SPACE TIME VARIABLE CORRELATION (STVC) CODES
CONCEPT AND FIRST SIMULATION RESULTS

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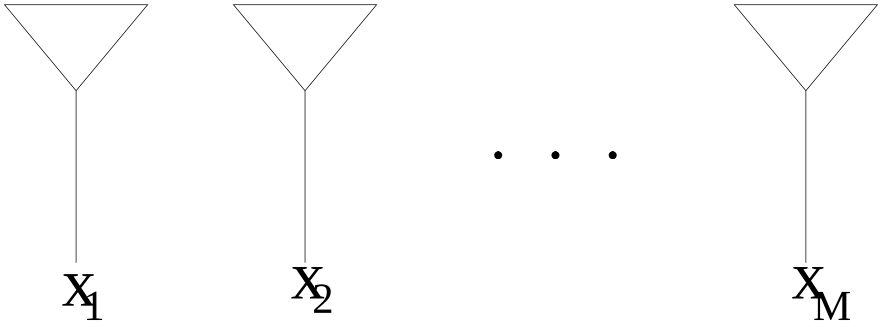
Lucent Technologies
Bell Labs Innovations

OVERVIEW

- A simple modification to the existing STTD/CLTD Tx diversity schemes with minimal impact on R99 specifications.
- Based on a new family of space-time codes with variable correlation that encompass orthogonal coding and beamforming as special cases.
- Optimal transmission method in the presence of partial channel knowledge at transmitter.
- Simple modifications to STTD encoder at Node-B transmitter and to channel estimator at the UE receiver.
- Performance better than the best of STTD and closed-loop transmit diversity over all ranges of UE velocity.

MULTIPLE ANTENNA TRANSMISSION



- Transmit signal correlation matrix: $R_{\mathbf{x}} = E\{\mathbf{x}(t)\mathbf{x}^{\dagger}(t)\}$
- Eigenvectors of $R_{\mathbf{x}}$ determine the transmission modes
- Eigenvalues of $R_{\mathbf{x}}$ determine the energy transmitted on each mode

ORTHOGONAL TRANSMISSION

- All eigenvalues of $R_{\mathbf{x}}$ are equal
- Equal transmit power on all M eigenmodes
- $x_i(t)$ and $x_j(t)$ are *orthogonal* for all i, j: $R_{\mathbf{x}}$ is diagonal
- Requires no channel knowledge at the transmitter
- Examples: *V-BLAST, STTD, STS*
- Orthogonal transmission is necessary to achieve capacity over uncorrelated channels, with no channel knowledge at the transmitter

COLLINEAR TRANSMISSION

- Only one eigenmode of transmission (non-zero eigenvalue): $R_{\mathbf{x}}$ has unit rank
- $x_i(t)$ and $x_j(t)$ are *collinear* for all i, j:

$$|E\{x_i x_j^*\}|^2 = E\{|x_i|^2\}E\{|x_j|^2\}$$

- Channel knowledge required at transmitter to select the eigenmode
- Examples:
  - Using long-term channel knowledge: *beamforming*
  - Using instantaneous channel knowledge: *closed-loop Tx diversity, MRT*
- Collinear transmission is necessary to achieve capacity with perfect channel knowledge at the transmitter assuming one receive antenna.

TRANSMISSION WITH PARTIAL CHANNEL KNOWLEDGE

- Neither collinear nor orthogonal transmission is optimal
- Capacity-achieving signals transmit unequally on several eigenmodes
- When confidence on channel knowledge is high, there should be one strong dominant eigenvalue
- When confidence on channel knowledge is low, there should be a uniform spread of eigenvalues
- *STVC* is a space-time block code that allows variation of eigenspread based on confidence on channel knowledge

SPACE-TIME VARIABLE CORRELATION (STVC) CODING

- Apply a linear transformation to an orthogonal block code
- Transmit $X = B_o L$ where B_o is an orthogonal block code
- Example: STTD block code for symbols s_1 and s_2

$$B_o = \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix}$$

- L is the STVC transformation matrix
- The transmit signal vector $\mathbf{x}$ at time t is the t^{th} row of X
- Correlation matrix: $R_{\mathbf{x}} = L^T L^*$
- Eigenmodes can be controlled by varying L

STVC FOR $M = 2$ TRANSMIT ANTENNAS

- Let $\mathbf{w} = [w_1 \; w_2]^T$ be a normalized weight vector computed for collinear transmission
- Let $R_{\mathbf{x}} = \left(\frac{1+\lambda}{2}\right) \mathbf{w}\mathbf{w}^\dagger + \left(\frac{1-\lambda}{2}\right) \mathbf{u}\mathbf{u}^\dagger$
- $\mathbf{u}$ is any unit vector orthogonal to $\mathbf{w}$. Example: $\mathbf{u} = [w_2^* \;\; - w_1^*]^T$
- $\lambda \in [0, 1]$ is called the *code correlation*
- Solve $L^T L^* = R_{\mathbf{x}}$ to obtain L
- We use the following solution that leads to simple implementation:

$$L = \frac{1}{\sqrt{2}} \begin{bmatrix} \sqrt{1+\lambda} w_1 & \sqrt{1+\lambda} w_2 \\ \sqrt{1-\lambda} w_2^* & -\sqrt{1-\lambda} w_1^* \end{bmatrix}$$

STVC FOR $M = 2$ TRANSMIT ANTENNAS

$$R_{\mathbf{x}} = \left(\frac{1+\lambda}{2}\right)\mathbf{w}\mathbf{w}^{\dagger} + \left(\frac{1-\lambda}{2}\right)\mathbf{u}\mathbf{u}^{\dagger}$$

- $\lambda = 1 \quad \Longrightarrow \quad R_{\mathbf{x}} = \mathbf{w}\mathbf{w}^{\dagger}$
  - Space-Time code: $X = \begin{bmatrix} w_1 s_1 & w_2 s_1 \\ w_1 s_2 & w_2 s_2 \end{bmatrix}$
  - Collinear transmission with weight vector $\mathbf{w}$
- $\lambda = 0 \quad \Longrightarrow \quad R_{\mathbf{x}} = I$
  - All eigenvalues are equal
  - Space-Time code: $X = \frac{1}{\sqrt{2}}\begin{bmatrix} w_1 s_1 - w_2^* s_2^* & w_2 s_1 + w_1^* s_2^* \\ w_2^* s_1^* + w_1 s_2 & -w_1^* s_1^* + w_2 s_2 \end{bmatrix}$
  - Orthogonal transmission (equivalent to STTD)
- $\lambda \in (0,1) \quad \Longrightarrow$ combination of collinear and orthogonal transmission

OPTIMAL SELECTION OF λ

- Intuitively, λ should increase with increase in the amount of channel knowledge at transmitter
- A convex cost function of λ can be minimized using a *stochastic gradient algorithm*
- Examples of cost functions that can be optimized using the algorithm:
  - Information theoretic capacity
  - Raw or coded bit error rate
  - Transmit power for a given target block error rate

STVC RECEIVER

- The optimal receiver is the same as the STTD receiver with a modified channel estimator
- Estimates of the *virtual channel* must be used in place of true channel estimates
- Virtual channel $= L \times$ True channel
- Virtual Channel can be estimated in two ways:
  1. directly from dedicated (per-user) pilot
  2. estimate true channel from common pilot and λ from dedicated pilot *(Recommended)*
- λ is very slowly varying $\Rightarrow$ easy to estimate

STVC FOR UMTS RELEASE 5

- Proposed for two transmit antennas (if desired could be extended to four transmit antennas)
- Closed-loop Tx diversity suffers at high speeds as channel changes during feedback delay
- STTD performs better at high speeds
- STVC transitions smoothly between STTD and closed-loop Tx diversity
- Simple modification to the STTD encoder at Node-B by using closed loop diversity weights
- STTD decoding with a simple modified channel estimator at UE

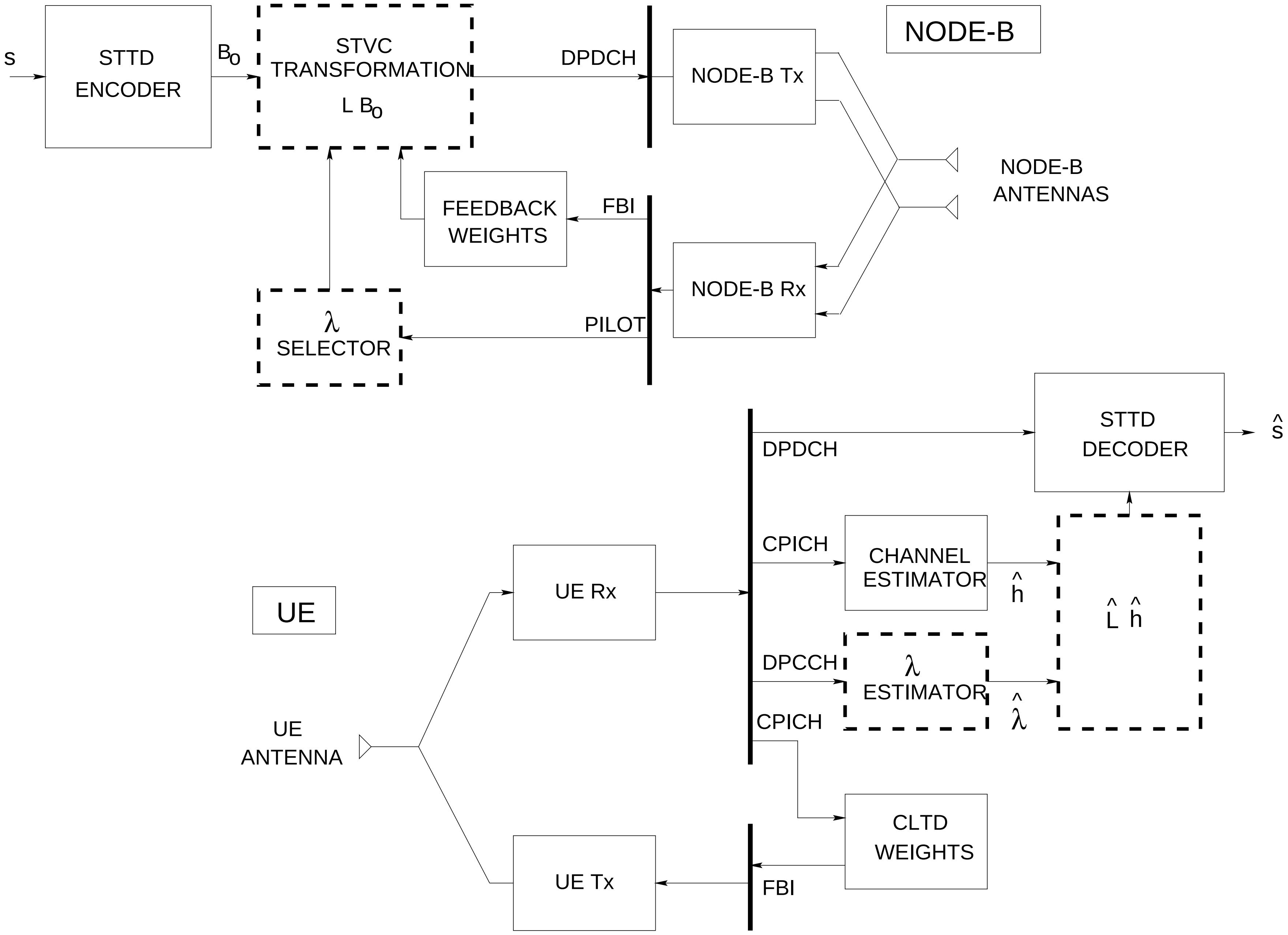
STVC–RELEASE 5: TRANSMITTER

- Transmitter uses closed-loop Tx diversity (mode 1 or 2) weights and λ to apply transformation matrix L to STTD-encoded signals
- Optimal λ depends on autocorrelation of channel
- Autocorrelation of reverse link pilot channel is estimated
- Optimal λ is chosen from a look-up table using the autocorrelation estimate
- Look-up table of autocorrelation versus optimal λ is generated off-line to minimize transmit E_c/I_{or}, using the stochastic gradient algorithm or exhaustive search

STVC–RELEASE 5: RECEIVER

- UE receiver uses an STTD decoder with virtual channel estimates
- Estimation of λ at UE yields an estimate of the STVC matrix L
- Virtual channel estimate $= \hat{L} \times$ True channel estimate
- True channel estimation using common pilot: as in the case of STTD, Release 99
- Simple maximum-likelihood estimation of λ using dedicated pilot
- UE must perform STTD decoding and estimation of optimal Mode 1/2 weights simultaneously

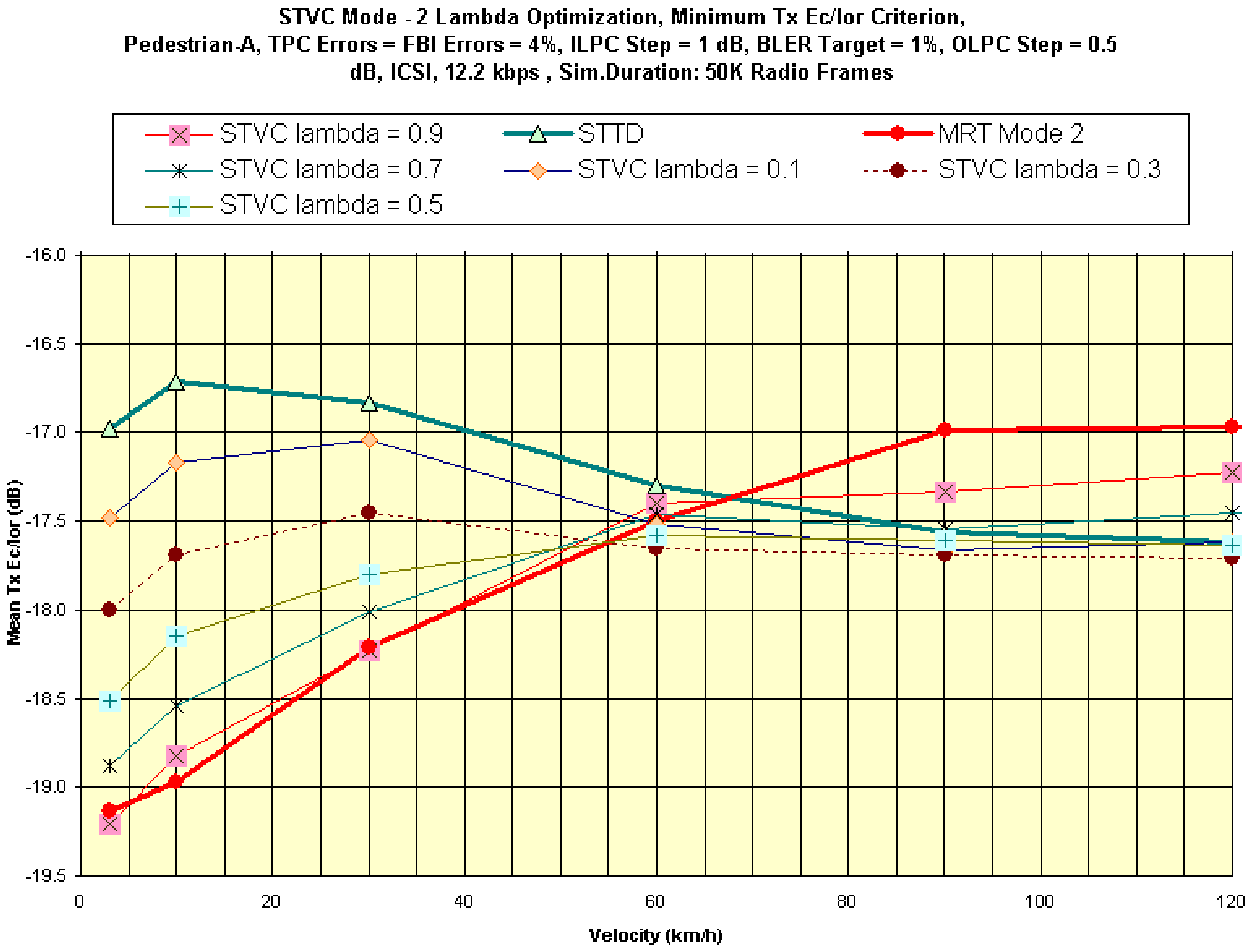
STVC SIGNAL FLOW DIAGRAM



COMPUTATIONAL COMPLEXITY

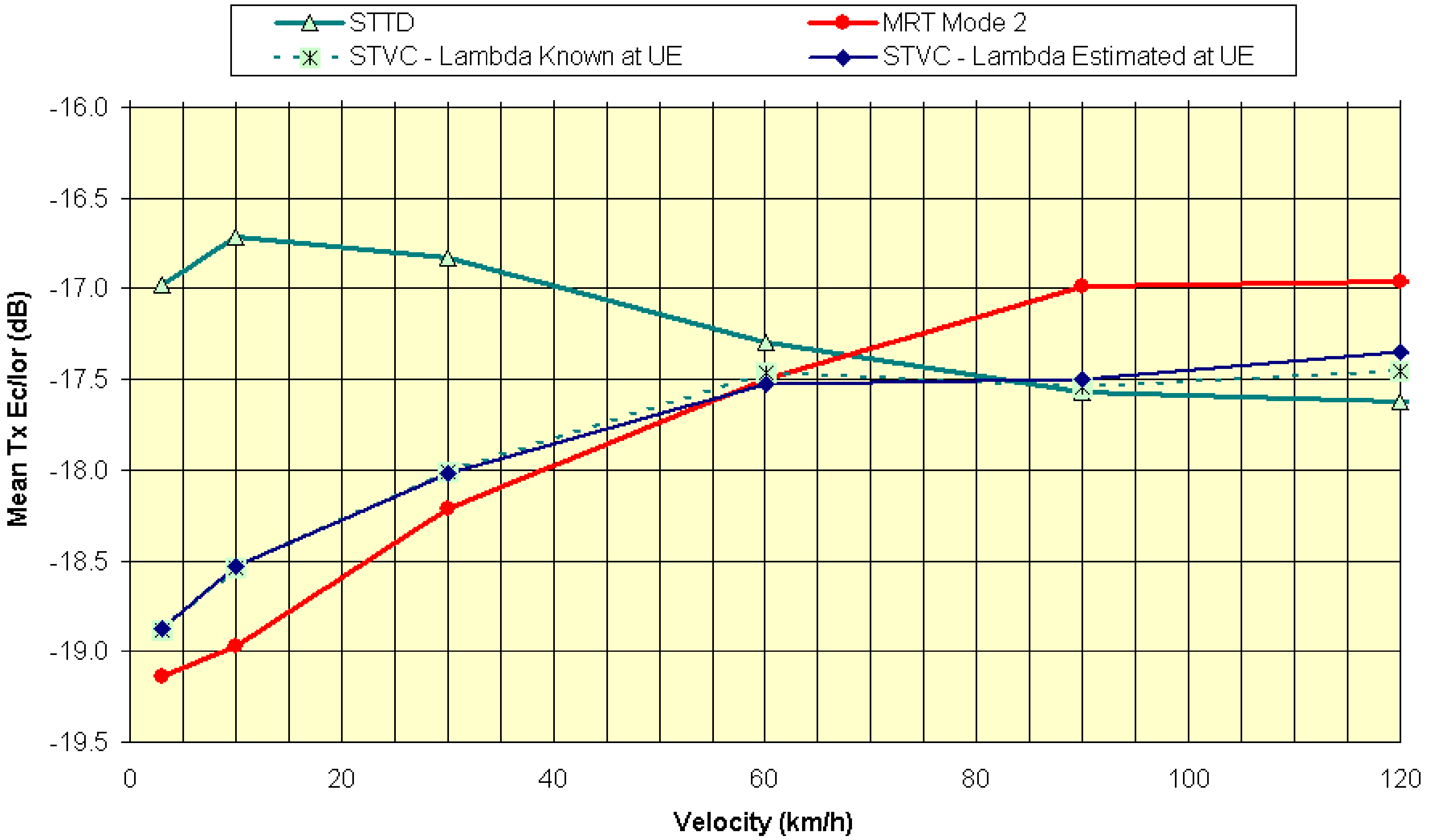
- STVC transformation at Node-B: 4 complex multiplications + 2 complex additions per complex symbol
- Virtual Channel estimator at UE: 8 complex multiplications + 4 complex additions per update
- Estimation of λ at UE: 8 real multiplications + 4 real additions per pilot symbol, and 4 real multiplications + 1 real division + 2 real additions per λ update

STVC PERFORMANCE RESULTS)



λ ESTIMATION PERFORMANCE

Effect of Lambda Estimation at the UE on STVC Mode - 2 Performance, Fixed Tx Lambda = 0.7, Pedestrian-A, TPC Errors = FBI Errors = 4%, ILPC Step = 1 dB, BLER Target = 1%, OLPC Step = 0.5 dB, ICSI, 12.2 kbps , Sim.Duration: 50K Radio Frames



STVC PERFORMANCE ISSUES

- The simulation results validate the expected behavior. STVC performs like STTD at high speeds and like Maximal Ratio Transmission (MRT) at low speeds. In the intermediate velocity region it offers better performance than both STTD and MRT.
- The non-ideal estimation of λ at the UE does not seem to affect the STVC gains. This is due to relative slow rate of change of λ by the Node-B and the large number of samples that can be used in the ML estimation.
- The selection of optimal λ by the Node-B is based on the temporal autocorrelation of the channel for the configuration of two uncorrelated antennas (widely spaced or cross-pol). Other choices are possible depending on the antenna configuration and other system variables (e.g. scheduled transmission).

CONCLUSIONS

- We presented a new transmit diversity technique for 2 transmit antennas that unifies the existing schemes (STTD and CLTD), providing performance gains over a wide range of speeds.
- STVC provides is an optimal transmission in the presence of imperfect channel feedback at the transmitter.
- STVC requires only simple modifications to the STTD encoder at Node-B transmitter and to the channel estimator at the UE receiver with minimal R99 spec changes.