Fundamental simulated downlink capacity with multiple antennas

3GPP TSG RAN WG1 Meeting #42 R1-050920
London, UK,29 August – 2 September, 2005

Agenda item: 10.5.2
Source: Lucent Technologies
Document for: Discussion

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Introduction

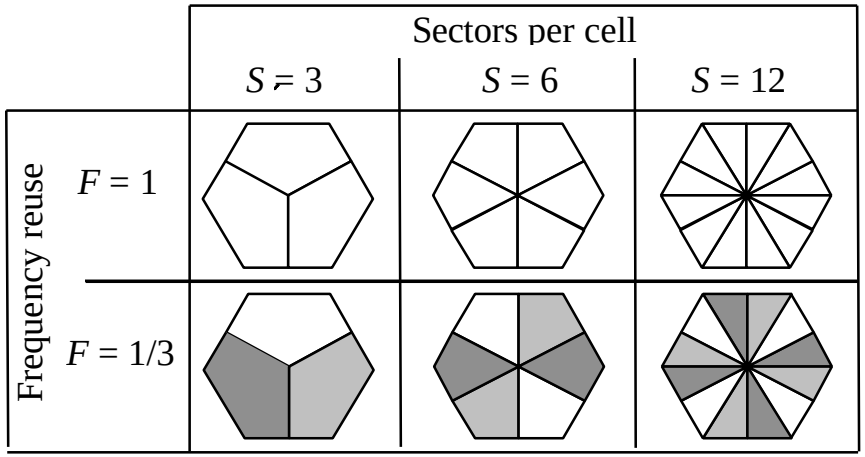
- Multiple antennas on the downlink can be used for
  - Spatial multiplexing (SM)
    - Transmit multiple simultaneous data streams using multiple antennas to a single user for achieving higher peak rate
    - Examples: PARC, DSTTD, RC-MPD, etc.
    - Typically requires multiple antennas at the terminal.
  - Space-division multiple access (SDMA)
    - Base in each cell transmits simultaneously to multiple users over separate spatial channels to increase system throughput.
    - Examples: Beamforming, sectorization
- Goal: to characterize and compare performance of SM and SDMA for scheduled packet data system.

Overview of methodology

- Fix the following parameters:
  - Frequency reuse plan (F = 1 or 1/3)
  - Number of sectors per cell (S): gives SDMA order
  - Number of transmit antennas per sector (M): gives SM order
  - Number of receive antennas per terminal (N)
- Generate CDF of SINR by dropping users randomly in space into the system.
- Generate CDF of achievable rates by mapping SINR to rate with a simple formula based on the Shannon bound.
  - Assume transmission to a single user at a time in each sector.
- Extract peak rate and median cell throughput metrics from CDF of rates.
- This methodology is very general and the qualitative results are widely applicable, especially for interference-limited systems.

Generating CDF of SINR

- Fix the sectorization and frequency reuse



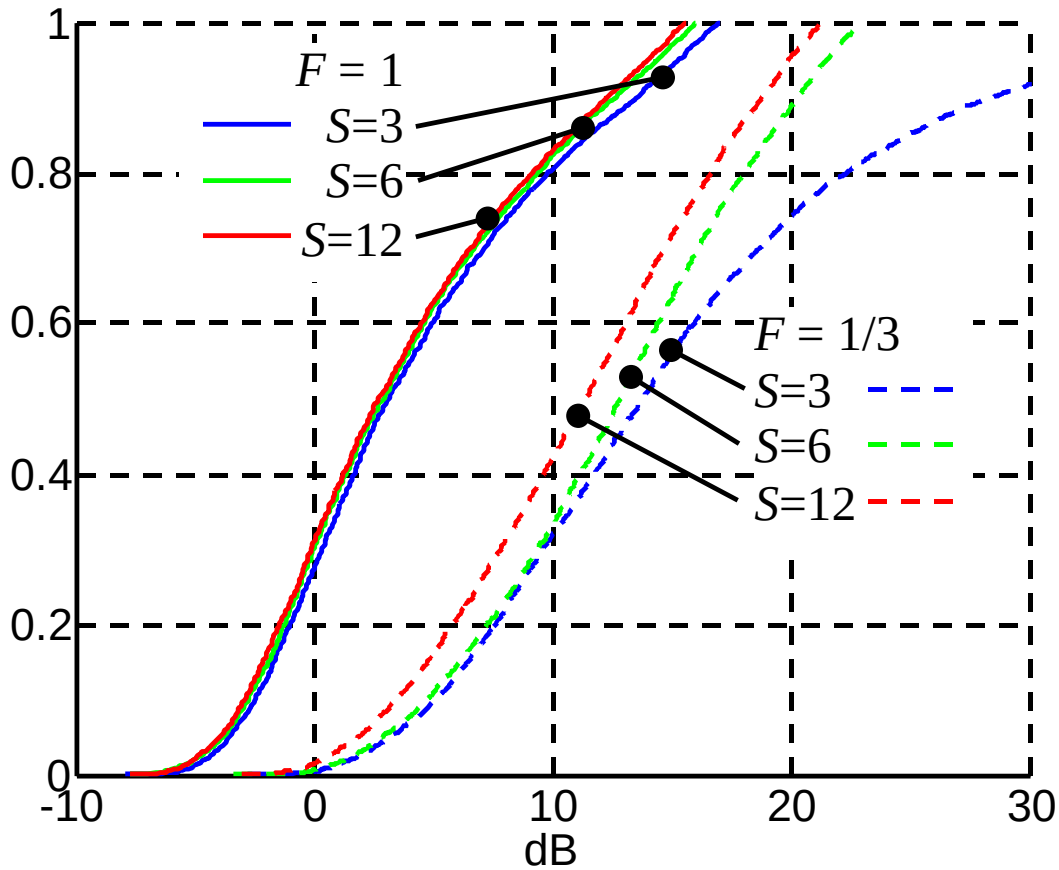
- To generate a single SINR realization
  - Drop user in the center cell of 19-cell system.
  - Determine the sector with the strongest signal (based on shadowing, pathloss, antenna patterns, etc.)
    - Assume all bases in each sector transmit with full power.
  - SINR is the strongest sector's power divided by the total interference plus noise power.
- Repeat to generate SINR CDF.

Overview of simulation assumptions

- Generating CDF of SINR
  - Antenna element patterns derived from SCM, scaled for various *S*.
  - Shadow fading with 8dB standard deviation (no spatial correlation).
  - Pathloss exponent: 4
  - 18dB reference SNR at cell vertex
- Determining achievable rates (discussed later)
  - Full power used for data, assumes full buffer model.
  - Ignore handoff and pilot overheads
  - Round robin scheduler
  - “Rayleigh” channel assumptions
    - Spatially uncorrelated, flat fading
    - Static (0 Hz doppler) for a given frame
    - Independent realizations from frame to frame
  - Perfect channel knowledge at transmitter and receiver.

CDF of SINR

- For F = 1, sectorization doesn't affect SINR much.
- For F = 1/3, reduced frequency reuse results in higher SINR.
- For F = 1/3, S = 3, no intracell interference from other sectors results in high peak SINR



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Consequences of CDF of SINR

- Transmission mode depends on SINR
  - For low SINR, transmit with single antenna and QPSK.
  - For higher SINR, switch to 16QAM.
  - For even higher SINR, switch to SM transmission.
- For $F = 1$, probability of high SINR is low, so probability of using SM is low.
  - The fraction of time in which SM is used would be small.
  - The marginal throughput gain of a system with SM versus a system with only single-antenna transmission is small.
  - Do not use SM in interference-limited ($F = 1$) systems.
- For $F = 1/3$, probability of high SINR is higher.
  - SM could be used efficiently in cases with low frequency reuse or isolated cells.

Link performance, Shannon capacity

- For a user with *N* antennas and a base with *M* transmit antennas, the baseband received signal is

$$\mathbf{y} = \sqrt{\Gamma}\mathbf{H}\mathbf{x} + \mathbf{n}$$

Received signal, Size: *N* x1	SINR Size: 1x1	MIMO channel, Size: *N*x*M*	Data signal, Size: *M*x1	Noise vector, Size: *N*x1

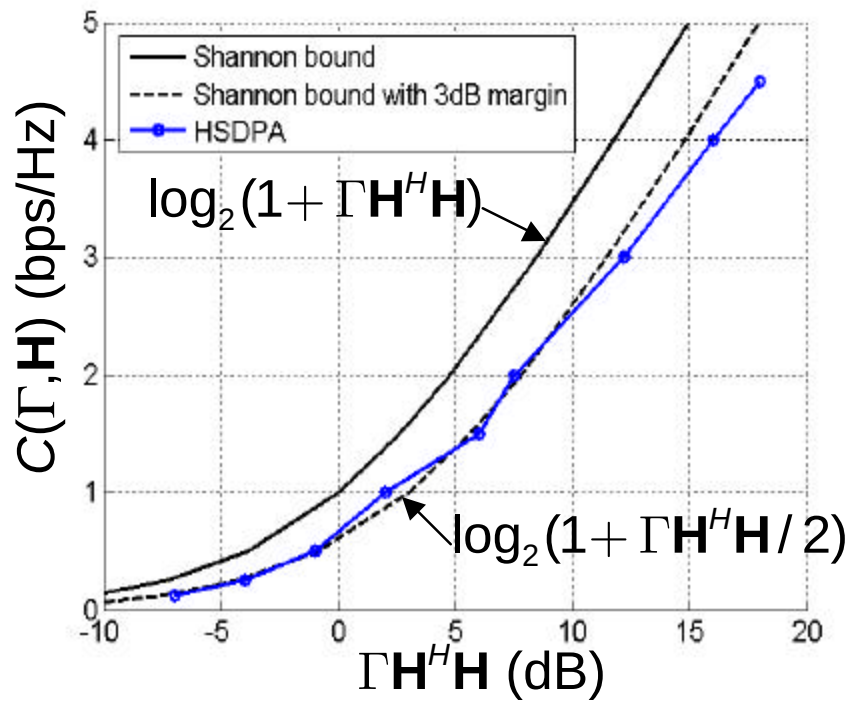
- Shannon bound ("closed-loop MIMO capacity"):

$$C(\Gamma,\mathbf{H}) = \max_{\mathbf{Q}:tr\mathbf{Q}\leq 1} \log_2 \left| \mathbf{I}_N + \Gamma\mathbf{H}\mathbf{Q}\mathbf{H}^H \right|$$

- For $M = 1$, $C(\Gamma,\mathbf{H}) = \log_2 \left[1 + \Gamma\mathbf{H}^H\mathbf{H}\right]$

Link performance, approximation

- For M = 1, link performance is well-approximated by Shannon bound with 3dB gap.
- Also, link spectral efficiency is typically limited to 6bps/Hz (64QAM, code rate 1).



- Apply these rules for general M > 1 case, so the approximate capacity for a user with SINR Γ and channel realization **H** is:

$$\tilde{C}(\Gamma,\mathbf{H}) = \min\left(\max_{\mathbf{Q}:tr(\mathbf{Q})\le 1} \log_2\left|\mathbf{I}_N + \frac{\Gamma}{2}\mathbf{H}\mathbf{Q}\mathbf{H}^H\right|, 6M\right)$$

Computing performance metrics

- For a given realization of the SINR, generate realization of MIMO channel (**H**) and determine the approximate capacity $\tilde{C}(\Gamma,\mathbf{H})$.
  - SM is valid even when $N < M$.
- Generate the CDF of $\tilde{C}(\Gamma,\mathbf{H})$
- Let $R(a) = \arg_R \left[\Pr\left(\tilde{C}(\Gamma,\mathbf{H}) \le R \right) = a \right]$
- Metrics:
  - Median throughput per cell = $SFR(0.5)$ bps/Hz/cell, where
    S is the number of sectors per cell, and
    F is the frequency reuse.
  - Peak rate per user = $R(0.9)$ bps/Hz

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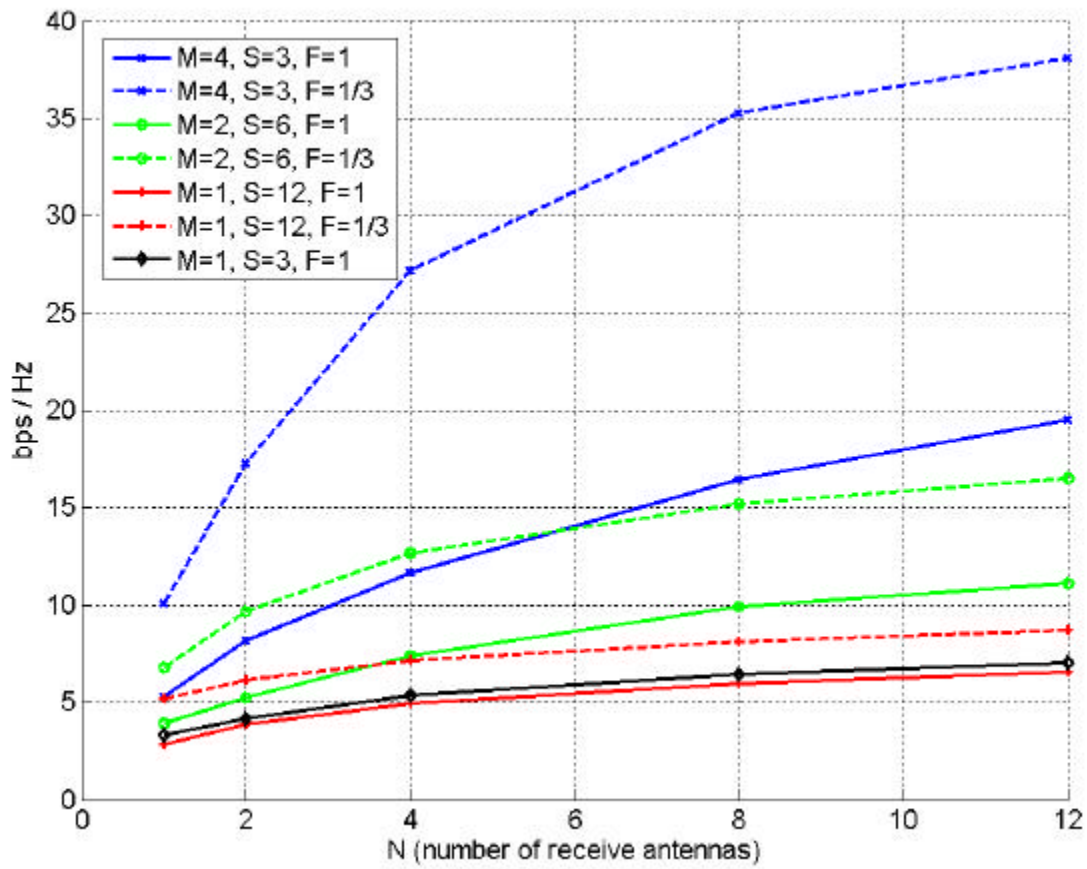
Architecture options

- Fix total number of antennas per cell to be 12 (except baseline).
- System architecture options
  - *S* = 3 sectors, 4 antennas per sector (SM with 4 antennas).
  - *S* = 6 sectors, 2 antennas per sector (SM with 2 antennas).
  - *S* = 12 sectors, 1 antenna per sector (no SM).
  - *S* = 3 sectors, 1 antenna per sector (baseline, no SM).

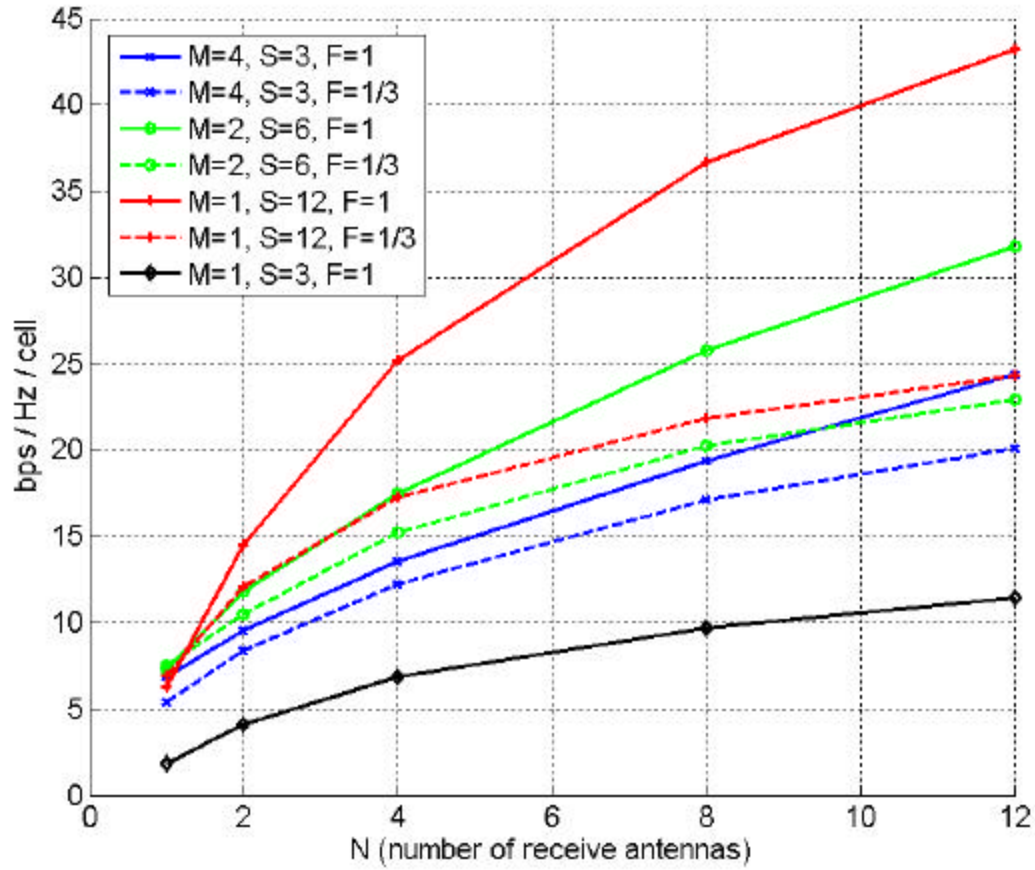
Peak rate per user: *R*(0.9)

- SM with *M* = 4 and *F* = 1/3 yields highest peak rate.
- Sectorization (SDMA) with *M* = 1, *S* = 12, *F* = 1 yields lowest peak rate.
- Sectorization reduces peak rate negligibly compared to baseline.
- Note that SM performance is optimistic because it is based on closed-loop capacity.



Median throughput per cell: *SFR*(0.5)

- SM has higher throughput than baseline
- But SDMA (M = 1, F = 1) yields highest throughput (for N > 1), despite optimistic SM curves.
- Hence the linear throughput increase due to SDMA always beats SM.
- SDMA (M=1, F=1, N=2) has higher throughput than SM (M=4, F=1,N=4)



Conclusions

- SM is effective for increasing peak rate.
  - However, it should be used only in cases of low intercell interference (e.g., isolated cells or low frequency reuse).
  - Otherwise in interference-limited systems, the probability of transmitting with more than one antenna is very low.
- SDMA is effective for increasing cell throughput.
  - To maximize cell throughput, cell should be divided into the most sectors possible using sectorization or beamforming. (Sector size must be larger than angle spread.)
  - For a given frequency reuse and number of antennas, SDMA provides higher cell throughput than SM.