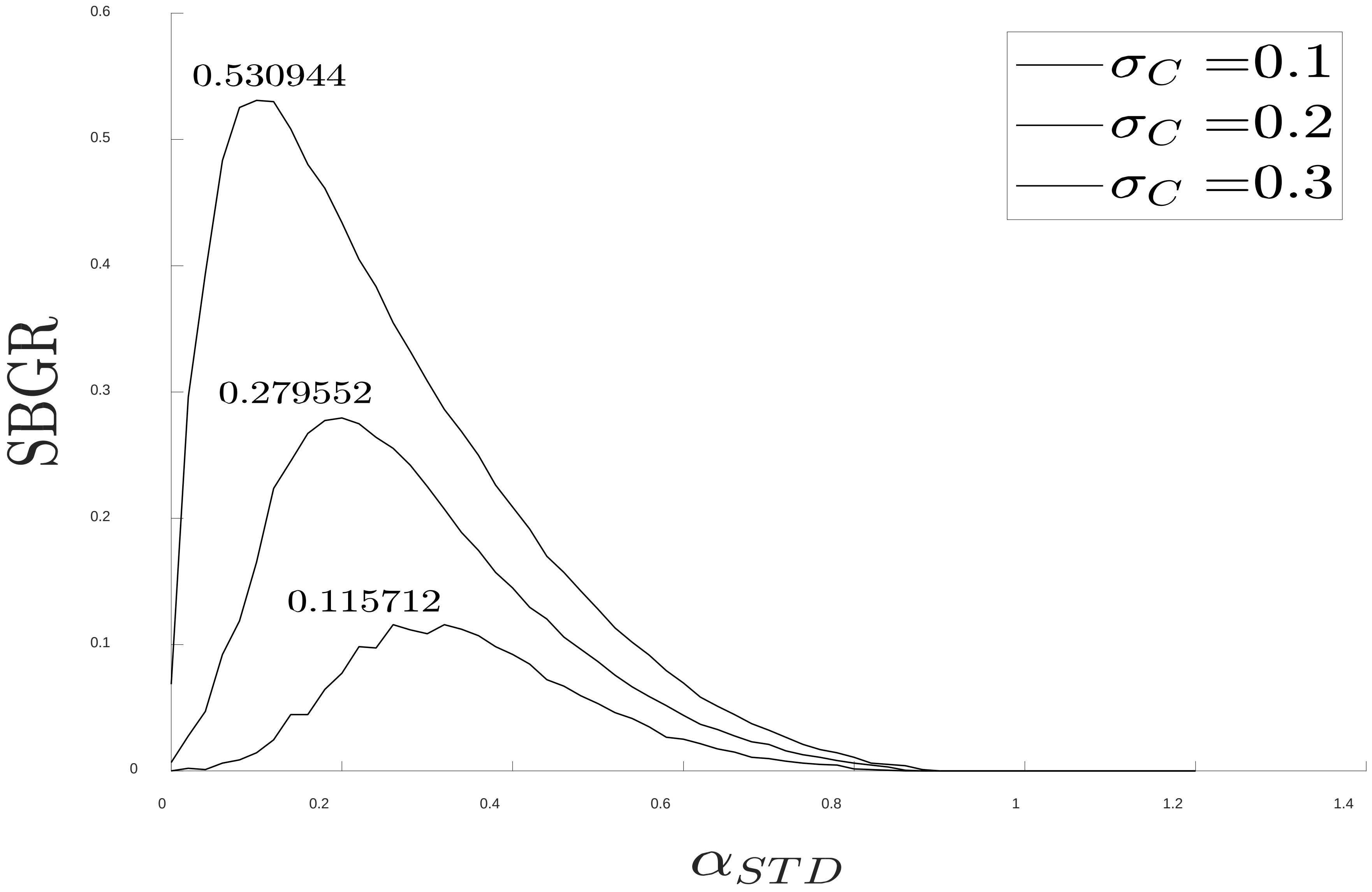
Simulated Received Signal Envelopes at both Vehicles

Novel Optimized Received Signal Quantization Formulations Informed by First – and Second – Order Statistics

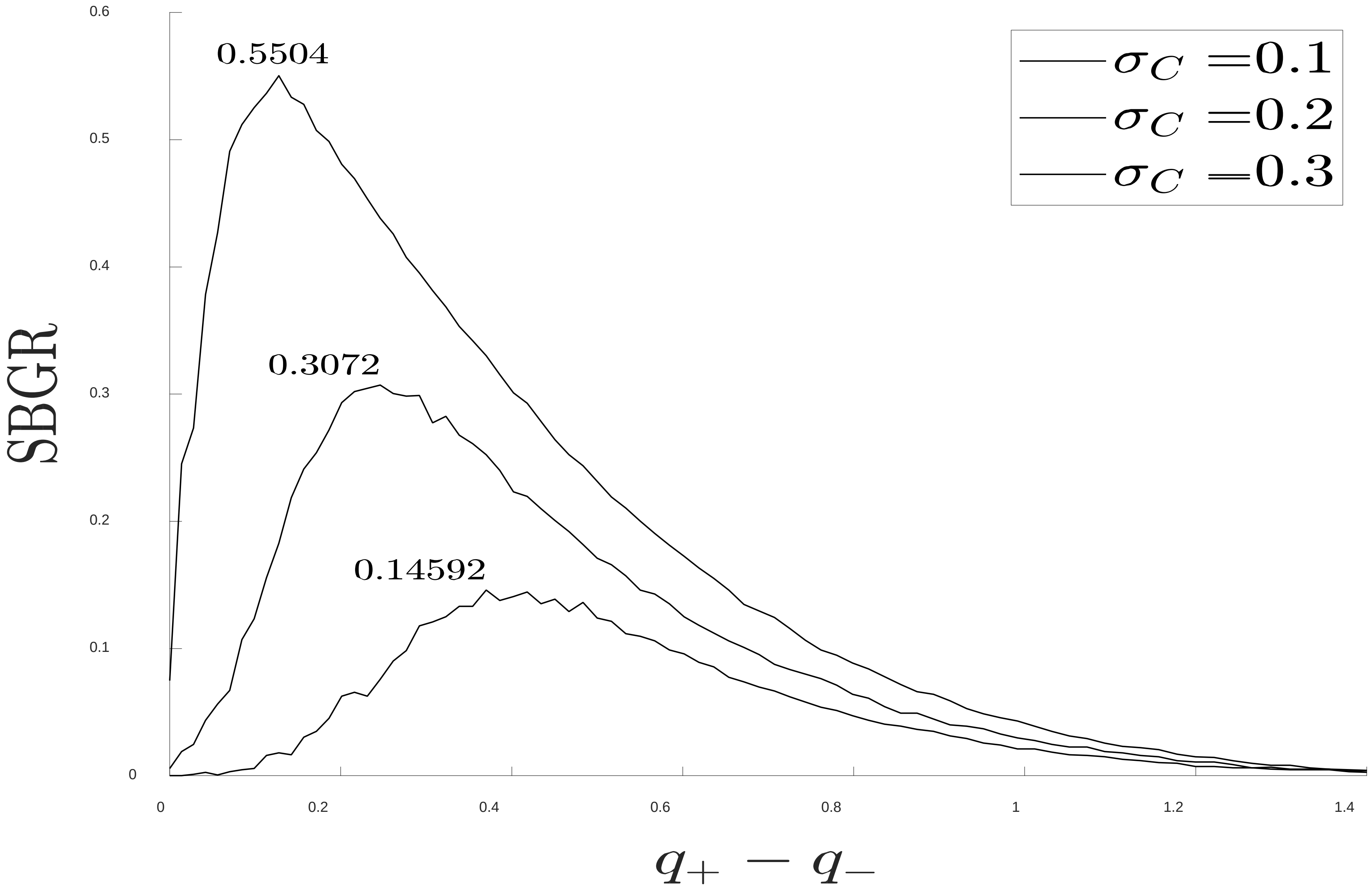
Information Reconciliation

Symmetric Cryptographic Key at both Vehicles

Secret Bit Generation Rate – No Optimization



Optimized Secret Bit Generation Rate



Thank you for your attention

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