Mm-Wave STSK-aided Single Carrier Block Transmission for Broadband Networking

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Outline

- Introduction to millimeter wave broadband networking;
- Related works;
- Proposed approach,
  - Motivation;
  - Why STSK vs SM comparison;
  - STSK-aided CP-SC.
- State-of-the-art approach: SM-aided CP-SC;
- Link Impairment analysis;
- Simulation results;
- Computational Complexity Analysis;
- Conclusion.

Introduction to mm-Wave broadband networking

Need for Millimeter wave

- Mobile subscribers and their demand for high speed data are increasing due to proliferation of smart devices;
- Current operating frequency bands (*sub-10GHz*) are not sufficing due to the existence of huge traffic;
- **Millimeter wave** technology for next generation networks;
- Next Generation networks to provide variety of services (Internet of Things, High speed data, Better quality of service, etc.);
- Wide spectrum spaces are available at higher frequency bands (28-38GHz, 60GHz, 70-80GHz);
- In particular, *10GHz of bandwidth* available in 70-80GHz (E-band);
- Propagation losses (**rain attenuation, free-space pathloss**) are higher at E-band as compared to *sub*-10GHz;
- Physical layer design is necessary to increase the robustness at millimeter wave frequency.

Physical layer design for mm-Wave

- Coldrey *et al*[1] suggested mm-Wave solution for non-Line of Sight (NLoS) using directional antennas;
- With directional antenna and beam-forming, mm-Wave can be a viable solution for LOS and NLOS;
- Multicarrier techniques (OFDM, SC-FDMA) are candidate waveforms for 5th Generation (5G) networks, because:
  - Exploiting spectral efficiency;
  - Flexible MIMO support;
- Multicarrier techniques exhibits high peak-to-average power ratio (PAPR) and prone to phase noise;
- As an alternative, single carrier technique is being considered for mm-Wave WLAN standard (IEEE 802.11ad) [2];
- Single carrier block transmission with frequency domain equalization (SC-FDE) shows robustness against non-linear amplifier distortion, phase noise and channel impairments;

Related works

- Authors in [3] studied *integrated circuit package development* for single carrier (SC) at mm-Wave aiming to achieve 1Gbps;
- MIMO Single carrier with iterative block FDE [4] shows significant resilience against *imperfect channel estimation in high mobile environments*;
- In another work, low complexity spatial modulation (SM) zero-padded SC [5] in dispersive channels is proposed achieving full multipath and receive diversity using interference cancellation receivers;
- Space-time shift keying (STSK) is considered with OFDM [6], allowing affordable maximum likelihood (ML) receiver complexity – attaining diversity N ▪ min(M, T) (notations taken from paper) .
- OFDM-STSK outperforms spatial modulation and spatial multiplexing – proves a viable solution for backhaul applications by achieving high link availability and better link-level performance [7];

Proposed approach: Motivation

- MIMO-OFDM allows simpler implementation of receiver but at the cost of disadvantages (high PAPR, phase noise, and deep fading) significantly impairing its performance at mm-Wave;
- Single carrier with cyclic prefix (CP-SC) – overcomes the issues related with OFDM at affordable computational complexity;
- CP-SC with linear dispersion code (LDC) [8] attains time-diversity over LDC-OFDM;
- Cyclic prefixed SC aided with STSK is proposed that is different from [8]:
  - For LOS and NLOS dispersive channels ;
  - Performance in the presence non-ideal oscillator and channel estimation impairments;
- STSK-aided CP-SC provides inherent frequency diversity in multipath channels by providing a flexible diversity-multiplexing trade-off, courtesy STSK;
- Performance of CP-SC STSK is compared with CP-SC SM.

Proposed approach: Why STSK vs SM comparison?

- Both techniques are single stream MIMO, making inter-stream interference negligible;
- Affordable narrowband maximum likelihood complexity;
- Spatial modulation (SM) attains only receiver diversity and spectral efficiency depends on transmitter antennas;
- Space-time shift keying (STSK) attains space-time diversity and efficiency does not depend on hardware entity;
- Overall, STSK outperforms SM in link level performance at the cost of lower multiplexing gain and slightly increased complexity;

STSK-aided CP-SC Block Transmission - 1

- Space-time shift keying (STSK) - tradeoff between diversity and multiplexing where $\eta = f(K, Q, T)$:

$$\text{Spectral efficiency}, \eta = \frac{\log_2(KQ)}{T}$$

where, K = modulation level (QAM/PSK), Q = number of dispersion matrix, $\mathbb{C}^{M \times T}$ and, T is the codeword time duration, $M \geq T$.

- STSK codeword symbol – spreading input energy over space and time dimensions;

- Space-time codeword, $\boldsymbol{X_{STSK}}$, to be transmitted is,

$$\boldsymbol{X_{STSK}} = \boldsymbol{0_{M \times T}} + \cdots + S_k \boldsymbol{A_q} + \cdots + \boldsymbol{0_{M \times T}}$$

where, S_k is complex QAM symbol and $\boldsymbol{A_q}$ is the selected dispersion matrix.

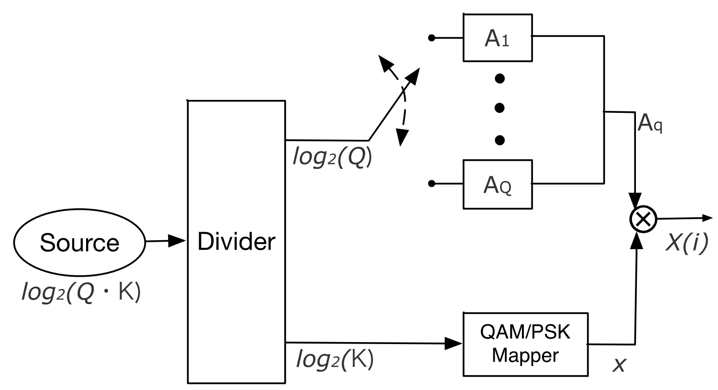

Fig. 1: *STSK codeword Generation*

Proposed approach: STSK-aided CP-SC

STSK-aided CP-SC Block Transmission - 2

- Dispersion matrix set $\boldsymbol{Q}$ is optimized using Genetic Algorithm [9] and available at receiver;

- Reduced complexity near-optimum MMSE receiver [10] applied to received signal $\boldsymbol{Y_{STSK}}$,

$$\boldsymbol{Y_{STSK}} = \boldsymbol{H S_{STSK}} + \boldsymbol{Z}$$

$$\boldsymbol{\bar{V}_{STSK}} = \boldsymbol{W^H Y_{STSK}}$$

where, **H** is the channel matrix $N \times M$ and $\boldsymbol{S_{STSK}}$ is codeword block of size B and **Z** is the AWGN with variance σ^2 .

$$W^H = [H^H H + \sigma^2 \mathbb{I}_M]^{-1} H^H$$

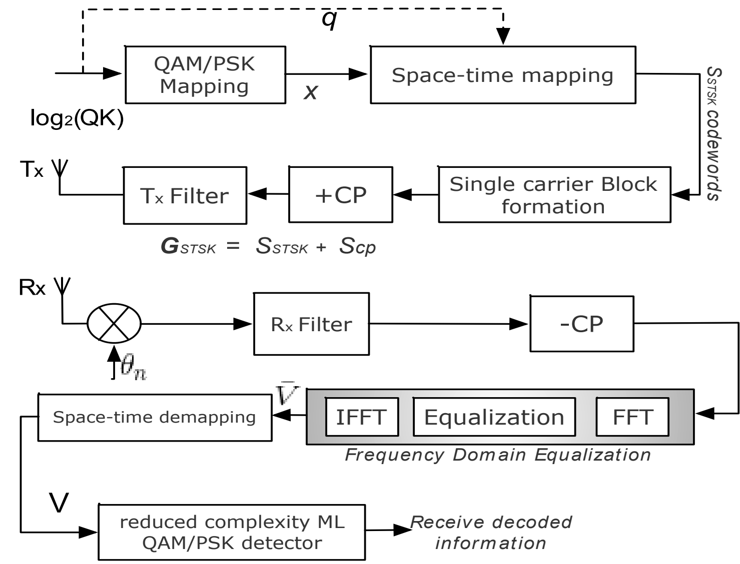

Fig. 2: *Proposed SC-STSK Transceiver*

Proposed approach: STSK-aided CP-SC

STSK-aided CP-SC Block Transmission - 3

- QAM symbol and dispersion matrix estimation can be performed as,

$$(\hat{q},\hat{S}) = arg\min_{q,x}\left\|\widehat{\Psi}_{STSK} - \kappa_{q,k}\right\|^2$$

where, $\widehat{\Psi}_{STSK}$ is the vectorial stacking of $\bar{\boldsymbol{V}}_{\boldsymbol{STSK}}$ and $\kappa_{q,k}$ is codeword generated at receiver using available $\boldsymbol{Q}$ matrix and K-QAM constellation.

- The spectral efficiency of proposed CP-SC-STSK is,

$$\eta = \frac{log_2(KQ)}{T(1+\alpha)} \quad \text{bps/Hz}$$

where, α is the roll-off factor of pulse shaping filter.

- Spectral efficiency reduces with the increase in time diversity. Hence flexible trade-off exists between spectral efficiency and diversity.

SM-aided CP-SC Block Transmission – 1

- Spatial modulation (SM) aided CP-SC [5] is considered for comparison purposes;

- SM activates only single RF antenna for each symbol duration hence inter-channel interference (ICI) is absent;

- The spectral efficiency for SM is dependent on QAM/PSK-symbol and number of transmitter antenna as $\eta' = f(K, M)$,

$$\eta' = log_2(KM)$$

- The input bit stream selects m^{th} antenna for K-QAM/PSK *x* symbols depending on input bit stream;

State-of-the-art Approach: SM-aided CP-SC

SM-aided CP-SC Block Transmission – 2

- The received MMSE-equalized spatial modulated signal after CP extraction is,

$$\bar{V}_{SM} = \bar{S}_{SM} + \bar{\zeta}$$

where, $\bar{\zeta}$ is noise at the output of equalizer.

- At the receiver, the detection can be performed as,

$$(\hat{m}, \hat{x}) = \min_{m,x} \|\bar{\Psi}_{SM} - \gamma(m,x)\|^2$$

where, $\bar{\Psi}_{SM}$ is the vectorial stacking of $\bar{V}_{SM}$ and $\gamma(m,x)$ is the targeted sample.

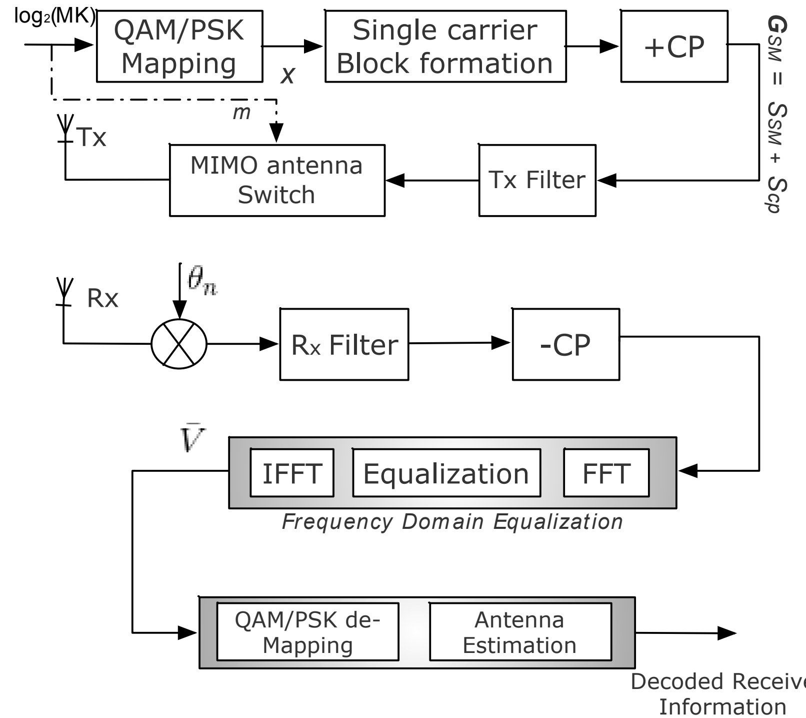

Fig. 3: *CP-SC-SM Transceiver*

- The effective spectral efficiency of pulse shaped SP is,

$$\eta' = \frac{\log_2(MK)}{1 + \alpha} \geq \eta$$

Millimeter wave multipath channel

- Statistical spatial channel model (SSCM) is used to model mm-Wave channel;
- Directional power delay profile (PDP) is given as,

$$h(t,\vec{\Theta}_d,\vec{\Phi}_d) = \sum_{p=1}^{P_t}\sum_{u=1}^{U_p} a_{u,p} e^{j\varphi_{u,p}\varrho(t-\tau_{u,p})} g_{TX}(\vec{\Theta}_d - \vec{\Theta}_{u,p}) g_{RX}(\vec{\Phi}_d - \vec{\Phi}_{u,p})$$

where, t is the absolute propagation time, $\vec{\Theta}_d$ is the angle of departure (AOD) and $\vec{\Phi}_d$ is the angle of arrival (AOA). Definition of rest of the symbols can be found in literature[1].

[1]T. S. Rappaport, G. R. MacCartney, M. K. Samimi and S. Sun, "**Wideband Millimeter-Wave Propagation Measurements and Channel Models for Future Wireless Communication System Design**," in IEEE Transactions on Communications, vol. 63, no. 9, pp. 3029-3056, Sept. 2015.

Link impairments analysis

Phase Noise Impact

- Front end components in wideband systems operate at higher bandwidths resulting in increasing the phase variations – results in phase noise;

- At the receiver, the equalized codeword symbol in the presence of phase noise,

$$\bar{V} = \bar{X} \sum_{n=0}^{N-1} \boldsymbol{c}_n e^{j\theta_n^X} + \bar{Z}$$

where, $e^{j\theta_n^X}$ is the phase noise on the codeword symbol X with PSD specified by receiver oscillator and $\boldsymbol{c}_n$ is the space-time gain matrix in STSK, whereas it is only maximum ratio combining matrix for SM. For $\theta_n \ll 1$, $e^{j\theta_n^X}$ can be approximated as $e^{j\theta_n} \approx 1 + j\theta_n$, we get,

$$\sum_{n=0}^{N-1} \boldsymbol{c}_n(1 + j\theta_n) = \boldsymbol{c}_0 + \boldsymbol{c}_1 + \cdots + \boldsymbol{c}_{N-1} + \underbrace{j(\boldsymbol{c}_0\theta_0 + \boldsymbol{c}_1\theta_1 + \cdots + \boldsymbol{c}_{N-1}\theta_{N-1})}_{\approx 0}$$

- Space-time diversity averages out the phase noise as in STSK and has performance improvement over SM.

- Increasing the receiver antenna array will improve the performance in the presence of phase noise - θ_n is Gaussian.

Channel Estimation Error Impact

- Channel Estimation is necessary for proper equalization;
- High channel estimation error results into inter-symbol interference;
- High fluctuating environments require frequency pilot transmission, results into reduced throughput;
- MIMO systems requires pilot transmission for each Tx-Rx antenna pair for coherent detection;
- In this work, the channel estimation error is modeled as Gaussian complex variable $\varepsilon, \sim CN(0, {\sigma_e}^2)$ as,

$$\widehat{H}_{m,n} = H_{m,n} + \varepsilon$$

Where, $\widehat{H}_{m,n}$ is the imperfect channel response between m-th Tx and n-th Rx antenna pair and $H_{m,n}$ is the perfect channel response between m-th Tx and n-th Rx.

Simulation Results

- Proposed CP-SC-STSK is compared with CP-SC-SM in different scenarios;
- Two series of results are obtained in LoS and nLoS environment – phase noise and imperfect channel estimation;

Table 1: *Simulation parameters*

Parameter	Values
Bandwidth (MHz)	500
Frequency Band	73GHz
Block Size, B	512
Cyclic Prefix, S_{cp} (Samples)	150
Pulse Shaping Filter	Root raised cosine (roll-off 0.35)
Channel Coding	½ convolutional coding

- Different MIMO configurations are considered in the work listed in Tab 2,

Space-time shift keying (STSK)		Spatial Modulation (SM)	
2x2 MIMO	4x4 MIMO	2x2 MIMO	4x4 MIMO
K = 4 (QPSK)	K = 4 (QPSK)	K = 2 (BPSK)	K = 4 (QPSK)
Q = 4, T = 2	Q = 4, T = 2	M = 2	M = 4

- The net data rate for different MIMO configurations are, *286.44Mbps* for (2,2,2,4) and for (4,4,2,4), whereas *286.44Mbps* for 2x2 SM and *572.89*Mbps for 4x4 SM.

Simulation results

Phase Noise Analysis-1

- Phase noise (PN) profile of an oscillator working in 73.9-83.5GHz is used with PSD as,

  [-90, -101, -111, -132] (dBc/Hz) at frequency offsets [1, 5, 10, 100] (MHz)

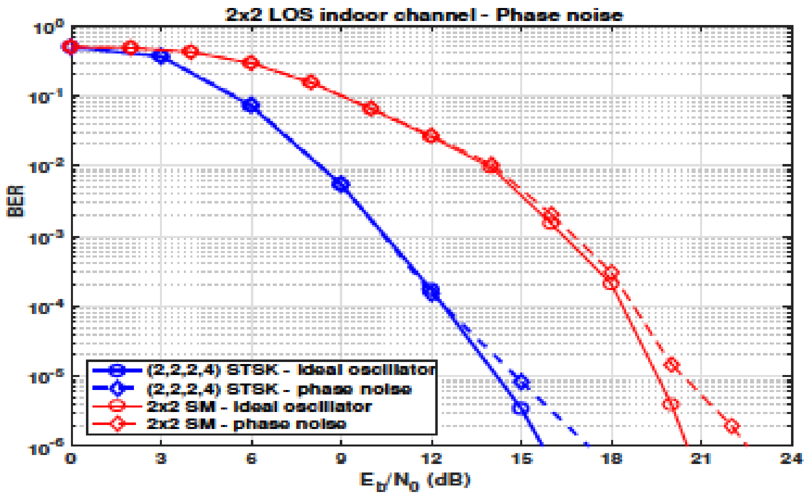

Fig. 4: *2x2 LOS scenario with PN*

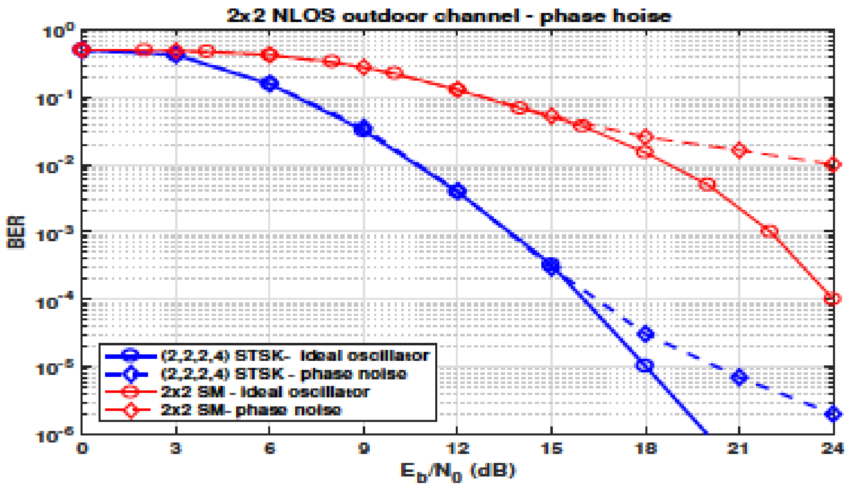

Fig. 5: *2x2 NLOS scenario with PN*

- STSK (2,2,2,4) has shown 4dB performance improvement w.r.t SM (2x2) in case of LOS, whereas more than 5dB is observed in case of NLOS;
- In case of LOS PN does not degrade the performance for both STSK and SM, in particular STSK shows greater resilience against PN;
- Due to augmented space-time diversity, STSK has shown slow decay of BER in case NLOS in the presence of PN, where SM is severely affected by PN with irreducible error rate.

Simulation results

Phase Noise Analysis-2

- Increasing the MIMO size enhances the performance improvement due to diversity incorporated in STSK (4,4,2,4) and SM (4x4);

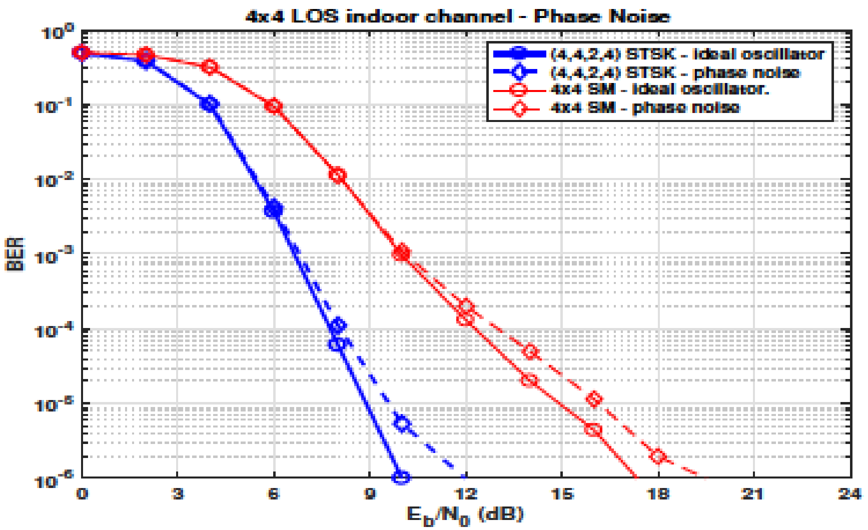

Fig. 6: *4x4 LOS scenario with PN*

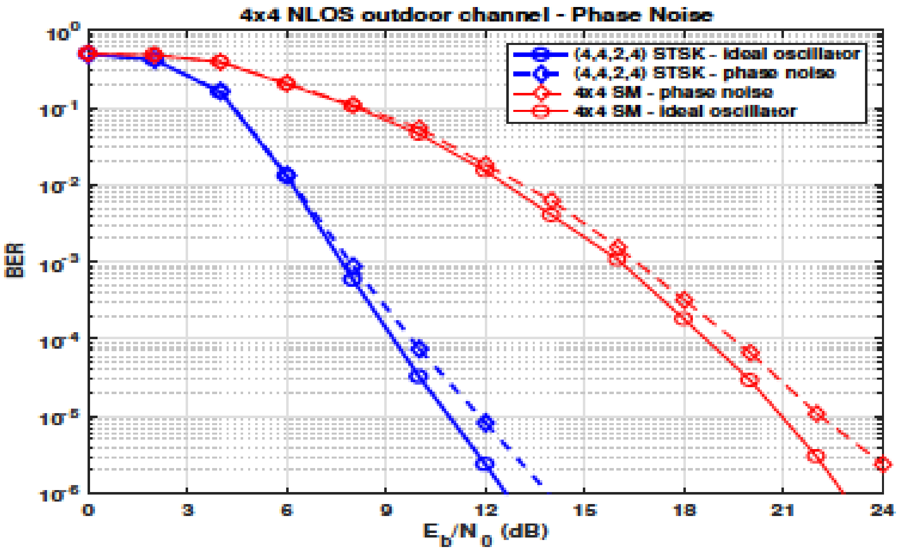

Fig. 7: *4x4 NLOS scenario with PN*

- As it can be seen in figures, STSK and SM have shown significant improvement against PN in both the scenarios (LOS and NLOS);
- Noticeably, a 10dB gain can be seen in Fig 6 where STSK is outperforming SM;
- STSK has spectral efficiency reduced by 3dB as compared to SM that is clearly overshadowed by excellent performance gain in both the scenarios;
- Thus STSK provides a flexible trade-off between diversity and multiplexing.

Simulation results

Channel Estimation Error Analysis -1

- Channel estimation error with two different error variances is considered in our work,

$$\sigma_e{}^2 = -10dB\ (\textbf{High}),\ -30dB\ (\textbf{low})$$

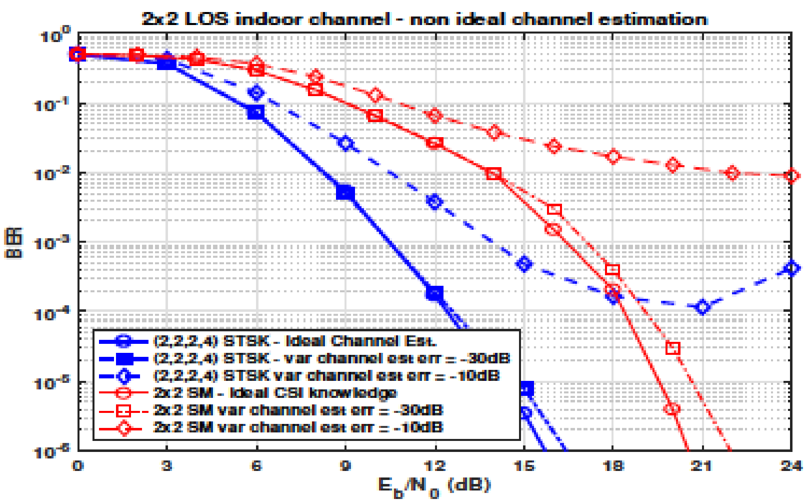

Fig. 8: *2x2 LOS with channel est. error*

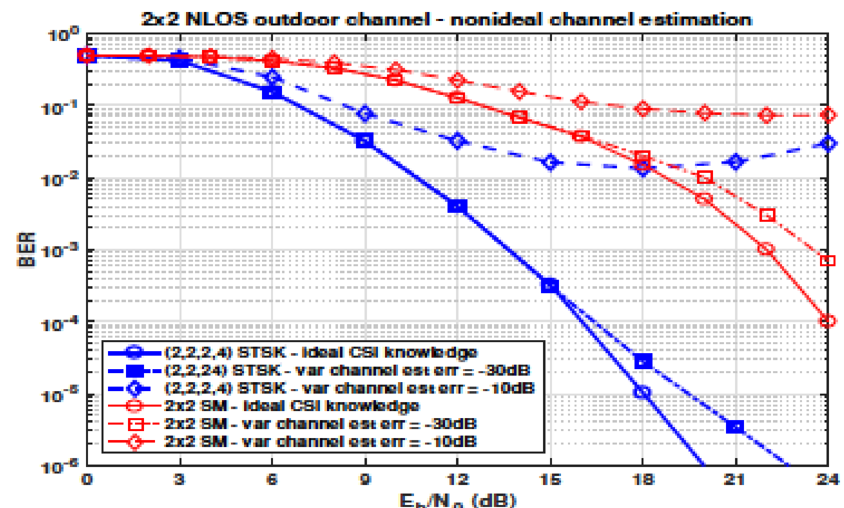

Fig. 9: *2x2 NLOS with channel est. error*

- Both STSK and SM perform considerably well against low channel estimation error with degradation less than 3dB in case of LOS and NLOS;
- At high channel estimation error, STSK and SM have performance degradation resulting into irreducible error floors.

Simulation results

Channel Estimation Error Analysis -2

- Increasing the diversity order in the system significantly improves the performance against channel estimation errors;

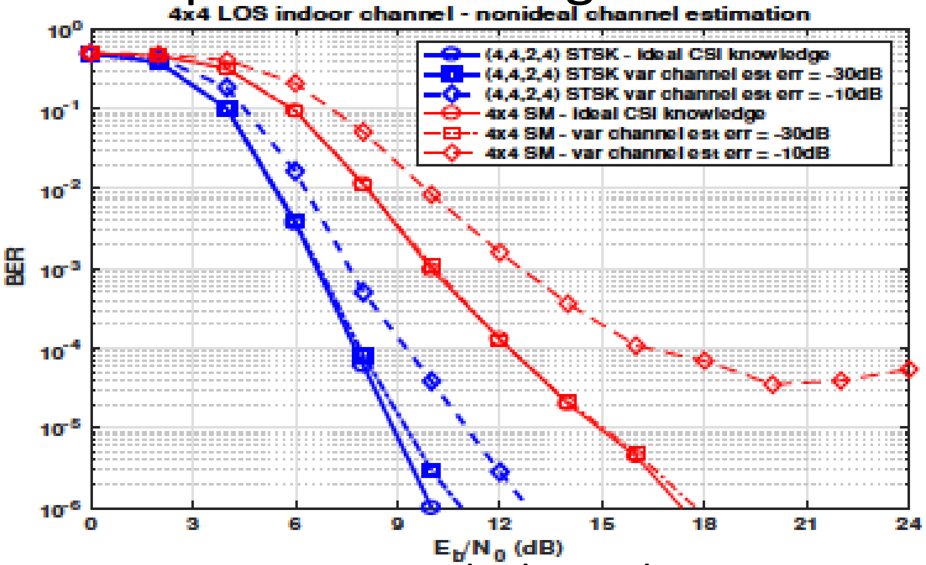

Fig. 10: *4x4 LOS with channel est. error*

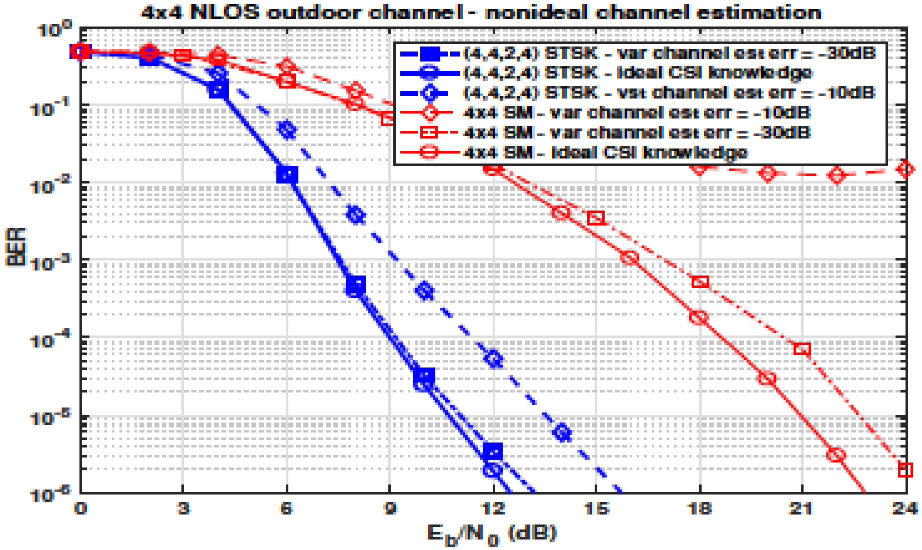

Fig. 11: *4x4 NLOS with channel est. error*

- It can be seen in Fig 10 and 11, STSK shows a great deal of resilience against channel estimation errors with 2dB and 3dB degradation in LOS and NLOS, respectively,
- On the other hand, SM suffers a lot in case of high channel estimation error in both LOS and NLOS;
- Clearly, space-time diversity provided by STSK has shown applaudable performance by providing a flexible trade-off between diversity and multiplexing with robustness against impairments.

Computational Complexity

Table 3: *Computational Complexity*

MIMO Configuration	Order of Computational Complexity	# of Elementary operations per Single carrier block symbol
Proposed Single Carrier STSK	$(4M^2N + 8MN + 4MTQ + 2QK' + Q + 2K)$	1.48 x 10^2 for (2,2,2,4)-QPSK
		5.32 x 10^2 for (4,4,2,4)-QPSK
Single carrier SM	$(4M^2N + 8MN + 2K)$	0.68 x 10^2 for 2x2 - BPSK
		3.92 x 10^2 for 4x4 - QPSK

- Computational complexity is specified in term of elementary operations per single carrier block symbol;
- The complexity of single carrier SM MIMO is the lowest with highly compromised BER performance as seen earlier.
- STSK (4, 4, 2, 4) is computationally intensive that is linear in terms of T and Q;

Conclusion

- A novel single carrier space-time shift keying (STSK) is proposed for LOS and NLOS in mm-Wave broadband networking;
- The proposed system is tested against single carrier spatial modulation in the presence of phase noise and channel estimation error;
- Due to augmented space-time diversity, STSK outperforms SM in the presence of phase noise even in critical NLOS environments;
- High antenna array STSK (4,4,2,4) has shown remarkable performance over SM when channel estimation is not perfect;
- However, STSK especially (4,4,2,4) paid the price in terms of reduced spectral efficiency and a bit higher computational complexity (still affordable).

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Thank you!