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Source: **Motorola**
Title: **EUTRA Downlink MIMO Requirements and Design**
Agenda Item: **10.5.2**
Document for: **Discussion**

1. Introduction

At the RAN1 Ad Hoc on LTE in Sophia-Antipolis, a baseline downlink OFDM numerology [1] was agreed upon, making it possible to efficiently proceed with the detailed downlink design (including pilot designs, control channels, MIMO schemes, etc.). In this contribution MIMO requirements and recommendations on the downlink are given.

For the control channel it is recommended to perform **cyclic shift diversity** or use a Space-Time Block Code (STBC). The reason for using a transmit diversity technique on the control channel is to improve its range and thus help improve the range imbalance between the broadcast control channel and the beamformed data. For the data channel it is proposed to use closed-loop (with switching options between single and multi-stream) instead of open-loop techniques when possible. The reason for primarily considering closed-loop techniques is because of the higher potential gains over open-loop techniques. Two promising closed-loop options for both single and multiple data streams are:

1. The UE computes and feeds back the transmit weights using a **codebook** method [8].
2. The UE provides the Node B with channel estimates using Direct Channel FeedBack (**DCFB**)[7].

While multi-stream MIMO is a promising method to meet E-UTRA's peak data rate requirements, we should ensure that candidate algorithms' complexity and performance compare favorably against techniques already in use for UTRA. This is consistent with, for example, the use of 6 sectors as a reference case that has already been agreed in the UTRA MIMO work [10], as well as the general E-UTRA requirements.

2. Multiple Antennas on the DL Control Channel

The control channel typically contains information needed by multiple UEs and hence cannot be easily beamformed since beamforming is typically UE specific. However it is still desirable for the control information to be broadcast from all antennas at Node B in order to take advantage of the transmit power of all transmit antennas (i.e., Node B would not be required to have one antenna be able to transmit at a higher power than the others). Also the use of transmit diversity can help improve the range imbalance between the broadcast control channel and the beamformed data. To enable this requirement, there are two primary options for supporting multiple transmit antennas on the downlink control channel:

1. Cyclic Shift Diversity [6]
2. STBCs [4][9]

<u>Cyclic Shift Diversity on the Control Channel</u>

The details of cyclic shift transmit diversity are now given. Cyclic shift transmit diversity [6] is an adaptation of the idea of delay diversity to OFDM systems. As shown in Figure 1 for cyclic shift transmit diversity in OFDM, each antenna element in a transmit array sends a circularly shifted version of the same OFDM time-domain symbol (for symbol b), $x(n,b)$ ($0 \le n \le N-1$, where N is the system FFT

size). For example if there are M_b transmit antennas at Node B and if antenna one sends an unshifted version of the OFDM symbol, then antenna m transmits the same OFDM symbol, but circularly shifted by $(m\text{-}1)D$ time-domain samples. Note that each antenna adds a cyclic prefix <u>after</u> circularly shifting the OFDM symbol and thus the delay-spread protection offered by the cyclic prefix is unaffected by the cyclic shift transmit diversity. In mathematical notation, the transmitted time-domain signal from antenna m ,$z_m(n,b)$, is given as (note that $z_m(n,b)$ is only defined for $-L_{cp} \le n \le N\text{-}1$ where L_{cp} is the cyclic prefix length):

$$z_m(n,b) = x((n - D(m-1))_N, b) \tag{1}$$

where $(n)_N$ mean n modulus N (i.e., $(n\text{-}d)_N = n+N\text{-}d$ for $0 \le d \le N\text{-}1$).

The cyclic shift in (1) is equivalent to the following phase shift in the frequency domain ($Z_m(k,b)$ is the N-point FFT of $z_m(n,b)$):

$$Z_m(k,b) = X(k,b)e^{-j2\pi k(m-1)D/N} \tag{2}$$

Thus the received frequency-domain signal at the receiver can be expressed as:

$$Y(k,b) = \sum_{m=1}^{M_b} H_m(k,b)Z_m(k,b) + N(k,b) = X(k,b)\sum_{m=1}^{M_b} H_m(k,b)e^{-j2\pi k(m-1)D/N} + N(k,b) \tag{3}$$

where $H_m(k,b)$ is the frequency-domain channel between the mth transmit antenna at Node B and the UE. The received signal can be modelled similar to a single transmit antenna case as:

$$Y(k,b) = H_c(k,b)X(k,b) + N(k,b) \tag{4}$$

where $N(k,b)$ is additive noise and the cyclic shift diversity channel, $H_c(k,b)$, is given as:

$$H_c(k,b) = \sum_{m=1}^{M_b} H_m(k,b)e^{-j2\pi k(m-1)D/N} \tag{5}$$

In order to obtain full diversity the input data needs to be coded and interleaved across all subcarriers and D should be chosen so that it is at least as long as the expected maximum delay spread of the channel. In particular D can be chosen to be the FFT size divided by M_b.

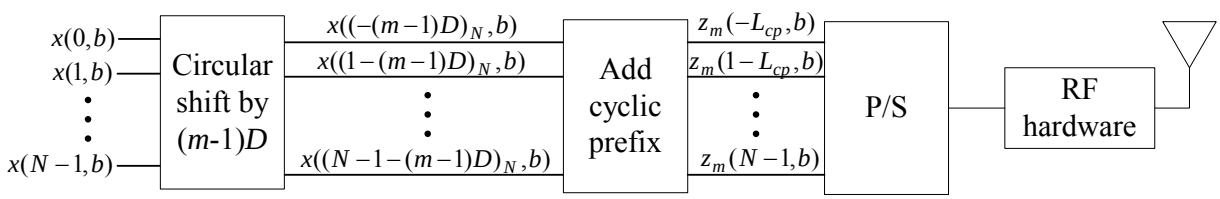

Figure 1. Block diagram of the cyclic shift diversity technique for transmit antenna m. Note that the cyclic prefix is added after the circular shift so the cyclic prefix still provides the same delay spread protection as with no cyclic shift diversity.

<u>STBC:</u>

STBCs (e.g., [4] and [9]) transmit data symbols from all antennas using multiple symbol times based on the number of transmit antennas. Thus for a given pilot symbol format the data symbols must be grouped either across time or across frequency or both. The ST coding of the data is complicated by the presence of symbols (e.g., pilot and/or control) not coded with the data, as well as differing numbers of OFDM symbols per frame for unicast and broadcast (e.g., 6 or 7). In general, techniques such as grouping (pairing) over time and frequency within the same subframe may be used, as well as skipping over an intermediate pilot or control symbol when grouping data symbols. Time-Division

Multiplexed (TDM) control (or localized, non-scattered control) also helps in developing the symbol pairing within the subframe.

Figure 2 shows a possible pairing for the two-element STBC when using two of the proposed pilot formats given in [2]. For space-time codes designed for more than two transmit antennas, similar groupings of symbols are possible. An example TDM control would occur on either the first or second symbol, either adjacent to the pilot or interlaced with the pilot (or both). In Figure 2 (right), for example, the frequency paired symbols on the first OFDM symbol could be allocated to control. Note that in Figure 2 (right), the second OFDM symbol with pilots (i.e., symbol seven) could be moved in to the third symbol from the end while maintaining the same pairing relationships.

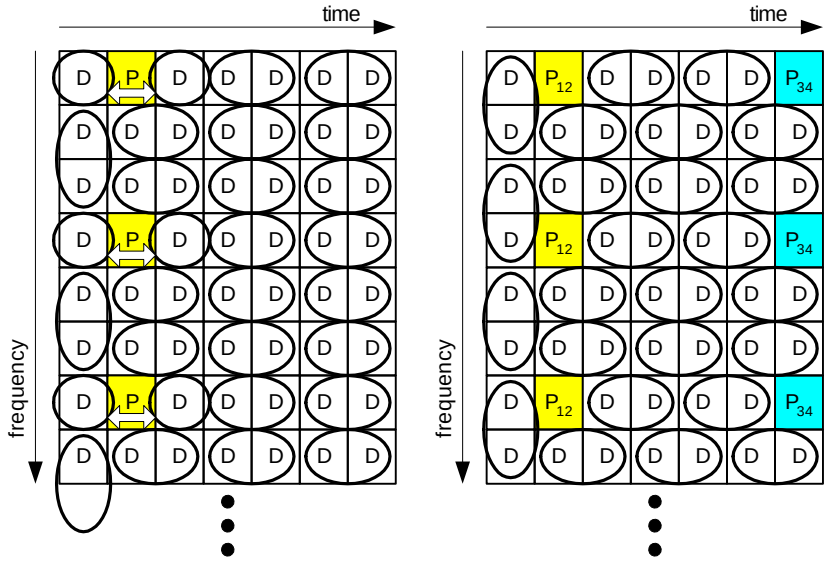

Figure 2. Examples of two-element ST encoding with two (left) and four (right) transmit antenna formats. The two symbols within an oval are coded together. For four antennas, if the control information is all contained on symbol one, then the control information is separately encoded from the data.

3. Performance

Results are given using the 5 MHz bandwidth version of EUTRA (i.e., 300 subcarriers are used for data, the DC subcarrier is skipped in the data allocation, and the FFT size is 512). Unless otherwise noted, the UE has two receive antennas. The 6-ray TU channel model was used for all simulations (with independent fading) with an UE speed of 3 kph. The 3GPP turbo code was used with an input codeword size of 900 bits for rate 1/4 QPSK and 1800 bits for rate 1/2 QPSK. The self-contained two antenna pilot format in [2] was used for the two-element STBC and the two-element version of cyclic shift diversity. The alternate four antenna pilot in [2] was used for the four-element version of cyclic shift diversity.

<u>Comparison of STBC to Cyclic-Shift Diversity</u>

For Cyclic-Shift Diversity (CSD) with two transmit antennas, the delay between each element, *D*, equals 256 samples and for CSD with four transmit antennas, *D*=128 samples. Figure 3 shows a comparison of the two-element STBC to CSD with both two and four transmit antennas for rate 1/4 QPSK and rate 1/2 QPSK. Results are shown both with and without Channel Estimation (CE) where

the channel estimate was the IFFT estimator with thresholding described in [2]. In both cases the CSD with four transmit antennas has the best performance due to the increase in transmit diversity over two transmit antennas. For the more powerful code, the two-element CSD approaches the performance of the two-element STBC (within 0.25 dB), but for the weaker code the performance gap between the two increases to about 0.5 dB.

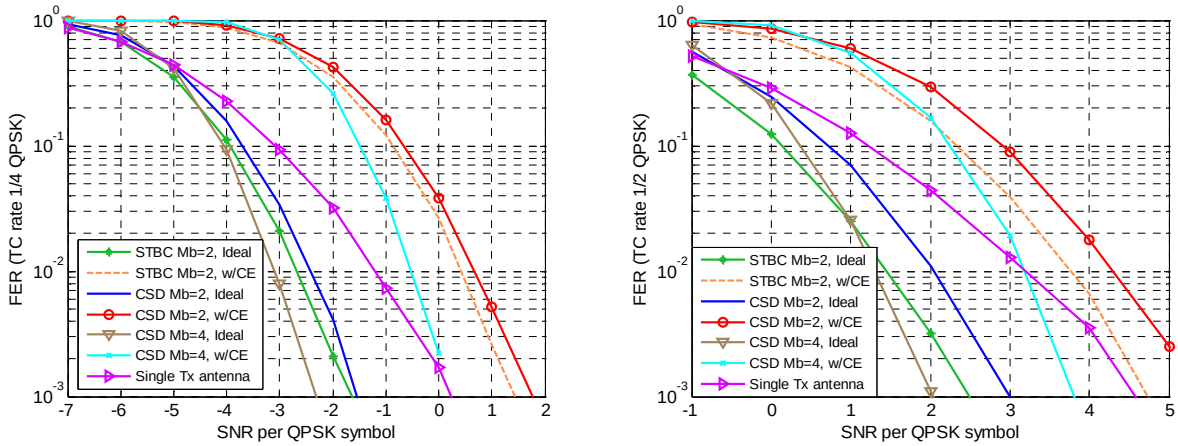

Figure 3. Comparison of the two element STBC to both two and four antenna cyclic shift diversity for rate 1/4 QPSK (left) and rate 1/2 QPSK (right). An IFFT channel estimator with thresholding as described in [2] is used for the Channel Estimation (CE) results (the single Tx antenna results are with ideal channel knowledge).

Observations on Cyclic Shift Diversity Versus STBCs

In light of the simulation results, some reasons for using cyclic shift diversity over STBCs are:

1. The control channel is coded and interleaved across frequency so the cyclic shift diversity scheme gets the transmit diversity through the coding/decoding process. Since the control channel will typically be using a low rate code, the coding should easily be able to pick up most of the transmit diversity.
2. Cyclic shift diversity enables simple symbol and data detection at the UE since the cyclic shift channel looks like a single transmit antenna channel. The lower complexity at the UE is especially true since advanced receiver techniques may be needed for detecting ST codes since there is potentially significant channel variations over the ST coding groups.
3. Rate-one orthogonal ST codes do not exist for complex constellations when M_b>2. Thus either quasi-orthogonal, non-rate-one ST codes, or real constellations must be used. However, either way, when M_b=4 at least four data symbol times or subcarriers must be used to transmit the code and thus the variations across time and frequency can be substantial. Thus cyclic shift diversity is a much simpler approach than ST codes especially when M_b>2.

4. Recommendations for Downlink 2 and 4 Antenna MIMO Design

Downlink MIMO techniques, both closed loop and open loop, should support the overall LTE requirements [3] and the goal of a competitive 3GPP long term evolution. The downlink MIMO techniques should support the following requirements.

MIMO requirements:

- Enable peak data rates of at least 100 Mbps for 20 MHz (5 bps/Hz)
- Increase the bit rate at the cell edge
- Enable solutions for up to four Node-B transmit antennas and 2 Rx antennas at UE

- Per [3]: Optimized for speeds up to 15kph, high performance 15 to 120kph, functional up to 350kph
- Improve the spectrum efficiency (3 to 4 times Release 6 HSDPA)
- Excellent performance in the Typical Urban (TU) channel specified in [1] (5 μsec excess delay)[1]
- Reasonable system and terminal complexity, cost, and power consumption
- System capacity gains must justify increase in feedback overhead for closed-loop MIMO methods
- Limit the number of options

Additional desired capabilities:

- Capability to support dedicated pilots
- Support for Tx-SDMA
- Closed-loop techniques preferred over Open loop techniques
- Switching between single and multi-stream based on channel quality
- Leverage the increased total power of multiple transmit antennas even for control channel transmissions

5. Channel/Transmit Weight Feedback Techniques to Support DL AAS Operation

Since there is a large number of multiple antenna array techniques, listing those techniques that appear most promising at an early stage may help build consensus about which methods merit in depth study. Two MIMO approaches[2] are therefore listed that in our view appear promising for both single and multiple stream MIMO: codebook feedback and Direct Channel FeedBack (DCFB).

Before presenting the details, it should be noted that there is typically antenna correlation present at Node B even in high mobility that can be exploited by closed-loop techniques to still provide a gain over open-loop techniques. Therefore closed-loop operation can be used at all UE speeds, but the manner in which the transmit weights are calculated may change. For example at low speeds the UE can provide Node B with codebook weights/channel estimates that track the frequency selectivity, and for high speeds the UE can provide Node B with a decimated (across frequency and/or time) version of the channel (which can be used to determine the long-term channel statistics) or a single codebook weight designed to the long-term statistics of the channel.

Codebook Methods

One option for obtaining the transmit beamform weights at Node B is for the UE to determine a single transmit weight for each data stream along with an optional power weighting on each stream. A different codebook weight is chosen by the UE for each data stream from a codebook of *B* bits where the codebook is designed using some reasonable criteria such as what was done in [8]. Then the UE has the option to choose a power weight for each data stream based on a criteria suited for the UE's receiver implementation. For example if the UE implements a successive cancellation reception

[1] Considering that the Typical Urban channel does not represent a worst-case channel that may be encountered in the field, and that closed-loop techniques are optimal when they track the frequency selectivity of the channel, the MIMO design should also work well for more severe channels (e.g., Bad Urban, Hilly Terrain) (10 μsec excess delay, 20 μsec excess delay, respectively).

[2] It should be noted that these solutions are primarily intended for FDD operation and that other more efficient methods of obtaining channel knowledge at Node B are available for TDD since the uplink and downlink RF channels are reciprocal. In TDD, uplink traffic can be used to compute the downlink transmit weights or the UE can sound the uplink on the subcarriers that Node B will transmit on the downlink.

method, then the UE might choose power weightings on each stream that makes the post-detector MSE equal on each data stream.

Note that either a single transmit weight per stream can be fed back for the entire downlink bandwidth, a single transmit weight per stream can be sent for the downlink assignment to the UE, or multiple transmit weights per stream can be sent back which vary across the UE's downlink assignment in order to track the frequency-selectivity of the channel.

Direct Channel FeedBack (DCFB) for Low to Moderate Speed

To obtain the full gains of beamforming techniques such as Maximal Ratio Transmission (MRT), Transmit SDMA (Tx-SDMA), and closed-loop MIMO, Node B must have channel knowledge from all transmit antennas to all received antennas at each subcarrier. DCFB [7] is a means of obtaining full broadband channel knowledge at Node B with low computational complexity at the UE and reasonable amounts of feedback. DCFB has much lower computational complexity at the UE than codebook methods [8] because while both methods need to perform downlink channel estimation, codebook methods require the UE to perform significant calculations to determine the transmit weights. In contrast, DCFB has relatively simple encoding of the channel and Node B performs the calculations to determine the transmit weights. Also, DCFB allows Node B to adaptively change its transmission strategy (e.g., by switching between maximal ratio transmission and Tx-SDMA).

In summary, DCFB operates as follows. First, the UE estimates the downlink channel from all transmit antennas at Node B to all of its receive antennas. Next the UE transmits these responses back to Node B using a DCFB waveform in place of the usual data symbols. Node B then equalizes the received feedback signal and recovers the channel information by using standard channel estimation techniques. As shown in [7], using signal processing techniques, multiple channel responses (from different transmit antennas) can be encoded together and sent back in a single feedback message (i.e., in a single IFDMA/DFT-SOFDM symbol on the uplink), making the feedback very bandwidth efficient. Additional gains in bandwidth efficiency are provided by allowing multiple UEs to transmit their feedback on the same time-frequency resource in a receive SDMA fashion.

It should be noted that the DCFB waveform given in [7] has a Peak to Average Power Ratio (PAPR) that is similar to that of OFDM. When sending this waveform in an OFDM system, the PAPR is no different than regular OFDM and does not pose a problem. However, assuming that the EUTRA uplink will employ a low PAPR communication method such as IFDMA or DFT-S-OFDM, the PAPR of DCFB should also be low. To keep the PAPR of DCFB low, it is proposed to clip the amplitude of the DCFB waveform to a level that gives it a PAPR similar to 16-QAM.

DCFB for High Speed

At high UE speeds (e.g., greater than 120 kph) the benefits of obtaining full channel knowledge with DCFB breaks down because the channel changes from the time it was measured and when it is used for transmit beamforming. However, the channel typically still has long-term statistics that do not change rapidly in time even for high UE speeds. In this case a reasonable beamforming method is to design weights matched to the long-term statistics of the channel (e.g., finding weights as the largest eigenvector of the spatial covariance matrix of the channel averaged over frequency and/or time). Since the beamforming weight is matched to the long-term statistics of the channel, only a single transmit weight needs to be used over all subcarriers in the UE's allocation. However, DCFB can still be used for this case. For high UE speeds, instead of trying to obtain the broadband channel at all subcarriers, a decimated version (across frequency) of the downlink channel is fed back using DCFB.

The decimated version of DCFB is designed to have just enough samples across frequency so that the long term statistics can be determined by Node B yet still keep the feedback overhead low.

DCFB Versus Codebook

The advantages of DCFB over codebook methods are that DCFB keeps the computational complexity low at the UE and DCFB allows for advanced beamforming techniques such as Transmit Spatial Division Multiple Access (Tx-SDMA). The advantage of codebook methods over DCFB is that codebooks can have lower feedback overhead especially when only a single transmit weight is used over a large bandwidth.

References

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[8] D. J. Love, and R. W. Heath Jr., "Grassmannian Beamforming for Multiple-Input Multiple-Output Wireless Systems," *IEEE Transactions on Information Theory*, Vol. 49, No. 10, October 2003.

[9] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-Time Block Codes from Orthogonal Designs," *IEEE Transactions on Information Theory*, Vol. 45, No. 5, July 1999.

[10] 3GPP TR 25.876, "Multiple-Input Multiple Output in UTRA", section A.2.1.9, revision 1.7.0, August, 2004

Appendix :Baseline Downlink OFDM Parameter Set

Parameter	Carrier Bandwidth (MHz)					
	20	15	10	5	2.5	1.25
frame duration (ms)	0.5	0.5	0.5	0.5	0.5	0.5
FFT size	2048	1536	1024	512	256	128
Sampling rate: M/N x 3.84 MHz	8/1	6/1	4/1	2/1	1/1	1/2
subcarriers (occupied)	1201	901	601	301	151	76
symbol duration (us)	71.42857	71.42857	71.42857	71.42857	71.42857	71.42857
useful (us)	66.67	66.67	66.67	66.67	66.67	66.67
guard (us)	4.76	4.76	4.76	4.76	4.76	4.76
CP Efficiency (%)	7.14%	7.14%	7.14%	7.14%	7.14%	7.14%
guard (samples)	146.2857	109.7143	73.14286	36.57143	18.28571	9.142857
subcarrier spacing (kHz)	15	15	15	15	15	15
occupied BW (MHz)	18.015	13.515	9.015	4.515	2.265	1.14
BW Efficiency (%)	90.08%	90.10%	90.15%	90.30%	90.60%	91.20%
subchannels	80	60	40	20	10	5
subcarriers/subchannel	15	15	15	15	15	15
subchannel BW (kHz)	225	225	225	225	225	225
symbols per frame	7	7	7	7	7	7
16QAM data rate (Mbps)	48.00	36.00	24.00	12.00	6.00	3.00