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Published in:
Personal, Indoor and Mobile Radio Communications Symposium 2009

DOI (link to publication from Publisher):
10.1109/PIMRC.2009.5450150

Publication date:
2009

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Wang, Y., Pedersen, K., Navarro, M., Mogensen, P., & Sørensen, T. B. (2009). Uplink Overhead Analysis and Outage Protection for Multi-Carrier LTE-Advanced Systems. In *Personal, Indoor and Mobile Radio Communications Symposium 2009* (pp. 370-374). IEEE Press. https://doi.org/10.1109/PIMRC.2009.5450150

Uplink Overhead Analysis and Outage Protection for Multi-Carrier LTE-Advanced Systems

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***Abstract*—in a multi-component carrier LTE-Advanced system, a user can simultaneously be scheduled on all component carriers (CCs). For the base station to perform radio channel aware packet scheduling, each user ideally has to feedback information corresponding to all CCs. This results in a potentially high amount of uplink overhead. Furthermore, a user in a power limited situation may experience outage because of insufficient power for the required feedback. In this paper we first propose several techniques at different layers for the overhead reduction, as well as protecting the users from being in the outage situation. Afterwards, we show how these techniques can be integrated in a LTE-Advanced system. A weighted proportional fair scheduler is also proposed to maintain good performance with a reduced amount of overhead. Extensive simulation results are presented in the end for analyzing the proper trade-off between performance and overhead reduction and outage protection.**

I. INTRODUCTION

The wireless communication systems have experienced dramatic growth since the introduction of the cellular concepts, and it is foreseen that this growth will continue in the future. In order to meet the increasing capacity requirement for the next generation systems, as specified by International Telecommunications Union – Radio Communication Sector (ITU-R) [1], the 3rd Generation Partnership Project (3GPP) is now evolving the current Long Term Evolution (LTE) system towards the advanced version, the so called LTE-Advanced [2].

LTE-Advanced supports a bandwidth of up to 100MHz, which is much wider than the maximum of 20MHz for Rel'8 LTE [3]. The current spectrum utilization pattern excludes the possibility of assigning a contiguous wideband; thereby it needs to be obtained via carrier aggregation (CA) of individual component carriers (CCs). This leads to multi-carrier LTE-Advanced. In order to maintain the backward compatibility, it has been decided to use independent layer-1 transmission, which contains Link Adaptation (LA) and Hybrid Automatic Repeat request (HARQ) etc, per CC in coherence with the LTE Rel'8 assumptions [4].

With independent layer-1 transmission on each CC, a user has to feedback the Channel Quality Indicator (CQI), which contains information about the channel quality, and the ack/nack per CC, which tells whether or not the reception is correct [5]. The uplink signaling may therefore contributes to a large amount of transmission overhead. When codebook based multiple-input multiple-output (MIMO) transmission is used, the base station also needs the information on which precoding matrix to use (the Precoding Matrix Indicator (PMI)), and the number of supported data-streams (the Rank Indication (RI)). This further increases the uplink overhead [5]. Feeding back this high amount of information for all CCs will also increase the outage probability for the cell-edge users, who are power limited.

The overhead reduction is briefly discussed in [6], where the performance of assigning single or multiple CCs to each user is evaluated and compared against each other. In this paper we first describe several techniques at different layers for the overhead reduction, as well as protecting of the users from being in the outage situation. Afterwards we show how these techniques can be integrated into a LTE-Advanced system. To help improve the cell-edge user performance with reduced feedback information, a weighted frequency domain Proportional Fair (PF) scheduler is proposed. Extensive system level simulations are carried out for evaluating the performance of these techniques.

The rest of the paper is organized as follows: Section II analyzes the overhead reduction with different techniques; How to integrate these techniques in a multi-carrier LTE-Advanced system is discussed in Section III; Section IV describes the simulation methodology and assumptions; Section V presents extensive system level simulation results; Section VI concludes the paper.

II. OVERHEAD ANALYSIS WITH DIFFERENT FEEDBACK REDUCTION TECHNIQUES

As discussed before, the feedback of CQI and ack/nacks for all CCs contributes to a large amount of uplink overhead. Many techniques are developed in order to reduce this overhead as well as the outage probability. These techniques are described in this section.

Single stream transmission is assumed in this study, thereby no PMI or RI feedback. Following the 3GPP specifications [5], we assume that the CQI reporting is carried out with a feedback interval of every 5 Transmission Time Intervals (TTIs), whereas the ack/nack is sent out every TTI if the user is scheduled.

A. Full CQI report with independent ack/nack per CC

This is the reference case with full uplink feedback. The overhead in this case is the largest among all investigated cases.

The CQI reporting mode is Mode 3-0 according to [5], which specifies for each CC, the feedback should contain the wideband CQI value plus the selective CQI reporting for each Physical Resource Block (PRB) group. According to [7], each PRB is constituted with 12 consecutive sub-carriers. We assume that one PRB group contains 3 neighboring PRBs. In a 10 MHz bandwidth, there are 50 PRBs in total, giving 17 PRB groups. With 2 dB resolution for the CQI reporting, 4 bits are enough for quantification of up to 32 different levels [8]. The total required number of bits for the full CQI reporting is:

$$N \times (4 \times 17 + 4) = 288 \cdot$$

where N is the number of aggregated carriers in a LTE-Advanced system. In this study we assume $N=4$. In each TTI, on average $288/5 = 57.6$ bits are required for full CQI reporting. As to ack/nack signaling, one bit is sufficient for one data-stream. The total required number of bits for the feedback of both full CQI and independent ack/nacks is:[1]

$$57.6(\text{CQI}) + 4(\text{ack/nack}) = 61.6 \cdot$$

B. CC selection

Although the LTE-Rel'8 users can access on only one CC, the LTE-Advanced users are capable of operating over all CCs. However, considering the uplink power limitation, it may be preferable to allocate some cell-edge users with only one CC, rather than allocate them with too many CCs that they cannot support. CC selection is a technique that based on some certain quality measurement, e.g. path loss, to select single or multiple CCs for the users.

By operating on only one CC, the uplink overhead is reduced by a factor of N. Only 15.4 bits are required on average per TTI for this case.

C. HARQ bundling

For users that are scheduled on all CCs, there will be separate HARQ processions per CC. However, it is possible to use a single ack/nack for the transmission over these CCs. This is called HARQ bundling. Originally, HARQ bundling was proposed for Time Division Duplexing (TDD) systems to combine the ack/nacks in time domain [5]. It has been shown that a reasonable good performance can be achieved with much reduced ack/nack overhead [9]. Applying HARQ bundling in frequency domain across multiple CCs, only 1 ack/nack is required for all 4 transport blocks. As a result, 58.6 bits are required in total.

D. CQI compression

Other than HARQ bundling, there are other ways to reduce uplink overhead for the users that are scheduled on multiple CCs. Here we propose a simple approach that compresses the CQI values for the multiple CCs. It works as follows:

1. Calculate the wide band CQI for each user on all CCs.
2. For the CC with the highest wideband CQI value, feedback both the wideband CQI and the frequency selective CQI values. This means, one CQI value for each PRB group.
3. For the rest of the CCs with low wideband CQI, only one CQI value is fed back per CC, which is the wideband CQI.

The required number of bits per TTI is:

$$(4 \times 17 + 4 \times N)/5 + 4 = 20.8 \cdot$$

E. Both CQI compression and HARQ bundling

To further reduce the uplink overhead, it is also possible to combine HARQ bundling and CQI compression together. In this case, one ack/nack is sent back for transmission over 4 CCs, and the full CQI report is available only for one CC. the number of required bits for feedback is:

$$(4 \times 17 + 4 \times N)/5 + 1 = 17.8 \cdot$$

Fig. 1 summarizes the overhead reduction using the different transmission schemes, as compared with full CQI reporting and independent ack/nack over all CCs. From this figure we can see, by assigning only 1 CC for the cell-edge users, the highest amount of overhead reduction (75%) can be obtained. Next is when both HARQ bundling and CQI compression are enabled, with a reduction of 71%. With only CQI compression, the reduction is 66%, which is slighter lower than the previous two cases. HARQ bundling gives only 5% overhead reduction, which is much lower than what the other three can offer.

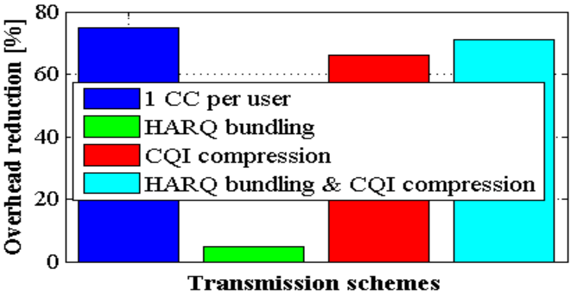

Fig. 1. Feedback overhead reduction with different techniques. Reference case is full CQI reporting and independent ack/nack on each CC.

III. INTEGRATION OF THE OVERHEAD REDUCTION TECHNIQUES IN LTE-ADVANCED

Having described the feedback reduction techniques in Section II, let us now look into the problem of how to integrate them in a LTE-Advanced system.

The current LTE systems use path loss based power control in the uplink, which means the uplink transmit power is proportional to the path loss value in decibel scale [5]. Therefore we also use the path loss value between one user and the serving base station as the indicator for enable/disable the proposed techniques.

Operating on only one CC reduces the overhead more than any other techniques, it should be used for the users with extremely high path loss. The second highest reduction is obtained by combining HARQ bundling with CQI compression. This is suitable for users that are able to transmit over multiple CCs, but still do not have enough power to feedback the full information. As channel quality further improved, CQI compression alone will be enough to prevent the users from being power limited. Finally, for users with small path loss, and hence need very little overhead reduction, HARQ bundling can be used. No protection is needed for cell-center users who are capable of feeding back the full information for all CCs. It is also worth mentioning that LTE-Rel'8 users should be assigned with only one CC, because of their capability constraints.

The threshold values for enabling the above mentioned techniques are: TS_1 for selecting only one CC to transmit; TS_2

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[1] Here the calculation is done for the raw number of required bits. In reality, the ack/nacks have much more strict Block Error Rate (BLER) target than the CQI values, leading to higher cost at the physical layer.

for CQI compression; TS_3 for HARQ bundling. Based on the discussion before, we have the following relationship for the thresholds: $TS_1 > TS_2 > TS_3$. If a user has path loss value lies in between TS_2 and TS_1, both HARQ bundling and CQI compression will be used.

When the feedback reduction techniques are used, it is straightforward to think that users with reduced feedback will sacrifice in terms of achievable throughput. In fact, users with poor channel quality are already in a disadvantaged situation than those with good channel quality, it is thereby not preferable to further decrease their performance. In order to maintain the cell-edge user throughput, we propose a weighted PF scheduler.

A frequency domain packet scheduler allocates resource to a user that maximizes a certain metric [10]:

$$k_{i,j} = \arg\max_{k} \{Metric_{k,i,j}\} \tag{1}$$

where $k_{i,j}$ is the selected user on the i^{th} CC at the j^{th} PRB group. The traditional way to calculate the PF metric is [10]:

$$Metric_{k,i,j} = \frac{R_{k,i,j}}{\tilde{R}_{k,i}} \tag{2}$$

with $R_{k,i,j}$ is the estimated throughput for user k on the i^{th} CC at the j^{th} PRB group and $\tilde{R}_{k,i}$ is the average throughput for user k on the i^{th} CC. In our pervious study we have found that, when users are assigned with different number of CCs, the independent packet scheduling per CC gives poor coverage performance. A solution to improve the coverage is to take the past user throughput over all aggregated CCs into consideration. Furthermore, by weighting the scheduling metric with a factor β_x ($x \in [1,2,3]$, see Fig. 2), the scheduling priority for the users with uplink overhead / outage reduction can be increased, and the new scheduling metric is calculated as:

$$Metric_{k,i,j} = \frac{R_{k,i,j}}{\sum_{i=1}^{N} \tilde{R}_{k,i}} \prod_{x=1}^{3} \beta_x^{I_x} \tag{3}$$

In (3), β_x is the weighting factor for the proposed technique. I_x equals 1 if the corresponding technique is used. Otherwise, it equals zero.

Fig. 2 shows how these techniques work together in a LTE-Advanced system. When a new user arrives, it is categorized according to the terminal type, i.e. a LTE-Advanced or a LTE-Rel'8 user. A LTE-Rel'8 user supports the transmission on only one CC, thereby the base station needs to select a proper CC, and assign it to the user. Depending on the user path loss value, a LTE-Advanced user may be assigned with only one CC, or multiple CCs but with different overhead reduction techniques. After these steps, the traditional LTE Rel'8-like transmissions [4, 11] will happen on each CC.

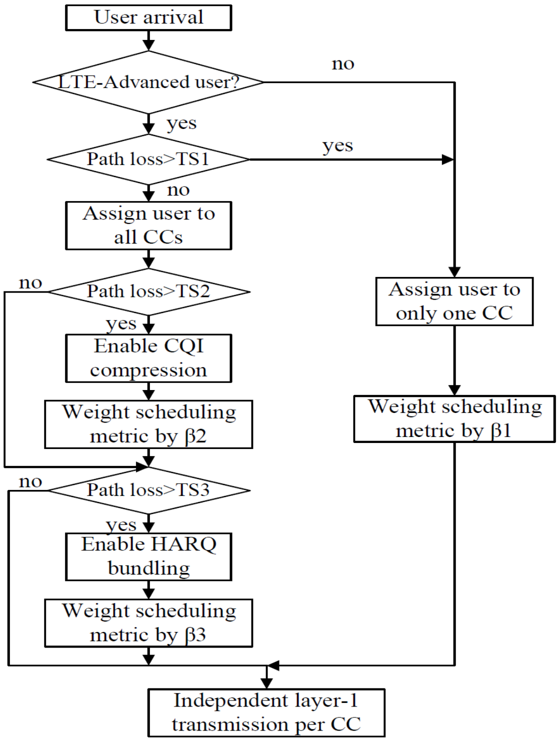

Fig. 2. Uplink feedback reduction techniques in different layers of a multi-component carrier LTE-Advanced system. The packet scheduling metric is also weighted so as to improve the performance of the cell-edge users.

IV. SIMULATION METHODOLOGY AND ASSUMPTIONS

TABLE I
SYSTEM SIMULATION SETTINGS

Parameter	Setting / description
Test scenario	3GPP Macro-cell case #1 (19 sites, 3 cells per site)
Carrier frequency	2 GHz
Aggregation configuration	4 CCs, with 10MHz per CC
Number of PRBs per CC	50 (12 subcarriers per PRB)
Sub-frame duration	1 ms (11 OFDM data symbols plus 3 control symbols)
Modulation and coding schemes	QPSK (1/5 to 3/4) 16-QAM (2/5 to 5/6) 64-QAM (3/5 to 9/10)
User receiver	2-Rx Interference Rejection Combining
HARQ modeling	Ideal chase combining
Max. number of retransmissions	4
Ack/nack & CQI feedback delay	6 ms, corresponds to 6 TTIs
Ack/nack feedback interval	1 ms
CQI frequency domain resolution	1 CQI per 3 PRBs
CQI reporting error	Log normal with 1dB std.
CQI reporting resolution	2 dB
CQI reporting interval	5 ms
Time domain PS	None (the eNB is able to schedule up to 20 users simultaneously)
Frequency domain PS	(Weighted) Proportional fair
1st transmission BLER target	10%
Number of UEs per cell	10
Traffic type	Full buffer

The performance of the algorithms is evaluated in a quasi static downlink multi-cell system level simulator that follows the LTE specifications defined in [12], including detailed implementations of layer-3 CC selection, layer-2 PS, HARQ and LA functionalities. The simulation scenario is Macro-cell case #1 as defined in [7]. The simulation parameters are summarized in Table I. The link to system mapping is based on the exponential effective metric model [13].

Note that, we aggregate 4 CCs, each of 10MHz to form a wide bandwidth of 40MHz. Only LTE-Advanced users are considered, which means, all users have the ability to be scheduled on multiple CCs. Simulation campaigns are conducted with 40 simulation runs (5.0 seconds in each run) with constant number of 10 users per cell. Multiple simulation runs are required for this traffic model in order to get sufficient statistics, since the traffic model is static in the sense that the 10 users per cell are active all the time.

Two kinds of throughput measures are used in our study as performance indicators:

- Cell throughput: Average throughput per cell, i.e. equals the summation of the user throughput in each cell.
- Coverage: This is the 5^{th} percentile worst user throughput, over the simulated users.

V. SIMULATION RESULTS

Extensive system level simulations are carried out for the evaluation of the downlink performance with the overhead reduction techniques and the results are presented in this section.

A. CC selection, HARQ bundling and/or CQI compression for all users

We start by enabling the proposed techniques for all users. Because all users are transmitting with reduced uplink feedback, the maximum overhead reduction can be achieved with the lowest downlink performance. The results are summarized in Fig. 3 and Fig. 4 for average cell throughput and coverage, respectively.

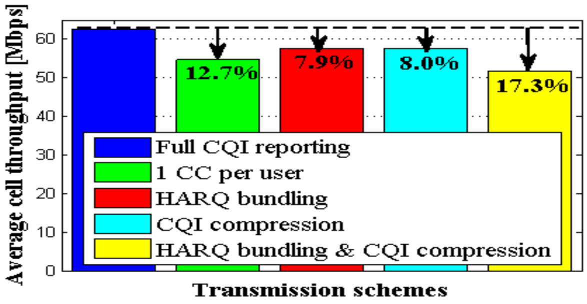

Fig. 3. Average cell throughput for different uplink overhead reduction techniques, assuming full protection to all users.

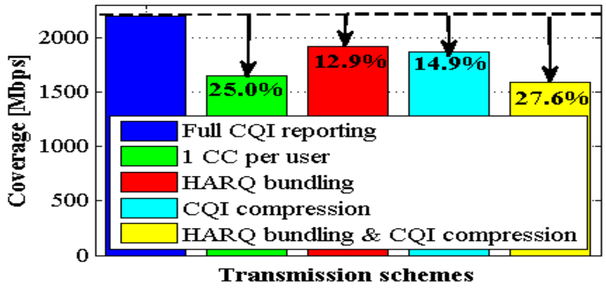

Fig. 4. Coverage performance for different uplink overhead reduction techniques, assuming full protection to all users.

From these results we observe that HARQ bundling has the least degradation in downlink performance. In terms of average cell throughput, it is only 7.9% lower than with full feedback; In terms of coverage, the loss is 12.9%. The Second best downlink performance is obtained via CQI compression, which has almost the same performance as HARQ bundling in cell throughput. Its coverage is 14.9% lower than full feedback, which is 2% more than the losses with HARQ bundling. Combine HARQ bundling with CQI compression results in almost a linear summation in the performance degradation, which is 17.3% in cell throughput and 27.6% in coverage. This performance is even worse than assigning only 1 CC to each user.

Although HARQ bundling provides the best downlink throughput among the proposed techniques, we can see from Fig. 1 that it has the least amount of uplink overhead reduction. CQI compression, on the other hand, offers almost as good the downlink performance as HARQ bundling, but with much higher reduction of the uplink overhead. Combine HARQ bundling and CQI compression has worse performance than assigning 1 CC to each user in both downlink performance and uplink overhead reduction, thereby should never be used.

B. CC selection, HARQ bundling and/or CQI compression for cell-edge users only

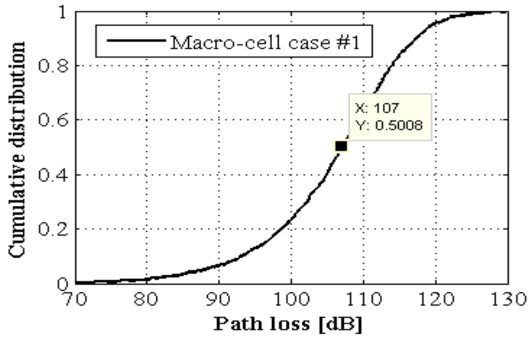

Fig. 5. Path loss distribution in a Macro-cell case #1 scenario.

As discussed in Section III, only cell-edge users that are in a power limited situation need to be protected from power outage by reducing the uplink transmission. With the path loss distribution in a Macro-cell case #1 shown in Fig. 5, we select a threshold value of 107 dB to offer protection to half of the users. Note that the different techniques are evaluated individually with the same threshold value. However, the amount of overhead reduction and the protection levels are different for each of them.

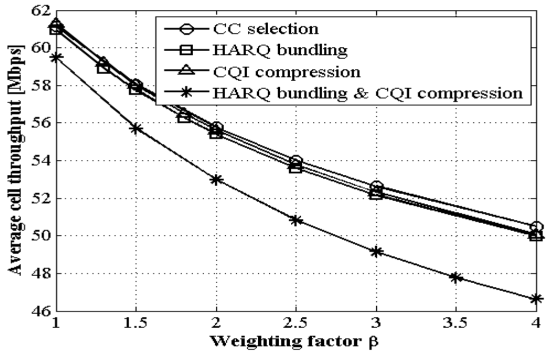

Fig. 6. Average cell throughput for different uplink overhead reduction techniques with weighted packet scheduling metric. 50% users are protected.

We have seen before that by reducing the uplink overhead, the loss in coverage is much larger than that in average cell throughput. In order to improve the coverage, the scheduling priority for the cell-edge users should be increased. Fig. 6 shows the average cell performance for different techniques when 50% of the users are protected by the feedback reduction techniques. The packet scheduler is performed in layer-2 with the weighted PF. The corresponding coverage performance is shown in Fig. 7.

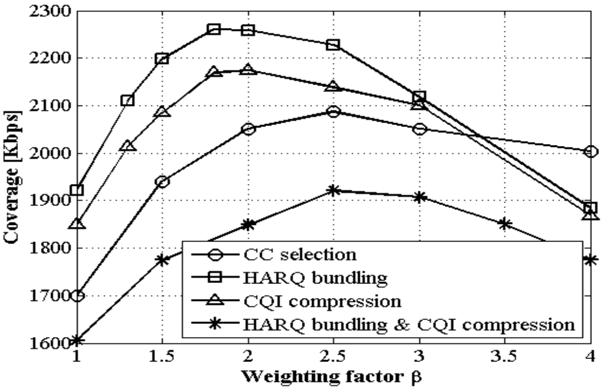

Fig. 7. Coverage performance for different uplink overhead reduction techniques with weighted packet scheduling metric. 50% users are protected.

The following observations are made from Fig. 6 and Fig. 7:

1. By increasing the weighting factor, there is a continuous loss in average cell throughput. This is because the good users are getting less and less resources for transmission.
2. In terms of coverage, increasing β up to a certain value will provide gain, as poor users are prioritized and they get more resources than with a low β value. However, a further increase of β beyond this level (around 2.0~2.5) will results in reduced coverage performance. The reason is: increasing the weighting factor will cause the poor users to be scheduled even if their channel quality is poor. It thereby decreases the frequency domain packet scheduling gain as the diversity is not fully exploited. When the loss in frequency domain diversity is larger than the gain in additional transmission resources, even the coverage performance will decrease.
3. Combine HARQ bundling with CQI compression provides the worst performance among the investigated techniques. CQI compression seems to be the most promising technique for reducing the uplink overhead with tolerable downlink loss. With a weighting factor of 2.0, CQI compression suffers from only 1% loss in coverage and 11% loss in cell throughput, as compared to the case when all users are feeding back the full information.

VI. CONCLUSION AND FUTURE WORK

In this paper we have studied the possibility of reducing the uplink feedback overhead and prevent the cell-edge users from being in the outage situation.

The downlink performance for the proposed techniques is investigated via extensive system level simulations. Based on the simulation results, the adaptive CQI compression technique, which compresses the CQI feedback in some of the CCs, achieves about the highest overhead reduction without penalizing too much the downlink performance. Together with CQI compression, it reduces the uplink overhead by 66% for half of the users with only 11% loss in downlink cell throughput and nearly no loss (only 1%) in coverage.

As the overall recommendation, we suggest to schedule users with very poor channel quality on a single CC. Other users with better channel quality, but who still suffer from uplink power outage, can be handled appropriately using the compressed CQI feedback. In order not to suffer from reduced coverage performance in this case, the weighted packet scheduler should be used in combination with the feedback reduction techniques.

In this paper, we have evaluated the performance for the proposed techniques individually. In future work, we would like to combine these techniques, and also consider other CQI compression techniques. Secondly, the downlink performance and uplink overhead under different traffic loads and traffic models, etc. is subject for further study. Finally, the study needs to be updated according to new LTE-Advanced standardization decisions to be fully applicable for that particular system.

ACKNOWLEDGMENT

The authors are grateful to Daniela Laselva, Jens Steiner and Mads Brix of Nokia-Siemens-Networks for their valuable suggestions and help in carrying out this study.

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