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Re : [IEEE 802.15.3c Channel modeling]
Abstract: [Parameters and Propagation Issues for 802.15.3c Channel Model]
Purpose:[This document discusses the propagation issues and parameters for IEEE 802.15.3c]

Generalization and Parameterization of the mmWave Channel Models

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Outline

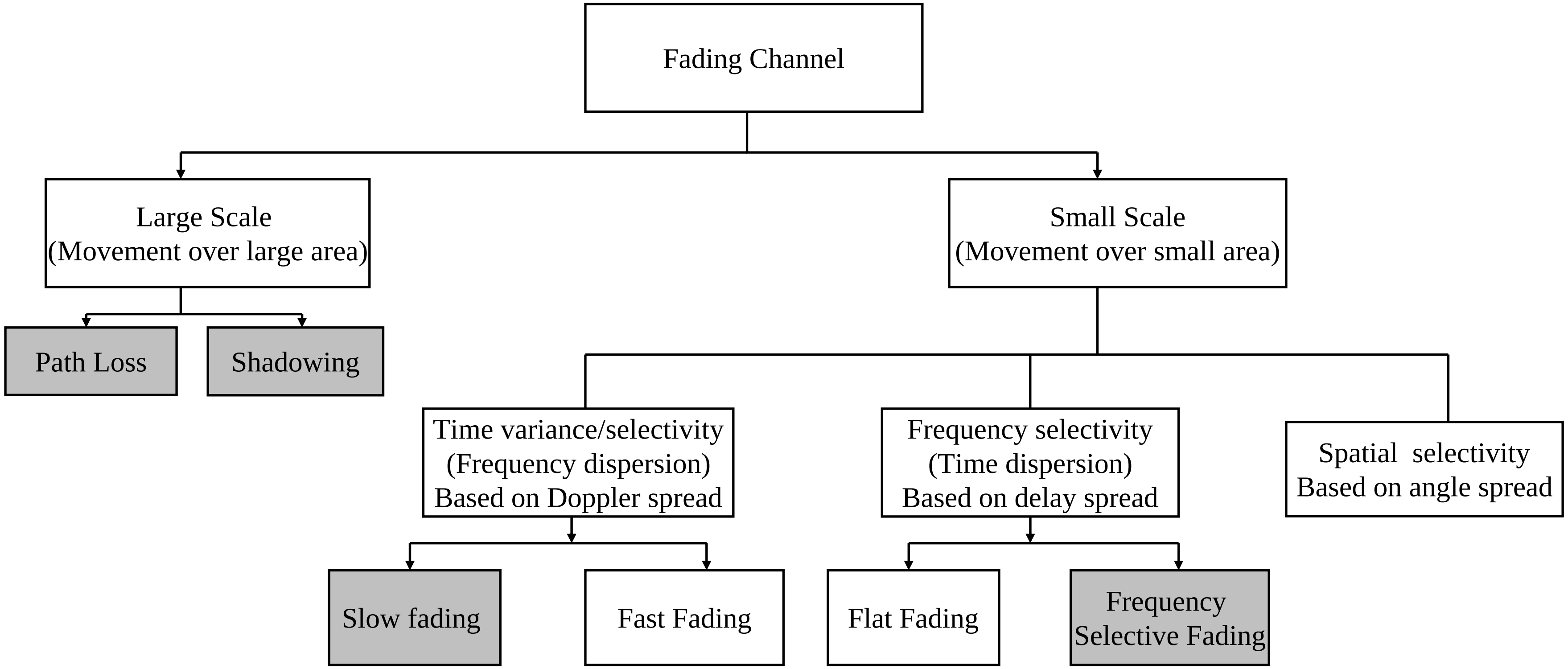
- Objectives
- Classification of channel models
- Channel structure and parameters
  - Large scale and small scale fading
- Other important parameters
- Problems and issues
- Conclusions

Objectives

- To develop a generic channel model that fits most measured results available in the literature.
- To define a list of parameters that can completely characterize the mmWave channel model suitable for IEEE 802.15.3c.

Classification of Channel Models

1. Deterministic models (DM)
   - E.g. ray tracing, ray launching → based on advanced theory e.g. UTD, FDTD
   - Environmental specific → huge materials and topographical database are required
   - Adv: Accurate coverage prediction
   - Disadv: Very high complexity
2. Empirical model (EM)
   - Extract specific parameters from measurement data
3. Statistical model (SM)
   - Derived from an extensive measurement database
   - Channel model is characterized by a set of statistical distributions and statistical moments
   - Adv: less complex than the DM and can provide sufficiently accurate channel information
   - Disadv: less accurate compare to DM
4. Geometrically-based model (GM)
   - Usually deployed for outdoor microcell and macrocell
   - Based on method of distributed scatterers on a planar disc → not suitable for indoor environment because in building scatterers are usually distributed all over the volume
   - E.g. GBSB model → assume that each MPC only interacts with a single object



Slow fading

- Negligible variation of CIR in one symbol duration
- Coherence time > symbol period
- Signal BW >> Doppler spread
- Error burst
- Lost in SNR

Fast Fading

- Fast variation of CIR in one symbol duration
- Coherence time < symbol period
- Signal BW < Doppler spread
- Pulse shape distortion
- Problem with synchronization as PLL fails
- irreducible BER

Flat Fading

- Narrowband channel
- RMS delay spread < Symbol Period
- Signal BW < Coherence BW
- Loss in SNR
- Coherence BW set an limit on the transmission rate that can be use without the equalizer in the receiver.

Frequency Selective Fading

- Wideband channel
- RMS delay spread > Symbol Period
- Signal BW > Coherence BW
- ISI and irreducible BER

Key Features of the Models

- Only “propagation channel” should be modeled, the effects of the antenna need to be modeled separately. Unfortunately, measurement results reported in the literature include the antenna effect i.e. “radio channel”
- Path loss
- Shadowing

} Large scale fading

- Small scale fading/multipath phenomena
  - Amplitude statistics
  - Delay/temporal properties (e.g. RMS delay spread, mean excess delay)
  - Power delay profile
  - Angle-of-arrival properties
  - Doppler spreading
- Polarization
  - Linear polarization and circular polarization
  - Circular polarized wave can be beneficial in NLOS condition

Path Loss

- Path loss is important for link budget analysis
- Depends on:
  - Distance → path loss exponent
  - Frequency → bandwidth of the system
  - Obstruction of LOS by partitions, e.g. walls, door, glass etc. → penetration loss of materials e.g. wall can completely attenuate the signal
  - Reflections and diffractions loss
  - Oxygen absorption → peak at 60GHz and must consider if > 200m
  - Rain attenuation → must take into account if distance of up to 1km is being considered
  - Water vapor absorption → generally can be neglected at 60GHz

Path Loss Model

$$PL(d)[dB] = \underbrace{20\log\left(\frac{4\pi d_0}{\lambda}\right)}_{\text{Free space path loss at reference distance}} + \underbrace{10 \cdot n \cdot \log_{10}\left(\frac{d}{d_0}\right)}_{\text{Path loss exponent at relative distance } d} + \underbrace{\sum_{q}^{Q} X_q}_{\text{Additional path loss due to various obstructions}} \quad ; \quad d \geq d_0$$

- Applicable for indoor and outdoor (must take into account oxygen and rain attenuation)
- Term 1 + Term 2 → Generic and simplified, LOS & NLOS
- Term 1 + Term 2 + Term 3 → NLOS, more site specific
- Term 2 can be made distance dependence power exponent
- For simplicity, only consider the first two terms

Path Loss Model – Indoor

$$PL(d)[dB] = \underbrace{20\log\left(\frac{4\pi d_0}{\lambda}\right)}_{\text{Free space path loss at reference distance}} + \underbrace{10\cdot n\cdot \log_{10}\left(\frac{d}{d_0}\right)}_{\text{Path loss exponent at relative distance } d} + \underbrace{kL_{Wall}}_{\text{Wall loss factor}} \qquad d \geq d_0$$

Reference	Scenario	Center Freq. [GHz]	*n*	Environment	Comments
[Kal95]	LOS LOS NLOS NLOS	21.6 37.2 21.6 37.2	1.2 1.65 2.95 3.3	Corridor Corridor 1-4 wall obstructions 1-4 wall obstructions	30m x 45m floor size with rooms and hallways of various sizes. Steel doors, double plaster board internal wall and 1ft^2 tile floor. Tx- Biconical Omni Rx-Biconical Omni. Both at 1.5m height
[Kaj97]	LOS LOS NLOS	94 94 94	1.2-1.8 1.2-1.8 3.6-4.1	In a hall and a room Corridor Office building floor	17m x 14.5m hall, 12.6m x 6m room and 3m width corridor. Plaster board walls and concrete floor. Tx-Horn with 25dBi (3dB beamwith 10°) Rx-Slot with 11dBi. Both at 0.9m height
[Bal98]	< 25m 25-40m	40 40	1.5 4	Open concept office Open concept office	Furnished with 1.22m high semi-permanent partitions dividing many work spaces Tx-Rx -Omnis
[SmCol97]	<15	60	4.4	Office building	3dB beamwidth 5° in vertical plane and 90° in horizontal plane
[Xu02]	LOS	60	1.88-2.0	Hallway	102 x 2.1 x 4.3m TX-open-ended waveguide with 6.7-dB HPBW are 90° azimuth and 125° elevation Rx- Horn antenna with 29-dB HPBW are 7° in azimuth and 5.6 ° in elevation

(1) The value *n* could be less than free-space power-law exponent (n = 2) due wave guiding effect

(2) The number of walls (k = 0) a best-fit value (in the root-mean-square sense) for *n* was obtained to satisfy the path-loss equation

Reference	Scenario	Environment	*n*	σ_L	Comments
[And02]	LOS NLOS	Typical office / laboratory	2.1	7.9	Tx and Rx – Horn 25dBi Typical office cubical and chairs
[Mat97]	LOS	Corridor (45x2.2.4m) Amphitheater (18/12x15m) Grass field (2 sides with bldgs)	1.87-188 0.78-1.27 1.9	NA	Omni-Tx, Rx-Direct. (19.5dBi, 15°),Omni Omni-Tx, Rx-High AP , Low AP
[Tho94]	LOS (330m) NLOS (60m)	Outdoor-street along axis of propagation	3.6 10	3.2	Tx-Horn (25dBi, 10°), Rx-horn (6dBi, 120°) Traffic density is about 25-50 cars.
[Mor04]	LOS NLOS	Laboratory 19.5x7.5m	1.8 2	NA	d_o=1.5m
[Fia98]	LOS	Small medium size room	1.67-1.72	NA	Omni-Tx and HW dipole-Rx
	LOS NLOS	Cell office	1.32 2.83	10.1 7.1	Tx-Omni, Rx-Horn
	LOS NLOS	Open office and cellular office	1.77 3.83	6 7.6	
	LOS NLOS	Open office with partition walls	1.16 3.74	5.4 8.6	Tx-Omni, Rx-Horn
[Rad98]	LOS	Office building	2	1.25	Tx-Omni, Rx-Horn (20dBi, 3dB beamwidth 20°)
[Boh00]	LOS NLOS	Corridor Canteen Office Corridor Office	1.51 1.79 1.26 1.97 3.77	1.79 1.88 0.74 1.44 3.45	Tx-Rx-Omni biconical at 1.8m
[Kob00]		Empty room (20x20x3m)	NA	4-8	Tx-Rx-Omni
[Cla02]		Small room (7x5m)	NA	2.98	Tx-Rx-Microstrip

Path Loss Model – Outdoor

$$PL(d)[dB] = \underbrace{20\log\left(\frac{4\pi d_0}{\lambda}\right)}_{\text{Free space path loss at reference distance}} + \underbrace{10\cdot n\cdot\log_{10}\left(\frac{d}{d_0}\right)}_{\text{Path loss exponent at relative distance } d} + (A_{Rain} + A_{Oxygen})[dB/km]\cdot d[km]; \quad d \geq d_0$$

Reference	Environment	Distance [m]	*n*	Antenna Height [m]	
				Tx	Rx
[Cor97]	Open area (grass)	200	2.3	1.5	1.5
	Open area (asphalt)	200	2.0	5	1.5
	Open area	-	2.2	-	-
	Urban street	120	2.2	5	1.5
	Campus street	120	2.1 2.3 1.4	1.5	2 5.5 7
	Tunnel	200	2.5	1.5	1.5
[Tho94]	Outdoor-street along axis of propagation	330 (LOS) 60 (NLOS)	3.6 10	20	2
[Boh00]	Parking	-	1.7	1.8	1.8

(1) Influence of antenna height on *n*
(2) Applicable for far field and at small distance the radiation pattern will be significant
(3) Need to check the validity at larger distances

Oxygen and Rain Attenuation

$$A_{Oxygen[dB/km]}(f_{[GHz]}) = \begin{cases} 15.1 - 0.104(f-60)^{3.26} & (60 \le f \le 63) \\ 11.35 + (f-63)^{2.25} - 5.33(f-63)^{1.27} & (63 \le f \le 66) \end{cases}$$

$$A_{Rain[dB/km]}(f_{[GHz]}) = a(f)R^{b(f)}$$

$$a(f) = 0.0409 f^{0.699} \qquad 54 \le f \le 180$$

$$b(f) = 2.63 f^{-0.272} \qquad 25 \le f \le 164$$

[OLS78]

or

$$a(f) = 10^{1.203\log(f) - 2.29}$$

$$b(f) = 1.703 - 0.493\log(f)$$

[ITU86]

Classifications of rainfall rate, *R* [Bro02], 0.25mm/h (light drizzle), 1mm/h (light rain), 4mm/h (moderate rain), 16mm/h (heavy rain)

Shadowing

- Due to the dynamic evolution of paths as the terminal moves or when there is a movement in the channel.
- Slow variation of local mean signal strength.
- Obstruction by human can be significant up to 18dB → can completely remove LOS path.
- Duration of shadowing effect is relatively long up to several hundreds of milliseconds and this duration increases with number of person within in the environment [Coll04].
- The shadowing is generally modeled by log-normal distribution [Rad98, And02, Tho94, Boh00, etc]
  - X_{σ}[dB]=$N(0, \sigma_L)$ where N is normal distribution with zero mean and σ_L standard deviation.
  - σ_L varies as a function of the antenna beamwidth, TX-RX height.

Small Scale Fading

- Amplitude statistics
- Power delay profile
- Delay properties (e.g. RMS delay spread, mean excess delay)
- Angle-of-arrival properties
- Doppler spreading

Generic Multipath Channel Model

- Use Saleh-Valenzuela (S-V) model?

$$h(\tau) = \sum_{k=0}^{\infty}\sum_{l=0}^{\infty} \beta_{k,l} e^{-j2\pi f\tau} \delta(\tau - T_l - \tau_{k,l})$$

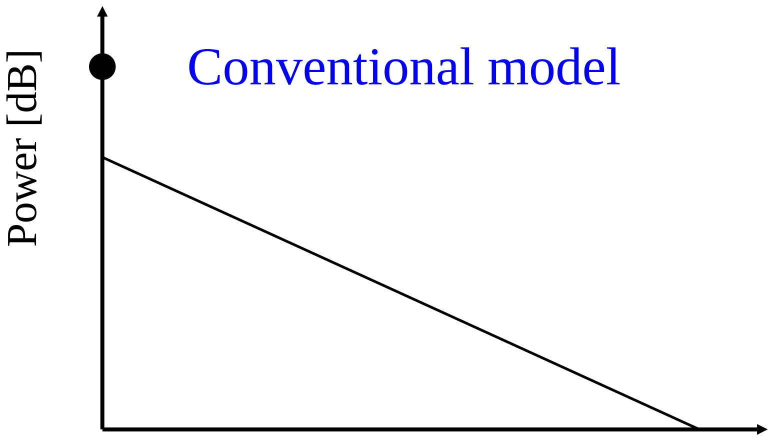
  - Clustering phenomena is typical in indoor due to superstructure
  - Fits several measurement and ray tracing results
  - Can always reduce to the conventional single cluster model
  - What dynamic range should be considered? E.g. 30 dB below the strongest path
- Power delay profile:
  - Delay parameters:
    - Mean excess delay , τ_{av} → estimate the search range of the RAKE receiver.
    - RMS delay spread, τ_{σ} → determine the maximum transmission data rate in the channel without equalization, OFDM cyclic prefix allocation.
    - Timing jitter and standard deviation → determine the update rate for a RAKE receiver or equalizer.

Small-Scale Amplitude Fading Statistics

- What is the small-scale amplitude distribution?
- Most literature results show that [Wit02, Smu95, Kun99, Kal95, etc]
  - Rice distribution (LOS)
  - Rayleigh distribution (NLOS)
  - Based on the measurement with resolutions of 5ns and 1ns
- At higher resolutions 1ns and 0.5ns, the amplitude distribution might not be Rayleigh distributed due to the invalidity of the central limit theorem.
- However, more measurements need to be carried out to verify this conjecture.

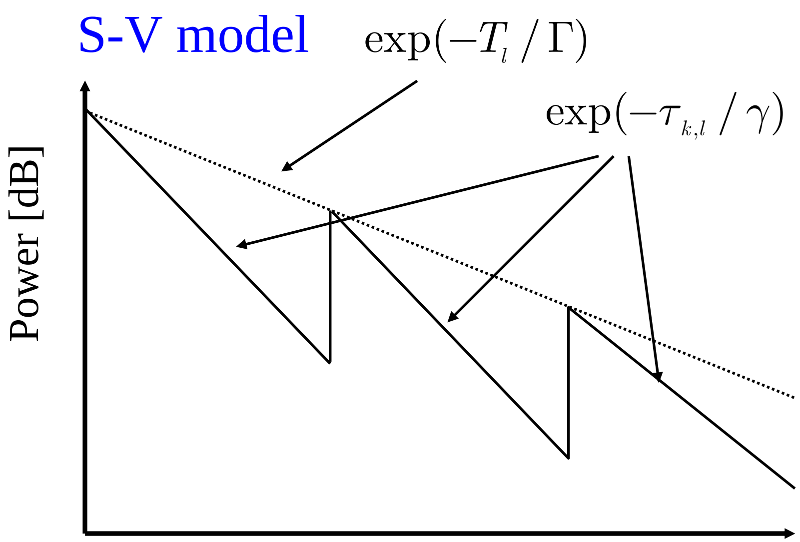
Power Delay Profile

- Four types of PDPs were reported in the literature:
  1. Single exponential decay → Conventional model [Kus99].
  2. Double exponential decay → S-V model [Fla02, Par98].
  3. Exponential decay preceded by constant value part → Smulders' model [Smu95, Wit02].
  4. Modified exponential decay preceded by constant value part → Broadway's model [Bro02].



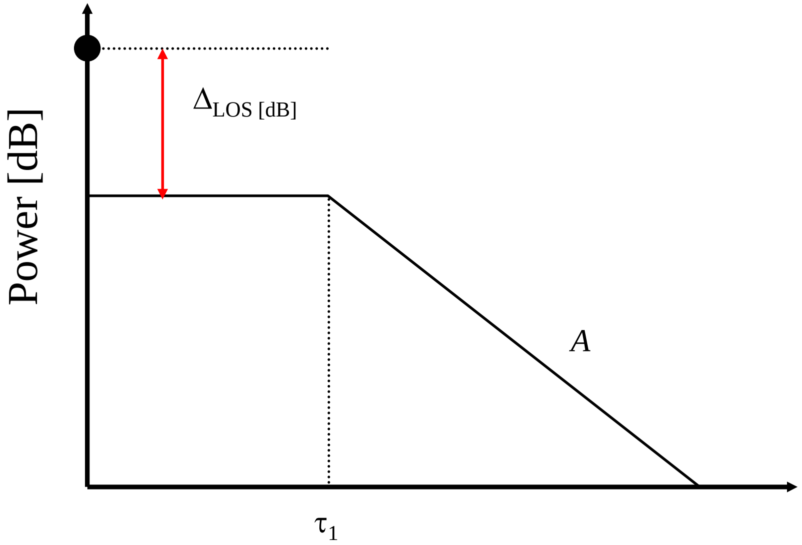
$$\overline{\beta_\tau^2} = \overline{\beta_0^2}\exp(-\tau/\gamma)$$

- Blocking of direct path is modeled by removing the direct path but is not verified by measurement
- When no direct path presence, $\overline{\beta_\tau^2}$ is Rayleigh distributed with variance $\overline{\beta_\tau^2}$
- When direct path is presence, it is assumed to be 0dB and Ricean distributed. The $\overline{\beta_0^2}$ is relative to the maximum value of the averaged PDP (direct path amplitude)
- The delay, amplitude and phase of the direct path can be determined using geometrical distances between the TX and the RX as well as the associated antenna gains.



$$\overline{\beta_{(k,l)}^2} = \overline{\beta_{(0,0)}^2}\exp(-T_l/\Gamma)\exp(-\tau_{k,l}/\gamma)$$

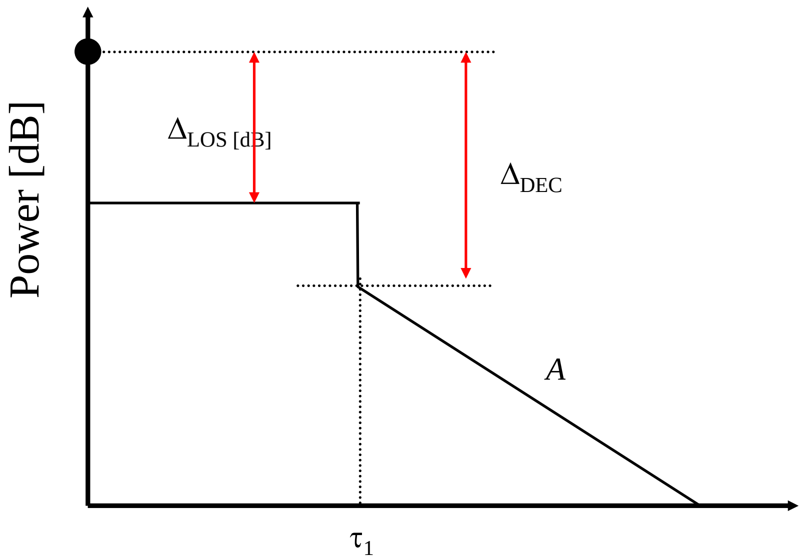
- Cluster's amplitudes are independent Rayleigh distributed whose variances decay exponentially over time with parameter Γ.
- Ray's amplitudes are independent Rayleigh distributed whose variances decay exponentially over time with parameter γ.
- The delay, amplitude and phase of the direct path can be determined using geometrical distances between the TX and the RX as well as the associated antenna gains.



$$\overline{\beta_\tau^2} = \begin{cases} 0 & \tau < 0 \\ \overline{\beta_0^2} & \tau = 0 \\ \overline{\beta_0^2} / \Delta_{LOS} & 0 < \tau < \tau_l \\ \overline{\beta_0^2} / \Delta_{LOS} \cdot e^{(\tau_1 - \tau)/\gamma} & \tau > \tau_l \end{cases}$$

$$\gamma = 1 \Big/ \left(\frac{A_{[db/ns]}}{10} \ln 10 \right)$$

- The delay, amplitude and phase of the direct path can be determined using geometrical distances between the TX and the RX as well as the associated antenna gains.
- For multipath amplitudes, $\overline{\beta_\tau^2}$ are Rayleigh distributed with variance $\overline{\beta_\tau^2}$



$$\overline{\beta_\tau^2} = \begin{cases} 0 & \tau < 0 \\ \overline{\beta_0^2} & \tau = 0 \\ \overline{\beta_0^2} / \Delta_{LOS} & 0 < \tau < \tau_l \\ \overline{\beta_0^2} / \Delta_{DEC} \cdot e^{(\tau_1 - \tau)/\gamma} & \tau > \tau_l \end{cases}$$

- Basically, the same model as proposed by Smulders except that there is an additional term, Δ_{DEC}

Smulders’ Model

- The constant level part and the slope, *A* are site and antenna dependent.
- In this model, the constant level part is due to the compensation of the free-space losses by:
  - Antenna gain due to the elevation dependence of the antenna radiation patterns
  - Difference between TX and RX height
- Two effects that determine the value of constant delay, τ_1:
  - Center frequency, f_c → higher f_c, longer τ_1
  - Material return loss → higher return loss, shorter τ_1
- RMS delay spread is not very sensitive to the variation of τ_1 in the range of $50\text{ns}<\tau_1<70\text{ns}$.

RMS Delay Spread

- Dependent on:
  - Room size
    - Generally increases as the room size increases.
  - Antenna directivity
    - Generally decreases as the directivity increases.
    - High directive antenna could also cause higher RMS DS if some reflected paths with larger delay are being intensified.
    - RMS delay spread can increase if the antennas are not directly pointed to each other.
  - Material
    - RMS DS is higher if more reflective materials are used in the construction of the environment.

Reference	Scenario/ Environment	RMS Delay spread, $\tau_{\sigma v}$ (ns)	Power Delay Profile	Comments
[Cor96]	Outdoor street with 300m long, no crossings and surrounded by rough concrete wall (measurement and ray tracing)		Exponential decay	BS=5m, MS=1.8m Tx and Rx antenna Isotropic antennas
	10m width	τ_a=4.1, $\tau_{\sigma v}$=7.1		
	50m width	τ_a=37.0 τ_σ=35.3		
	-presence of trees (direct ray not obstructed)	Both τ_a and τ_σ decreased by 3-4ns		
[Dan94]	Large area with water canal and rows of trees. NLOS (Measurement)	<100ns	NA	Tx-Rx-biconical antenna at 0.5m height Distance from 2 to 150m
[Man96]	Empty conference room 90m^2 area and 2.6m height in a modern office building. (Measurement)		NA	Tx- Horn 3dB beamwidth 60° Rx- Lens-horn 3dB beamwidth 4.6° both 1.46m
	VV	11.05		
	HH	10.01		
	RR	5.17		

Reference	Scenario/Environment	RMS Delay spread, $\tau_{\sigma v}$ (ns)		Power Delay Profile	Comment
[Man95]	Empty room (13.5x7.8x2.6m) with plasterboard and concrete wall (Measurement)	Meas.	Simul.	NA	Tx-Omni-directional with 2.36m height Rx-1.5m height
		1.05	0.79	NA	Narrow (3dB beamwidth 5°) – Lens Horn
		4.7	2.22	NA	Medium (3dB beamwidth 10°)-Gain horn
		13.59	10.91	NA	Broad (3dB beamwidth 60°)- Feed horn
		18.08	15.35	NA	Omni (halfwave dipole)
[Cla01]	Meeting room (5x7m) Computer lab (5.1x7.1m) (Measurement)	$\tau_{\sigma v}$	τ_{max}		
		0.66	(53.8)		Tx-waveguide, Rx-waveguide LOS
		1.1	(59.6)		Tx-waveguide, Rx-waveguide NLOS
		0.42	(48.1)		Tx-Patch, Rx-4 patches, linear polarization
		0.77	(53.1)		Tx-Patch, Rx-16 patches, linear polarization
		0.70	(58.8)		Tx-4 Patches, Rx-4 patches, linear polarization
		0.25	(62.7)		Tx-4 Patches, Rx-4 patches, circular polarization
		0.42	(55.1)		Tx-4 Patches, Rx-16 patches, linear polarization
		0.61	(61.0)		Tx-4 Patches, Rx-16 patches, circular polarization

Reference	Scenario/ Environment	RMS Delay spread (ns)	Power delay profile	Comment
[Mor02]	Long corridor 44x2.2x2.75m Brick wall with plasterboard (Simulation)	 2.13 1.18 1.58	NA	Assume one direct path, 4 single reflected rays and 4 double reflected rays. Tx height 2m and Rx height 1.5m Isotropic, 20dBm output power Omni-Omni, 8.5 dBi, vertical radiation pattern 8° Horn-Horn, 20.8dBi, vertical radiation pattern 15°
[Hub97]	Empty room 8x12.4m 62 GHz center frequency. LOS and NLOS case (Measurement)	Calculate from the relative delay of the path from table 1 and 2.	Complex FIR filter with specific coefficients	Tx-biconical horn (6dBi gain) Rx-shaped monopole (4 dBi gain) Both Tx and Rx are with omni-direc. pattern in horizontal and 1.5m height
[Sia01]	Corridor (windows) (41x1.9x2.7m) Corridor (no windows) (Measurement)	31.59 (36.75) 31.72 (32.4)	NA	Tx, Rx - Horn (10dBi with 3dB beamwidth of 69° and 55° in vertical and horizontal planes, respectively. Both at 1.7m height
	Room (furnished) 12.8x6.9x2.6m Room (empty) (Measurement)	9 9	NA	Tx-Horn, Rx-Omni

Reference	Scenario/ Environment	RMS Delay spread (ns)	Power Delay Profile	Comment
[Gue96]	4.65x6x3m room with plasterboard and concrete Empty (LOS) Furnished (LOS) (Measurement)	 2.9 2.7	NA	Tx-3dB aperture around 70° in horizontal and vertical planes. Rx-3dB aperture around 10° Both at 1.5m height
[Pur98]	Common room with wooden table and chair (56x10m) – 3 sides with concrete wall and one side with glass	4.89 (mean K-factor 11.25)	Smulders's PDP model	Tx-Rx- Omni directional antennas (120°) Both are at 1.6m
	Workshop with heavy machines	7.81 (mean K-factor 8.19)		
[Fla02]	Typical indoor	NA	SV $1/\Lambda$=15ns $1/\lambda$=2ns Γ=20ns γ=9ns	Tx-3dBi Rx-Omni directional
[Par98]	Typical office with brick/stone and plasterboard. Partitions, desks and PCs in the room.	11	SV $1/\Lambda$=75ns $1/\lambda$=5ns Γ=20ns γ=9ns	Tx-Omni 120° beamwidth at 2.6m Rx-Omni 60° beamwidth (and 15° directional) at 1.3m All circular polarization. Tx is in the edge of the room and Rx is omni.

Reference	Scenario/ Environment	RMS Delay spread (ns)	Power Delay Profile	Comment
[Boh00]	Corridor (LOS) Canteen (LOS) Office (LOS) Corridor (NLOS) Office (NLOS) Parking	14.7 (mean K factor 0.64) 13.5 (mean K factor 2.18) 5.22 (mean K factor 0.58) 7.53 (mean K factor -1.12) 7.54 (mean K factor -1.07) 26.51(mean K factor 3.74)		Tx-Rx-Omni biconical at 1.8m
[Smu95]	**Small Room**		Smulders's PDP	Tx-Rx – 9dBi Biconical Horn
	Reception room (24.3x11.2x4.5m)	45		
	Computer Room (9.9x8.7x3.1m)	42		
	Lecture Room (12.9x8.9x4.0m	18		
	Lab room (11.3x7.3x3.1m)	29		
	Large Room			
	Amphi-theather (30x21x6m)	30		
	Hall (43x41x7m)	55		
	Vax Room (33.5x32.2x3.1m)	55		
	Corridor (44.7x2.4x3.1m)	70		

Other Important Parameters

- Polarization
  - Vertical, horizontal and circular polarizations.
  - Multipath dispersion can be greatly suppressed by using circular polarization compared to the linear polarization since the for odd reflections the direction of circular polarization is reversed and thus is not received by the receiver.
- Do we need angle-of-arrival statistics?
- Does TG3c anticipate the use of antenna arrays to
  - Increase coverage
  - Avoid interference (beamforming)
  - Diversity gain
  - Limited results and how to proceed?
    - Adopt existing models
- Doppler spreading due to the movement

What are the Problems and Issues?

- Difficult to compare/analyze measurement results
  - Different measurement techniques and apparatus used
  - Different antenna characteristics and configurations
  - Different types of environment setup
- There is no “propagation model” available in the literature based on measurements that
  - Excludes the effects of antennas used
  - Excludes the positions of the antennas in which the measurements were taken
- Results in different RMS delay spread, shadowing effects etc.

Directional vs. Omni-directional

- Directional antenna is required to overcome severe path loss.
- Omni-directional antenna is more useful in NLOS.
- Influence on the received power and thus RMS delay spread due to the suppression of multipath by directional antenna.
- Alignment of TX and RX is critical for LOS condition → the exact location of the access point (AP) has to be known and LOS must also present
- High directivity:
  - Only good for point-to-point communication
  - Subject to severe shadowing effects
- Also depends on the antenna setup in the environment
- How to account the effects of using directional antennas? Antenna model is required → $G(\phi,\theta)$.
- In general, a directional antenna reduces multipath dispersion and the degree of reduction depends on the antenna beamwidth and environment.
- What type of antenna combination is the most popular choice? Omni and high gain?

[Bal98] shown that in open concept areas, there is no advantage of using directional antenna at the BS (as low as $\pm 6^{\circ}$) over omni directional in reducing the multipath dispersion.

Conclusions

- Large-scale fading can be modeled by path loss exponent and log-normal shadowing.
- Small-scale fading:
  - Power delay profile can be based on conventional, S-V, Smulders or Broadway’s model.
  - Amplitude distribution is either Rayleigh or Rice – dependent on the scenario i.e. LOS/NLOS.
- Open issues like the effect of antenna on RMS delay spread need further investigations.

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