processing matrix of user $\boldsymbol{i} \in \{\mathbf{1,2,\ldots k\ldots, K}\}$ in null space of previously coded matrix for $(\boldsymbol{i-1})_{th}$ user. As each user faces different power constraint $\boldsymbol{P_k}$, given by

$$\boldsymbol{P_k} \geq \boldsymbol{tr}(\boldsymbol{Q_k}) \quad (5)$$

where $\boldsymbol{Q_k}$ is interference and noise covariance matrix, given by

$$Q_k = \sigma_{n_k}^2 I_{n_{R,k}} + E\{[X_k X_k^H] \mid H\} \quad (6)$$

assuming interference is only contributed by precoded transmit processing matrix of previously added users, $\sigma^2$ being variance of random Gaussian variable $z$. $\sigma^2$ is 1 for $z \sim$ N(0,1) as proved mathematically in literature.

Using noise energy spectrum for $\boldsymbol{k_{th}}$ user as in eq. (3) , expanding eq. (6) further, we get

$$Q_i = \sigma_{n_k}^2 I_{n_{R,k}} + \sum_{j=1}^{i-1} (H_i W_j)(H_i W_j)^H \quad (7)$$

$$Q_i = \left( I_{n_{R,k}} + \frac{1}{\sigma_{n_k}^2} \sum_{j=1}^{i-1} (H_i W_j)(H_i W_j)^H \right) \quad (8)$$

The date rate for $\boldsymbol{i_{th}}$ added user will be given by

$$R_i = \log_2 \left| I_{n_T,k} + \frac{1}{\sigma_{n_k}^2} H_i Q_i H_i^H \right| \quad (9)$$

eq (9) can be re-written in terms of SNR as

$$R_i = \log_2 \left| I_{n_T,k} + \frac{\gamma}{n_{R_k}} H_i H_i^H \right| \quad (10)$$

where $\gamma$ is average SNR per user given by $P_k/\sigma_{n_k}^2$

The sum of data rate for all K users will be

$$R_{sum} = \log_2 \left| I_{N_T} + \sum_{i=1}^{K} \frac{\Gamma}{\sum_{k=1}^{K} n_{R_k}} H_k H_k^H \right| \quad (11)$$

where $\boldsymbol{\Gamma}$ is average SNR for all $\boldsymbol{K}$ users for total selected antennas given by $\sum_{k=1}^{K} \boldsymbol{n_{R_k}}$

To maximize the data sum rate expression in eq. (11) while selecting antennas for $\boldsymbol{k_{th}}$ user, keeping minimum threshold for SNR, requires maximization of

$$\sum_{i=1}^{K} H_k H_k^H = \|H_k\|_F^2 = \|H\|_F^2 \quad (12)$$

which is frobenius norm.

So individual antenna from pool of $\boldsymbol{N_R}$, user antennas can be selected if the frobenius norm as per eq. (12) for the channel row is maximum for that antenna thus contributing to maximization of data sum rate viz. throughput.

*E. Algorithm for combined user and antenna selection*

Assuming set of users as $\boldsymbol{\mathcal{U}} = \{\mathbf{1}, \mathbf{2}, \ldots\ldots, \boldsymbol{K}\}$, and possible subsets of selected users at any time slot for which channel is static, is given by $\boldsymbol{\mathcal{U}_l}$ where $\boldsymbol{l} = \left\{\mathbf{1}, \mathbf{2}, \ldots., \binom{\boldsymbol{K}}{\boldsymbol{K_0}}\right\}$, for $\boldsymbol{K_0}$ number of users selected from $\boldsymbol{K}$.

Number of antennas on each user and transmitter is same but denoted by $\boldsymbol{N_R}$ and $\boldsymbol{N_T}$ respectively for reason specified above. $\boldsymbol{\mathcal{A}_j}$, represent the possible subset of antennas for $\boldsymbol{k_{th}}$ user. $|\boldsymbol{\mathcal{A}_j}| = \mathbf{N_R}$, maximum number of antennas available on user, $\boldsymbol{j} = \left\{\mathbf{1}, \mathbf{2}, \ldots\ldots, \binom{\boldsymbol{N_R}}{\boldsymbol{n_{R_k}}}\right\}$ where $\boldsymbol{n_{R_k}}$ antennas are selected out of $\boldsymbol{N_R}$ antennas.

$$H = \left\{h_1, h_2, \ldots\ldots, h_l, \ldots., h_{n_{R_k}}\right\} \quad (13)$$

where in eq(13) $\boldsymbol{h_l}\ \forall\ \boldsymbol{l}$ **is** $\boldsymbol{l_{th}}$ row of matrix given by

$$\boldsymbol{h_l} = \left\{\boldsymbol{h_{l1}}, \boldsymbol{h_{l2}}, \ldots, \boldsymbol{h_{ll}} \ldots, \boldsymbol{h_{l n_{T_k}}}\right\} \quad (14)$$

$$h_{ll} = \left\{ \begin{bmatrix} h_{l_1} & \cdots & h_{l\,N_{T_l}} \\ \vdots & \ddots & \vdots \\ h_{l\,N_{R_l}} & \cdots & h_{l\ N_{R_l} N_{T_l}} \end{bmatrix} \in \mathcal{C}^{n_{R_l} \times n_{T_l}} \right\} \quad (15)$$

where $\boldsymbol{h_{ll}}$ is channel matrix for $\boldsymbol{l_{th}}$ user

considering $\boldsymbol{n_{T_l}}$ beamforming transmit antennas selected for user $\boldsymbol{l}$ and $\boldsymbol{n_{R_l}}$ user antennas selected at user side. For selecting users and antennas, find $\|\boldsymbol{h_l}\|_F^2\ \forall\ \boldsymbol{l}$ **in** $\boldsymbol{\mathcal{U}_l}$.

The algorithm has following steps:

**Step 1** : identify row $h_l$ from eq. (11), giving best frobenius norm resulting in selection of $l_{th}$ user

**Step 2**: for $l_{th}$ user select $n_{R_l}$ user antennas and $n_{T_l}$ transmit antennas

- selecting $n_{R_l}$ antennas at $l_{th}$ user
- from matrix in eq. (15) select column u < v column iff $\|h_u\|^2 > \|h_v\|^2$ , otherwise choose $v_{th}$ column so as to maximize the equation

$$\max_{2 \le u,v \le n_{T_l}} \left\{ \sum_{i=1}^{N_{R_l}} \left|h_{i,u}\right|^2 + \left|h_{i,v}\right|^2 \right\} \quad u \neq v$$

  delete $u_{th}$ or $v_{th}$ column, repeat till we check all columns, and finally select $n_{R_l}$ antennas
- repeat above step for rows to select $n_{T_l}$ transmit antennas

$$\max_{2\le u,v\le n_{R_l}} \left\{ \sum_{i=1}^{n_{R_l}} \left|h_{u,j}\right|^2 + \left|h_{v,j}\right|^2 \right\} \quad u \neq v$$

delete $u_{th}$ or $v_{th}$ rows, repeat till we check all rows, and finally select $n_{T_l}$ antennas

## RESULTS AND DISCUSSION

Simulations have been carried to evaluate the performance of MU-MIMO in VANET. Simulations have been done with 500 different channel realizations considering linear precoding and singular value decomposition (SVD).

**Table 1:** Parameters for MU-MIMO VANET simulations

| **Parameters** | **Values** |
|---|---|
| Frequency | 5.9 GHz |
| Bandwidth | 40 MHz/160 MHz |
| Modulation Scheme | 64 QAM/256 QAM |
| Convolution Code | 5/6 |
| Channel Model | Nakagami –m fading model |
| Number of Antennas | 8 |
| Payload Size | 100 bytes |
| Beacon Time Interval | 100 ms |
| Signal to Noise Ratio | 20 dB |
| Transmission Range | 250-300 m |
| Area of Simulation | 1000 x 1000 $m^2$ |
| Number of Vehicles | 10/20/40/60/80 |
| Speed of Vehicles | 20 -100 km/hr |

The analytical results may have limited validity in practical scenario, so we have considered the vehicular movement scenario on urban and highway roads with vehicles ranging from 10 to 80 vehicles in 1000 x 1000 $m^2$ area with vehicle speed ranging from 20 km/hr to 100 km/hr considering the maximum permissible speed limit on urban roads and practical speeds on highway. Results have been obtained for safety messages with packet size of 100 bytes with beacon time interval of 100 ms, without much change in topology during message transmission, as the time taken for safety message dissemination are in order of microseconds analyzed in section IV. Transmission range of 250-300 m can simulate sparse traffic scenario with average of 1-2 vehicles in specified area. The antennas on all vehicular nodes are same, but for notational convenience, on transmitter it is denoted by $\boldsymbol{N_T}$ and on users as $\boldsymbol{N_R}$, with $\boldsymbol{K}$ users for VANET scenario. Maximum of 8 antennas have been considered on vehicle, mounted on roof-top in linear array. Performance has been evaluated in term of throughput, packet delivery ratio, delay and compared with results of SU-MIMO.

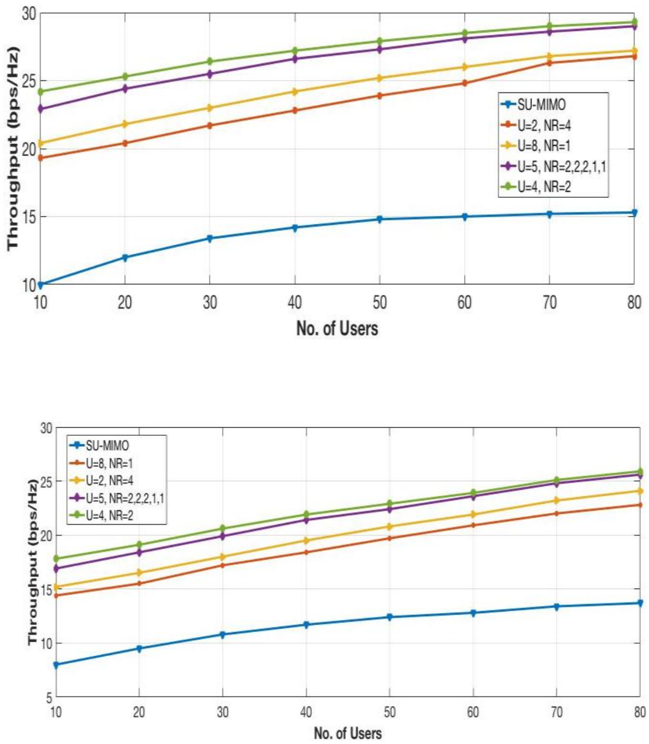


**Figure 4:** Throughput for SU-MIMO, and MU-MIMO for different number of user antennas and $N_T$=8 for a) urban road scenario b) highway scenario

Fig. 4 depicts the throughput for urban and highway scenario. SU in legend is for SU-MIMO, U2 for K=2, $n_{R_k} = 4$, $N_T$=8 in all cases. U8 for K=8, $n_{R_k} = 1$ , U5 for K=5, $n_{R_k} = \{2,2,2,1,1\} \forall K = \{1,2,3,4,5\}$ , U4 for K=4, $n_{R_k} = 2$ on each user. Performance of SU-MIMO is very low as compared to others. The scheme that make best use of multipath fading is benefitted most from MU-MIMO. Performance of U5 scheme is much closer to U4 for more number of users. Performance on highway scenario is low as multipath fading is less and LOS component is strong hence neutralizing the benefit of multipath fading for enhancing throughput.

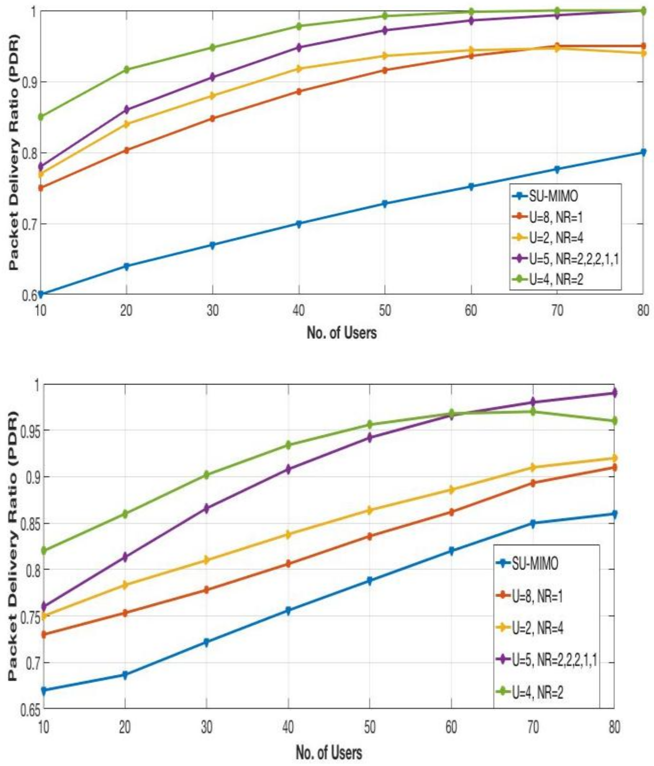


**Figure 5:** Packet Delivery Ratio for SU-MIMO, and MU-MIMO for different number of user antennas and $N_T$=8 for a) urban road scenario b) highway scenario

Fig. 5 shows the variation of packet delivery ratio (PDR) with number of antennas. PDR are the packets transmitted successfully versus the packets generated. PDR increases with increase in number of vehicles due to restricted mobility of vehicles resulting in successful packet transmission. User and antenna numbers are assumed to be same as in previous scenario. Transmission Scheme with 4 users having 2 antennas each outperforms others, as it exploits the benefit of multipath fading and spatial diversity owing to multiple users added in topology. The difference between SU-MIMO and MU-MIMO is wide in sparse vehicle scenario as the vehicles are distant located and connectivity becomes problem. Performance of all schemes in highway scenario is low in comparison to urban as a benefit of MIMO diversity due to buildings and obstacles creating multipaths is more prevalent on urban roads. Performance of MU-MIMO scheme with 4 users is better for sparse traffic from 5 users scheme than for dense traffic as the multipath diversity benefits are overpowered by congestion resulting in packet drops. PDR of 0.9 and above are required for reliable transmission in wireless networks but for VANETs it is difficult to achieve with SU-MIMO due to stringent network conditions as observed in fig. 5(a) and (b), but with MU-MIMO PDR above 0.9 is achievable.

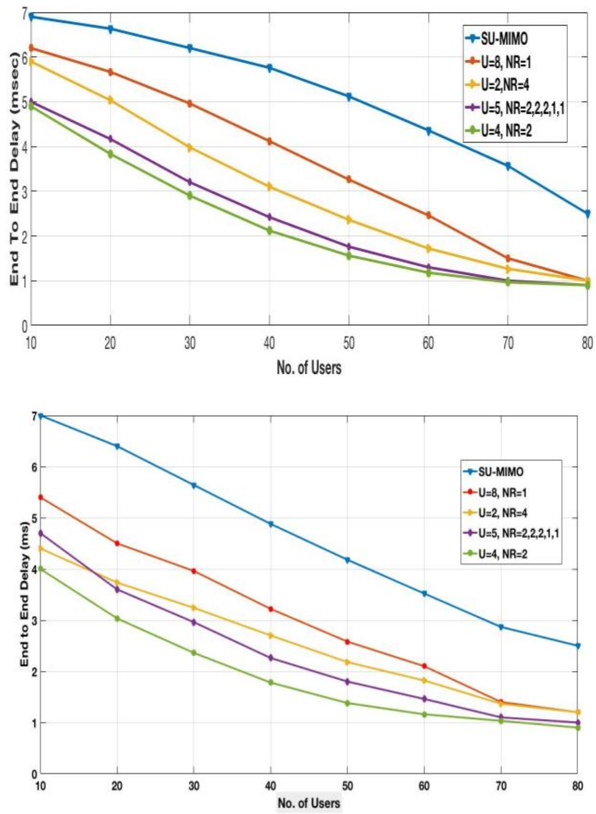


**Figure 6:** End to End for SU-MIMO, and MU-MIMO for different number of user antennas and $N_T$=8 for a) urban road scenario b) highway scenario

Fig. 6, compares the end to end delay in MU-MIMO VANET scenario. Delay is in order of milliseconds, and is least with 4 users having two selected antennas, giving maximum of 8 streams. For the obvious reason delay is more for sparse traffic as compared to dense, further as we reach to 80 vehicles on road it gives a breakeven and further increase in nodes may result in longer delay.

The results so obtained in terms of basic metrics are better for MU-MIMO, but involves complexity in terms of user and antennas selection. Hence it is worth analyzing the complexity of algorithm that is also one of the contributors in delay. For small number of antennas it may work but for the algorithm to work in wider perspective, scalability is important. Matrix calculations, frobenius norm calculations are major contributors in complexity.

In this algorithm vector calculations have to be done for finding frobenius norm to select users in step 1 for $U_l \times N_{R_l} \times N_{T_l}$ matrix given in eq. (15), vector calculations has complexity O( $U_l N_{R_l} N_{T_l}$). For step 2, vector calculations are required to find antennas for single user by selecting columns and then rows, adding complexity $O(N_{R_l} N_{T_l})$ and $O\ (n_{R_l} N_{T_l})$ respectively. For simplicity, selected users are represented by U and receive and transmit antennas, which are same on vehicles is represented by N. Complexities of three vector calculations are $O(UN^2)$, $O(N^2)$, $O(N^2)$. Without loss of generality, considering large number of antennas and limited users U<<N, the complexity can be given by $O(N^2)$ whereas the exhaustive search has complexity of the $O(N^3)$. Hence there is significant reduction in complexity as compared to exhaustive search hence contributes in delay reduction even for large number of antennas.

## CONCLUSION

Realizing the underutilization of MIMO and visualizing the benefits of MU-MIMO in future applications, we have explored the possibility to implement MU-MIMO in VANET. The challenging task of user and antenna selection has been simplified by proposing joint user and antenna selection algorithm for VANET scenario. The results thus obtained in terms of throughput, PDR and end-to-end delay indicated MU-MIMO benefits in VANET. Throughput has doubled whereas PDR has shown significant increase as compared to SU-MIMO VANET, thus indicating the benefit of MU-MIMO for VANET. Further reduction in end-to-end delay to nearly half, indicate its benefit in VANET safety applications. Though the VANET realization has been done considering realistic scenario of urban and highway roads with sparse and dense traffic but due to limitations of simulator environment the practical results may vary but are still expected to be significantly better than SU-MIMO. The results obtained suggest the performance enhancement using MU-MIMO for applications other than safety in VANETs.

## REFERENCES

[1] White Paper, "802.11ac MU-MIMO: Bridging the MIMO gap in wi-fi", *Qualcom*, January 2015

[2] Q. H. Spencer et.al., "An Introduction to Multi-User MIMO Downlink", *IEEE Communications Magazine*, vol. 42, issue 10, pp. 60-67, October 2004

[3] M. Weigle, "Standard: DSRC/ WAVE/ IEEE 802.11p", *Old Dominian University*

[4] "Wireless LAN Medium Access Control (MAC) and Physical (PHY) Layer Specifications, Wireless Access in Vehicular Environment", *IEEE Computer Society*, July 2010

[5] B. Badic et.al., "MU-MIMO System Concepts and Implementation Aspects", *Intel Technology Journal*, vol. 18, issue 1, pp. 92-105, 2014

[6] S. Sur, "Practical MU-MIMO User Selection on 802.11ac Commodity Networks", Proceedings of the 22nd Annual *International Conference on Mobile Computing and Networking (MobiCom'16)*, pp. 122-134, October 2016

[7] C. Shepard, A. Javed, and L. Zhong, "Control Channel Design for Many-Antenna MU-MIMO", Proceedings of the 21st Annual *International Conference on Mobile Computing and Networking (MobiCom'15)*, pp. 578-591, September 2015

[8] C. Shepard et.al. "Argos: Practical Many-Antenna Base Stations", Proceedings of the 18th Annual *International Conference on Mobile Computing and Networking (MobiCom'12)*, pp. 53-64, August 2012

[9] Hironori Kusumoto et.al., "Performance Comparison between Single-User MIMO and Multi-User MIMO in Wireless Mesh Networks", Proceedings of 15th *International Symposium on Wireless Personal Multimedia Communications (WPMC)*, pp. 202-206, December 2012

[10] F. M. Maciel-Barboza, "User Selection Algorithms for MU-MIMO Systems with Coordinated Beamforming", *ETRI Journal*, vol. 38, num. 1, pp. 62-69, February 2016

[11] S. Nam, "A User Selection Algorithm Using Angle between Subspaces for Downlink MU-MIMO Systems", *IEEE Transactions On Communications*, vol. 62, no. 2, pp. 616-624, February 2014

[12] White paper, " 802.11ac In-Depth", *Aruba Networks Inc*, 2014

[13] White Paper, "802.11ac: The Fifth Generation of Wi-Fi" *CISCO*, March 2014

[14] White Paper, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016–2021", *CISCO* February 2017

[15] "Ericsson Mobility Report On The Pulse Of The Networked Society", *Ericsson*, June 2016

[16] "Automotive Industry Trends: IoT Connected Smart Cars & Vehicles," *Businessinsider.com*, December 2016

[17] Qi Wang, "Multi-User MIMO in IEEE 802.11ac Networks", *University of Delawar and CISCO Systems*, February 2012

[18] M. Bahadori, and K. Psounis. "On the Performance of Multiuser MIMO Mesh Networks." pp. 1-12, *University of Southern California* (2010), 2010

[19] K. Yamaguchi et.al, "Computer Simulation and Field Experiment for Downlink Multiuser MIMO in Mobile WiMAX System", *The Scientific World Journal* , vol. 2015, September 2015

[20] C. Lin X., et al. "A distributed multi-user MIMO MAC protocol for wireless local area networks." Proceedings of *Global Telecommunications Conference (IEEE GLOBECOM'08)*, December 2008

[21] J. Mirkovic, "A Mac Protocol With Multi-User MIMO

Support For Ad-Hoc WLANs", 18th Annual *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'07)*, September 2007

[22] M. Kountouris, "Transmission Capacity of Multiuser MIMO in Wireless Ad Hoc Networks", *SCEE Seminar Series*, February 2010

[23] White Paper, "802.11AC WAVE 2", *XIRRUS Inc.*

[24] J. Flordelis et.al., "Spatial Separation of Closely-Spaced Users in Measured Massive Multi-User MIMO Channels", Proceedings of *IEEE International Conference on Communications (ICC'15)*, June 2015

[25] E.G. Larsson et.al, "Massive MIMO for Next Generation Wireless Systems", *IEEE Communications Magazine*, vol. 52, issue 2, pp. 186-195, February 2014

[26] S. Heinrichs, "LTE: Multiple Antenna Techniques", *Seminar*, January 2010

[27] S. Moser et.al., "An Approach for the Integration of Smart Antennas in the Design and Simulation of Vehicular Ad-Hoc Networks", Proceedings of *International Conference on Future Generation Communication Technology (FGCT'12)*, December 2012

[28] White Paper, "Antenna Selection And Positioning Guide -The dos and don'ts of antenna selection and placement", *7-signal, Wi-Fi Performance Company*

[29] "Antenna designs for MIMO systems", *University of Queens Maryland*, 2004

[30] S. Kaul et.al., "Effect of Antenna Placement and Diversity on Vehicular Network Communications", Proceedings of 4th Annual *IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Network (SECON'07)*, June 2007

[31] Project "Chase – the wirless future with Antenna Systems Excellence from CHALMERS", *Chalmers University of Technology, Sweden*

[32] B.D. Pell et.al., "Advancements in Automotive Antennas", *www.intechopen.com*

[33] White Paper, "Technical Analysis Baemforming vs. MIMO Antennas" *Radio Frequency Systems*, March 2014

[34] J. Gozalvez et.al., "Impact of the radio channel modelling on the performance of VANET communication protocols", *Spring Link Telecommunication Systems*, vol. 50, issue 3, pp. 149-167, July 2012

[35] Steffen Moser et.al., "MIMO-Enabling PHY Layer Enhancement for Vehicular Ad-Hoc Networks", Proceedings of *IEEE Wireless Communications and Networking Conference Workshops (WCNCW'15)*, March 2015

[36] A. Goldsmith, "Capacity Limits of MIMO Channels", *IEEE Journal of Selected Areas in Communications*, vol. 21, no. 5, pp. 684-702, June 2003

[37] T. Eng et.al., "Comparison of diversity combining techniques for Rayleigh-fading channels", *IEEE Transactions on Communications*, vol. 44, iss. 9, pp. 1117-1129, September 1996

[38] P. Liu, "Multi-user MIMO Linear Precoding Schemes in OFDM Systems", 3rd *IEEE International Conference on Computer Science and Information Technology (ICCSIT'10)*, July 2010

[39] F. Kaltenberger, "Capacity Of Linear Multi-User Mimo Precoding Schemes With Measured Channel Data", 9th *IEEE Workshop on Advances in Signal Processing in Wireless Communication (SPAWC'08*), July 2008

[40] R. Pizzio et.al., "Generalized Spatial Modulation for Downlink Multiuser MIMO Systems with Multicast", IEEE 27th Annual *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'16)*, September 2016

[41] D. Gesbert et.al., "Shifting the MIMO Paradigm", *IEEE Signal Processing Magazine*, vol. 24, no.5, pp. 36-46, September 2007

[42] H.Q. Ngo et.al., "Energy and Spectral Efficiency of Very Large Multiuser MIMO Systems", *IEEE Transactions On Communications*, vol. 61, no. 4, pp. 1436-1449, April 2013

[43] M.Raja, P. Muthuchidambaranathan, "Joint Precoding and Decoding in MU-MIMO Downlink Systems with Perfect Channel State Information (CSI)", Proceedings in *Science direct* -2nd *International Conference on Communication, Computing and Security (ICCCS'12)*, pp.708-715, 2012

[44] N. Ravindran, N. Jindal, "Multi-User Diversity vs. Accurate Channel State Information in MIMO Downlink Channels", *IEEE Transactions on Wireless Communications*, volume: 11, issue: 9, pp. 3037-3046, September 2012

[45] T.E. Bogale et.al., "Pilot optimization and channel estimation for multiuser massive MIMO systems", Proceeding in IEEEXplore of 48th *Annual Conference on Information Sciences and Systems (CISS'14)* March 2014

[46] N. Anand et.al., "Mode and User Selection for Multi-User MIMO WLANs without CSI", Proceeding in IEEEXplore of *IEEE Conference on Computer Communications (INFOCOM'15),* August 2015

[47] A. Thiel et.al., "In-Situ Vehicular Antenna Integration and Design Aspects for Vehicle-to-Vehicle Communications", Proceeding in IEEEXplore of The *Fourth European Conference on Antennas and*

*Propagation (EuCAP'10)*, July 2010

[48] Patent, " Method of maximizing MIMO throughput by placing antennas in a vehicle", US 9571172 B2; *https://www.google.com/patents/US9571172*

[49] H. Boeglen et.al., "A survey of V2V channel modeling for VANET simulations", Proceedings in IEEEXplore of Eighth *International Conference on Wireless On-Demand Network Systems and Services (WONS'11)*, February 2011

[50] K.W. Yip, Tung-Sang Ng, "A Simulation Model for Nakagami-m Fading Channels, m<1", *IEEE Transactions On Communications*, vol. 48, no. 2, pp. 214-221, February 2000

[51] H.Q Ngo, Erik G. Larsson, "EVD-based Channel Estimations for Multicell Multiuser MIMO with Very Large Antenna Arrays", Proceeding in IEEEXplore of *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP'12)*, August 2012