28GHz POWDER Measurements

Spatial Consistency Modeling

Bharath Keshavamurthy

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1 Spatial Autocorrelation Coefficient

The small-scale spatial autocorrelation coefficient is a metric to characterize the coherence between the voltage amplitudes of received signals across variations in distances, alignment accuracies, and relative velocities.

1.1 Separation in Distance

The spatial autocorrelation coefficient ρ vis-à-vis a separation in distance Δd:

$$\rho(\Delta d) = \rho\Big(\mathbf{x}_{\mathrm{Tx}},\ \|\mathbf{x}_{\mathrm{Rx}}(t')-\mathbf{x}_{\mathrm{Rx}}(t)\| = \Delta d,\ \phi(t') = \phi(t),\ v(t') = v(t)\Big),\ \text{where}$$

- $\mathbf{x}_{\mathrm{Tx}}(t)=\mathbf{x}_{\mathrm{Tx}}, \forall t$ denotes the 3-D position vector of the Tx (fixed);
- $\mathbf{x}_{\mathrm{Rx}}(t)$ and $\mathbf{x}_{\mathrm{Rx}}(t')$ denote the Rx 3-D position vectors at times t and t', respectively, with Δd being the 3-D Euclidean distance between them;
- $\phi(t)$ and $\phi(t')$ are the absolute errors in alignment between Tx and Rx antennas (deviation from perfect alignment) at times t and t', respectively;
- $v(t)$ and $v(t')$ denote the relative velocities of the receiver with respect to the transmitter at times t and t', respectively; and
- The conditions $\phi(t')=\phi(t)$ and $v(t')=v(t)$ ensure that while studying the signal coherence characteristics vis-à-vis a separation in distance Δd, other variables in our measurements (i.e., alignment and velocity) are unchanged.

Mathematically, this spatial autocorrelation coefficient $\rho(\Delta d)$ is given by

$$\frac{\mathbb{E}\Big[\Big(\mathbf{A}\big(\mathcal{P}_{\mathrm{Tx}}(t),\mathcal{P}_{\mathrm{Rx}}(t)\big)-\boldsymbol{\mu}\big(\mathcal{P}_{\mathrm{Tx}}(t),\mathcal{P}_{\mathrm{Rx}}(t)\big)\Big)\cdot\Big(\mathbf{A}\big(\mathcal{P}_{\mathrm{Tx}}(t'),\mathcal{P}_{\mathrm{Rx}}(t')\big)-\boldsymbol{\mu}\big(\mathcal{P}_{\mathrm{Tx}}(t'),\mathcal{P}_{\mathrm{Rx}}(t')\big)\Big)\Big]}{\sqrt{\mathbb{E}\Big[\Big\|\mathbf{A}\big(\mathcal{P}_{\mathrm{Tx}}(t),\mathcal{P}_{\mathrm{Rx}}(t)\big)-\boldsymbol{\mu}\big(\mathcal{P}_{\mathrm{Tx}}(t),\mathcal{P}_{\mathrm{Rx}}(t)\big)\Big\|^2\Big]\mathbb{E}\Big[\Big\|\mathbf{A}\big(\mathcal{P}_{\mathrm{Tx}}(t'),\mathcal{P}_{\mathrm{Rx}}(t')\big)-\boldsymbol{\mu}\big(\mathcal{P}_{\mathrm{Tx}}(t'),\mathcal{P}_{\mathrm{Rx}}(t')\big)\Big\|^2\Big]}}.$$

For a route $\mathcal{R}$, we define the terms employed in this equation as follows.

Tx configuration: $\mathcal{P}_{\text{Tx}}(t) = \mathcal{P}_{\text{Tx}}(t') = \{\mathbf{x}_{\text{Tx}},\ \theta_{\text{Tx}}\},\ \forall t,\ t' \in \mathcal{R}$;

Rx configuration: $\mathcal{P}_{\text{Rx}}(t) = \{\mathbf{x}_{\text{Rx}}, \theta_{\text{Rx}}, v_{\text{Rx}}\}, \mathcal{P}_{\text{Rx}}(t') = \left\{\mathbf{x}^{'}_{\text{Rx}}, \theta^{'}_{\text{Rx}}, v^{'}_{\text{Rx}}\right\},\ \forall t, t'{\in}\mathcal{R}$;

Evaluation conditions E1: $\left\|\mathbf{x}^{'}_{\text{Rx}}{-}\mathbf{x}_{\text{Rx}}\right\|{=}\Delta d, \phi(\theta^{'}_{\text{Tx}}, \theta^{'}_{\text{Rx}}){=}\phi(\theta_{\text{Tx}}, \theta_{\text{Rx}}), v^{'}_{\text{Rx}}{=}v_{\text{Rx}}$.

Let N be the number of resolvable Multi-Path Components (MPCs) extracted via the SAGE algorithm at time t at Rx config $\mathcal{P}_{\text{Rx}}(t)$, with Tx config being $\mathcal{P}_{\text{Tx}}(t)$; $\boldsymbol{\tau}$ represents the discretized delay levels kept consistent throughout our evaluations, i.e., $\boldsymbol{\tau}{=}\{\tau_1, \tau_2, \ldots, \tau_N\}$; and let $A(\tau_i)$ be the amplitude of the i^{th} MPC, i.e., the MPC at a delay of τ_i. Then, the amplitude mean of the MPC at $\tau_i, \forall i{\in}\{1, 2, \ldots, N\}$, for Rx config $\mathcal{P}_{\text{Rx}}(t)$ with Tx config being $\mathcal{P}_{\text{Tx}}(t)$:

$$\mu_{t,i} = \mu\Big(\tau_i, \mathcal{P}_{\text{Tx}}(t), \mathcal{P}_{\text{Rx}}(t)\Big) = \frac{1}{M}\sum_{j=1}^{M}\ A_j(\tau_i),$$

where M denotes the set of measurements collected at Rx config $\mathcal{P}_{\text{Rx}}(t)$ with Tx config being $\mathcal{P}_{\text{Tx}}(t)$, and $A_j(\tau_i)$ denotes the amplitude of the i^{th} MPC for the j^{th} measurement at this specific Tx-Rx config. Therefore,

$$\boldsymbol{\mu}\Big(\mathcal{P}_{\text{Tx}}(t), \mathcal{P}_{\text{Rx}}(t)\Big) = [\mu_{t,1}, \mu_{t,2}, \ldots, \mu_{t,N}]^{\intercal}.$$

$\mathbf{A}\Big(\mathcal{P}_{\text{Tx}}(t), \mathcal{P}_{\text{Rx}}(t)\Big)$ denotes the vector of amplitudes of the MPCs extracted from the measurements collected at the receiver at time t when the Rx config is $\mathcal{P}_{\text{Rx}}(t)$ and the Tx config is $\mathcal{P}_{\text{Tx}}(t)$. Mathematically,

$$\mathbf{A}\Big(\mathcal{P}_{\text{Tx}}(t), \mathcal{P}_{\text{Rx}}(t)\Big) = [A(t,\tau_1), A(t,\tau_2), \ldots, A(t,\tau_N)]^{\intercal} = [A_{t,1}, A_{t,2}, \ldots, A_{t,N}]^{\intercal}.$$

Note that the dot-product in the numerator denotes the vector inner product of the mean-shifted amplitude vectors at times t and t'.

The expectation $\mathbb{E}[\cdot]$ in the above equation for $\rho(\Delta d)$ is taken over all Tx and Rx configs along the route $\mathcal{R}$ that satisfy the evaluation conditions **E1**. Let $\mathcal{R}_{\mathbf{E1}}$ denote the set of Tx-Rx configs along the route that satisfy these evaluation conditions **E1**. Then, we can elaborate $\rho(\Delta d)$ as

$$\rho(\Delta d) = \frac{\frac{1}{|\mathcal{R}_{\mathbf{E1}}|}\sum_{(t,t')\in\mathcal{R}_{\mathbf{E1}}}\ \left[\sum_{i=1}^{N}\ \Big(A_{t,i} - \mu_{t,i}\Big)\Big(A_{t',i} - \mu_{t',i}\Big)\right]}{\frac{1}{|\mathcal{R}|}\sum_{t\in\mathcal{R}}\ \left[\sum_{i=1}^{N}\ \Big(A_{t,i} - \mu_{t,i}\Big)^2\right]}.$$

1.2 Separation in Alignment

The spatial autocorrelation coefficient ρ vis-à-vis a separation in alignment ϕ:

$\rho(\Delta\phi) = \rho\Big(\mathbf{x}_{\text{Tx}},\ \mathbf{x}_{\text{Rx}}(t') = \mathbf{x}_{\text{Rx}}(t),\ |\phi(t') - \phi(t)| = \Delta\phi,\ v(t') = v(t)\Big),$ where

- $\mathbf{x}_{\mathrm{Tx}}(t){=}\mathbf{x}_{\mathrm{Tx}}, \forall t$ denotes the 3-D position vector of the Tx (fixed);
- $\mathbf{x}_{\mathrm{Rx}}(t)$ and $\mathbf{x}_{\mathrm{Rx}}(t')$ denote the 3-D position vectors of the Rx, at times t and t', respectively;
- $\phi(t)$ and $\phi(t')$ are the absolute errors in alignment between Tx and Rx antennas (deviation from perfect alignment) at times t and t', respectively, with $\Delta\phi$ being the difference in alignment accuracies between them;
- $v(t)$ and $v(t')$ denote the relative velocities of the receiver with respect to the transmitter at times t and t', respectively; and
- The conditions $\mathbf{x}_{\mathrm{Rx}}(t'){=}\mathbf{x}_{\mathrm{Rx}}(t)$ and $v(t'){=}v(t)$ ensure that while studying the signal coherence characteristics vis-à-vis a separation in alignment $\Delta\phi$, other variables (i.e., distance and velocity) remain unchanged.

Mathematically, this spatial autocorrelation coefficient $\rho(\Delta\phi)$ is given by

$$\frac{\mathbb{E}\left[\left(\mathbf{A}\Big(\mathcal{P}_{\mathrm{Tx}}(t),\mathcal{P}_{\mathrm{Rx}}(t)\Big)-\boldsymbol{\mu}\Big(\mathcal{P}_{\mathrm{Tx}}(t),\mathcal{P}_{\mathrm{Rx}}(t)\Big)\right)\cdot\left(\mathbf{A}\Big(\mathcal{P}_{\mathrm{Tx}}(t'),\mathcal{P}_{\mathrm{Rx}}(t')\Big)-\boldsymbol{\mu}\Big(\mathcal{P}_{\mathrm{Tx}}(t'),\mathcal{P}_{\mathrm{Rx}}(t')\Big)\right)\right]}{\sqrt{\mathbb{E}\left[\left\|\mathbf{A}\Big(\mathcal{P}_{\mathrm{Tx}}(t),\mathcal{P}_{\mathrm{Rx}}(t)\Big)-\boldsymbol{\mu}\Big(\mathcal{P}_{\mathrm{Tx}}(t),\mathcal{P}_{\mathrm{Rx}}(t)\Big)\right\|^2\right]\mathbb{E}\left[\left\|\mathbf{A}\Big(\mathcal{P}_{\mathrm{Tx}}(t'),\mathcal{P}_{\mathrm{Rx}}(t')\Big)-\boldsymbol{\mu}\Big(\mathcal{P}_{\mathrm{Tx}}(t'),\mathcal{P}_{\mathrm{Rx}}(t')\Big)\right\|^2\right]}}.$$

For a route $\mathcal{R}$, we define the terms employed in this equation as follows.

Tx configuration: $\mathcal{P}_{\mathrm{Tx}}(t) = \mathcal{P}_{\mathrm{Tx}}(t') = \{\mathbf{x}_{\mathrm{Tx}},\ \theta_{\mathrm{Tx}}\},\ \forall t,\ t' \in \mathcal{R}$;

Rx configuration: $\mathcal{P}_{\mathrm{Rx}}(t) = \{\mathbf{x}_{\mathrm{Rx}}, \theta_{\mathrm{Rx}}, v_{\mathrm{Rx}}\}, \mathcal{P}_{\mathrm{Rx}}(t') = \left\{\mathbf{x}^{'}_{\mathrm{Rx}}, \theta^{'}_{\mathrm{Rx}}, v^{'}_{\mathrm{Rx}}\right\},\ \forall t, t'{\in}\mathcal{R}$;

Evaluation conditions E2: $\mathbf{x}^{'}_{\mathrm{Rx}}{=}\mathbf{x}_{\mathrm{Rx}}, \left|\phi(\theta^{'}_{\mathrm{Tx}}, \theta^{'}_{\mathrm{Rx}}){-}\phi(\theta_{\mathrm{Tx}}, \theta_{\mathrm{Rx}})\right|{=}\Delta\phi, v^{'}_{\mathrm{Rx}}{=}v_{\mathrm{Rx}}$.

Let N be the number of resolvable Multi-Path Components (MPCs) extracted via the SAGE algorithm at time t at Rx config $\mathcal{P}_{\mathrm{Rx}}(t)$, with Tx config being $\mathcal{P}_{\mathrm{Tx}}(t)$; $\boldsymbol{\tau}$ represents the discretized delay levels kept consistent throughout our evaluations, i.e., $\boldsymbol{\tau}{=}\{\tau_1, \tau_2, \ldots, \tau_N\}$; and let $A(\tau_i)$ be the amplitude of the i^{th} MPC, i.e., the MPC at a delay of τ_i. Then, the amplitude mean of the MPC at $\tau_i, \forall i{\in}\{1, 2, \ldots, N\}$, for Rx config $\mathcal{P}_{\mathrm{Rx}}(t)$ with Tx config being $\mathcal{P}_{\mathrm{Tx}}(t)$:

$$\mu_{t,i} = \mu\Big(\tau_i, \mathcal{P}_{\mathrm{Tx}}(t), \mathcal{P}_{\mathrm{Rx}}(t)\Big) = \frac{1}{M}\sum_{j=1}^{M} A_j(\tau_i),$$

where M denotes the set of measurements collected at Rx config $\mathcal{P}_{\mathrm{Rx}}(t)$ with Tx config being $\mathcal{P}_{\mathrm{Tx}}(t)$, and $A_j(\tau_i)$ denotes the amplitude of the i^{th} MPC for the j^{th} measurement at this specific Tx-Rx config. Therefore,

$$\boldsymbol{\mu}\Big(\mathcal{P}_{\mathrm{Tx}}(t), \mathcal{P}_{\mathrm{Rx}}(t)\Big) = [\mu_{t,1}, \mu_{t,2}, \ldots, \mu_{t,N}]^{\mathsf{T}}.$$

$\mathbf{A}\Big(\mathcal{P}_{\text{Tx}}(t), \mathcal{P}_{\text{Rx}}(t)\Big)$ denotes the vector of amplitudes of the MPCs extracted from the measurements collected at the receiver at time t when the Rx config is $\mathcal{P}_{\text{Rx}}(t)$ and the Tx config is $\mathcal{P}_{\text{Tx}}(t)$. Mathematically,

$$\mathbf{A}\Big(\mathcal{P}_{\text{Tx}}(t), \mathcal{P}_{\text{Rx}}(t)\Big) = [A(t,\tau_1), A(t,\tau_2), \ldots, A(t,\tau_N)]^{\mathsf{T}} = [A_{t,1}, A_{t,2}, \ldots, A_{t,N}]^{\mathsf{T}}.$$

Note that the dot-product in the numerator denotes the vector inner product of the mean-shifted amplitude vectors at times t and t'.

The expectation $\mathbb{E}[\cdot]$ in the above equation for $\rho(\Delta\phi)$ is taken over all Tx and Rx configs along the route $\mathcal{R}$ that satisfy the evaluation conditions **E2**. Let $\mathcal{R}_{\mathbf{E2}}$ denote the set of Tx-Rx configs along the route that satisfy these evaluation conditions **E2**. Then, we can elaborate $\rho(\Delta\phi)$ as

$$\rho(\Delta\phi) = \frac{\frac{1}{|\mathcal{R}_{\mathbf{E2}}|}\sum_{(t,t')\in\mathcal{R}_{\mathbf{E2}}}\left[\sum_{i=1}^{N}\Big(A_{t,i}-\mu_{t,i}\Big)\Big(A_{t',i}-\mu_{t',i}\Big)\right]}{\frac{1}{|\mathcal{R}|}\sum_{t\in\mathcal{R}}\left[\sum_{i=1}^{N}\Big(A_{t,i}-\mu_{t,i}\Big)^2\right]}.$$

1.3 Separation in Velocity

The spatial autocorrelation coefficient ρ vis-à-vis a separation in velocity v:

$$\rho(\Delta v) = \rho\Big(\mathbf{x}_{\text{Tx}},\ \mathbf{x}_{\text{Rx}}(t') = \mathbf{x}_{\text{Rx}}(t),\ \phi(t') = \phi(t),\ |v(t') - v(t)| = \Delta v\Big),\ \text{where}$$

- $\mathbf{x}_{\text{Tx}}(t)$=$\mathbf{x}_{\text{Tx}}, \forall t$ denotes the 3-D position vector of the Tx (fixed);
- $\mathbf{x}_{\text{Rx}}(t)$ and $\mathbf{x}_{\text{Rx}}(t')$ denote the 3-D position vectors of the Rx, at times t and t', respectively;
- $\phi(t)$ and $\phi(t')$ are the absolute errors in alignment between Tx and Rx antennas (deviation from perfect alignment) at times t and t', respectively;
- $v(t)$ and $v(t')$ denote the relative velocities of the receiver with respect to the transmitter at times t and t', respectively, with Δv being the difference in Rx velocities to get to positions $\mathbf{x}_{\text{Rx}}(t)$ and $\mathbf{x}_{\text{Rx}}(t')$; and
- The conditions $\mathbf{x}_{\text{Rx}}(t')$=$\mathbf{x}_{\text{Rx}}(t)$ and $\phi(t')$=$\phi(t)$ ensure that while the signal coherence characteristics vis-à-vis a separation in velocity Δv are being studied, other variables (i.e., distance and alignment) remain unchanged.

Mathematically, this spatial autocorrelation coefficient $\rho(\Delta v)$ is given by

$$\frac{\mathbb{E}\left[\Big(\mathbf{A}\Big(\mathcal{P}_{\text{Tx}}(t),\mathcal{P}_{\text{Rx}}(t)\Big)-\boldsymbol{\mu}\Big(\mathcal{P}_{\text{Tx}}(t),\mathcal{P}_{\text{Rx}}(t)\Big)\Big)\cdot\Big(\mathbf{A}\Big(\mathcal{P}_{\text{Tx}}(t'),\mathcal{P}_{\text{Rx}}(t')\Big)-\boldsymbol{\mu}\Big(\mathcal{P}_{\text{Tx}}(t'),\mathcal{P}_{\text{Rx}}(t')\Big)\Big)\right]}{\sqrt{\mathbb{E}\left[\Big\|\mathbf{A}\Big(\mathcal{P}_{\text{Tx}}(t),\mathcal{P}_{\text{Rx}}(t)\Big)-\boldsymbol{\mu}\Big(\mathcal{P}_{\text{Tx}}(t),\mathcal{P}_{\text{Rx}}(t)\Big)\Big\|^2\right]\mathbb{E}\left[\Big\|\mathbf{A}\Big(\mathcal{P}_{\text{Tx}}(t'),\mathcal{P}_{\text{Rx}}(t')\Big)-\boldsymbol{\mu}\Big(\mathcal{P}_{\text{Tx}}(t'),\mathcal{P}_{\text{Rx}}(t')\Big)\Big\|^2\right]}}.$$

For a route $\mathcal{R}$, we define the terms employed in this equation as follows.

Tx configuration: $\mathcal{P}_{\text{Tx}}(t) = \mathcal{P}_{\text{Tx}}(t') = \{\mathbf{x}_{\text{Tx}},\ \theta_{\text{Tx}}\},\ \forall t,\ t' \in \mathcal{R}$;

Rx configuration: $\mathcal{P}_{\text{Rx}}(t) = \{\mathbf{x}_{\text{Rx}}, \theta_{\text{Rx}}, v_{\text{Rx}}\}, \mathcal{P}_{\text{Rx}}(t') = \left\{\mathbf{x}^{'}_{\text{Rx}}, \theta^{'}_{\text{Rx}}, v^{'}_{\text{Rx}}\right\},\ \forall t, t' \in \mathcal{R}$;

Evaluation conditions E3: $\mathbf{x}^{'}_{\text{Rx}} = \mathbf{x}_{\text{Rx}}, \phi(\theta^{'}_{\text{Tx}}, \theta^{'}_{\text{Rx}}) = \phi(\theta_{\text{Tx}}, \theta_{\text{Rx}}), \left|v^{'}_{\text{Rx}} - v_{\text{Rx}}\right| = \Delta v$.

Let N be the number of resolvable Multi-Path Components (MPCs) extracted via the SAGE algorithm at time t at Rx config $\mathcal{P}_{\text{Rx}}(t)$, with Tx config being $\mathcal{P}_{\text{Tx}}(t)$; $\boldsymbol{\tau}$ represents the discretized delay levels kept consistent throughout our evaluations, i.e., $\boldsymbol{\tau} = \{\tau_1, \tau_2, \ldots, \tau_N\}$; and let $A(\tau_i)$ be the amplitude of the i^{th} MPC, i.e., the MPC at a delay of τ_i. Then, the amplitude mean of the MPC at $\tau_i, \forall i \in \{1, 2, \ldots, N\}$, for Rx config $\mathcal{P}_{\text{Rx}}(t)$ with Tx config being $\mathcal{P}_{\text{Tx}}(t)$:

$$\mu_{t,i} = \mu\Big(\tau_i, \mathcal{P}_{\text{Tx}}(t), \mathcal{P}_{\text{Rx}}(t)\Big) = \frac{1}{M}\sum_{j=1}^{M} A_j(\tau_i),$$

where M denotes the set of measurements collected at Rx config $\mathcal{P}_{\text{Rx}}(t)$ with Tx config being $\mathcal{P}_{\text{Tx}}(t)$, and $A_j(\tau_i)$ denotes the amplitude of the i^{th} MPC for the j^{th} measurement at this specific Tx-Rx config. Therefore,

$$\boldsymbol{\mu}\Big(\mathcal{P}_{\text{Tx}}(t), \mathcal{P}_{\text{Rx}}(t)\Big) = [\mu_{t,1}, \mu_{t,2}, \ldots, \mu_{t,N}]^{\intercal}.$$

$\mathbf{A}\Big(\mathcal{P}_{\text{Tx}}(t), \mathcal{P}_{\text{Rx}}(t)\Big)$ denotes the vector of amplitudes of the MPCs extracted from the measurements collected at the receiver at time t when the Rx config is $\mathcal{P}_{\text{Rx}}(t)$ and the Tx config is $\mathcal{P}_{\text{Tx}}(t)$. Mathematically,

$$\mathbf{A}\Big(\mathcal{P}_{\text{Tx}}(t), \mathcal{P}_{\text{Rx}}(t)\Big) = [A(t,\tau_1), A(t,\tau_2), \ldots, A(t,\tau_N)]^{\intercal} = [A_{t,1}, A_{t,2}, \ldots, A_{t,N}]^{\intercal}.$$

Note that the dot-product in the numerator denotes the vector inner product of the mean-shifted amplitude vectors at times t and t'.

The expectation $\mathbb{E}[\cdot]$ in the above equation for $\rho(\Delta v)$ is taken over all Tx and Rx configs along the route $\mathcal{R}$ that satisfy the evaluation conditions **E3**. Let $\mathcal{R}_{\mathbf{E3}}$ denote the set of Tx-Rx configs along the route that satisfy these evaluation conditions **E3**. Then, we can elaborate $\rho(\Delta v)$ as

$$\rho(\Delta v) = \frac{\frac{1}{|\mathcal{R}_{\mathbf{E3}}|}\sum_{(t,t')\in\mathcal{R}_{\mathbf{E3}}}\left[\sum_{i=1}^{N}\Big(A_{t,i} - \mu_{t,i}\Big)\Big(A_{t',i} - \mu_{t',i}\Big)\right]}{\frac{1}{|\mathcal{R}|}\sum_{t\in\mathcal{R}}\left[\sum_{i=1}^{N}\Big(A_{t,i} - \mu_{t,i}\Big)^2\right]}.$$

2 References

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