Energy Efficiency and Capacity Evaluation of LTE-Advanced Downlink CoMP Schemes Subject to Channel Estimation Errors and System Delay

Gencer Cili, Halim Yanikomeroglu, and F. Richard Yu
Department of Systems and Computer Engineering, Carleton University, Ottawa, Canada
Email: {gecili, halim}@sce.carleton.ca, {richard_yu}@carleton.ca

Abstract— **Due to the increased energy consumption of cellular access networks, energy efficiency of the systems should be considered jointly with spectral efficiency to obtain the overall performance metrics and trade-offs. Downlink coordinated multipoint (CoMP) joint transmission aided cell switch off schemes can mitigate inter-cell interference and increase energy efficiency by using the active cells to serve the users in the switched off cell. However, the performance of this newly proposed scheme is heavily dependent on the accuracy of the selected CoMP joint transmission set. In this paper, we model the multi-point channel estimation enabled via channel state information reference symbols (CSI-RS) introduced in 3GPP release 10 systems and simulate possible scenarios that would lead to inaccurate transmission set clustering: multi-point channel estimation errors and possible CoMP system delays due to CSI transfers, node processing delays and network topology limitations. In order to mitigate the effects of channel estimation errors and system delay, we propose a framework for multi-point channel estimation in CoMP systems using a time-varying interpolation filter which tracks each multipath delay tap separately for every measured point. Possible performance gains with different filter lengths are demonstrated. Simulation results are presented to show the effectiveness of the proposed scheme. In addition, proof of concept is provided for CoMP adaptive time-varying multi-point estimation filter designs, where the UEs which are being served by higher cluster degrees need to enlarge the estimation filter memory spans only for the points which are more likely to be included in the joint transmission set.**

I. INTRODUCTION

Exponential rise in cellular device usage in the recent years along with the increase in the minimum required received quality of service lead the innovation in the direction of cellular enhancements enabling spectrally efficient systems. Future wireless standards like LTE-A (Long Term Evolution Advanced) and beyond are making significant changes to the overall system architecture, air interface and quality of service offered to the users [1]. Increased complexity of these cellular features and the rising mobile usage rates create a major power consumption burden on the overall systems. As a result, the key features considered by future wireless technologies should be jointly reviewed under the "green radio" umbrella to check for possibilities of energy saving implementations and increased total system capacity.

A joint consideration of energy and spectrally efficient heterogonous LTE systems is demonstrated in [2], where the capacity boosting small cells are switched off according to a pre-determined traffic threshold in the energy saving region. CoMP joint transmission is listed as one of the key features and work items for LTE-A systems to improve cell edge performance and spectral efficiency by mitigating the inter cell interference [3]. An alternative energy saving method for the access networks was demonstrated in [4] by complementing the traditional cell switch off schemes with downlink (DL) CoMP use in the remaining active cells to serve the users located in the switched off cell.

Technical challenges for downlink CoMP were listed by [5] and [6] as increased backhaul traffic, time/frequency synchronization of the cooperating points, multi-point channel estimation, prediction and feedback procedures, clustering of CoMP sets, delays in the overall system and cross point scheduling of users. Effect of traffic intensity on the optimum downlink CoMP scheduling scheme is analyzed in [7] where the multi-user joint processing was shown to outperform single-user joint processing in terms of capacity gains.

To tackle signaling delays within the CoMP active set, a centralized UL scheduling approach was demonstrated in [8], where the backhaul usage was tried to be minimized using pre-known statistical channel feedback information. Feasibility of various CoMP deployment scenarios is investigated in [9] and intra-cell cooperation is chosen to be a successful candidate for joint processing DL scheme. Energy efficient CoMP network backhaul design proposed in [10] pre-calculated the set of points that can be used in the CoMP transmission set and excluded the remaining points from the CoMP measurement set due to network latency constraints.

Most of the existing proposed methods in the academia and the 3GPP standardization for CoMP [6] focus on the effects of system delays, clustering strategies and scheduling schemes on CoMP system capacity or the power efficiency of the backhaul network. However, to the best of our knowledge, the impacts of channel estimation errors and system delays on the overall CoMP access network energy efficiency and capacity gains are not studied in existing literature. Distinct contributions of this paper are listed as follows:

- We investigate both the individual and joint effects of channel estimation errors and system delays on a DL CoMP system that is integrated to a cell switch off model and execute realistic performance analysis.
- Inaccuracy of the CoMP active set clustering due to the faulty time-varying channel feedback and the impacts on overall system bits/Joule energy efficiency and capacity performance are analyzed. We formulate both energy and capacity metrics according to joint transmission schemes and show that both the cluster member choices and the degrees affect the performance metrics.
- Performance degradation sensitivities of various user locations in the cellular deployment are characterized both for

low and high mobility conditions. We demonstrate that the users with higher clustering degrees get affected more severely due to inaccurate joint transmission sets.

- A framework for multi-point channel estimation in CoMP systems using a time-varying interpolation filter in time domain is described and the possible performance gains with different filter lengths are demonstrated.

The rest of the paper is organized as follows: Sec. II describes the downlink CoMP + Cell Switch Off scheme used in our study. Sec. III describes the stochastic modeling of the channel impulse response and possible time-varying channel estimation schemes, Sec. IV analyzes the performance sensitivity of the proposed scheme for various users under different channel conditions and Sec. V concludes the paper.

II. CoMP + Cell Switch off System Model

Joint transmission DL CoMP with inter-eNB deployment configuration in homogenous macro networks is a complex scheme that yields the high gains in terms of system performance. A traditional cell switch off scheme is modeled composed of 19 hexagonal cells that have full frequency re-use. Center cell is switched off for energy savings and the users located in this cell are served by the remaining 3 tiers of 18 cells that use CoMP. Random user locations are simulated in the switched off cell denoted by $i \in [1,..,500]$, and the unique cell IDs of the cooperating cells are denoted as $n \in [1,..,18]$. Urban macro (UMa) large-scale pathloss model is used according to ITU-R report M.2135 for radio interfaces in [11]. Small scale fading for time-varying multipath channels for each UE-eNB link is modeled independently according to Winner SCME model [12]. Channel samples, $t \in [1,..,1000]$ are obtained with a 1 ms granularity to synchronize with the LTE MAC scheduling decisions that are performed every TTI at the serving eNB.

A. LTE-Advanced Downlink CoMP Procedures

In joint transmission CoMP, multiple eNBs that are part of the transmission set can transmit the same user plane data over the PDSCH (Physical Downlink Shared Channel) to a single UE using the same resource blocks as demonstrated in Fig. 1. Serving cell acts as the anchor of the CoMP transmission which can change with time and location due to mobility. CoMP measurement set is sent to the users via DL RRC signaling. CSI-RS (Channel State Information – Reference symbols) inserted to the assigned downlink resource blocks enables the user to perform measurements for the members of the CoMP set. It should be noted that multi-point channel estimation is more vulnerable to estimation errors due to the lack of reference symbols allocated for each eNB compared to single point channel estimation. Although the CoMP measurement set is a subset of the complete cooperation set, we assumed all the 18 eNBs are passed as members of the CoMP measurement set without any down-selection performed at both ends. UE can either send channel and noise observations or CQI/RI values as part of CoMP feedback for the points in measurement set which are defined as explicit and implicit feedback respectively. Actual measured received power from eNB n by user i at TTI t can be expressed as

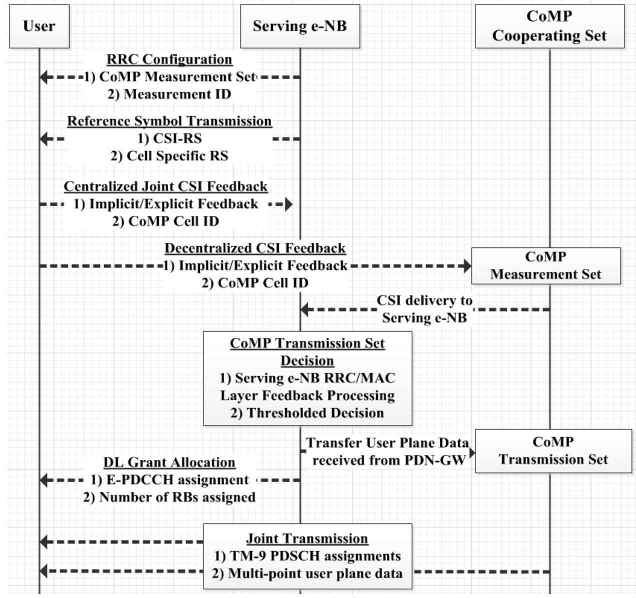

Fig. 1. Inter - eNB joint transmission DL CoMP procedures.

$$P_{RX}(n,t,i) = P_{TX}(n) - PL(n,i) - P_{Fading}(n,t,i), \quad (1)$$

where $P_{TX}(n)$ is the transmitted power from the eNB n, $PL(n,i)$ is the large scale pathloss observed between user i and eNB n, and $P_{Fading}(n,i,t)$ is the time-varying power loss observed due to small scale fading which is explained thoroughly in Sec. III. Due to the transmission over noisy channel, lack of reference symbols inserted in the resource blocks, and the feedback exchange and processing delay for CSI shown in Fig. 1, serving cell RRC/MAC layer performs the thresholded CoMP transmission set decisions based on

$$P_{RX\_err}(n,t,i) = P_{RX}(n,t-\Delta,i) + P_{err}(\mu,\sigma), \quad (2)$$

where Δ is the delay observed in milliseconds during the CSI exchange and serving cell feedback processing, and $P_{err}(\mu,\sigma)$ models the effect of channel estimation errors on measured received power calculation as a Gaussian random variable with mean μ and standard deviation σ expressed in dB scale. Feedback in (1) is sorted according to decreasing measured received power values and the cells that are within a certain pre-defined threshold $P_{threshold}\ (dB)$ compared to the best measured cell, which is taken as 3 dB in our simulations, are added to the CoMP transmission set $N_{JT}(i,t)$ for user i on particular TTI t. Members N_{JT} perform joint scheduling on PDSCH and transfer the same user plane data using TM-9 (Transmission Mode 9). As a result, the received PDSCH power is calculated as

$$P_{JT}(t,i) = \sum_{n \in N_{JT}} P_{RX}(n,t,i)\,. \quad (3)$$

Inter cell interference, which is a performance bottleneck in cellular systems, is mitigated significantly as shown in (3); however it should be noted that the scheduling and clustering decisions are performed based on the delayed and incorrectly estimated values of received power measurements shown in (2) which will degrade the overall system gains.

B. Downlink CoMP Performance Metrics Formulization

Performance metrics of the system include both the time-varying energy efficiency $EE(i,t)$ and perceived downlink capacity $C(i,t)$ for each user simulated in the layout. Capacity of each user (bits/sec) is calculated on every TTI using Shannon's formula as

$$C(i,t) = W(i,t)\log_2\left(1+\frac{P_{JT}(i,t)}{\sum_{n\in N\setminus N_{JT}(i)} P_{RX}(n,i,t)+P_{noise}}\right), \quad (4)$$

where $W(i,t)$ is the assigned frequency bandwidth to user *i*. CoMP transmission set is performing joint PDSCH scheduling, and the remaining cells that are excluded from the transmission set due to multi-point measurement reports, $n \notin N_{JT}(i,t)$, act as interference. Energy efficiency of the access network while serving user *i* is expressed in bits/joule and calculated by dividing the received downlink capacity $C(i,t)$ by the total power consumed by the eNBs that are part of $N_{JT}(i,t)$ adapting the model from [13] as

$$EE(i,t) = \frac{C(i,t)}{P_{CoMP} + (N_C(i,t)-1)(P_{CoMP}-P_{Base})}, \quad (5)$$

where $N_C(i,t)$ is the number of eNBs in $N_{JT}(i,t)$. The power consumption of a single eNB performing CoMP operation is formulized as

$$P_{CoMP} = N_s N_{\frac{PA}{sector}}\left(\frac{P_{TX}}{PA_{eff}} + P_{SP}\right)(1+C_C)(1+C_{BB}) + P_{BH}. \quad (6)$$

None CoMP related contributing factors in the power consumption model are N_s, $N_{\frac{PA}{sector}}$, $\frac{P_{TX}}{PA_{eff}}$, C_C and C_{BB} which denote the number of sectors, power amplifier – sector ratio, actual transmitted power form the cell, cooling and battery backup losses respectively, whereas P_{BH} and P_{SP} are the backhauling and signal processing power which are heavily dependent on $N_C(i,t)$ as demonstrated in Fig. 1. It can be observed from (5) and (6) that the inaccurate decisions in $N_{JT}(i,t)$ will have a direct impact on the energy efficiency and the capacity performance of the system.

III. Statistical Channel Estimation Schemes

A. Stochastic Characteristics of Channel Impulse Response

The radio channel between each user and CoMP measurement set member is modeled independently. As a result, the chosen points for transmission,$N_{JT}(i,t)$, at each TTI are subject to change. Time varying and dispersive complex baseband CIR can be expressed as

$$h_{n,i}(t,\tau) = \sum_{l=1}^{L} A_l(t) e^{j2\pi f_{d_l} t} e^{j2\pi f_c \tau_l} e^{j\phi_l} \delta(\tau-\tau_l). \quad (7)$$

Received power measurement fluctuation due to small scale fading between the eNB *n* and user *i* is derived using (7) as

$$P_{Fading}(n,t,i) = 10\log_{10}\left[\left(\frac{\left|\sum_{l=1}^{L} h_{n,i}(t,\tau_l)\right|}{2}\right)^2\right] \quad (8)$$

due to the narrowband subcarrier structure of OFDMA. A_l and f_{d_l} represent the amplitude and the doppler shift, $\frac{v}{\lambda}\cos(\theta_l)$, at delay tap τ_l, respectively. Main contributors to the phase shift of the multipath delay tap are f_{d_l} and $\emptyset_l$, however the difference in propagation of each multipath also contributes to the phase shift of each multipath component as $2\pi f_c \tau_l$. Channel impulse response $h_{n,i}(t,\tau_l)$ is a two dimensional complex stochastic process since various selections of the random variables A_l, f_{d_l}, $\emptyset_l$, and τ_l yield different realizations and an indexed family of random variables. First and second order characteristics of the random process should be modeled in both time and delay domains to estimate and predict the amplitude and phase of the complex impulse response to perform accurate coherent detection. Time invariant channel transfer function (CTF) estimation and interpolation is done using the CIR autocorrelation function in delay domain,

$$R_h(\Delta t = 0, \Delta\boldsymbol{\tau_L}) = \begin{bmatrix} E[h(\tau_1)h(\tau_1)^*] & \cdots & E[h(\tau_1)h(\tau_L)^*] \\ \vdots & \ddots & \vdots \\ E[h(\tau_L)h(\tau_1)^*] & \cdots & E[h(\tau_L)h(\tau_L)^*] \end{bmatrix}, \quad (9)$$

where the diagonal components correspond to channel power delay profile (PDP), and the CTF auto-correlation function which is the Fourier transform of the PDP in delay domain [15]. CIR estimation and interpolation in time domain is done by tracking the variations in each multipath tap *l* using the CIR autocorrelation in time domain,

$$R_h(\Delta\boldsymbol{\tau_M}, \tau_l) = \begin{bmatrix} E[h(t_1,\tau_l)h(t_1,\tau_l)^*] & \cdots & E[h(t_1,\tau_l)h(t_M,\tau_l)^*] \\ \vdots & \ddots & \vdots \\ E[h(t_M,\tau_l)h(t_1,\tau_l)^*] & \cdots & E[h(t_M,\tau_l)h(t_M,\tau_l)^*] \end{bmatrix}, \quad (10)$$

over *M* TTIs separately for each CoMP measurement set member *n*. Overall time correlation function can be obtained by integrating (10) over all the existing multipath delay taps as: $R_h(\Delta\boldsymbol{\tau_M}) = \int_{l=1}^{L} R_h(\Delta\boldsymbol{\tau_M}, \tau_l)dl$. Coherence time of the channel is defined as $R_h(\Delta\boldsymbol{\tau_M})$ being equal to a certain correlation value *c*. It reflects the similarity of the channel impulse response over time and is inversely proportional to the receiver velocity. The rate of change of the complex baseband CIR for a particular tap *l* over time is limited by $R_h(\Delta\boldsymbol{\tau_M}, \tau_l)$ derived by the Markov inequality explained in [16] as

$$Prob\left(\left|h(t_i,\tau_0) - h(t_j,\tau_0)\right| > \varepsilon\right) \leq 2\left(R_h(|\Delta t = 0, \Delta\tau = 0|) - R_h\left(|t_i - t_j, \Delta\tau = 0|\right)\right)/\varepsilon^2. \quad (11)$$

Thus, multi-point feedback with greater system delay or high Doppler scenarios will degrade the accuracy of the joint PDSCH transmission clustering significantly due to the decreasing nature of $R_h(\Delta\boldsymbol{\tau_M}, \tau_l)$ that has a peak at $R_h(0, \tau_l)$. This is explained by the outdated multi-point CSI feedbacks being less correlated with the instantaneous feedbacks.

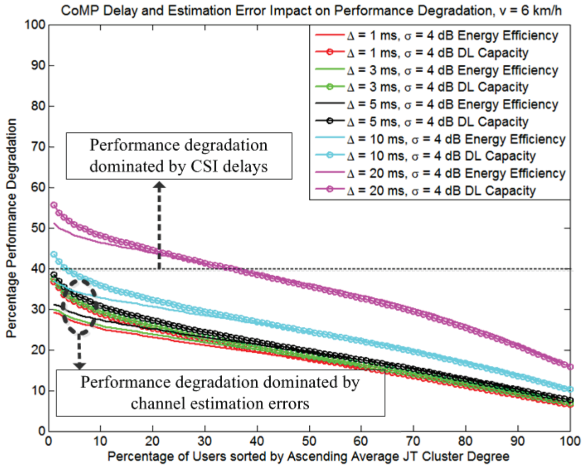

Fig. 2. CoMP joint transmission performance degradation in low mobility condition.

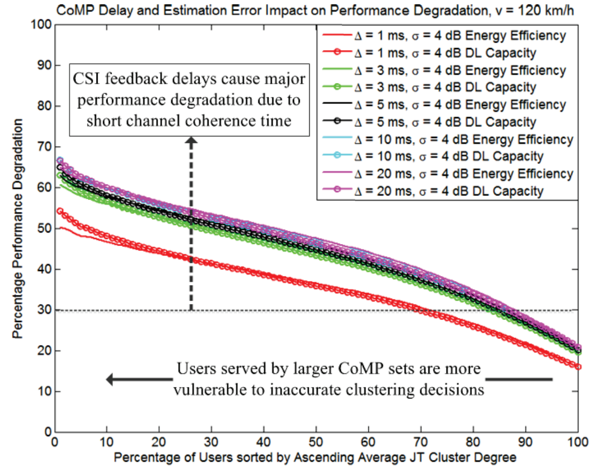

Fig. 3. CoMP joint transmission performance degradation in high mobility condition.

B. Time Varying Channel Estimation and Interpolation

Due to the scarce structure of CSI-RS used for each CoMP measurement member's channel estimation, time-varying channel estimation and interpolation is very crucial for performance of Release 11 coordinated LTE-A systems. Each measured link should be estimated independently to correct the reported UE channel feedback and avoid inaccurate joint transmission clustering. The time varying estimation filter is formulized as

$$\tilde{h}_{t,\tau_l} = [(R_h(\Delta t,\tau_l) + \sigma^2_{noise} I_{MxM})^{-1} r_h(\Delta t,\tau_l)]^H \hat{\boldsymbol{h}}_{t,\dots t-M+1;\tau_l}\,, \quad (12)$$

where the regularized CIR autocorrelation function component, $R_h(\Delta t,\tau_l) + \sigma^2_{noise} I_{MxM}$, is formed using the variance of the channel estimation error for a particular tap and the delay-cross power density formulated by

$$R_h(\Delta t = M_{UE} - 1, \tau_l) = E[h(t - M_{UE} + 1, \tau_l) h(t,\tau_l)^*]. \quad (13)$$

Channel estimation filter of length M is formed by the product of the inversed regularized CIR autocorrelation function matrix shown in (10) and the autocorrelation vector, $r_h(\Delta t,\tau_l)$, between the most recent channel sample $h(t,\tau_l)$ and M previously estimated channel samples. The contents of the multipoint channel estimation filter of length M are used to take a weighted sum of the most recent M channel samples, $\hat{\boldsymbol{h}}_{t,\dots t-M+1;\tau_l}$ to smoothen the channel estimation at time t and delay tap l. The same procedure is applied independently to each CoMP link n assuming the inter-eNB deployment does not contain any spatial correlation between the coordinating points. Autoregressive coefficients of the filter are formed using the minimum mean square error (MMSE) criterion, where the more recent measured channel estimates are given higher weights due to (11), as explained in [17] and [18].

IV. Simulation Results & Performance Analysis

In this section, we evaluate the performance of the proposed CoMP joint transmission aided cell switch off scheme subject to channel estimation errors, $P_{err}(\mu,\sigma)$, and system delays, Δ, according to the system model described in Sec. II for inter-eNB deployment. We consider both high and low mobility scenarios. Time averaged energy efficiency, $\overline{EE}(i)$, and the downlink capacity, $\bar{C}(i)$, for each user location i is calculated according to multi-point channel samples over 1000 TTIs.

We first evaluate the sole effect of system delays, which cause outdated multi-point CSI feedback at the serving eNB, on overall energy efficiency and downlink capacity for high and low mobility scenarios according to 120 km/h vehicular and 6 km/h pedestrian receiver velocities, respectively. Multi-point CSI aggregation and processing delays of 1 ms, 3 ms, 5 ms, 10 ms, and 20 ms are simulated as shown in Fig. 2 and Fig. 3. Users in low mobility conditions that were supposed to have the highest 1% of CoMP set degrees in ideal radio conditions, $P_{err}(0\text{ dB}, 0\text{ dB})$ and $\Delta = 0$ ms, face 32% system energy efficiency and 34% downlink capacity degradation when subject to 20 ms CSI feedback processing delays, whereas users in high mobility conditions suffer 35% $\overline{EE}$ and 37% $\bar{C}$ degradation even under 1 ms overall system delay. This is due to the steep decreasing slope of $R_h(\Delta t,\tau_l)$ in high Doppler scenarios that reduce the coherence time of the channel causing inaccurate CoMP joint transmission clustering even under small system delays. Therefore, users in low mobility conditions start facing performance degradations after Δ =10 ms, when the channel samples become less correlated.

Realistic performance degradations of CoMP schemes with inaccurate clustering are revealed when estimation errors and systems delays are jointly considered according to (2) as shown in Figs. 2 and 3. $\overline{EE}$ and $\bar{C}$ degradations can reach up to 51% and 57% for low mobility users and 64% and 66% for high mobility users, respectively, for $P_{err}(0\text{ dB}, 4\text{ dB})$ and $\Delta = 20$ ms. The users having higher CoMP set degrees in ideal clustering conditions are more sensitive to delays and estimation errors and face major performance degradation due to inaccurate clustering. For instance, average energy efficiency and capacity degradation considering all the users in high mobility conditions for $P_{err}(0\text{ dB}, 4\text{ dB})$ and $\Delta = 20$ ms reached around 9.2 kbits/Joule and 0.9 Mbits/sec; whereas the users with the highest 1% of joint transmission set degrees suffered from 14 kbits/Joule and 3.8 Mbits/sec, respectively. It should be noted that the impacts on $\overline{EE}$ and $\bar{C}$ slightly vary. This can be explained by the energy efficiency metric shown in (5) being dependent to the power consumption of the network which is solely a function of the CoMP set degree rather than the clustering set member choices; whereas, capacity metric is

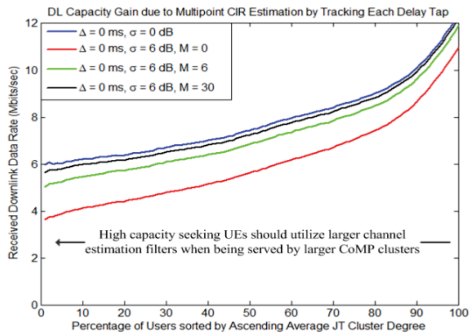

Fig. 4. Capacity increase due to multi-point channel estimation using CSI-RS.

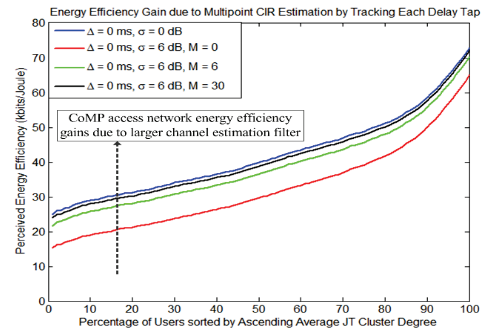

Fig. 5. Energy efficiency increase due to multi-point channel estimation using.

dependent on both the number of the CoMP joint transmission points along with the choice of the points.

We implemented a multi-point auto-regressive MMSE filter that tracks and estimates channel gains at each delay tap l for every CoMP measurement set member n as explained in Sec. III-B. The filter length, M, should be chosen with great attention since unnecessarily long estimation filters increases the complexity of the estimator and since the $R_h(\Delta t, \tau_l)$ decreases with increased time differences, the gain of the filter length increase does not bring much advantage to the estimator. Therefore, single point channel estimators determine the filter memory spans according to the receiver velocity and the coherence time of the channel. Multi-point tracking/estimation filters with a memory spans, M, of 6 and 30 TTIs are simulated and performance increases up to 40% and 52% are observed in low mobility conditions compared to CoMP receivers lacking any memory span, $M = 0$, as shown in Figs. 4 and 5. As a result, multi-point channel estimation filter lengths of LTE-A and beyond devices should be chosen according to both the user velocity and the CoMP measurement set degree since increasing the memory span of the multi-point estimators yields major performance improvements for users with higher joint transmission clustering sets compared to less CoMP dependent users.

V. Conclusions and Future Work

In this paper, we analyzed the performance of LTE-A CoMP schemes in terms of bits/joule energy efficiency and downlink capacity when used jointly with cell switch off technique. Technical challenges of joint transmission scheme for inter-eNB CoMP deployment are analyzed. We demonstrated that the accuracy of the joint transmission set clustering is a key performance determining factor both for the user perceived quality of service in terms of downlink capacity and the overall access network energy efficiency of CoMP supporting networks. It was shown that high mobility scenarios yield major joint transmission clustering inaccuracy due to high Doppler Effect, which can lead up to 64% capacity and 66% energy efficiency degradation in cellular access networks. Appropriate decomposed CIR estimation implemented by tracking each multipath component of measurement set members can tackle the channel estimation errors caused by the scarce CoMP reference symbol structure.

Realistic performance analysis of CoMP schemes is done by jointly considering the channel estimation errors and system delays. We showed that the users served by higher CoMP set degrees are more sensitive to CSI delays and estimation errors which yield more severe performance degradation, therefore, need higher memory spans for multi-point channel estimation filters. Simulation results and proof of concept provided in this work have been used to design CoMP adaptive channel estimation filters and UE aided clustering schemes explained in the patent filings [19] and [20]. Future work will focus on implementing dynamic filter lengths for each point in CoMP measurement set, so that only the points that are more likely to be included in the joint transmission sets are estimated with larger filter memory spans.

References

[1] S. Bahrenburg. *Long Term Evolution from A-Z.* Karlsruhe, Germany: Inacon Gmbh, 2010, pp. 1-107.

[2] 3GPP R3-100162, "Overview to LTE energy saving solutions to cell switch off/on," *3GPP RAN3 Meeting*, Valencia, Spain, Jan. 2010.

[3] T. Abe, "Further enhancements for LTE-Advanced." Internet: http://www.3g4g.co.uk/LteA/, Sept. 2010 [Jan. 31, 2012].

[4] G. Cili, H. Yanikomeroglu, and F. R. Yu, "Cell switch off technique combined with coordinated multi-point (CoMP) transmission for energy efficiency in beyond-LTE cellular networks," in *Proc. IEEE ICC'12 Workshops,* Ottawa, Canada, June 2012.

[5] R. Irmer, H. Droste, P. Marsch, M. Grieger, G. Fettweis, S. Brueck, H.-P. Mayer, L. Thiele, and V. Jungnickel, "Coordinated multipoint: Concepts, performance, and field trial results," *IEEE Commun. Mag.*, vol. 49, no. 2, pp. 102–111, Feb. 2011.

[6] 3GPP TS 36.819 V11.1.0, "Coordinated multi-point operation for LTE physical layer aspects," Dec. 2011.

[7] A. Vergne and S. E. Elayoubi, "Evaluating the capacity gains from coordinated multipoint transmission and reception," in *Proc. IEEE WiOpt'10,* Avignon, France, June 2010.

[8] F. Diehm and G. Fettweis, "On the impact of signaling delays on the performance of centralized scheduling for joint detection cooperative cellular systems," in *Proc. IEEE WCNC'11,* Cancun, Mexico, Mar. 2011.

[9] X. Shang-hui and Z. Zhong-pei, "Coordinated multipoint transmission systems with the clustered super-cell structure configuration," in *Proc. IEEE WiCOM'09*, Bejing, China, Sept. 2009.

[10] L. Scalia, T. Biermann, C. Choi, K. Kozu, and W. Kellerer, "Power efficient mobile backhaul design for CoMP support in future wireless access systems," in *Proc. Infocom'11 Workshop on Green Commun.*, Shanghai, China, Apr. 2011.

[11] International Telecommunication Union, "Guidelines for evaluation of radio interface technologies for IMT-Advanced," Rep. ITU-R M.2135, 2008.

[12] J. Salo, G. Del Galdo, J. Salmi, P. Kyösti, M. Milojevic, D. Laselva, and C. Schneider. MATLAB Implementation of the 3GPP Spatial Channel Model (3GPP TR 25.996) [Online]. http://www.tkk.fi/Units/Radio/scm/ (Jan 2005)

[13] A. J. Fehske, P. Marsch, and G. P. Fettweis, "Bit per joule efficiency of cooperating base stations in cellular networks," in *Proc. IEEE Globecom'10 Workshops,* Miami, FL, Dec. 2010.

[14] 3GPP TS 36.211 V10.4.0, "Physical channels and modulation," Dec. 2011.

[15] L. Somasegaran. "Channel Estimation and Prediction in UMTS LTE." M.Sc. thesis, Aalborg University, Germany, 2007.

[16] A. Leon-Garcia. *Probability and Random Processes for Electrical Engineering.* Reading, MA: Addison-Wesley, 1994, pp. 330-389.

[17] S. Sesia, I. Toufik, and M. Baker. *LTE, the UMTS Long Term Evolution: From Theory to Practice*. Croydon, UK: Wiley, 2011, pp. 121 - 246.

[18] A. Duel-Hallen, "Fading Channel Prediction for mobile radio adaptive transmission systems," *Proc. IEEE*, vol. 95, no. 12, pp. 2299- Dec. 2007.

[19] G. Cili, H. Yanikomeroglu, and F. R. Yu, "CoMP adaptive channel estimation prediction filter design," Filed by Apple Inc., U.S. Patent Application No: 61/674,852 (filing date: July 23, 2012).

[20] G. Cili, H. Yanikomeroglu, and F.R. Yu, "UE anchored down-selection for CoMP joint transmission cluster," Filed by Apple Inc., U.S. Patent Application No: 61/674,854 (filing date: July 24, 2012).