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Introduction

This is a brief documentation on the MATLAB implementation of estimating the average channel capacity using the Mathworks 5G New Radio (NR) clustered delay line (CDL) channel model that is provided in the 5G Toolbox [1]. The `nrCDLChannel` System object™ implements the CDL model as specified in the 3GPP TR 38.901, in which the CDL-A, CDL-B and CDL-C models are for non-line-of-sight (NLOS) links while the CDL-D and CDL-E models are for LOS links [2]. In this example, the CDL-A model is implemented assuming NLOS links. The `nrCDLChannel` System object™ can generate channel coefficients and filter the input signal.

Assumptions

<table>
<tr><th>Parameters</th><th>Assumptions</th><th>Notes</th></tr>
<tr><td>Scenario</td><td>Urban macro-cell outdoor scenario</td><td rowspan="11">1. The multipath DS is 200 ns in the simulation. This value is obtained from the calibration data of the 3GPP CDL model (Section 7.5 in [2]), considering the reasonable range of the median value of DS [4]. The default symbol period in the Mathworks CDL-A model is 32.55 ns, which is much smaller than the DS. Hence, the narrowband hybrid precoding algorithm proposed in [3] can be adopted for estimating the channel capacity.
2. The transmit/receive antenna gain is fixed for different carrier frequencies.
3. The hybrid precoding algorithm is adopted for estimating the channel capacity at mmWave frequency bands [3]. In this algorithm, each radio frequency (RF) precoder at the transmitter or/and receiver is selected from the corresponding array response vectors, which requires the linear independence of the vectors from all paths. Therefore, for one departure/arrival angle, two antennas cannot be cross-polarized (at the same position) to have the same response vector.
4. A single RF chain is used for transmitting one data stream.</td></tr>
<tr><td>Transmission type</td><td>Downlink, NLOS, single data stream</td></tr>
<tr><td>Delay spread (DS)</td><td>200 nanoseconds (ns)</td></tr>
<tr><td rowspan="2">Antenna array configuration</td><td>BS: Uniform rectangular array (4 x 4), vertically-polarized</td></tr>
<tr><td>UE: Uniform rectangular array (2 x 2), vertically-polarized</td></tr>
<tr><td>Antenna pattern</td><td>Isotropic radiators</td></tr>
<tr><td rowspan="2">Large-scale fading</td><td>Path loss effects included by default</td></tr>
<tr><td>Shadow fading effects modelled as an optional feature that can be switched on/off</td></tr>
<tr><td>Additional modelling</td><td>Oxygen absorption effects modelled as an optional feature that can be switched on/off</td></tr>
<tr><td>Bandwidth</td><td>Bandwidth scaling linearly with the carrier frequency ($BW = 0.005 \times Fc$)</td></tr>
</table>

Requirements

- MATLAB
- Communications Toolbox
- DSP System Toolbox
- Signal Processing Toolbox
- 5G Toolbox
- Phased Array System Toolbox (used in the writer's implementation, not required for the CDL channel model)

Launcher Script

AverageCapacityCDL_A.m

Launch the whole simulation for a predefined carrier frequency, e.g., 30 GHz. The average capacity is estimated from 1000 random channel realizations, with an approximate simulation time, 81 seconds.

Simulation Results

The average channel capacity is estimated at 6 GHz, 30 GHz, 60 GHz and 90 GHz, respectively, considering single-link transmissions. Two examples of the achievable capacity are demonstrated: one with path loss effects only (Fig. 1) and the other one with path loss and oxygen absorption effects (Fig. 2). The capacity is calculated according to formulas (1) and (2), with denotations listed in the following table. For detailed information on the calculation, please refer to [3]. When an `nrCDLChannel` System object™, `cdl`, is created, the channel coefficients of each path in the matrix $\mathbf{H}$ can be extracted by setting the `ChannelFiltering` property of `cdl` to be false and using the function `[pathGains, sampleTimes] = cdl()`, where `pathGains` contains the complex MIMO channel gains of the underlying fading process, as specified in [1].

$$C = BW \times \log_2\left(\left|\mathbf{I}_{N_s} + \frac{P_t}{N_s}\mathbf{R}_\mathrm{n}{}^{-1}\mathbf{W}_\mathrm{BB}^\mathrm{H}\mathbf{W}_\mathrm{RF}^\mathrm{H}\mathbf{H}\mathbf{F}_\mathrm{RF}\mathbf{F}_\mathrm{BB}\mathbf{F}_\mathrm{BB}^\mathrm{H}\mathbf{F}_\mathrm{RF}^\mathrm{H}\mathbf{H}^\mathrm{H}\mathbf{W}_\mathrm{RF}\mathbf{W}_\mathrm{BB}\right|\right) \quad (1)$$

$$\mathbf{R}_\mathrm{n} = BW \times \sigma_\mathrm{n}^2\mathbf{W}_\mathrm{BB}^\mathrm{H}\mathbf{W}_\mathrm{RF}^\mathrm{H}\mathbf{W}_\mathrm{RF}\mathbf{W}_\mathrm{BB} \quad (2)$$

Scalar		**Vector/Matrix**	
BW	Bandwidth (Hz)	$\mathbf{R}_\mathrm{n}$	Noise covariance matrix
N_s	Number of data streams	$\mathbf{H}$	Channel matrix
P_t	Transmit power (watt)	$\mathbf{F}_\mathrm{BB}/\mathbf{W}_\mathrm{BB}$	Baseband precoder at the transmitter/receiver
σ_n^2	Noise power(watt)	$\mathbf{F}_\mathrm{RF}/\mathbf{W}_\mathrm{RF}$	RF precoder at the transmitter/receiver
C	Capacity (bits/s)	$(\cdot)^\mathrm{H}$	Conjugate transpose
		$\mathbf{I}_N$	Identity matrix, $N \times N$

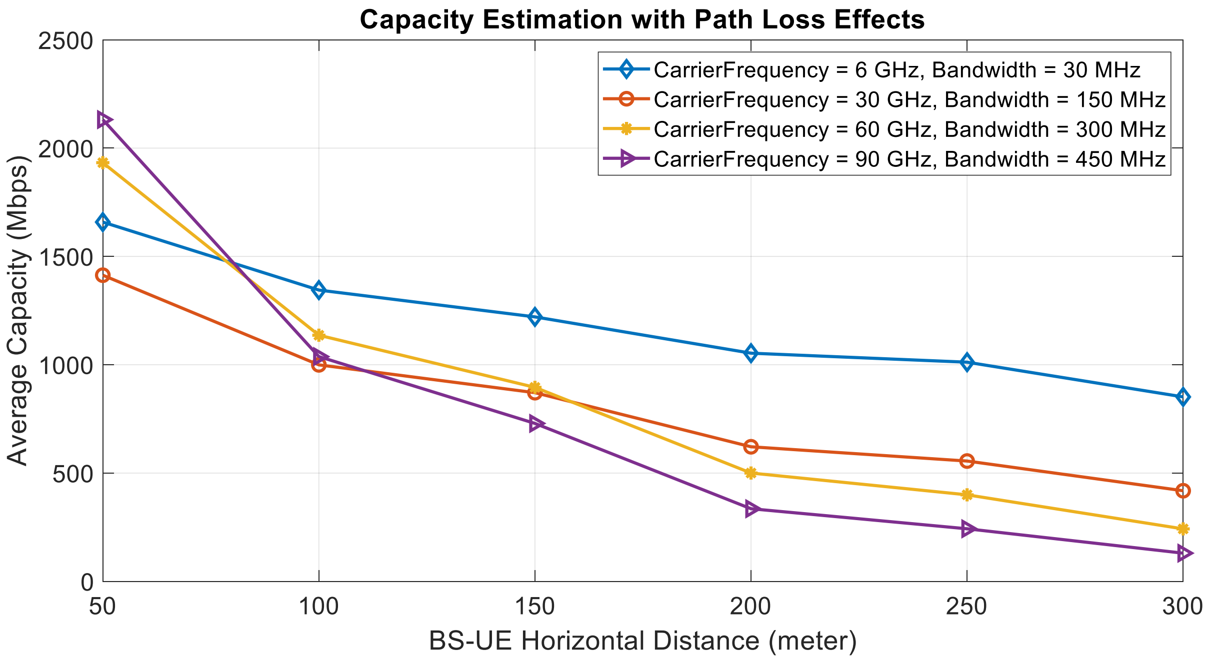

Fig. 1 Capacity estimation with path loss effects

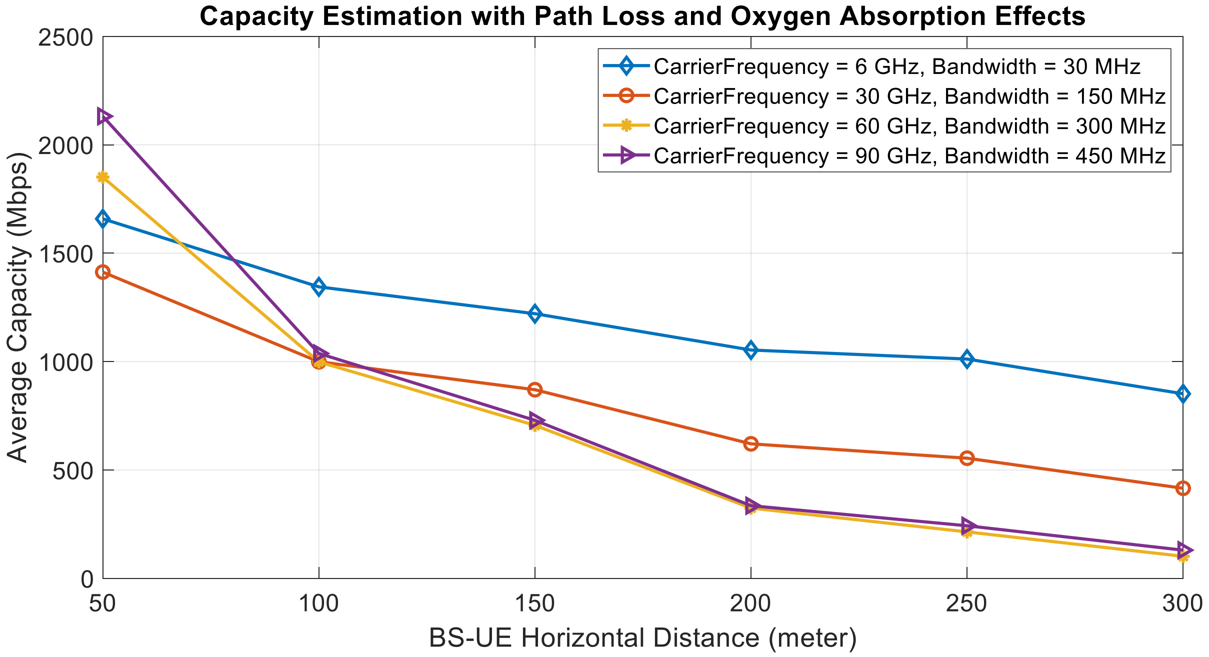

Fig. 2 Capacity estimation with path loss and oxygen absorption effects

Comments

The capacity is estimated in a simple way by adopting the narrowband hybrid precoding approach at both ends of the link, which only gives a rough estimation on the achievable channel capacity from the channel model. To be more accurate, one can consider adopting a precoding method with frequency selectivity for wideband channels.

The purpose of this simulation is to give an example of applying the Mathworks 5G NR CDL channel model to link-level estimations. Please do not hesitate to point out any incorrection or deficiency, I shall be very grateful.

Reference

[1] Mathworks, 5G Toolbox, https://uk.mathworks.com/help/5g/
[2] 3GPP, "Study on channel model for frequencies from 0.5 to 100 GHz," 3rd Generation Partnership Project (3GPP), TR 38.901 V14.3.0, Dec. 2017.
[3] O. E. Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi and R. W. Heath, "Spatially sparse precoding in millimeter wave MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 13, pp. 1499-1513, Mar. 2013.
[4] 3GPP, "Full calibration results," 3rd Generation Partnership Project (3GPP), R1-165975, May 2016.