COURSE 11
RADIO CHANNEL MODELING FOR V2V AND V2I

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COMMUNICATIONS DEPARTMENT

INTRODUCTION

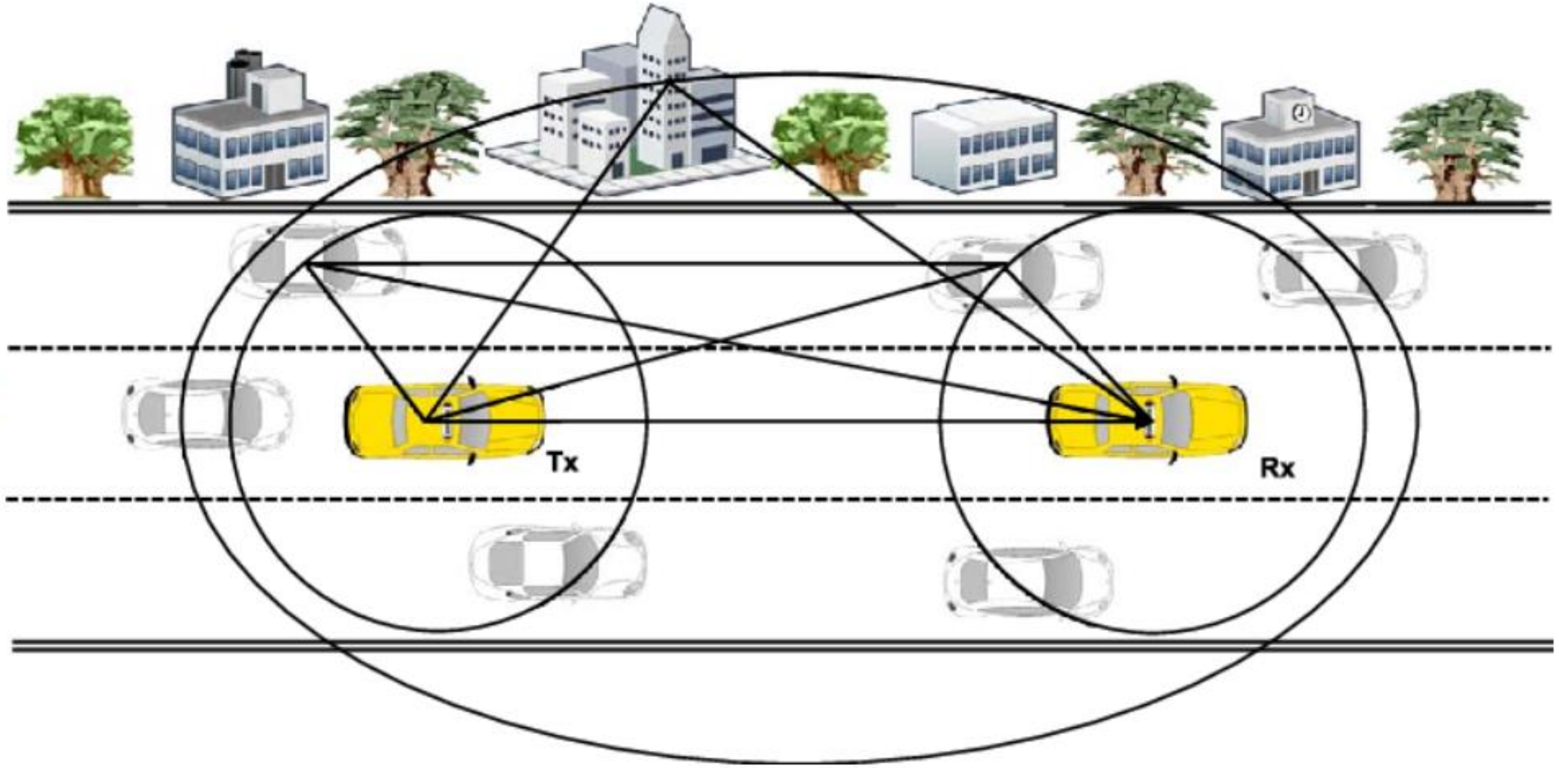
- Communication systems require the message source, transmitter, channel, receiver, message destination
  - The channel is uncontrolled or very loosely controlled by system designer and user
  - In case of vehicular communications, the channel is dynamic, lossy and distorting
    - Good channel models are required
- Specific channel characteristics for V2V and V2I applications:
  - Propagation path loss limits the performance, but these effect is often of secondary importance
    - Shadowing (obstructions by large building) is also of secondary importance
  - Small scale fading, caused by multipath propagation, is of primary importance
  - V2V and V2I channels are very dynamic, with time variation rates up to double those of cellular radio channels
  - Due to low antenna heights radio line of sight (LOS) is more frequently and more thoroughly obstructed
    - V2V and V2I channels exhibit more severe fading than conventional channels
    - V2V and V2I channels are best modeled as statistically non-stationary

V2V AND V2I CHANNELS

- The V2V channel is the wireless channel between two terrestrial vehicles
  - Network of vehicles may be communicating with one another
  - The most common environments for V2V communications is on roadways in cities and suburbs on throughways and highways between such locales
  - In open off-road areas the V2V channel exhibits characteristics similar to those of highways in open area
  - The off-road forest or mountainous area exhibits differences in the form of greater attenuation and obstruction.
  - The V2V channel may include a LOS path, or it may be an obstructed or NLOS path
- The V2I channel is the channel between a vehicle and another transmitter/receiver (transceiver) located on the roadside
  - In most cases the roadside transceivers are above vehicle height
    - The V2I channel has only one platform (TX or RX) in motion

V2V AND V2I CHANNELS

- V2V and V2I with multipath propagation



V2V/V2I COMMUNICATION FREQUENCY BANDS

- V2V/V2I communication can take place at any frequency band that is available & convenient for use
- In practice, based on desired system characteristics (range, costs) and on external factors (regulatory constraints), limitation arise, and the system will be designed to specific bands
  - Many desirable VHF and UHF bands are dedicated to other services
- Some “sort” of V2V communications:
  - Ad hoc voice transmissions in the “citizen band” (CB): carrier 27Mhz, band: ~440kHz; military systems that operate V2V modes – several bands are used
- Dedicated Short Range Communication (DSRC) standard uses the 5.9GHz band
  - The standard was moved to the IEEE under the 802.11p group
  - It is also known as Wireless Access for Vehicular Environments (WAVE)
- The 700MHz public safety band is also considered for V2V communications

V2V/V2I VS. MOBILE CHANNELS

- ❑ Traditional mobile channels, in the terrestrial case are referred to as land mobile radio channels
  - ○ One end of the channel is at a stationary base station
    - Base stations are carefully engineered in terms of location and facilities
  - ○ A prominent feature is the elevated antenna, often on a tower, possibly a tower on a hilltop
    - This is one feature that distinguishes traditional mobile channels from the V2V channel where both the Tx and Rx antennas are attached to vehicles, with heights of at most a few meters
    - The V2I channel provide an elevated antenna for one end of the link, but the antenna height is expected to be less than 10m, below surrounding building heights in urban areas
  - ○ In the V2V case there may be significant scatterers around both Tx and Rx not only around one or another as in the land mobile case
    - For the V2V case (due to obstructions and power limitations) the link distances are short, from a few meters to a few tens of meters

V2V/V2I VS. MOBILE CHANNELS

    - In open environments (suburban/rural, highways) the link distance can increase, but not planned to be as large as those in cellular radio (several tens of kms)

- In the V2V case (but not the V2I case) both Tx and Rx may be in motion
  - The rates of the V2V channel variation can be as much as double that of the land mobile case
    - Traditional statistical models that assume wide sense stationarity WSS (the invariance of channel statistics over some moderate time period) may not be applicable, or it is applicable only for a shorter duration
- Characterization of V2V and V2I channels can be done by using multiple channel classes, as it is commonly done in land mobile communications
  - Each class aims to represent a particular type of physical situation: urban, suburban, rural (replaced by highway in case of V2V/V2I)
  - Similar classes are defined also for V2V communications
    - Some characterizations explicitly identify the presence of an LOS component: LOS and NLOS

STATISTICAL CHANNEL CHARACTERISTICS

- Generally, the wireless channel is modeled as a linear, time-varying filter
  - The channel is completely described by the channel impulse response (CIR) $h(\tau)$, or by the Fourier transform of this, the channel transfer function (CTF) $H(f)$
  - Variable τ represents usually the delay variable
  - $H(f) = \int h(\tau)e^{-j2\pi\tau}d\tau$
  - In the case of time variation h and H can be generalized as $h(\tau, t)$ and $H(f, t)$
  - $h(\tau, t)$ is the channel output at time t due to an impulse applied at time $t-\tau$
  - Time linearity relies on the rate of channel time variation being slow enough to allow the usual
  - convolution relation between the input and output signal
  - $y(t) = \int v(t-\tau)h(\tau, t)d\tau = \int v(t)h(t-\tau, t)d\tau$
  - The relation is valid if $h(\tau, t)$ is constant during at least one symbol interval T_s of $v(t)$

STATISTICAL CHANNEL CHARACTERISTICS

- Physical channels must be casual, $h(\tau, t) = 0, \tau < 0$ they have finite duration T_h CIRs
- $y(t) = \int_0^{T_h} v(t-\tau)h(\tau, t)d\tau$
- CIR $h(\tau, t)$ is typically complex
- The bandpass channel response is obtained as $h_B(\tau, t) = 2Re\{h(\tau, t)e^{-j\omega_c t}\}$, $Re(x)$ is the real part, $\omega_c = 2\pi f_c$, f_c is the carrier frequency
- For a distortionless channel the CIR is: $h(\tau, t) = A(t)\delta(\tau - \tau_0(t))$
    - Where $\delta(t)$ is the Dirac impulse, $A(t) = \alpha(t)\exp[(j\theta(t)]$, $\alpha(t) = |A(t)|$, $\theta(t) = \measuredangle A(t)$
- Channel transfer function: $H(f, t) = A(t)e^{-j2\pi f\tau_0(t)} = \alpha(t)e^{-j[2\pi f\tau_0(t) - \theta(t)]}$
- Distortionless channel: only scales and delays the time domain signals

STATISTICAL CHANNEL CHARACTERISTICS

- For time invariant case the variations of $A(t)$ and $\tau_0(t)$ are slow compared to the rate of input signal variations
- For time invariant case: $h(\tau, t) = h(\tau) = A\delta(\tau - \tau_0) \leftrightarrow H(f, t) = H(f) = \alpha e^{j\theta} e^{-j2\pi f \tau_0}$
- The term of fading refers to variation of the channel’s characteristics over time or space
  - Channel amplitude variations are usually more significant to communication systems performance than the phase variations
  - Variations of the delay are typically very slow compared to the symbol rates for terrestrial communications
  - The functions describing these variations are well modeled as random
    - For V2V channels stochastic models are generally preferable to deterministic ones
    - In complex environments with mobility, the interest is not on exact field strength values in some specific points, but in some average values over a small spatial extent
    - Deterministic channel models are site specific and to be accurate they are computationally intensive

MULTIPATH CHANNEL IMPULSE RESPONSE

- The multipath CIR can be expressed as:
  - $h^{e}(\tau,t)=\sum_{k=0}^{L(t)-1} z_k(t)\alpha_k(t) exp\left\{j\left[\omega_{D,k}(t)\left(t-\tau_k(t)\right)-\omega_c(t)\tau_k(t)\right]\right\}\delta\left(\tau-\tau_k(t)\right)$
  - $h(\tau,t)$ is the channel response at time t to an impulse applied at time $t-\tau$
  - The impulses are discrete, the channel imposes specific discrete attenuations, phase shifts and delays upon any signal transmitted
  - This approximation is very good for signal bandwidths of tens of MHz or more
    - The model is not appropriate for wideband signals
    - In some channels the discreteness of impulses may not apply, and the baseband CIR is a continuous function
  - α_k is the amplitude of propagation path *k*
  - The argument of the exponential is the phase inserted on propagation path *k*
  - τ_k is the delay on propagation path *k*

MULTIPATH CHANNEL IMPULSE RESPONSE

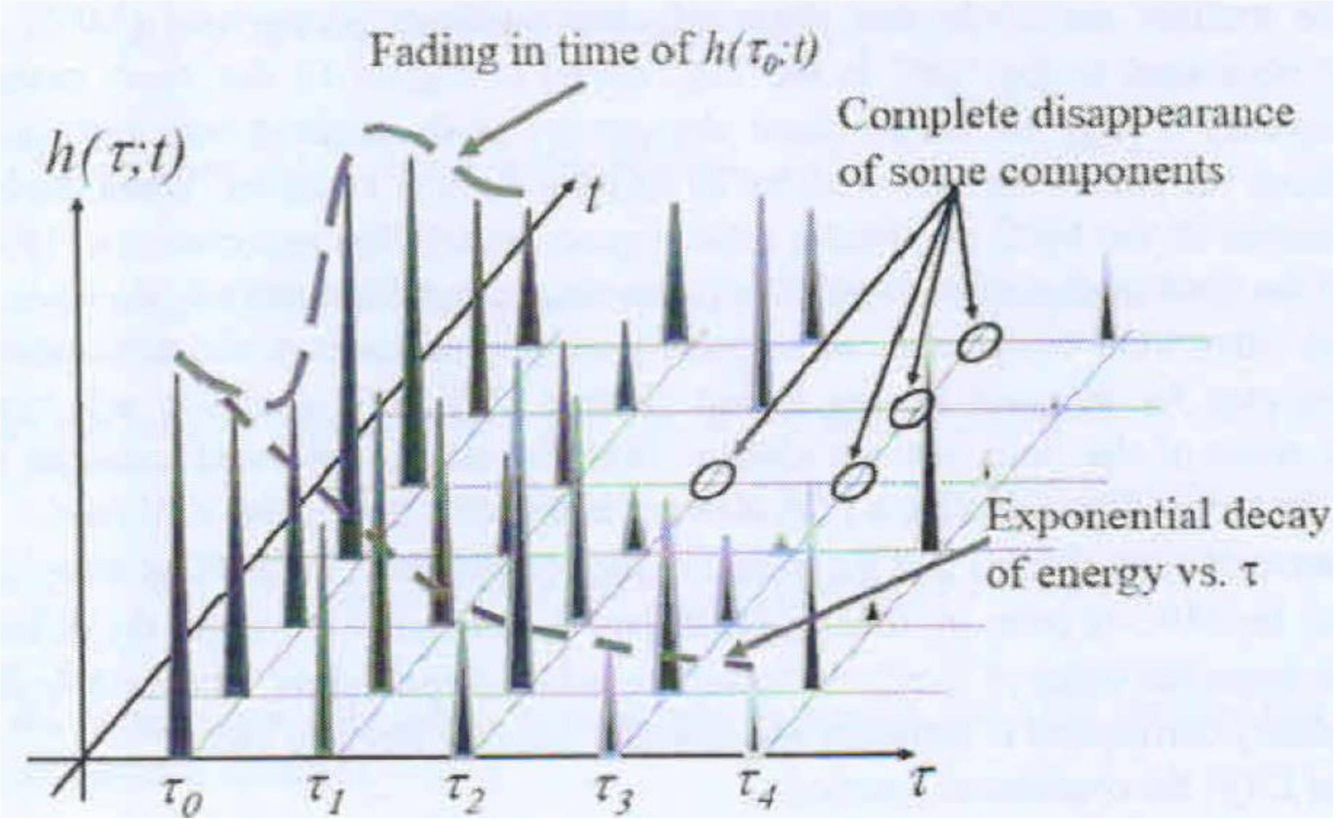
- $h^e(\tau,t) = \sum_{k=0}^{L(t)-1} z_k(t)\alpha_k(t)exp\{j[\omega_{D,k}(t)\big(t-\tau_k(t)\big)-\omega_c(t)\tau_k(t)]\}\delta\left(\tau-\tau_k(t)\right)$
- $f_c = \omega_c/(2\pi)$ is the carrier frequency
- $f_{D,k} = \omega_{D,k}/(2\pi)$ is the Doppler frequency on propagation path *k*
- $f_{D,k}(t) = v(t)f_c\cos[\theta_k(t)]\,/c$
  - $v(t)$ is the relative speed between Tx and Rx
  - $\theta_k(t)$ is the aggregated phase angle of all components arriving in the *k*-th delay bin
    - The delay bin width is approximately equal to the reciprocal of the signal bandwidth, e.g. for 10 MHz it is 100 ns
    - V2V communications use omnidirectional antennas, except some stationary V2I antennas mounted at roadside
  - c is the speed of light

MULTIPATH CHANNEL IMPULSE RESPONSE

- The equation is a generalization which allows:
    - An environmental classification, can be used to denote CIRs for the channel classes
    - A time-varying number of transmission paths
    - A persistence process $z(t)$ accounting for the finite lifetime of propagation paths
    - The time variation of carrier frequency $\omega_c(t)$ to account for transmitter oscillator variations and/or carrier frequency hopping
- The corresponding CFT is:
    - $H^e(f,t) = \sum_{k=0}^{L(t)-1} z_k(t)\alpha_k(t)e^{j2\pi f_{D,k}(t-\tau_k(t))}\, e^{-j2\pi f_c\tau_k(t)} e^{-j2\pi f\tau_k(t)}$
        - f_c is considered constant over time
        - The second exponential can change significantly with small changes in delay when f_c is large – nanosecond delay changes can cause 2π shifts when the frequency is 1 GHz

MULTIPATH CHANNEL IMPULSE RESPONSE

- ❑ Time-varying CIR



CIR AND CFT CORRELATION FUNCTIONS AND DOPPLER

- For channels modeled as random, a complete specification contains all the probability density functions for all parameters
- The CIR correlation function is: $R_{hh}\left(\tau,\tau_{1,},t,t_1\right) = E\left[h(\tau,t)h^*(\tau_{1,},t_1)\right]$
- The CIR of the channel can be rewritten as:
  - $h^e(\tau,t) = \sum_{k=0}^{L-1}\beta_k(t)e^{j\phi_k(t)}\delta[\tau-\tau_k(t)]$
    - The phase and amplitude of each multipath component (MPC) is expressed explicitly
    - For cases where carrier frequency is large the phases are well modeled as uniform random variables
    - When these phases are independent of the MPC amplitudes the CIR is zero because of the random phase uniformity
    - The zero mean condition breaks down when there is a dominant LOS component, with a slowly varying or constant non-zero mean phase Rician channel model
    - V2V channel have LOS conditions some of the time, but not always
    - With the slightly elevated antennas of V2I channels, the probability of having a LOS component is larger

CIR AND CFT CORRELATION FUNCTIONS AND DOPPLER

- R_{hh} measures the correlation of the MPC at delay τ time t and MPC at delay τ_1 time t_1
  - Generally, the larger the difference in delay the lower the value of correlation, since widely differing delays correspond to different and spatially separated physical paths
- For CFT the correlation function is: $R_{HH}(f, f_1, t, t_1) = E[H(f,t)H^*(f_1, t_1)]$
  - R_{HH} measures the correlation of MPC at frequency f time t and MPC at frequency f_1 time t_1
- The relationship between R_{hh} and R_{HH} is the double Fourier transform
  - $R_{HH}(f, f_1, t, t_1) = \iint R_{hh}\left(\tau, \tau_{1,}, t, t_1\right) e^{-j2\pi f\tau} e^{-j2\pi f_1 \tau_1} d\tau d\tau_1$
- The delay-Doppler correlation function – double Fourier transform of R_{hh} with respect to t
  - $R_{SS}(\tau, \tau_1, v, v_1) = \iint R_{hh}\left(\tau, \tau_{1,}, t, t_1\right) e^{-j2\pi vt} e^{-j2\pi v_1 t_1} dt dt_1$
  - R_{SS} is the correlation of MPC at delay τ and Doppler shift v and MPC at delay τ_1 and Doppler v_1

UNCORRELATED SCATTERING

- When the MPCs at different delays are uncorrelated, the channel is termed an uncorrelated scattering (US) channel
- Assuming that phases are independent from amplitudes, the amplitude functions satisfy:
  $R_{\beta\beta}(t,\Delta t) = E\left[\beta_k(t)\beta_j(t+\Delta t)\right] = E[\beta_k(t)]E\left[\beta_j(t+\Delta t)\right]$
- Noting $e^{j\phi_k(t)} = \chi_k(t)$, then $R_{\chi\chi}(t,\Delta t) = E\left[\chi_k(t)\chi_j(t+\Delta t)\right] = E[\chi_k(t)]E\left[\chi_j(t+\Delta t)\right]$
  - If the random phases ϕ_k are uniform, then $R_{\chi\chi} = 0$, since $E[\chi_k(t)] = 0$
- In the case of US $R_{hh}(\tau,\tau_1,t,t_1) = E[h(\tau,t)h^*(\tau_1,t_1)] = R_{hh}(\tau,t,t_1)\delta(\tau-\tau_1)$
  - R_{hh} is non-zero only when $\tau = \tau_1$

UNCORRELATED SCATTERING

- The CFT function for uncorrelated scattering becomes:
- $R_{HH}(f, f_1, t, t_1) = E[H(f,t)H^*(f_1, t_1)] = R_{HH}(\Delta f, t, t_1)$
  - Where $\Delta f = |f - f_1|$
  - In the case of US, the CFT correlation function does not depend on absolute values of f and f_1 , but only on their difference, case named WSS (Wide Sense Stationary) in frequency
- In the case of US the delay-Doppler correlation function becomes:
- $R_{SS}(\tau, \tau_1, v, v_1) = R_{SS}(\tau, v, v_1)\delta(\tau - \tau_1)$

WIDE SENSE STATIONARY

- A process is WSS if its mean is constant, and its autocorrelation depends only on the time difference and not on absolute times
- CIR in case of WSS becomes: $R_{hh}(\tau,\tau_1,t,t_1) = E[h(\tau,t)h^*(\tau_1,t_1)] = R_{hh}(\tau,t,\Delta t)$
  - Where $\Delta t = |t - t_1|$
- If CIR is WSS in time, CFT becomes:
- $R_{HH}(f,f_1,t,t_1) = E[H(f,t)H^*(f_1,t_1)] = R_{HH}(f,f_1,\Delta t)$
- The delay-Doppler correlation function becomes:
- $R_{SS}(\tau,\tau_1,v,v_1) = \delta(v - v_1)\int R_{hh}(\tau,\tau_1,\Delta t)e^{-j2\pi v_1 \Delta t}d\Delta t = \delta(v - v_1)P_S(\tau,\tau_1,v)$
  - Where $P_S(\tau,\tau_1,v)$ is the delay Doppler cross power spectral density

WSS AND UNCORRELATED SCATTERING

- When both US and WSS apply (WSSUS) the correlation functions reduce to:
  - $R_{hh}(\tau, \tau_1, t, t_1) = E[h(\tau, t)h^*(\tau_1, t_1)] = R_{hh}(\tau, \Delta t)\delta(\tau - \tau_1)$
  - $R_{HH}(f, f_1, t, t_1) = E[H(f, t)H^*(f_1, t_1)] = R_{HH}(\Delta f, \Delta t)$
  - $R_{SS}(\tau, \tau_1, v, v_1) = \delta(\tau - \tau_1)\delta(v - v_1)P_S(\tau, v)$
    - R_{HH} is the spaced-frequency spaced-time (SFST) correlation function, $P_S(\tau, v)$ is the scattering function
    - For CIR correlation function when $\Delta t = 0$, $R_{hh}(\tau, 0) = \psi_h(\tau)$ is the power delay profile (PDP), the channels average power output vs. delay
    - The Fourier transform of PDP is $R_{HH}(\Delta f, 0) = \psi_{Hf}(\Delta f)$ is the spaced-frequency correlation function, and measures the correlation between channel effects at frequencies separated by Δf
    - The width of $\psi_h(\tau)$, the multipath delay spread T_M is reciprocally related to the width of $\psi_{Hf}(\Delta f)$, the coherence bandwidth of channel B_C

WSS AND UNCORRELATED SCATTERING

- ○ Setting $\Delta f = 0$, $R_{HH}(0, \Delta t\ ) = \psi_{Ht}(\Delta t)$ gives the spaced-time correlation function which measures the correlation between channel effects separated in time by Δt
  - The scattering function is the double Fourier transform of the SFST correlation function
  - $P_S(0, v) = P_S(v)$ is the Doppler spectrum, whose width the Doppler spread f_D is reciprocally related to the width of $\psi_{Hf}(\Delta t)$, which is the coherence time of the channel t_C

- ❑ $T_M = width\ of\ \psi_h(\tau) \sim 1/B_C$ and $f_D = width\ of\, P_S(v) \sim 1/t_C$
  - ○ The delay spread T_M measures the amount the channel spreads an input impulse in delay
  - ○ The Doppler spread f_D measures the amount the channel spreads an input tone in frequency
  - ○ The coherence bandwidth B_C measures the channel's frequency selectivity
  - ○ The coherence time t_C measures the channel's time selectivity (or time rate variation)

NON-STATIONARY CHANNELS AND CORRELATED SCATTERING

- Real channels are statistically stationary only for a limited time
- Statistical models for dynamic wireless channels can be at best only stationary in the wide sense
- The WSS (and WSSUS) assumption is widespread used due to their relative mathematical simplicity – it has inherently limited application
  - Wireless standards model the distribution of channel delay spreads this implies non-stationarity without explicitly modeling it
- Modeling channels over long terms (modeling over wide areas) requires the use of the channel’s changing statistics
  - Just a few NS models exist for terrestrial communications
  - For small time/frequency intervals, the non-WSSUS model can be considered as WSSUS

V2V CHANNEL STATISTICS

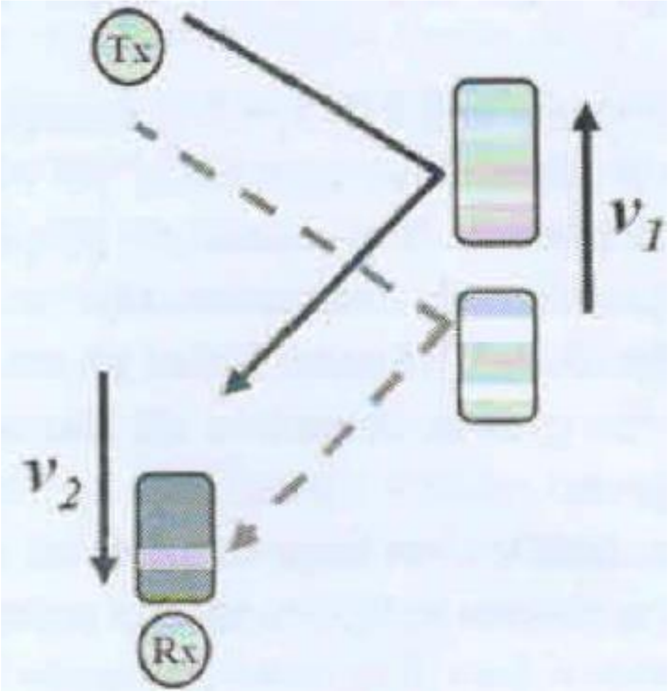
- ❑ V2V channels with Tx and Rx in motion have more rapid variations than traditional channels
    - ○ For a given environment, the V2V coherence time is smaller, the Doppler spread is larger
    - ○ $t_c(V2V)$ can be half of $t_c(cell)$ or $t_c(V2I)$, Doppler spread is double: $f_D(V2V) \sim 2f_D(cell)$
    - ○ The duration for which V2V channel can be considered WSS is smaller
- ❑ Delay spread for V2V channels is similar to those of V2I channels
    - ○ The scatterers in the local environment will be largely the same for these two cases
- ❑ The V2V channel delay spread is typically smaller than those of cellular channels in urban environment
    - ○ V2V link distance is smaller than cellular link distances

V2V CHANNEL STATISTICS

- For open or highway V2V/I conditions, delay spreads can be larger than in the urban scattering
  - Generally, are smaller than the delay spreads for cellular channels, since cellular base stations have elevated antennas that can radiate energy to farther distances that can low height V2V antennas
- For a given environment the following relations are satisfied: $T_M(V2V) \sim T_M(V2I) < T_M(cell)$; $B_c(V2V) \sim B_C(V2I) > B_C(cell)$

☐ Uncorrelated scattering: scattering emanates from distinct physical objects

- It is not the case always for V2V communications
  - Scattering from two separated cars moving uniformly at the same velocity can yield fully correlated effects



V2V CHANNEL STATISTICS

- ○ Even if V2V channels can be NS and exhibit correlated scattering, PDPs and CIRs can be measured, and delay spread, and coherence bandwidth can be quantified
  - The channel correlation functions R_{hh} and R_{HH} may not be available, but representative CIR and CFT can be obtained
  - Doppler spreads can be measured for V2V/V2I environments, and the coherence times estimated
  - Complete SFST correlation functions and scattering functions are not generally available

- ☐ To completely specify a V2V channel model the following must be defined:
  - ○ Number of MPC (obtained from T_M)
  - ○ The tap's time rate of change (obtained from f_D)
  - ○ A statistical model for the tap amplitude random processes
  - ○ The relative energy of each tap

DETERMINISTIC V2V/V2I CHANNEL MODELS

- For the simplest of situations, deterministic models can be used effectively
  - “Plane earth” model: single LOS path and a single ground reflected path between Tx Rx → a very good model for V2V channel between two cars on open highway
    - If vehicle velocities and the-inter vehicle distances vary, keeping track of the channel parameters becomes complicated, it is difficult to create an accurate time varying deterministic model
    - Uncertainties in model parameters reduce the accuracy
  - Other deterministic models use ray tracing
    - Local environment data is used to build a model for all objects in the physical setting; electrical parameters (e.g., conductivities) are also needed as input
    - High frequency approximations allow plane waves to be modeled as rays (between Tx and Rx) with reflections, diffractions, attenuations; for accuracy, a large number of rays must be used
    - Reasonably accurate ray tracing channel models can be obtained for site specific cases → these cases can be generalized by random generation of object properties → hybrid statistical and deterministic models
    - These model are site specific and computationally intensive

THEORETICAL STATISTICAL V2V/V2I CHANNEL MODELS

- ❑ Several simplifying assumptions can be used to obtain the spaced-time correlation function $\psi_{Ht}(\Delta t)$ and the Doppler spectrum $P_S(v)$ for V2V channels
  - Assumptions: isotropic scattering
  - Fading amplitude statistics are Rayleigh
  - The channel is WSSUS
    - The spaced time correlation function is a product of two Bessel functions, extension of the cellular channel result of a single Bessel function: $\psi_{Ht}(\Delta t) = J_0(2\pi f_1 \Delta t) J_0(2\pi f_2 \Delta t)$
      - Where f_i is the maximum Doppler shift due to motion of mobile *i*, given by $f_{Di} = v_i/\lambda$, where v_i is the speed of mobile *i*, λ is the wavelength
- ❑ Two-dimensional scattering model is generalized, and the spaced-time autocorrelation function and Doppler spectrum is obtained for three-dimensional scattering case
  - These functions depend upon antenna patterns and distributions of angles of arrival and must be numerically evaluated

THEORETICAL STATISTICAL V2V/V2I CHANNEL MODELS

- Another theoretical model considers non-isotropic scattering; a closed-form expression for the spaced-time autocorrelation function is:: $\psi_{Ht}(\Delta t) = \prod_{i=1}^{2} \frac{I_0\left[\sqrt{\kappa_i^2 - 4\pi^2 f_i^2 \Delta t^2 + j4\pi\kappa_i f_i \Delta t cos(\mu_i)}\right]}{I_0(\kappa_i)}$
  - where f_i is the maximum Doppler shift due to motion of mobile *i*, μ_i is the mean angle of arrival of plane wave for mobile *i*, κ_i is a parameter of the von Misses density analogous to a standard deviation of the angle of arrival
- No, well established, theoretical models exist for V2V channel PDP $\psi_h(\tau)$ and the spaced-frequency correlation function $\psi_{Hf}(\Delta t)$
  - A wide range of PDP shapes and delay spreads exist in practice
  - For analysis and simulation purposes two forms of PDPs are used: uniform and exponentially decaying → it is in better agreement with measurements of the V2V channel

EMPIRICAL STATISTICAL V2V/V2I CHANNEL MODELS

- Empirical statistical model exist for a number of V2V/V2I cases
  - For frequency non-selective fading channel the Ricean distribution fits best the data taken in urban, suburban and highway environments in 5GHz band
    - Doppler spectra best fit a Gaussian shape with a standard deviation of ≈ 85Hz in urban environment and ≈ 120Hz in highway environment
  - Another model was developed based on measurements performed in a 20MHz bandwidth in the 2.4GHz band for highway environment
    - A 10-tap TDL (Tapped-Delay Line) model was provided, with Rice factors for each tap
    - The maximum delay of the model is 450ns, with RMS DS less than 100ns
    - Doppler spectra were provided only for a few taps
    - Non-isotropic scattering was considered (not surprising for highway environment)

EMPIRICAL STATISTICAL V2V/V2I CHANNEL MODELS

- Narrowband (frequency non-selective) measurements in suburban environment in the 5GHz band were considered for a single tap model and Nakagami amplitude fading, more severe fading than the Rayleigh distribution modeled one
- Several sets of empirical models for the 5GHz band and 10MHz bandwidth were provided for urban, suburban and highway scenarios
    - The models contains up to 8 taps, each tap has associated energy level, Ricean K-factor, frequency shift and Doppler spectrum
    - Maximum Doppler spreads are on the order of 1500Hz for highway cases, 900Hz for urban cases
    - The performed measurements of the time-varying Doppler spectral shapes largely imply non-isotropic scattering and statistical non-stationarity

NON-STATIONARY V2V CHANNEL MODELS

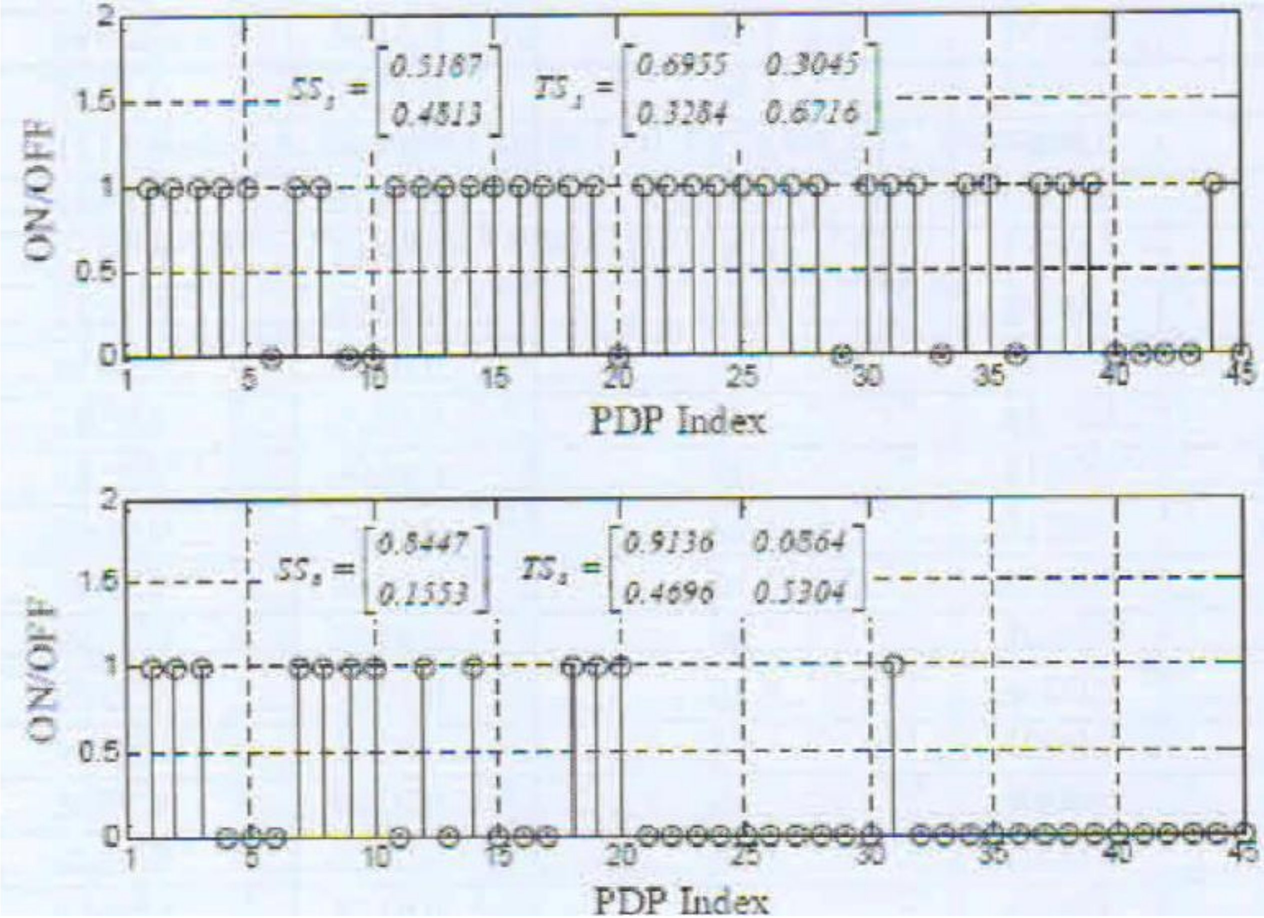
- Non-stationary V2V channel models were developed based upon 50Mhz bandwidth measurements in the 5GHz band
- The “appearance” and “disappearance” of MPC can be modeled by the persistence process $z_k(t)$
  - Persistence models are “medium scale” fading effects
    - For a given velocity this fading is slower than the small scale multipath fading, but faster than large scale shadowing
  - Persistence process improves the model fidelity, but increase the model complexity
    - In terms of RMS DS statistics inclusion of persistence in the models yields better agreement with measured data
  - Models for persistence employ 1st order (homogeneous) Markov chains for each tap
    - These models are described by the transition (TS) matrix and steady state (SS) matrix

NON-STATIONARY V2V CHANNEL MODELS

- $TS = \begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix}$, s$S = \begin{bmatrix} P_{00} \\ P_{10} \end{bmatrix}$
  - Where P_{ij} is the probability of transition from state *i* in state *j*, P_i denotes the long-term probability of being in state *i*
  - State *0* denotes MPC off, *1* denotes MPC on, $z_k(t)$ is either *0* or *1*
  - $P_0 = 1 - P_1; P_{01} = 1 - P_{00}; P_{10} = 1 - P_{11}$
- In real environments vehicles moves from type of region to other and velocities change
  - Transition should be allowed between models
    - The challenge is the smoothing the transitions between models
  - Changing velocities yield changing Doppler spectra
    - Models for time-varying Doppler are needed

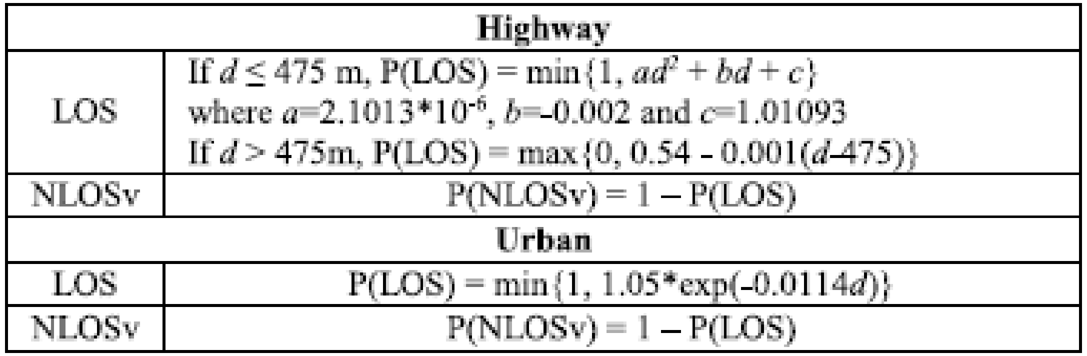
NON-STATIONARY V2V CHANNEL MODELS

- Fig. 6 Persistence process of the taps of the TDL model



3GPP REL. 16 V2V CHANNEL MODEL

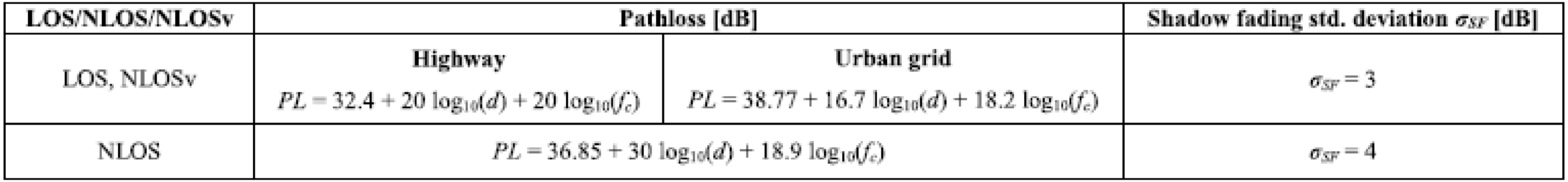
- Rel. 16 V2X SL channel models introduce the NLOSv state besides the LOS and NLOS
  - The NLOSv state describes V2V SL channels where the LOS path is blocked by another vehicle
    - Measurements showed that blockage of SL LOS by vehicles exhibits different properties compared to NLOS channels
      - NLOS assumes blockage by objects considerably larger than vehicles (e.g., buildings)
    - In highways, there are no other objects that block the LOS other than vehicles
    - Dynamics of NLOSv blockage is different to NLOS blockage
- LOS probability equations



Highway	
LOS	If $d \leq 475$ m, $P(LOS) = \min\{1, ad^2 + bd + c\}$ where a=2.1013*10^{-6}, b=–0.002 and c=1.01093 If $d > 475$m, $P(LOS) = \max\{0, 0.54 - 0.001(d\text{–}475)\}$
NLOSv	$P(NLOSv) = 1 – P(LOS)$
Urban	
LOS	$P(LOS) = \min\{1, 1.05*\exp(-0.0114d)\}$
NLOSv	$P(NLOSv) = 1 – P(LOS)$

3GPP REL. 16 V2V CHANNEL MODEL

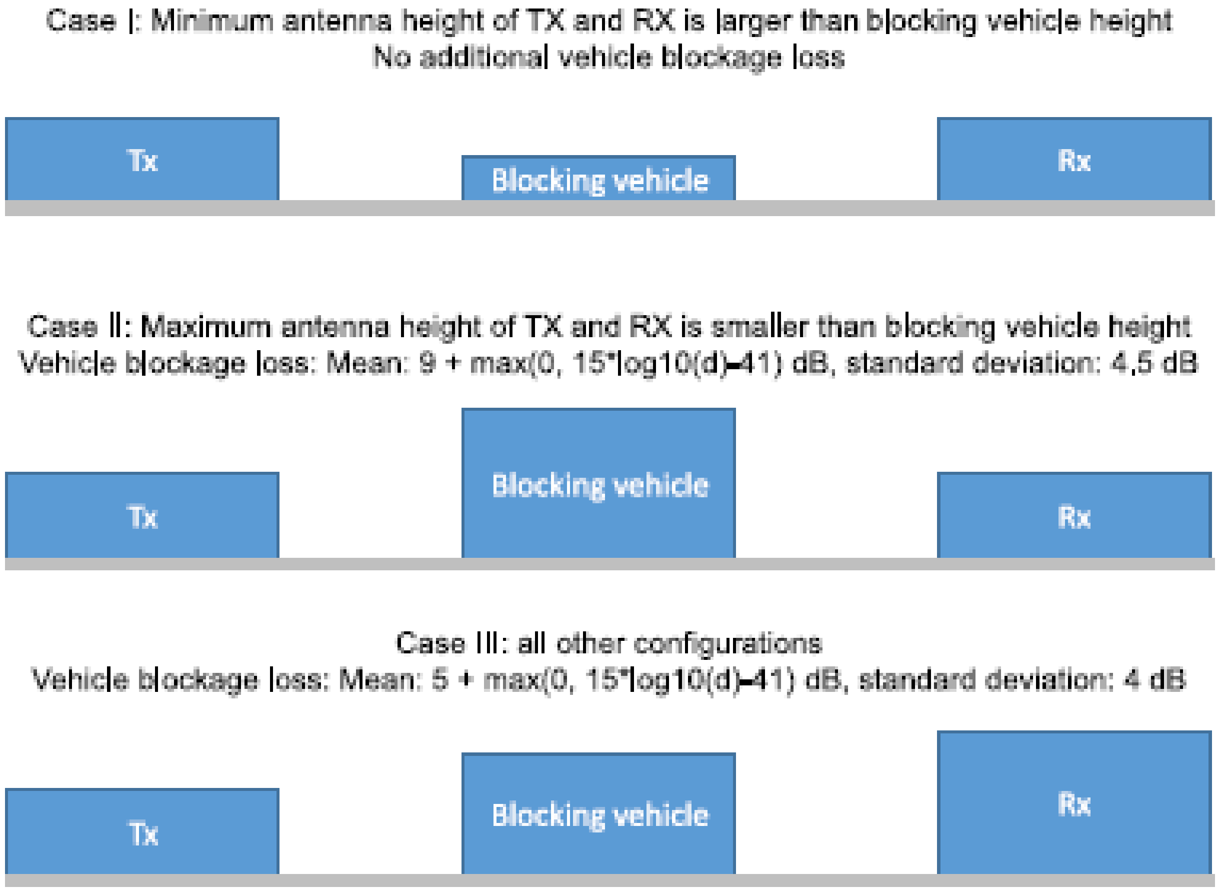
- The shadow fading is modeled with a random variable according to a lognormal distribution with zero mean
  - For each V2V link, shadow fading is an independent and identically distributed lognormal random variable; the LOS shadowing model applies to NLOSv as well
- Pathloss expressions for highway and urban grid scenarios
  - f_c denotes the carrier frequency in GHz
  - d denotes the Euclidean distance between a TX and RX UE considering also the heights of the Tx and Rx antennas



LOS/NLOS/NLOSv	**Pathloss [dB]**		**Shadow fading std. deviation σ_{SF} [dB]**
	Highway	**Urban grid**	
LOS, NLOSv	$PL = 32.4 + 20\log_{10}(d) + 20\log_{10}(f_c)$	$PL = 38.77 + 16.7\log_{10}(d) + 18.2\log_{10}(f_c)$	$\sigma_{SF} = 3$
NLOS	$PL = 36.85 + 30\log_{10}(d) + 18.9\log_{10}(f_c)$		$\sigma_{SF} = 4$

3GPP REL. 16 V2V CHANNEL MODEL

- Additional vehicle blockage loss is introduced for NLOSv for different relationships of the height of Tx antenna, Rx antenna and the blocking vehicle



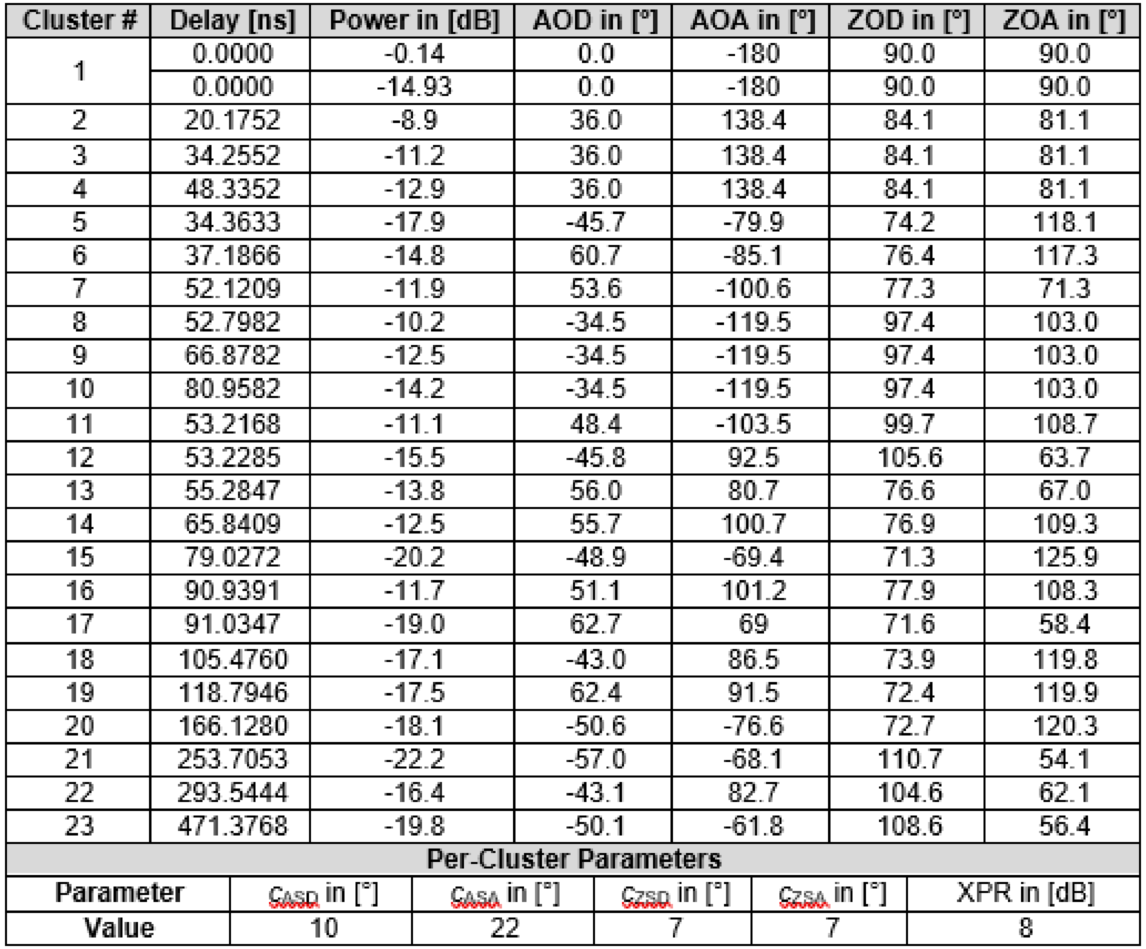
Case I: Minimum antenna height of TX and RX is larger than blocking vehicle height
No additional vehicle blockage loss

Case II: Maximum antenna height of TX and RX is smaller than blocking vehicle height
Vehicle blockage loss: Mean: 9 + max(0, 15*log10(d)-41) dB, standard deviation: 4,5 dB

Case III: all other configurations
Vehicle blockage loss: Mean: 5 + max(0, 15*log10(d)-41) dB, standard deviation: 4 dB

3GPP REL. 16 V2V CHANNEL MODEL

- ❑ Fast fading parameters for V2X communications are defined in 3GPP TR 37.885 via the CDL (Cluster-Delay Line) models in Chapter 6.2.3.1 considering urban LOS, NLOS, NLOSv and highway LOS, NLOSv
  - ○ CDL model for urban NLOSv V2X channel
    - AOD/AOA azimuth departure/arrival angle
    - ZOD/ZOA elevation departure/arrival angle
    - XPR – cross-polarization ratio



Cluster #	Delay [ns]	Power in [dB]	AOD in [°]	AOA in [°]	ZOD in [°]	ZOA in [°]
1	0.0000	-0.14	0.0	-180	90.0	90.0
	0.0000	-14.93	0.0	-180	90.0	90.0
2	20.1752	-8.9	36.0	138.4	84.1	81.1
3	34.2552	-11.2	36.0	138.4	84.1	81.1
4	48.3352	-12.9	36.0	138.4	84.1	81.1
5	34.3633	-17.9	-45.7	-79.9	74.2	118.1
6	37.1866	-14.8	60.7	-85.1	76.4	117.3
7	52.1209	-11.9	53.6	-100.6	77.3	71.3
8	52.7982	-10.2	-34.5	-119.5	97.4	103.0
9	66.8782	-12.5	-34.5	-119.5	97.4	103.0
10	80.9582	-14.2	-34.5	-119.5	97.4	103.0
11	53.2168	-11.1	48.4	-103.5	99.7	108.7
12	53.2285	-15.5	-45.8	92.5	105.6	63.7
13	55.2847	-13.8	56.0	80.7	76.6	67.0
14	65.8409	-12.5	55.7	100.7	76.9	109.3
15	79.0272	-20.2	-48.9	-69.4	71.3	125.9
16	90.9391	-11.7	51.1	101.2	77.9	108.3
17	91.0347	-19.0	62.7	69	71.6	58.4
18	105.4760	-17.1	-43.0	86.5	73.9	119.8
19	118.7946	-17.5	62.4	91.5	72.4	119.9
20	166.1280	-18.1	-50.6	-76.6	72.7	120.3
21	253.7053	-22.2	-57.0	-68.1	110.7	54.1
22	293.5444	-16.4	-43.1	82.7	104.6	62.1
23	471.3768	-19.8	-50.1	-61.8	108.6	56.4

Per-Cluster Parameters

Parameter	c_{ASD} in [°]	c_{ASA} in [°]	c_{ZSD} in [°]	c_{ZSA} in [°]	XPR in [dB]
Value	10	22	7	7	8

3GPP REL. 16 V2V CHANNEL MODEL

    - c_{ASD}/c_{ASA} – cluster-wise rms azimuth spread of departure/arrival angles
    - c_{ZSD}/c_{ZSA} – cluster-wise rms elevation spread of departure/arrival angles

- In V2V SL, transmitter and receiver are highly mobile
  - Rel. 16 NR V2X introduces for the first time a dual mobility model addressing different Doppler components
  - The model takes into account the relative speed difference between a TX UE and RX UEs as well as the relative speed of delayed paths coming from scatterers.