Uplink Closed Loop Transmit Diversity for HSPA

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Abstract

The closed loop transmit diversity scheme is a promising technique to improve the uplink transmission performance in HSPA. This paper provides an introduction to the motivation and theoretical analysis of a closed loop transmit diversity (CLTD) beamforming scheme for the HSPA system. Details are also provided on the algorithm description, the user equipment and Node B transmitter/receiver implementation and the corresponding system performance.

Introduction

Uplink transmit diversity (ULTD) schemes employ more than one transmit antenna (usually two) at the UE to improve the uplink transmission performance, e.g., reduce the user equipment (UE) transmit power, or increase the UE coverage range, or increase the UE data rate, or the combination of the above (see [1],[2],[3] for academic research on transmit diversity). It can also help improve the overall system capacity. Based on the feedback requirements, ULTD schemes can be categorized into closed-loop (CL) and open-loop (OL) schemes. From the transmitter perspective, ULTD schemes can be classified as beamforming (BF) and antenna switching (AS) schemes.

In general, closed-loop (CL) transmit diversity (TD) schemes require the receiver to provide explicit feedback information about the spatial channel to assist the transmitter in choosing a transmission format over multiple transmit antennas. On the other hand, open-loop (OL) TD schemes do not. In the context of the WCDMA uplink, the term *OL TD schemes* includes the schemes without core standards change, i.e., without introducing new feedback channels.

There are two categories of CLTD schemes. In the CLTD beamforming scheme, the NodeB feeds back to the UE a precoding (or beamforming) vector to be used over multiple transmit antennas so that the signals received at the Node B are constructively added. This in turn maximizes the receiver signal to noise ratio (SNR) and achieves the beamforming effect. In the CLTD antenna switching scheme, the NodeB feeds back to the UE its choice on which transmit antenna the UE should use. This choice results in the largest channel gain between the UE transmit antenna and the NodeB receive antennas. Between the two schemes, CLTD BF can achieve a better tradeoff between how fast to track the channel vs. how often the scheme may disrupt the channel phase. In this paper, we focus on the CLTD BF scheme.

Several questions naturally arise about the CLTD beamforming algorithm. The first one is about CLTD beamforming's benefits to subscribers. Due to the transmit power gain from beamforming, it allows subscribers to enjoy an increase in uplink data rates, or an improved uplink range. The second question is about CLTD beamforming's benefits to operators. CLTD beamforming allows the operators to provide subscribers a better user experience with increased UL data rates throughout the deployment area, and cost-effective incremental infrastructure upgrade – CLTD beamforming schemes can be introduced in coverage-limited area, e.g., high-rise metro area, to extend the coverage and enhance the user experience. Furthermore, due to the reduction of interference to the other cells, there will be gain in the cell throughput as well. CLTD beamforming does not necessarily require a hardware upgrade to the network infrastructure. Although new devices are required, they can be introduced gradually into the subscriber base. The CLTD beamforming scheme considered here is backward compatible. Existing 3GPP R99, R5/6/7 devices will continue to work with a network that supports CLTD beamforming. Additionally, a CLTD beamforming device can switch to non-CLTD mode in an area that does not support CLTD beamforming. Moreover, the CLTD beamforming scheme is under the control of the network since the Node B makes the decision on which beamforming vector to use.

This paper is organized as follows. First, we will provide the motivation to study the closed loop beamforming transmit diversity. Then, we will analyze the theoretical gain of CLTD BF under some ideal assumptions. It will be followed by the description of a CLTD BF algorithm, including the transmit and receive algorithms for both UE and Node B. Finally, we will present the simulation results, on both the transmit power gain and throughput gain, and draw some conclusions.

Motivation of CLTD Beamforming

For a mobile user in the HSPA cellular system, the user experience is often limited by the UE's transmit power. In the case of a cell edge user, due to transmit power limitation, it has to transmit at a low date rate, or possibly not establish a call. The technique of transmit diversity is useful to improve these situations. Assume multiple transmit antennas are utilized in the UE. The UE transmitter can apply a weighting vector to the transmit antennas such that the signals from these antennas are coherently combined at the Node B receive antennas.

Consider a simple example. In the baseline case of non-transmit diversity, both the UE and the Node B have one antenna. Assume the channel between the UE and the Node B is static:

$$H = [1]$$

The receive signal to noise ratio (SNR) is

$$\text{SNR} = \frac{P}{N_0}$$

where P is the UE transmit power and N_0 is the noise power. Next, consider the case where beamforming transmit diversity is deployed at the UE. Assume the channel between the UE and the Node B is static:

$$H = [1 \quad e^{j\theta}]$$

where θ is the phase offset between two channel links. If the UE applies the following beamforming weight vector:

$$\begin{bmatrix} 1 & e^{-j\theta} \end{bmatrix} / \sqrt{2}$$

to achieve the same receive SNR, the UE transmitter only needs to use transmit power $P/2$. This 3 dB reduction in the UE transmit power (beamforming gain) will improve the link budget and the user experience. Furthermore, when the signals across different antennas experience independent fading, coherent signal combining results in a more stable composite channel with a smaller probability of deep fading. Thus beamforming can provide diversity gain.

The motivation of considering the closed loop beamforming scheme is that, via the Node B processing and feedback, the UE transmitter can apply a beamforming phase to achieve the aforementioned gains (possibly at the expense of more complexity and more downlink feedback power).
Since the UE forms the beam only toward the serving cell, the signals from the two UE transmit antennas are typically received at all other cells without constructive addition. Thus from the network level point of view, the amount of interference caused by this UE at other Node B receivers is reduced. This interference reduction will lead to network throughput improvement. On the other hand, since in CLTD beamforming, the UE is beamforming toward the serving cell, the performance gain in the soft handover state may not be as large as the non-soft handover state.

Gain Analysis of CLTD Beamforming

In this section, we provide a theoretical analysis of the transmit power gain achievable from beamforming under various channels. For the non-transmit diversity baseline, the UE has one transmit antenna. For the beamforming transmit diversity case, the UE has two transmit antennas. On the Node B side, we consider two cases: the first with one receive antenna and the second with two receive antennas. For simplicity, we assume perfect knowledge of channel state information at the Node B receiver, ideal feedback of the beamforming weight vector to the UE, and perfect uplink power control.

One Node B Receive Antenna

Although today's network deployments have two receive antennas at the Node B, for the sake of analysis, we consider the case of one receive antenna as well, which will show more significant gain in the fading channels than the case of two receive antennas. In this case, the uplink channel for the non-transmit diversity UE is a 1x1 channel:

$$H = [h_1],$$

and the uplink channel for the beamforming UE is a 2x1 channel:

$$H = [h_1 \quad h_2].$$

The transmit power gain of beamforming depends on the channel models. We will derive the gains for additive white Gaussian noise (AWGN) channel and single path Rayleigh fading channel respectively.

AWGN Channel

As shown in the section of motivation of CLTD beamforming, to achieve the same receive SNR at the Node B, the beamforming UE requires half of the transmit power of the non-transmit diversity UE. Therefore, the transmit power gain in this case is 3 dB.

Single Path Rayleigh Fading Channel

For the non-transmit diversity UE, its uplink channel $[h_1]$ has a complex Gaussian distribution with zero mean and variance 0.5 per dimension (real or imaginary part). Assume the required SNR for the uplink transmission is

$$\mathrm{SNR} = \frac{P}{N_0}$$

To achieve that, due to perfect power control, the instantaneous transmit power is

$$\frac{P}{|h_1|^2}$$

On average, the required transmit power for this baseline UE is

$$E\left[\frac{P}{|h_1|^2}\right] = \int_0^{\infty} \frac{P}{x} e^{-x} dx = \infty$$

On the other hand, for the beamforming UE, assume h_1 and h_2 are independent and identically distributed (i.i.d.) complex Gaussian random variables with zero mean and variance 0.5 per dimension. After the UE applies the following weight vector at its transmitter:

$$\frac{1}{\sqrt{|h_1|^2 + |h_2|^2}} \begin{bmatrix} |h_1| \\ |h_2| e^{j(\angle h_1 - \angle h_2)} \end{bmatrix}$$

the channel power gain seen by the beamforming UE is

$$|h_1|^2 + |h_2|^2.$$

To achieve the required $\mathrm{SNR} = \frac{P}{N_0}$ for the uplink transmission, due to perfect power control, the instantaneous transmit power is

$$\frac{P}{|h_1|^2 + |h_2|^2}$$

On average, the required transmit power for the beamforming UE is

$$E\left[\frac{P}{|h_1|^2 + |h_2|^2}\right] = \int_0^{\infty} \frac{P}{x} x e^{-x} dx = P$$

Therefore, the theoretical transmit power gain due to beamforming is infinity. However, in reality, since the power control is not perfect, and the maximum power limitation on the UE transmit power, the gain of beamforming is finite.

Two Receive Antennas

In this case, the uplink channel for the non-transmit diversity UE is a 1x2 channel:

$$H = \begin{bmatrix} h_{11} \\ h_{21} \end{bmatrix},$$

and the uplink channel for the beamforming UE is a 2x2 channel:

$$H = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}.$$

The transmit power gain of beamforming depends on the channel models. We will derive the gains for an AWGN channel and single path Rayleigh fading channel respectively.

AWGN Channel

In this case, the baseline UE sees the uplink channel

$$H = \begin{bmatrix} 1 \\ e^{j\theta} \end{bmatrix}$$

Assume the required SNR for the uplink transmission is

$$\text{SNR} = \frac{P}{N_0}$$

To achieve that, the transmit power is

$$\frac{P}{2}$$

On the other hand, for the beamforming UE, it sees the uplink channel

$$H = \begin{bmatrix} 1 & e^{j\theta} \\ e^{j\psi} & e^{j\theta+\psi} \end{bmatrix} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ e^{j\psi} & -e^{j\psi} \end{bmatrix} \cdot \begin{bmatrix} 2 & 0 \\ 0 & 0 \end{bmatrix} \cdot \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & e^{j\theta} \\ 1 & -e^{j\theta} \end{bmatrix}.$$

If the beamforming UE applies the following weight vector

$$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ e^{-j\theta} \end{bmatrix},$$

after pilot weighted combining at the Node B receiver, the channel power gain is 4. Thus the required transmit power is

$$\frac{P}{4}.$$

Therefore, the transmit power gain due to beamforming is 3 dB.

Single Path Rayleigh Fading Channel

For the non-transmit diversity UE, its uplink channel is

$$H = \begin{bmatrix} h_{11} \\ h_{21} \end{bmatrix}.$$

Assume the two entries h_{11} and h_{21} are i.i.d. complex Gaussian random variables with zero mean and variance 0.5 per dimension. To achieve the required $\text{SNR} = \frac{P}{N_0}$ for the uplink transmission, due to perfect power control, the instantaneous transmit power is

$$\frac{P}{|h_{11}|^2 + |h_{21}|^2}$$

On average, the required transmit power for the non-transmit diversity UE is

$$E\left[\frac{P}{|h_{11}|^2 + |h_{21}|^2}\right] = \int_0^\infty \frac{P}{x} x e^{-x} dx = P$$

For the beamforming case, the uplink channel is

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} = [\mathbf{u_1} \quad \mathbf{u_2}] \cdot \begin{bmatrix} s_1 & 0 \\ 0 & s_2 \end{bmatrix} \cdot [\mathbf{v_1} \quad \mathbf{v_2}]^{\dagger},$$

where the single value decomposition (SVD) is performed on the channel matrix. Assume the singular values are ordered, i.e. $s_1 \geq s_2$. Then the beamforming vector applied at the UE transmitter shall be $\mathbf{v_1}$, which has unit length. The channel power gain seen by the Node B receiver (after pilot weighted combining) is s_1^2, which has the following probability density function:

$$e^{-x}(x^2 - 2x + 2) - 2e^{-2x}, x \geq 0$$

To achieve the required $\text{SNR} = \frac{P}{N_0}$ for the uplink transmission, due to perfect power control, the instantaneous transmit power is

$$\frac{P}{s_1^2}$$

On average, the required transmit power for the beamforming UE is

$$E\left[\frac{P}{s_1^2}\right] = \int_0^\infty \frac{P}{x}\left[e^{-x}(x^2 - 2x + 2) - 2e^{-2x}\right]dx = 0.386P$$

Thus relative to the baseline, there is ideally a 4.1 dB gain through the use of beamforming.

Table 1: The Theoretical Transmit Power Gain for Several Channels

	2x1 AWGN	2x1 Single Path Rayleigh	2x2 AWGN	2x2 Single Path Rayleigh
Tx Power Gain (dB)	3	∞	3	4.1

Multi-path Channels

For uplink channels with multiple paths, the transmit power gain due to beamforming tends to be smaller than the single path channel. The reason is that there is no single beamforming weight vector that can be optimal for all the paths. Since it is difficult to obtain a closed form formula for the theoretical beamforming gain in the multipath channel, we will rely on simulations to estimate the gain.

Impact of Antenna Pattern

In the analysis of the theoretical transmit power gain, so far we have assumed omni-directional antennas without correlation and imbalance. In real field applications, transmit antennas used by the UE will have antenna patterns. Again, the transmit power gain after taking into account these antenna patterns will be obtained through simulation.

Algorithm Description of CLTD Beamforming in HSPA

In this section, we will describe a practical closed loop transmit diversity (CLTD) beamforming (BF) algorithm for HSPA system.

The closed loop beamforming algorithm consists of the following:

- The UE transmits 2 pilot channels on the uplink
- Estimate the 2x2 uplink channel at the Node B based on the pilot channels transmitted from the UE
- From the estimated uplink channel estimates, the Node B receiver determines the optimal phase and/or amplitude of the beamforming weight vector that maximizes the receive SNR.
- Feedback the beamforming information to the UE.
- After the UE receives the beamforming phase and/or amplitude, the UE will apply them for the uplink transmission.

The CLTD beamforming scheme is illustrated in Figure 1.

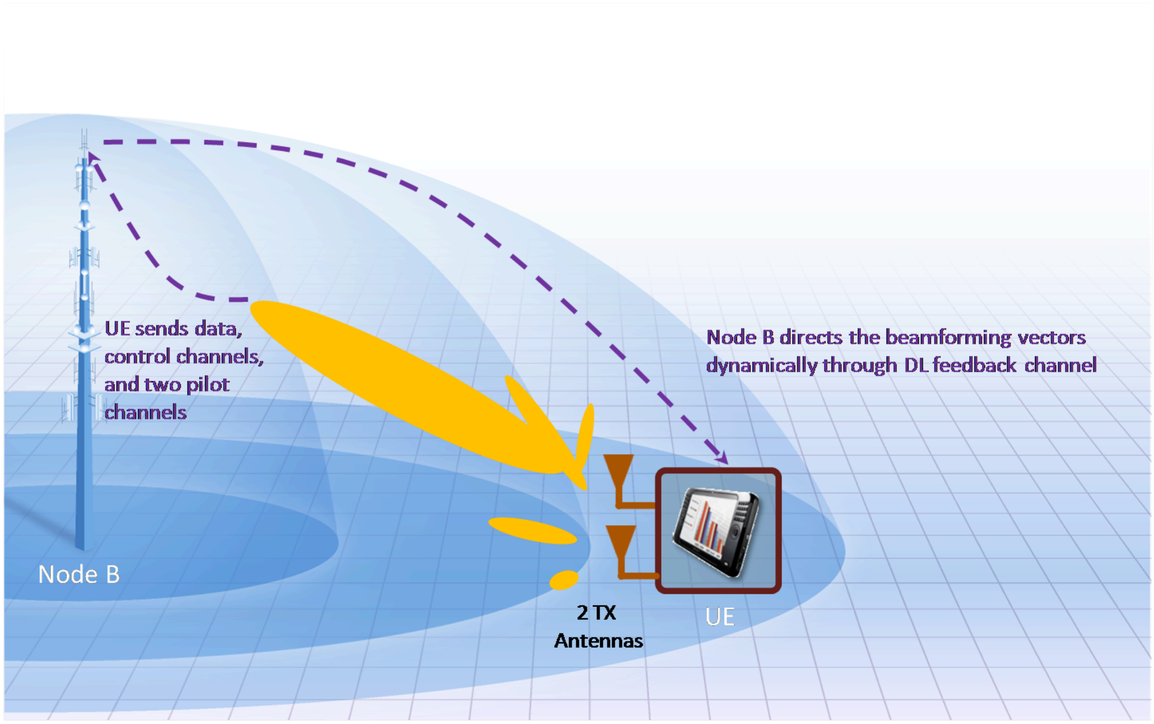

Figure 1: Illustration of the CLTD Beamforming Scheme

Next, we will describe the CLTD beamforming system in more details.

UE Transmitter

We have the following system view of the UE transmitter.

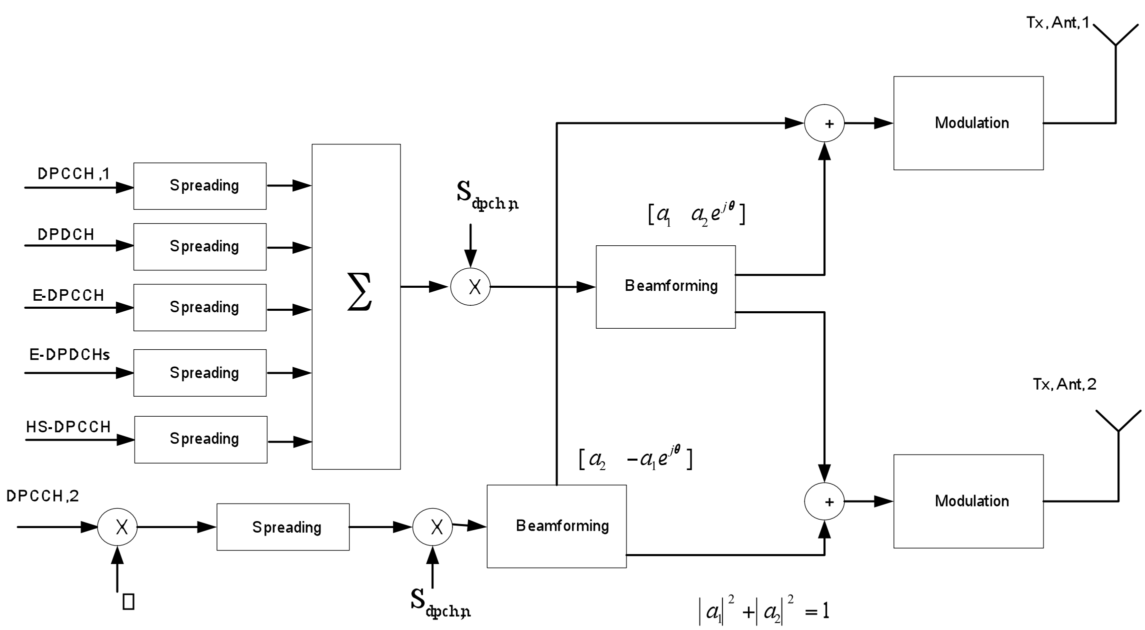

Figure 2: The CLTD Beamforming UE Transmitter: System View

The uplink system model for the CLTD beamforming scheme is

$$\mathbf{y} = \mathbf{H} \cdot \mathbf{B} \cdot \mathbf{d} + \mathbf{n} = \mathbf{H} \cdot [\mathbf{v_1} \quad \mathbf{v_2}] \cdot \begin{bmatrix} d + c + p_1 \\ p_2 \end{bmatrix} + \mathbf{n}$$

In this scheme, the EUL data and control channels, E-DPDCHs, E-DPCCH, HS-DPCCH, R99 data channel DPDCH, and the primary pilot channel DPCCH,1 are always transmitted on the stronger beamforming vector v_1 (or called virtual antenna), and the secondary pilot channel DPCCH,2 is transmitted on the weaker beamforming vector v_2. Mathematically, the dominant virtual antenna is represented by the following beamforming vector:

$$[a_1 \quad a_2 e^{j\theta}]$$

where $a_1^2 + a_2^2 = 1$ and the beamforming phase is denoted by θ. Usually, the beamforming phase θ is quantized into a finite set, such as {0, 90, 180, 270} degrees. Similarly, the amplitude variables $[a_1 \quad a_2]$ typically belong to a finite set.

The scaled secondary pilot channel is transmitted on the weaker virtual antenna:

$$[a_2 \quad -a_1 e^{j\theta}]$$

Obviously, this beamforming weight vector is orthogonal to the stronger virtual antenna.

Node B Receiver

Since all the data and control channels are running on the same beamforming vector as the primary pilot channel, in the receiver, all the functionalities related to finger processing, such as DCH searcher, finger assignment, time tracking loop, frequency tracking loop, etc, are running on the primary pilot channel P_1. The demodulation part works as if the UE is a non-transmit diversity UE, except for the additional channel estimator running on the secondary pilot channel to determine the beamforming weights. The Node B receiver estimates the composite channels from both the primary and secondary pilot, by inverting the beamforming weight matrix

$$\begin{bmatrix} a_1 & a_2 \\ a_2 e^{j\theta} & -a_1 e^{j\theta} \end{bmatrix}.$$

Then it estimates the physical channels $h_{r,t,k}, r = 1,2, t = 1,2, k = 1,\cdots,L$, where *r* is the receive antenna index, *t* is the transmit antenna index, and *k* is the finger index. After that, the Node B receiver can compute the new beamforming weight vector. We use a received power maximization based beamforming algorithm which is more general than the SVD algorithm [1] (equivalent in single path scenario), since there may be more than one path in the uplink channel. For a given set of quantized phase θ, e.g. {0, 90, 180, 270} degree, and/or amplitude quantized value a_1, we can compute the received power for each phase and/or amplitude combination, given current channel estimate $\hat{H}$. Then, the phase and/or the amplitude corresponding to maximum receive power is chosen as the optimal beamforming phase and/or amplitude.

$$\arg\max_{a_1,\theta} \sum_{l=1}^{L_1}\left[\left|a_1 h_{1,1,k} + \sqrt{1-a_1^{\,2}}\,e^{j\theta} h_{1,2,k}\right|^2\right] + \sum_{l=1}^{L_2}\left[\left|a_1 h_{2,1,k} + \sqrt{1-a_1^{\,2}}\,e^{j\theta} h_{2,2,k}\right|^2\right]$$

CLTD Beamforming Performance

Modeling of Antenna Patterns in System Simulations

In the CLTD beamforming performance study performed here, realistic antenna patterns were modeled via transmit antenna correlation matrices due to both handset and laptop antenna form factors. Figure 3 illustrates the test configuration used to obtain measurements from multiple antennas in a laptop while Figure 4 illustrates the basis under which the antenna pattern measurements that were made. In Figure 3, measurements from the antenna pair (2,3) were used to derive the correlation matrices that were used in the system simulation assumptions.

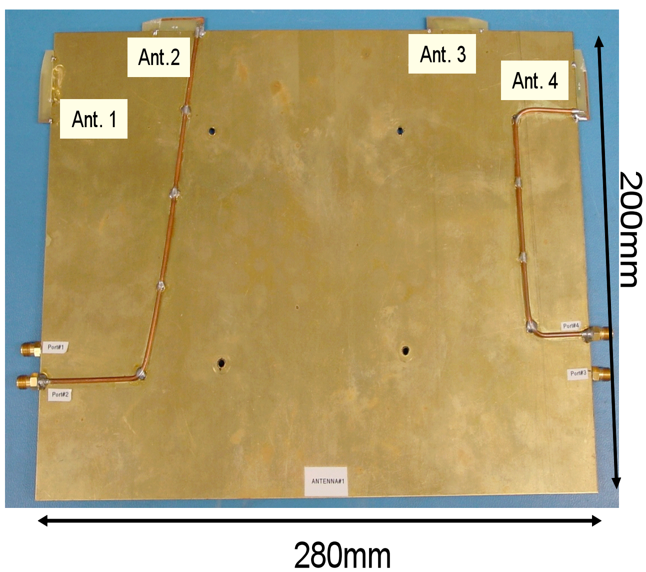

Figure 3: Test configuration to obtain measurements from multiple antennas in a Laptop

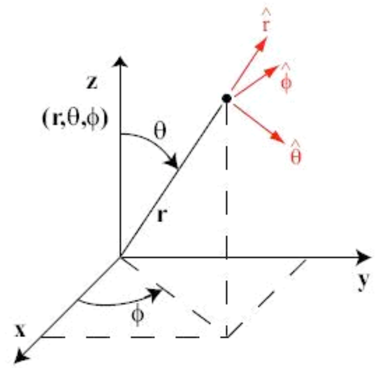

Figure 4: Measurement basis for the capture of the 3-D complex response of the antenna

The 3-D antenna radiation pattern was obtained via measurements in the far field. The objective was to find the far field antenna gain at an azimuthal angle of departure ϕ_0 which is in turn obtained based on the location of the UE with respect to the NodeB.

Given a particular Angle of Departure (AoD), the components of the antenna correlation matrix [$\rho_{ij}(\phi_0)$] at AoD ϕ_0 is given by

$$\rho_{ij}(\phi_0) = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} \left\{ E_\theta^i(\theta,\phi) E_\theta^j(\theta,\phi)^* + E_\phi^i(\theta,\phi) E_\phi^j(\theta,\phi)^* \right\} p_{\phi_0}(\theta,\phi) \cdot \sin(\theta) \cdot d\theta d\phi$$

where

$E_\theta^i(\theta,\phi)$ is the vertical (V-pol) polarization component

$E_\phi^i(\theta,\phi)$ is the horizontal (H-pol) polarization component

i is the antenna index,

ϕ is the azimuth angle,

θ is the angle of elevation (inclination), and

$\hat{\phi}, \hat{\theta}, \hat{r}$ are the unit vectors that form the bases and

$p_{\phi_0}(\theta,\phi)$ is the pdf to model the 3-D angle of spread

Single UE Performance

First, via system simulation, we present the single UE performance in terms of the transmit power gain, which is defined as the transmit power difference between a CLTD beamforming UE and a regular UE (with single antenna transmission) under identical uplink transmission conditions. The measured antenna patterns of both handset and laptop terminals are used in the simulations.

All the simulations are run with the phase only mode ($a_1 = a_2 = \frac{1}{\sqrt{2}}$), and for the ITU Pedestrian A 3 km/h (PA3) channel, ITU Pedestrian B 3 km/h (PB3) channel, and ITU Vehicular A 30 km/h (VA30) channel.
In the simulation, we use a fixed payload size with 10ms EUL and target 2 transmissions to measure the transmit power reduction (we expect to see similar or better performance in the case of 2 ms TTI transmission). Table 2 summarizes the detailed pay load size and the power settings. CLTD beamforming needs a secondary pilot transmission. The simulation uses a secondary pilot power setting of 0.35dB which has been accounted for in the transmit power reduction computation.

Table 2: Single UE fixed Payload Simulation Setup

Payload Size (TBS)	546 bits
E-DPDCH T2P	6dB
E-DPCCH C2P	-4.4dB
HS-DPCCH C2P (Duty Cycle 100%)	-1.9dB
Secondary Pilot C2P (Only For CLTD beamforming)	-3dB

Table 3: CLTD beamforming gain assuming a handset antenna pattern (non-soft-handover)

Channel Type	PA3	PB3	VA30
Tx Power Gain (dB)	2.3	1.7	0.9

Table 4: CLTD beamforming gain assuming a laptop antenna pattern (non-soft-handover)

Channel Type	PA3	PB3	VA30
Tx Power Gain (dB)	2.4	1.5	0.6

In Table 3 and Table 4, we can see that in the non-soft-handover state, the slow fading channels show significant transmit power gain. In the fast fading channel, the gain is smaller.

Next, we consider the case of the beamforming UE in the soft handover state. When the two links are balanced, Table 5 and Table 6 summarize the CLTD beamforming gain.

Table 5: CLTD beamforming gain assuming a handset antenna pattern (balanced links soft-handover)

Channel Type	PA3	PB3	VA30
Tx Power Gain (dB)	0.5	0.2	0.2

Table 6: CLTD beamforming gain assuming a laptop antenna pattern (balanced links soft-handover)

Channel Type	PA3	PB3	VA30
Tx Power Gain (dB)	0.7	0.4	0

In these two cases, since the UE beamforms toward the serving cell, the non-serving cell performance may be degraded. Thus, overall, we observe less transmit power gain than the non-soft-handover cases.

Next, we consider the case of the beamforming UE in the soft handover state with a 3 dB imbalance (the serving cell is 3 dB stronger). Table 7 and Table 8 summarize the CLTD beamforming gain. In these two cases, since the non-serving cell is 3 dB weaker, the transmit power gain is larger than the cases in Table 5 and Table 6.

Table 7: CLTD beamforming gain assuming a handset antenna pattern (Imbalanced links soft-handover)

Channel Type	PA3	PB3	VA30
Tx Power Gain (dB)	1.2	0.9	0.3

Table 8: CLTD beamforming gain assuming a laptop antenna pattern (Imbalanced links soft-handover)

Channel Type	PA3	PB3	VA30

Tx Power Gain (dB)	1.2	0.9	0.5

Finally, we consider the case of the beamforming UE in the softer handover state with balanced links. Table 9 and Table 10 summarize the CLTD beamforming gain. In these two cases, since a single Node B handles the two cells, the beamforming performance is better than the soft handover cases.

Table 9: CLTD Beamforming Gain assuming a handset antenna pattern (balanced links softer-handover)

Channel Type	PA3	PB3	VA30
Tx Power Gain (dB)	1.3	1.1	0.7

Table 10: CLTD Beamforming Gain assuming a laptop antenna pattern (balanced links softer-handover)

Channel Type	PA3	PB3	VA30
Tx Power Gain (dB)	1.5	1.1	0.6

System Performance

In this section, we will present the CLTD beamforming performance from multi-user network simulations in the ITU PA3 and PB3 channels. Throughout, a measured laptop antenna pattern was used. The cell site-to-site distance (ISD) is either 1 km or 2.8 km. We use 10ms EUL with target 2 transmissions (we expect to see similar or better performance in the case of 2 ms TTI transmission). Since the largest payload in 10 ms TTI is 20000, the maximum data rate each UE could achieve is around 1Mbps.

Best Effort Traffic Model

To evaluate the Best Effort throughput performance, we load each cell with 10 UEs. First, in the case of 1 km cell ISD and the PA3 channel, from Figures 5, 6, and 7, we observe a 19% cell throughput gain and simultaneously a 1.93 dB average transmit power gain. A portion of the transmit power gain is translated into the UE and cell throughput gain. As seen in Figure 6, the cell edge UEs (i.e. low percentile UEs) have more percentage throughput gains than the UEs closer to the Node B.

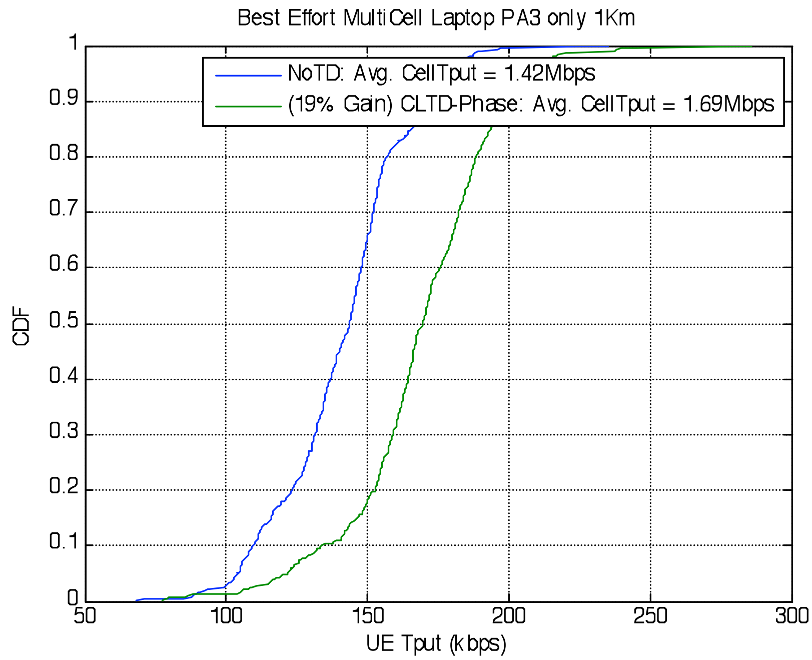

Figure 5: The Cumulative Distribution Function (CDF) of the UE Throughput (PA3, 1km ISD, 10UEs/Cell)

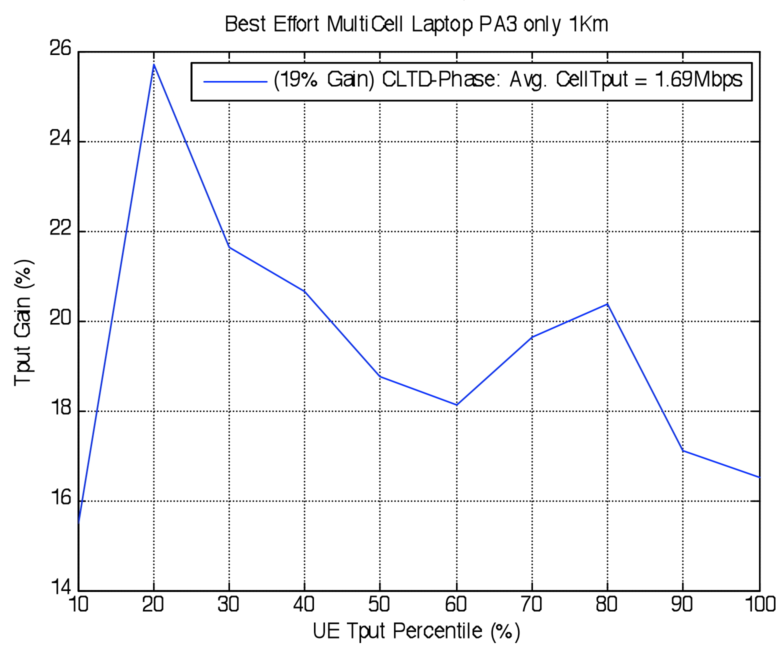

Figure 6: UE Percentage Throughput Gain vs UE Throughput Percentile (PA3, 1km ISD, 10UEs/Cell)

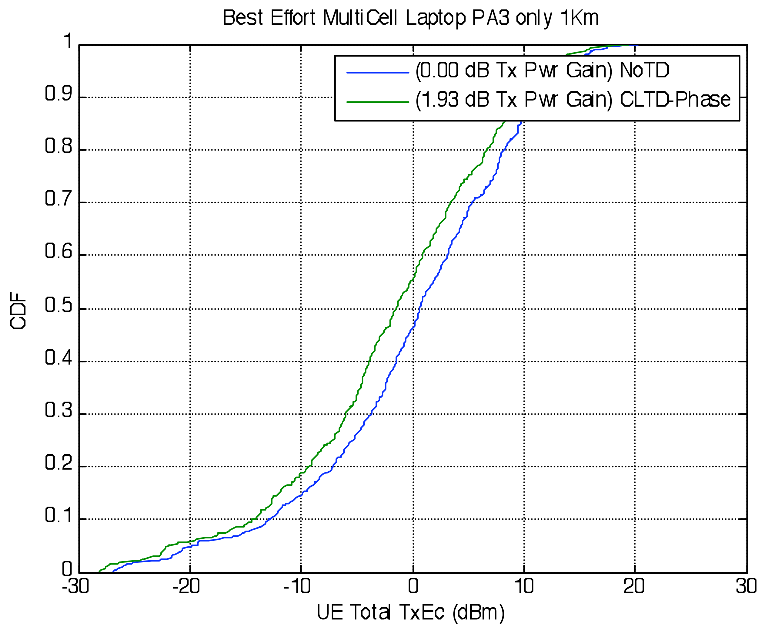

Figure 7: The CDF of UE Transmit Power (dBm) (PA3, 1km ISD, 10UEs/Cell)

For the case of 2.8 km cell ISD and the PA3 channel, from Figures 8, 9 and 10, we observe a 17% cell throughput gain and simultaneously a 1.33 dB average transmit power gain. Part of the transmit power gain is translated into the UE and cell throughput gain. As seen in Figure 9, the cell edge UEs (i.e. low percentile UEs) have much more percentage throughput gains than the UEs closer to the Node B. Furthermore, compared to the case of the smaller cell size (1 km), cell edge UEs are more limited in their transmit power. Hence CLTD beamforming provides more throughput gains to those UEs.

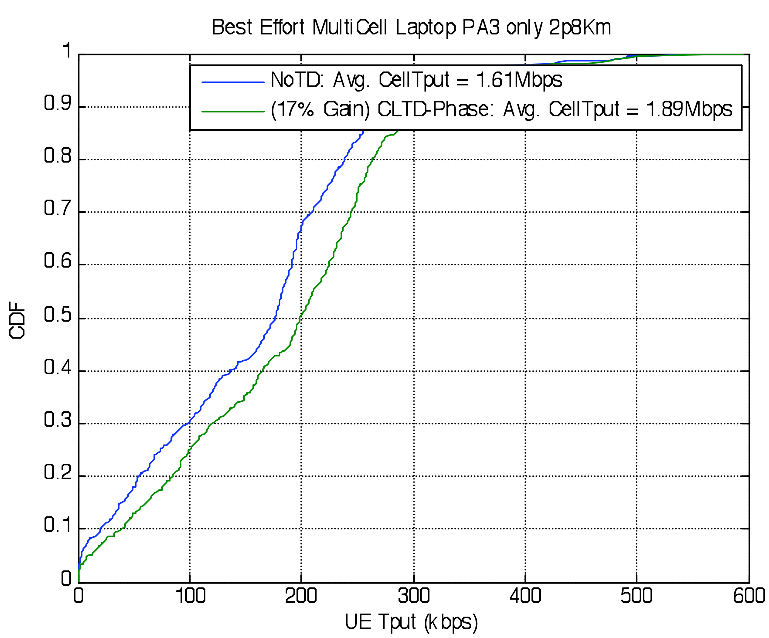

Figure 8: The CDF of the UE Throughput (PA3, 2.8km ISD, 10UEs/Cell)

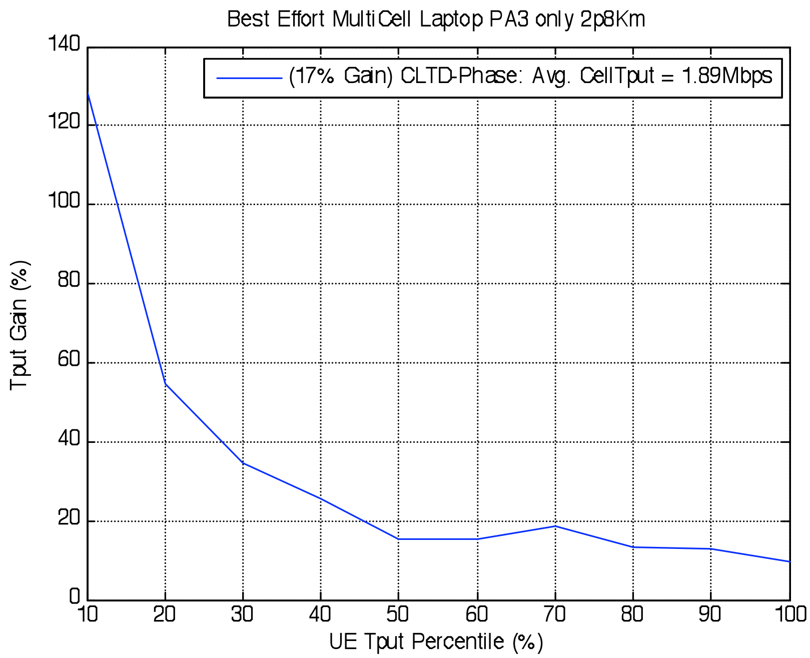

Figure 9: UE Percentage Throughput Gain vs UE Throughput Percentile (PA3, 2.8km ISD, 10UEs/Cell)

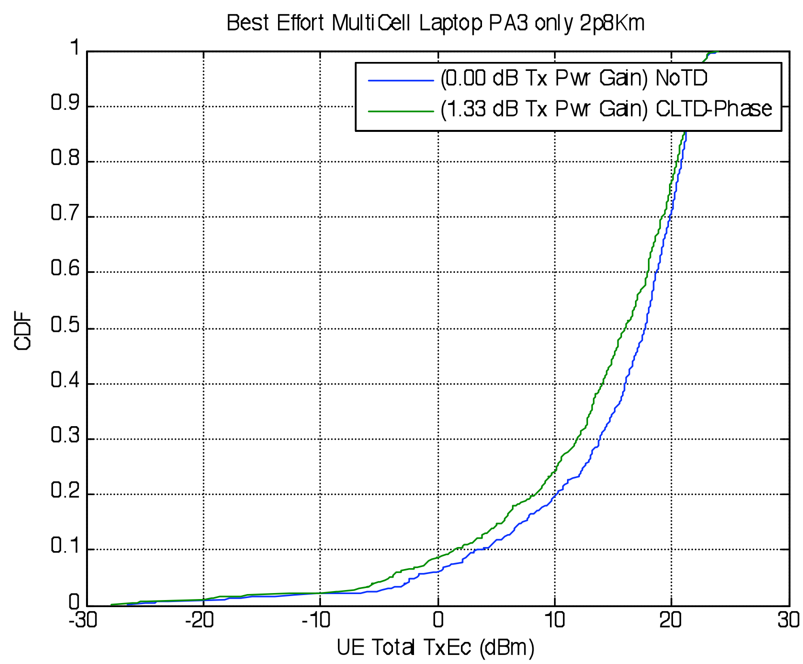

Figure 10: The CDF of UE Transmit Power (dBm) (PA3, 2.8km ISD, 10UEs/Cell)

Finally, in the case of 2.8 km cell ISD and the PB3 channel, from Figures 11, 12, and 13, we observe 18% cell throughput gain and simultaneously 0.89 dB average transmit power gain. As seen in Figure 12, similar to the PA3 channel case, the cell edge UEs (i.e. low percentile UEs) have much more percentage throughput gains than the UEs closer to the Node B.

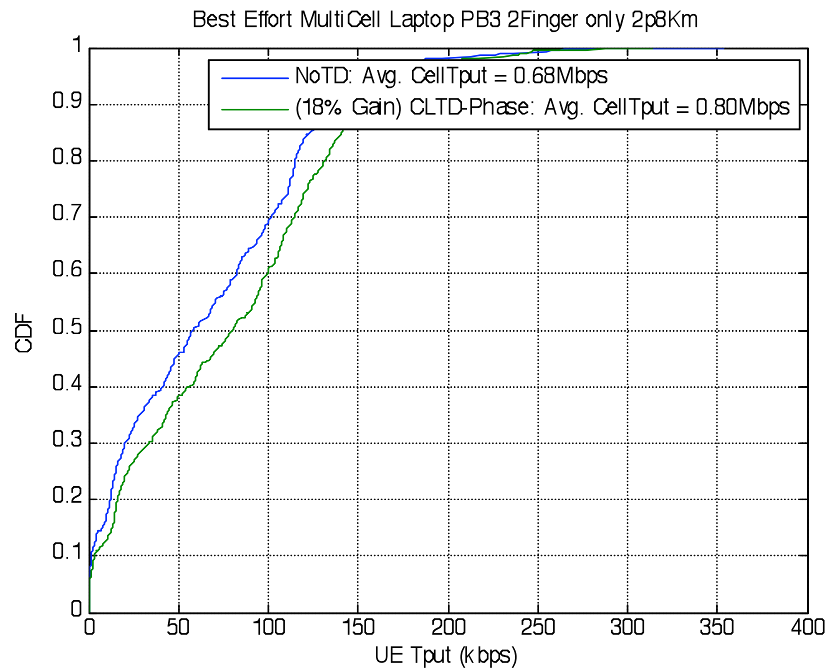

Figure 11: The CDF of the UE Throughput (PB3, 2.8km ISD, 10UEs/Cell)

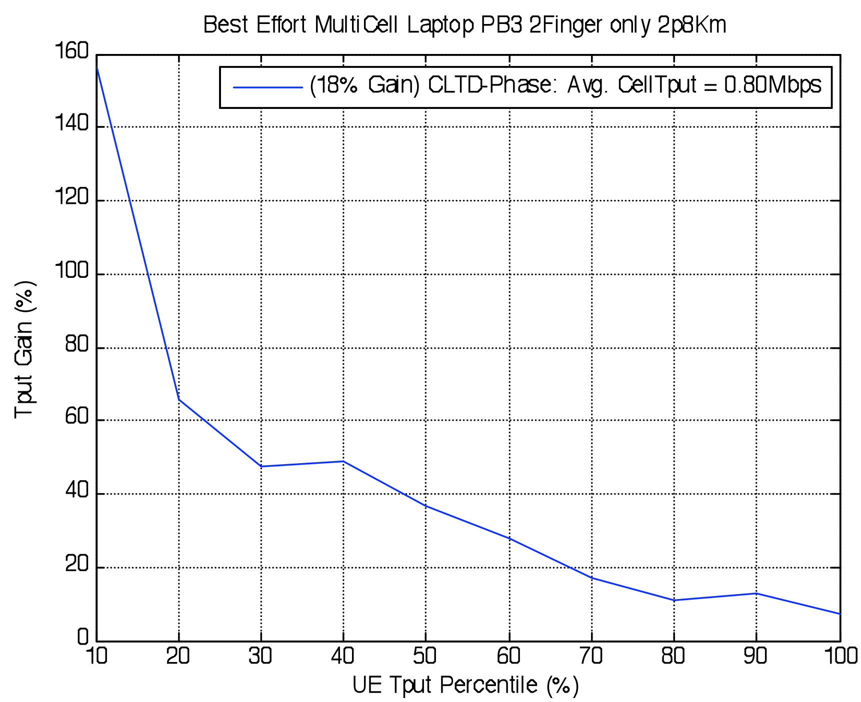

Figure 12: UE Percentage Throughput Gain vs UE Throughput Percentile (PB3, 2.8km ISD, 10UEs/Cell)

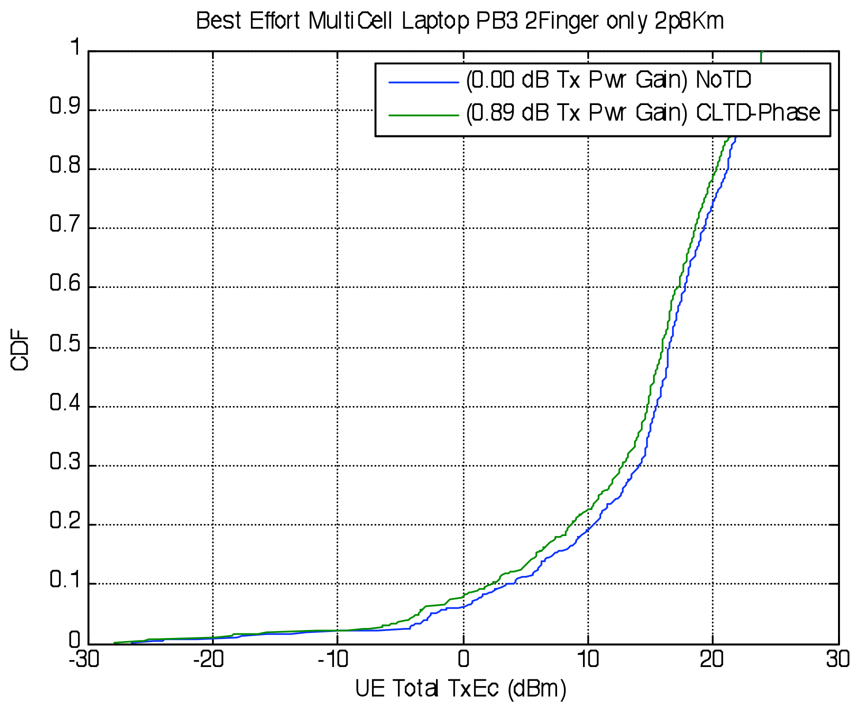

Figure 13: The CDF of UE Transmit Power (dBm) (PB3, 2.8km ISD, 10UEs/Cell)

Bursty Traffic Model

As seen in the Best Effort traffic simulation, for larger ISD, CLTD beamforming could significantly improve the UE throughput at the cell edge. To further demonstrate this benefit, we evaluate the CLTD beamforming performance under a bursty traffic model. We used an open loop burst traffic model where a burst of 1M bits arrives at the UE queue every 5 seconds regardless of the UE queue status. Effectively, the offered load at each UE is 200kbps. The new performance metric we look at is the UE burst rate which is defined as the burst size (1M bits) divided by the time from the first bit of the burst arrived at the UE queue to the time the last bit of the burst was successfully received at the UE. This definition of the burst rate includes the queuing delay.

In order to better understand the simulation data, we need to emphasize that as the offered load to the UE is 200kbps, it is critical for the UE to sustain a physical layer throughput greater than 200kbps in order to maintain a stable queue.

In the following, the results are presented in terms of the UE average burst rate CDF, the percentile-wise UE average burst rate gain as well as the average UE Tx power reduction.

Figures 14, 15 and 16 demonstrate the results for the case of 1 km cell ISD, PA3 channel and a loading of 2 UEs per cell. As shown in Figure 14, even for the case when transmit diversity is disabled, due to the small site to site distance and small loading of 2 UEs per cell, all UEs could sustain a throughput higher than 200kbps. CLTD beamforming does not offer much improvement in terms of the burst rate. The reason is that, in this case, no

UE in the system is power limited. The burst rate cannot reach the maximum UE throughput of 1Mbps primarily due to the queuing delay when both UEs have bursts that arrive at the same time and they compete at the NodeB for scheduling opportunities. However, to achieve the same burst rate, the CLTD beamforming is capable of a 3.35dB reduction in average UE transmit power. This transmit power reduction is larger than the single UE fixed payload test as shown in the previous section (2.4dB) which reveals the additional benefit of CLTD beamforming in terms of reducing the interference to the other cells. In the multi-UE scenario, each UE could further reduce its transmit power since it needs to combat less interference at the NodeB receiver which cannot be seen in the single UE simulation.

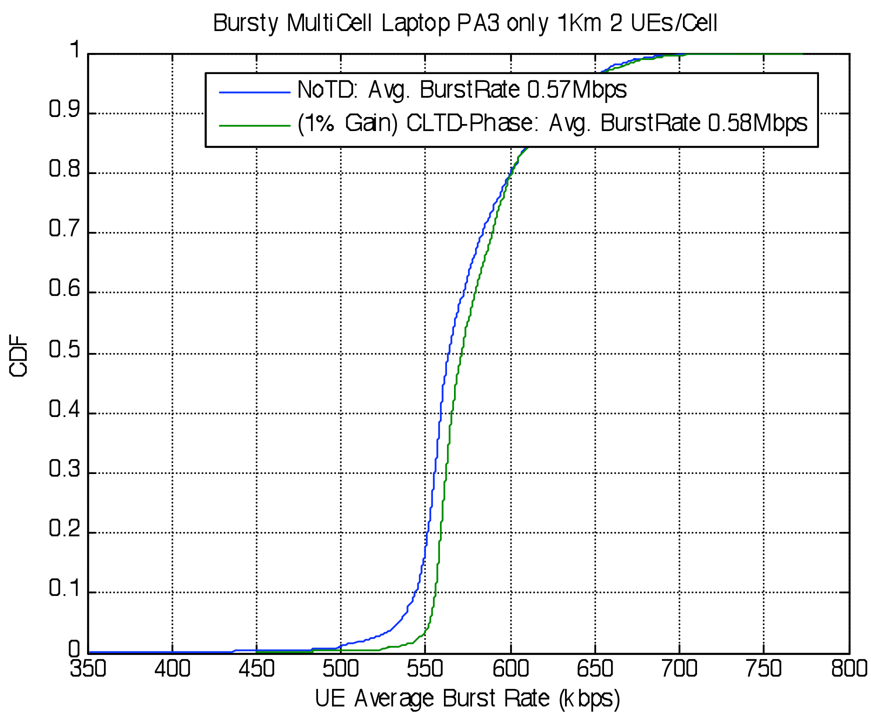

Figure 14: CDF of UE Average Burst Rate (PA3, 1km ISD, 2UEs/Cell)

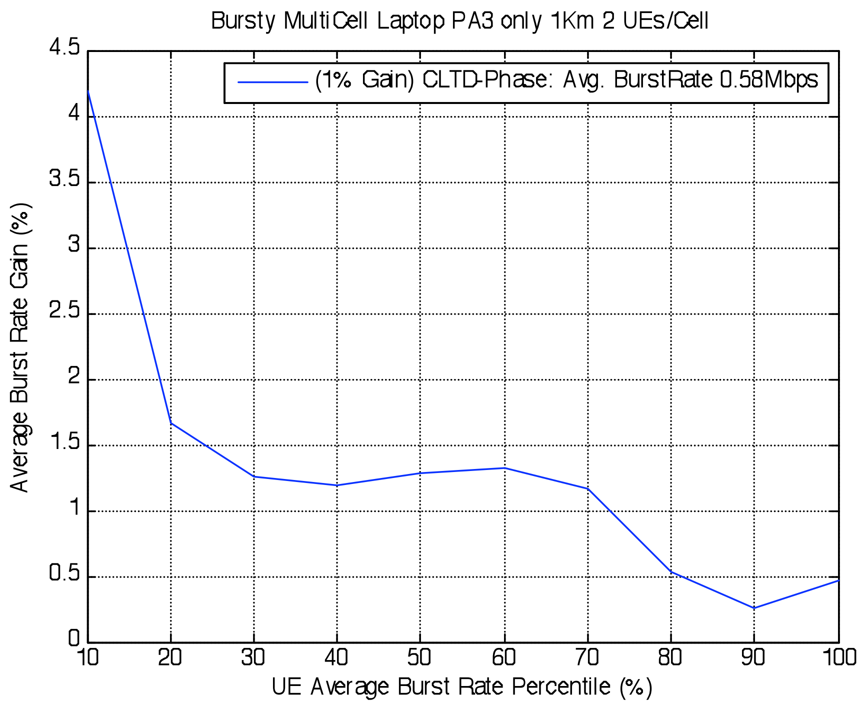

Figure 15: Percentile-Wise UE Average Burst Rate Gain (PA3, 1km ISD, 2UEs/Cell)

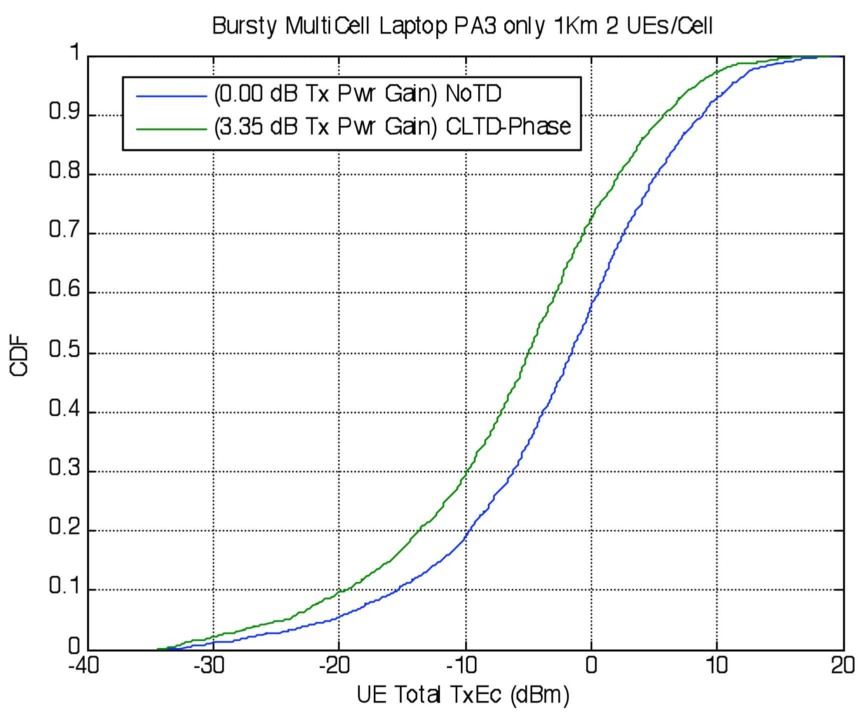

Figure 16: UE Tx Power CDF (PA3, 1km ISD, 2UEs/Cell)

In the next step, we increased the loading from 2 UEs/Cell to 8 UEs/Cell. The results for this case are demonstrated in Figures 17, 18 and 19. As the loading increases, we start to see UEs that cannot sustain 200kbps transmission. In this case, CLTD beamforming significantly improves the UE burst rate especially for the UEs at the cell edge as shown in Figure 18. In addition to the burst rate improvement, Figure 19 shows that CLTD beamforming also helps to reduce the UE average transmit power by 2.69dB.

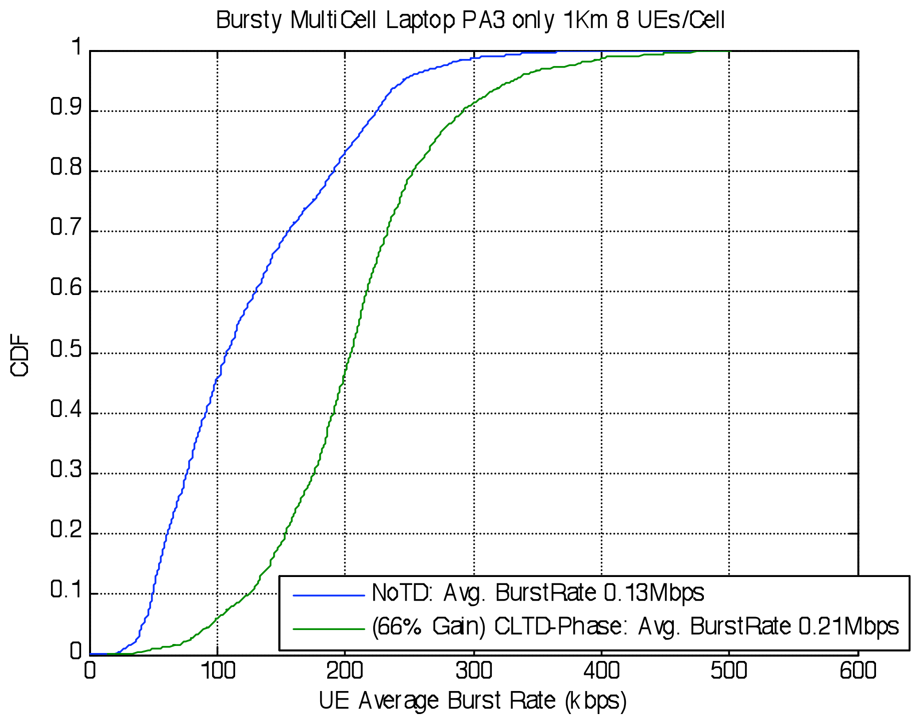

Figure 17: CDF of UE Average Burst Rate (PA3, 1km ISD, 8UEs/Cell)

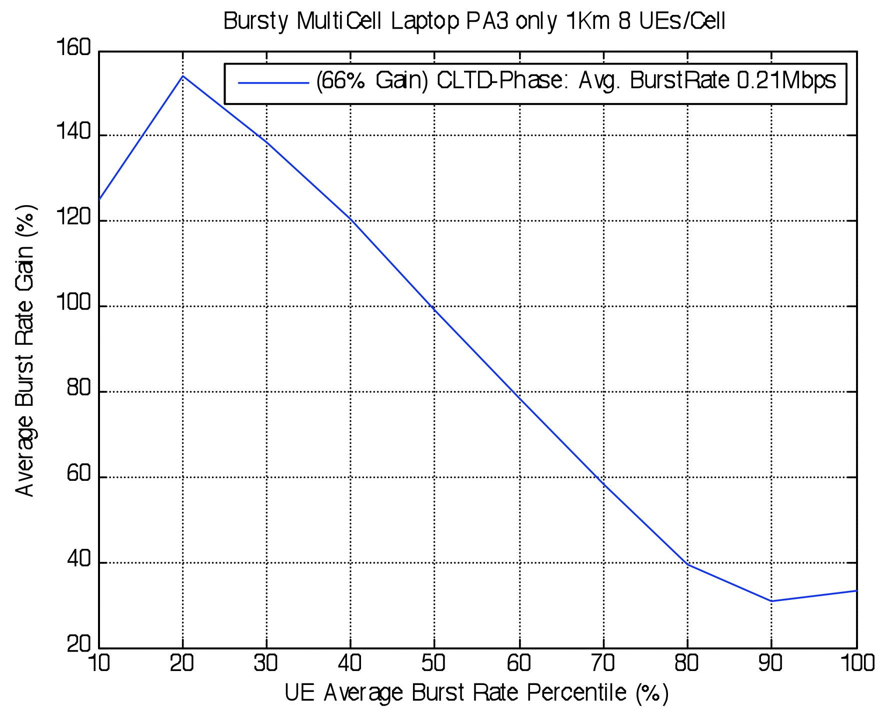

Figure 18: Percentile Wise UE Average Burst Rate Gain (PA3, 1km ISD, 8UEs/Cell)

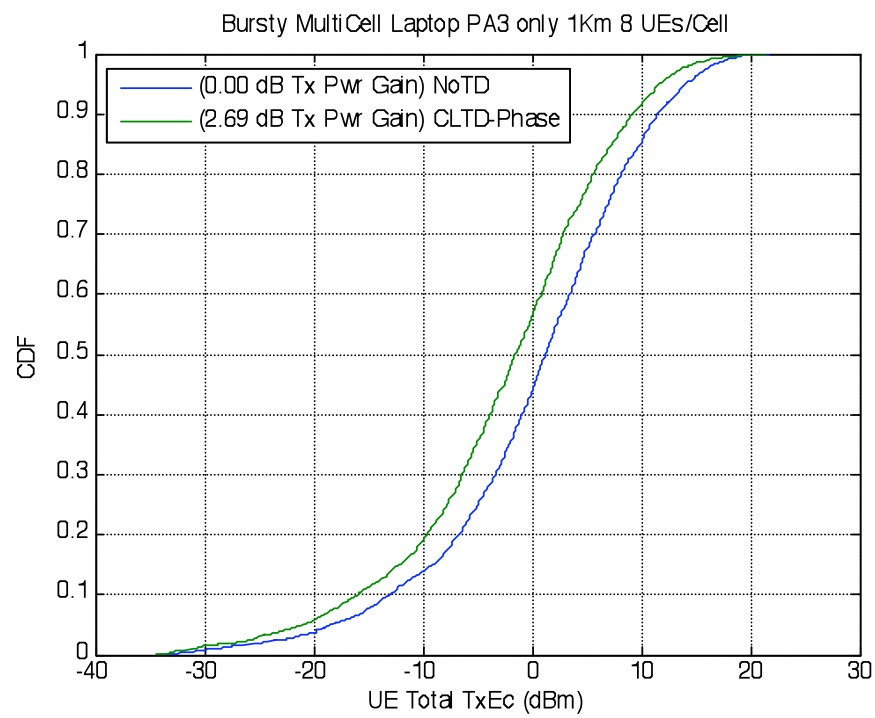

Figure 19: UE Tx Power CDF (PA3, 1km ISD, 2UEs/Cell)

To further demonstrate the cell coverage improvement, we also simulated the 2.8km ISD. As illustrated in Figures 20, 21 and 22, even with 2UEs per cell loading, due to the large site-to-site distance, we start to see some UEs in the cell edge that cannot support 200kbps transmission. CLTD beamforming improves the cell edge UE burst rate by up to

200%. In addition, while achieving higher UE burst rates, CLTD beamforming also helps reduce the UE average transmit power by 2.12dB.

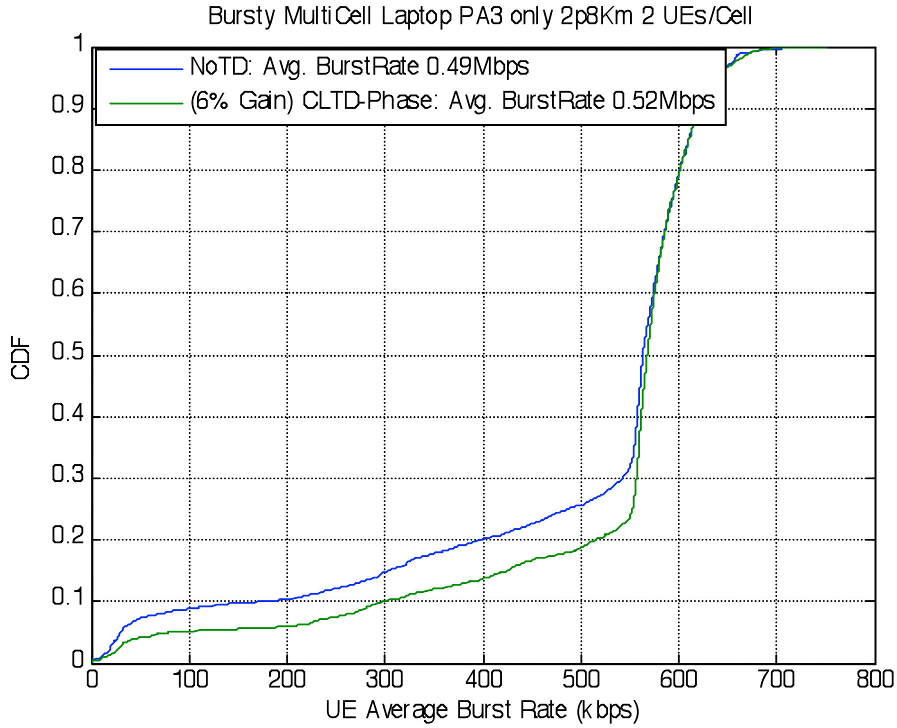

Figure 20: CDF of UE Average Burst Rate (PA3, 2.8km ISD, 2UEs/Cell)

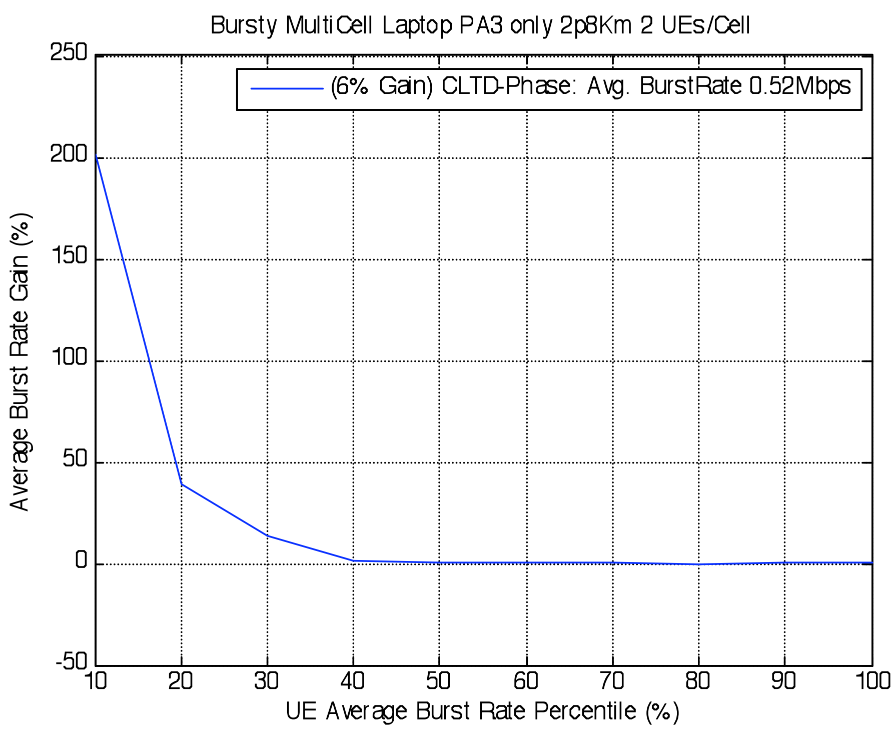

Figure 21: Percentile Wise UE Average Burst Rate Gain (PA3, 2.8km ISD, 2UEs/Cell)

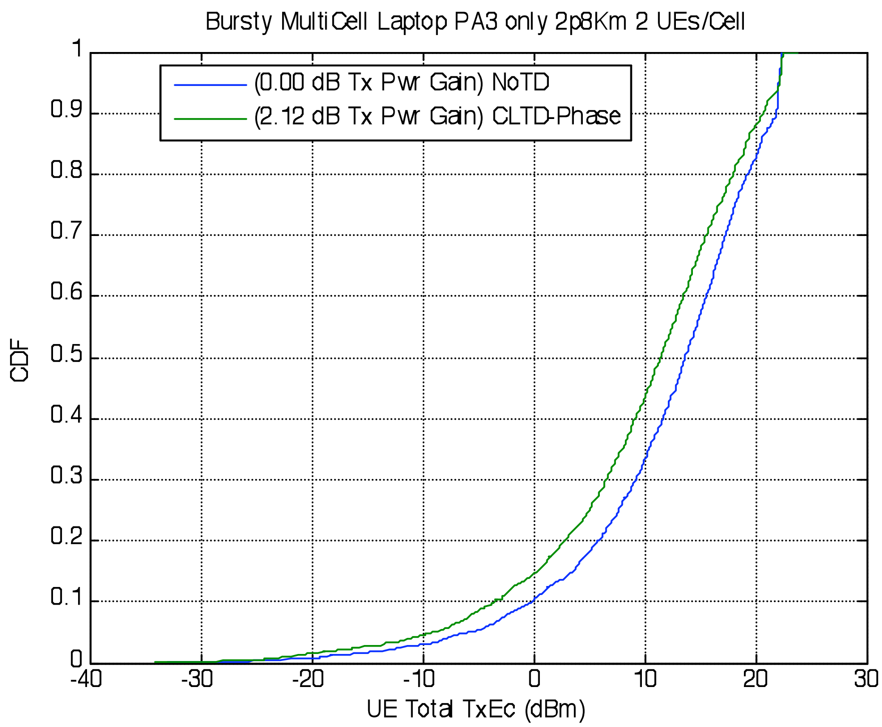

Figure 22: Percentile Wise UE Average Burst Rate Gain (PA3, 2.8km ISD, 2UEs/Cell)

We have also evaluated the bursty traffic model for different levels of loading for the PB3 channel, and we observe similar benefit from CLTD beamforming in terms of improving the UE burst rate, as well as reducing the average UE transmit power.

3GPP Standards Impact due to CLTD Beamforming

The introduction of CLTD beamforming will affect the physical layer, MAC and RRC specifications, including:

- Introduction of a secondary pilot uplink channel in the UE transmitter
- Feedback of the CLTD beamforming information
- Introduction of new minimum performance tests due to CLTD beamforming

Conclusion

In this paper, we have analyzed the potential transmit power gains achievable by the CLTD beamforming scheme on the uplink in HSPA. The transmit power gain not only extends the cell coverage, but can also be translated into user throughput gain. Furthermore, in the multi-cell scenario, the CLTD beamforming scheme can further improve the cell throughput. We also discussed an implementation method forCLTD beamforming, and provided some details of the Node B processing in order to support the CLTD beamforming scheme. With realistic antenna patterns, the CLTD beamforming scheme shows a UE transmit power reduction of more than 2 dB for the ITU PedA 3km/h channel, more than 1 dB gain for ITU PedB 3km/h channel, and more than 0.6 dB gain for ITU VehA 30km/h channel in the non-soft handover state, and some gains in the soft-handover state (depending on the uplink imbalance).

From the system performance point of view, the benefits of CLTD beamforming have three primary areas: (i) Improved cell coverage or UE performance in the cell edge when UE becomes transmit power limited. (ii) Reduced interference to other cells and, in return, increases the average UE as well as the Cell throughput. (iii) Reduced e UE transmit power.

When a cell is mostly serving slow speed channels, for full buffer type of traffic, we observe around 18% cell throughput gain, while simultaneously reducing the average UE transmit power by 1-2 dB. For the UEs that are transmit power limited or in the cell edge, the UE experiences a significant improvement (over 150%) in throughput.

For a bursty traffic source, with CLTD beamforming, more UEs will be able to enjoy the high date rate transmission. CLTD beamforming can significantly increase the UE burst rate at the cell edge as well as reduce the UE transmit power by up to 3dB.

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