



MIMO and Transmit Diversity for SC-FDMA

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- Benefits of using MIMO and transmit diversity for uplink transmission
- General description of MIMO/transmit diversity for SC-FDMA
- Transmit diversity techniques
- MIMO techniques
- MIMO receivers
- MIMO performance
- SC-FDMA vs. OFDMA MIMO comparisons



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Benefits of using MIMO for uplink transmission

- Improved spectrum efficiency for the uplink
- Take maximum advantage of a multiple antenna solution for the terminal
- Improved bit rate and robustness at the cell edge
- Reduced inter-cell and intra-cell interference due to beamforming
- Improvement in system capacity even when considering additional feedback signaling overhead
- Reduced average transmit power requirements at the terminal by operating at a lower received SNR.
- Use of transmit diversity for control information in the uplink © 2009 InterDigital, Inc. All rights reserved **InterDigital**[®]



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Single-codeword MIMO beamformer block diagram [1]

Reverse Link for Transmitter Beamforming



- Single codeword requires only one HARQ process and less signaling overhead
- Channel state info, fed back from base station, based on channel sounding from terminal
- Spatial transformer can implement beamforming, precoding or transmit diversity
- Pilots are shown beamformed/precoded by time/frequency multiplexing with data

Dual-codeword MIMO beamformer block diagram [1]



- Dual codewords shown requires two HARQ processes
 - Can use simple CRC-based SIC receiver to improve performance
- Precoder can implement spatial multiplexing beamforming or codebook precoding
- Codebook index, fed back from base station, based on channel sounding from terminal
- Pilots, shown not precoded, can be used for both channel estimation and channel sounding to select precoder



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Transmit diversity techniques

- Transmit antenna selection/switching (TAS) [18]
- Precoding vector switching (PVS)
- Space-time block code (STBC) [19]
- Space-frequency block code (SFBC) [2]
- Frequency switch transmit diversity (FSTD) [2]
- Cyclic-delay diversity (CDD) [2]





Summary of uplink 2-TxD schemes

Scheme	Pros	Cons
Slot-based TAS/PVS	Low PAPRTransparent to the receiver	 Low diversity gain
CDD	 Preserves single-carrier (SC) property Requires one set of precoded pilots 	Poor performance in correlated channelsNo uncoded diversity
STBC	Preserves SC propertyUncoded diversity	Needs even number of symbolsRequires two sets of precoded pilots
SFBC	 Uncoded diversity 	Breaks SC propertyRequires two sets of precoded pilots
FSTD	 Preserves SC property (with two DFTs) 	No uncoded diversityRequires two sets of precoded pilots

Refs [3], [4]





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- Spatial multiplexing
- Eigenbeamforming
- Codebook precoding





- Separate streams, either single or multiple codewords, are sent on separate antennas
 - No precoder feedback overhead
 - Each antenna can be rate controlled
 - Selective per-antenna rate control (S-PARC) [17]





• For eigenbeamforming [20] the channel matrix is decomposed using a single-value decomposition (SVD) or equivalent operation as

$$H = UDV^{H}$$

 The 2-D transform for spatial multiplexing, beamforming, etc. can be expressed as

$$x = Ts$$

where the matrix T is a generalized transform matrix.

- In the case when transmit eigen-beamforming is used, the transform matrix T is chosen to be a beamforming matrix V which is obtained from the SVD operation above, i.e., T = V.
- Requires feedback of either channel matrix *H* or beamformer matrix *T*



Codebook precoding

- The precoder takes as input a block of vectors *x(i)* from the layer mapping and generates a block of vectors *y(i)* to be mapped onto resources on each of the antenna ports, where *y^(p)(i)* represents the signal for antenna port *p*.
- Precoding for spatial multiplexing is defined by

$$\begin{bmatrix} y^{(0)}(i) \\ \vdots \\ y^{(P-1)}(i) \end{bmatrix} = W(i) \begin{bmatrix} x^{(0)}(i) \\ \vdots \\ x^{(\nu-1)}(i) \end{bmatrix}$$

- The values of the precoding matrix *W(i)* are selected among the precoder elements in the codebook configured in the BS and the terminal.
- The codebook index is fed back to the terminal



LTE downlink codebook for 2 antenna ports [5]

Downlink codebooks may be used for uplink (TBD)

Codebook	Number of layers v									
IIIdex	1	2								
0	$\frac{1}{\sqrt{2}} \begin{bmatrix} 1\\1 \end{bmatrix}$	$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$								
1	$\frac{1}{\sqrt{2}} \begin{bmatrix} 1\\ -1 \end{bmatrix}$	$\frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$								
2	$\frac{1}{\sqrt{2}} \begin{bmatrix} 1\\ j \end{bmatrix}$	$\frac{1}{2} \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix}$								
3	$\frac{1}{\sqrt{2}} \begin{bmatrix} 1\\ -j \end{bmatrix}$	-								

- Precoding matrices/vectors have constant modulus property
- Number of layers depends on rank of channel



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- Linear Minimum Mean-Square Error (LMMSE)
- LMMSE-Successive Interference Canceller (SIC)
- Turbo-SIC [12]
- Maximum Likelihood Detector (MLD)
 - List sphere decoder [13]
 - QRD-ML [14]
 - Note that MLD is too complex to be used for SC-FDMA but can be used for OFDMA [7]



LMMSE receiver for dual codewords

MIMO detection using an LMMSE receiver can be expressed as

$$R = R_{ss} \widetilde{H}^{H} (\widetilde{H} R_{ss} \widetilde{H}^{H} + R_{vv})^{-1}$$

where R is the receive processing matrix, R_{ss} and R_{yy} are the signal and interference correlation matrices and \tilde{H} is the effective channel matrix which includes the effect of the precoding matrix on the estimated channel response.





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SC-FDMA MIMO performance

- Comparison with SIMO and TAS [21]
- Comparison with transmit diversity [8]





Simulation parameters

Carrier frequency	2.0 GHz
Symbol rate	4.096 million symbols/sec
Transmission bandwidth	5 MHz
TTI length	0.5 ms (2048 symbols)
Number of data blocks per TTI	6
Number of data symbols per TTI	1536
FFT block size	256
Cyclic Prefix (CP) length	7.8125 µsec (32 samples)
Channel model	Typical Urban (TU6)
Antenna configurations	1x2 (SIMO), 1x2 (TAS), 2 x 2 (MIMO)
Fading correlation between transmit/receive	$\rho = 0$
antennas	
Moving speed	3 km/h
Data modulation	QPSK and 16QAM
Channel coding	Turbo code with $R = 1/2$, $1/3$ and
	soft-decision decoding
Equalizer	LMMSE
Feedback error	None
Channel Estimation	Perfect channel estimation



Comparison of MIMO with SIMO and TAS

- The figure below compares throughputs for TxBF without AMC [21] compared with a single transmit antenna or transmit antenna switching with AMC [18]
 - At 5 Mbps TxBF using coding rate 1/3 exhibits about 4.5 dB advantage over TAS and about 5 dB over a SIMO
 - At 8 Mbps TxBF using a coding rate of ½ exhibits about 4 dB advantage over TAS and about 5 dB over SIMO.







Comparison of TxBF with AMC vs. transmit diversity

TxBF achieves much higher throughput, 9.2 Mbps, than SFBC 1/2 and 1/3 which achieve maximum data rate 6.1 and 4.1 Mbps [8]

Throughput	TxBF vs SFBC (16QAM, ½)	TxBF vs SFBC (16QAM, 1/3)
1 Mbps	5.5	4.2
2 Mbps	4.5	3.6
3 Mbps	2.9	1.4
4 Mbps	1.9	0.9

gain (dB) TxBF to SFBC vs. throughput





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- Multiple access schemes:
 - SC-FDMA: As in LTE, contiguous RBs are allocated for each UE.
 - Clustered DFT-Spread-FDMA (2,3,4,8 equal sized clusters): DFT precoding output is mapped to multiple clustered RBs [11].
 - OFDMA: As in LTE DL, per RB (or sub-band) based frequency dependent scheduling is considered.
- MIMO techniques:
 - Assuming 2 transmit antennas at the UE, we consider Rank-1 and rank-2 precoding with the E-UTRA downlink precoding codebook [5].
 - In SC-FDMA, wideband precoding is used such that a selected precoding vector/matrix is used for all the allocated RBs. In clustered DFT-S-FDMA, one precoding matrix/vector is used per cluster, while in OFDMA two options are considered, precoding per RB and per 3 RB [10].





Clustered DFT-S-OFDMA with chunk specific filter

- Clustered transmission in the frequency domain is realized using non-contiguous sub-carrier mapping [11]
 - Unlike in SC-FDMA, the DFT precoded data is mapped to multiple subcarrier clusters each having contiguous sub-carrier mapping in frequency





System simulation assumptions for uplink throughput

Parameter	Assumption
Transmission bandwidth	20 MHz
Total number of RBs allocated	24
Subband (cluster) size for DFT-S-FDMA	24, 12, 8, 6, 3 RBs
Subband size for OFDMA	1, 3 RBs
MCS	As per [15]
Antenna configurations	2 x 2
Multiple access (MA) scheme	SC-FDMA, Clustered DFT-S-FDMA, OFDMA
MIMO configuration	LTE downlink precoding: Rank-1 and 2
Channel type	SCM, PA, VA
Resource allocation	Best M clusters from partition system BW
Receiver	LMMSE





Throughput performance with non-power limited geometry [10]

Rank-1 MIMO (SCM channel)

Rank-2 MIMO (VA channel)



- OFMDA outperforms Clustered DFT-S-OFDMA and SC-FDMA, due to its inherent advantage [16].
- The performance of Clustered DFT-S-OFDMA improves as the number of clusters increases, for a given total number of RBs (equivalently, the cluster size gets smaller). This is due to more frequency-scheduling flexibility.



Throughput gain relative to SC-FDMA, using Rank-1 precoding under various channels

Throughput gain relative to SC-FDMA, using Rank-2 precoding under various channels

		2x2 SCM			2x2 PA			2x2 VA				2x2 SCM			2x2 PA			2x2 VA		
MA	Es/No (dB)	-2	6	14	-2	6	14	-2	6	14	⁰ -2	-2	6	14	-2	6	14	-2	6	14
OFDMA	$(\mathbf{u}\mathbf{z})$	-4%	5%	8%	-36%	-15%	-11%	-4%	-3%	-2%	B 6%	6%	17%	22%	-13%	-13%	-4.4%	3.3%	14%	24%
		170	0,0	070	0070	10 / 0	11/0	170	070	-/•	3s 3%	3%	12%	15%	-13%	-13%	-4.5%	3.0%	10%	21%
OFDMA	(3 KB s)	-11%	-1%	2%	-36%	-16%	-11%	-6%	-5%	-3%										
Clustered	I DFT:	11%	11%	9%	3%	2%	1%	18%	9%	9%	9% rs	9%	17%	18%	4.9%	4.9%	5.4%	6.9%	20%	25%
Max. 8 cl	usters																			
Clustered	1 DFT:	=0/	=0/	(0/	20/	20/	10/	100/	0.07	0.07	5%	5%	13%	12%	4.9%	4.9%	5.3%	6.1%	18%	22%
Max. 4 cl	usters	7%	7%	6%	3%	2%	1%	18%	9%	9%	rs									
Clustered	DFT:	(0)	=0/	=0/	20/		10/	1.40/	00/		4%	4%	9%	9%	4.9%	4.7%	5.0%	4.5%	15%	17%
Max. 3 cl	usters	0%	5%	5%	3%	2%	1%	14%	8%	7%	rs	.,.				,.				
Clustered	1 DFT:	20/	40/	40/	20/	20/	10/	00/	40/	40/	20	20/	60/	<u>(</u> 0/	4 40/	2.00/	4 20/	1.00/	Q 10/	0.70/
Max. 2 cl	usters	5%	4%	4%	2%	2%	1%	δ%	4%	4%	rs 3%	370	0%	0%	4.4%	3.8%	4.2%	1.9%	ð . 4%	9./%

- In Rank-1 precoding MIMO, OFDMA performs worse than other MA schemes in most of the channel types/conditions under consideration.
- For Rank-2 MIMO, OFDMA performs slightly better than other MA schemes in SCM and VA channels but performs much worse in the PA channel which is less frequency selective.
- In both Rank-1 and Rank-2 MIMO options, Clustered DFT-S-OFDMA can provide better performance than SC-FDMA

Conclusions on UL transmission schemes for LTE-A [10]

- In non-power limited geometry OFMDA outperforms Clustered DFT-S-OFDMA and SC-FDMA due to its inherent performance advantage
 - Greatest gains are in more frequency-selective channels.
- In power limited geometry where the power is backed off by the CM increase, OFDMA performs worse than other MA schemes in many of the considered channel types/conditions.
 - The inherent performance advantage of OFDMA cannot make up for the SNR loss due to backoff at cell edges.
- Clustered DFT-S-OFDMA provides better performance than SC-FDMA, even when the UE maximum power must be backed off by the CM increase
 - The benefit is a function of the maximum number of clusters and the frequency selectivity of the channel.





SC-FDMA vs. OFDMA MIMO comparisons [12]



- With 2x4 the performance of SC-FDMA with Turbo SIC is equal to that of OFDMA
- MLD outperforms SIC only in the highest MCS: 64QAM 8/9
- With 2x2 OFDMA performs a bit better at higher SNR

•However, the required SNR is extremely high making this scenario impractical



- Use DFT precoding for Uplink Shared Channel (PUSCH) transmission, both in MIMO and non-MIMO modes
 - SC-FDMA (contiguous subcarriers)
 - Clustered DFT-Spread-FDMA
- For multiple component carriers use noncontiguous data transmission with a single DFT per component carrier





Concluding remarks

- SC-FDMA used as uplink air interface for 3GPP LTE Rel 8
 - Transmit Antenna Selection is the only transmit diversity scheme supported
 - Uplink MIMO, although shown to offer higher throughput, was not included in Rel 8 due to lack of time
- SC-FDMA continues as uplink air interface for 3GPP LTE-Advanced
 - Clustered DFT-Spread-FDMA
 - MIMO will be incorporated (2x2 and 4x4)
 - Multiple transmitter diversity will be added



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 - Robert Olesen
 - Nirav Shah
 - Sung-Hyuk Shin
 - Erdem Bala
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