Channel Measurement and Channel Quality Reporting in LTE-Advanced Relaying Systems

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***Abstract*—In 3GPP LTE-Advanced, relaying is considered as an important means for extending cell coverage and improving capacity. Channel measurement with the introduction of backhaul subframe needs to be carefully designed to achieve the performance advantage of relay. In this paper, we propose a simple yet effective channel measurement and corresponding channel quality reporting scheme for an inband relaying system based on subframe grouping. The proposed channel measurement scheme estimates the interference level at different subframes and helps scheduler make decisions in different subframes. Our evaluations show that the proposed framework can improve the cell average and cell-edge user performance, for different deployment scenarios.**

I. Introduction

A. Background

Relaying is considered for 3GPP LTE(Long Term Evolution)-Advanced as a tool to improve for instance the coverage of high data rates, group mobility, temporary network deployment, the cell-edge throughput and/or to provide coverage in new areas [1].

Relaying implies that the terminal communicates with the network via a low-power relay node that is wirelessly connected to a donor cell using the LTE radio-interface technology. From a terminal point of view, the relay node will appear as an ordinary cell. In conjunction with relaying, the terms backhaul link and access link are often used to refer to the eNB(evolved Node B)-relay connection and the relay-UE(User Equipment) connection respectively. The cell to which the relay is connected using the backhaul link is known as the donor cell and the donor cell may, in addition to one or several relays, also serve UEs not connected via a relay.

With respect to the relay node's usage of spectrum, its operation can be classified into *inband* and *outband* types. Inband relaying implies that the eNB-relay link shares the same carrier frequency with relay-UE links. Outband relaying implies that the backhaul link does not operate in the same carrier frequency as access links.

A "Type 1" relay node is an inband relaying node which has the following characteristics [2]. It controls cells, each of which appears to a UE as a separate cell distinct from the donor cell. The cells shall have their own Physical Cell ID and the relay node shall transmit its own synchronization channels, reference symbols, and so on. In the context of single-cell operation, the UE shall receive scheduling information and HARQ feedback directly from the relay node and send its control channels to the relay node.

For Type 1 relay, due to the relay transmitter causing interference to its own receiver, simultaneous eNB-to-relay and relay-to-UE transmissions on the same frequency resource may not be feasible unless sufficient isolation of the outgoing and incoming signals is provided. One possibility to handle the interference problem is to operate the relay such that the relay is not transmitting to terminals when it is supposed to receive data from the donor eNodeB (DeNB), i.e. to create "gaps" in the relay-to-UE transmission. These "gaps" during which terminals are not supposed to expect any relay transmission can be created by configuring MBSFN (Multicast and Broadcast Single Frequency Network) subframes as exemplified in Fig.1. eNB-to-relay transmissions can be facilitated by not allowing any relay-to-UE transmissions in some subframes. These subframes are called *backhaul subframes*. Subframes in which relay-to-UE transmissions are allowed are called *access subframes*.

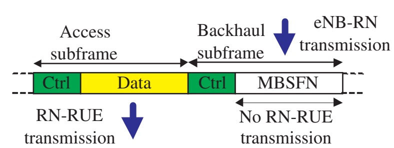


Fig. 1. Example of normal subframe and MBSFN subframe at relay node

There is another type of subframe named Almost Blank Subframe (ABS) which contains only control channel information and some important reference signals in the subframe. This "muted" subframe configured at eNB is used for interference avoidance from macro cell to small cells (such as picocell, femto-cell, or relays) in a heterogeneous network as a way to do time-domain inter-cell interference coordination.

Channel and interference information is essential in making channel-dependent scheduling decisions and choosing proper MCS (Modulation and Coding Scheme) for each UE. Besides, due to the smaller coverage area of the relays and their high deployment density, interference management between these relays becomes more important to improve the network capacity and the service quality to the users. To facilitate efficient interference management and radio resource reuse among the relays, it is vital to provide relevant information regarding the interference caused by the relays and the eNBs to each other. Different macro cells may use different backhaul or ABS subframe configurations for purpose like resource allocation according to traffic, or interference coordination.

Interference estimation and channel quality reporting within non-uniform backhaul/ABS subframe configuration environment needs careful design to match the actual interference condition.

B. Related Work

Due to the fact that Type 1 relay is defined in recent 3GPP LTE release 10, only very few work from academia or industry addresses the problem of interference measurement and channel quality reporting in LTE-advanced relaying systems. In [3], a bitmap sent by eNB to UE may indicate whether each subframe covered by the bitmap is of a first type or second type. A UE may perform channel estimation or measurement for the subframes of one type and may skip channel estimation or measurement for the subframes of the other type. Backhaul subframe configurations may vary from different relays in the neighboring area. The proposed scheme in [3] may work well with uniform backhaul subframe configurations, but may not work well in situation where each cell has independent backhaul/ABS subframe configuration.

In this paper, we propose a bitmap based subframe grouping method to measure interference and report channel quality. This method will address the interference estimation problem under non-uniform backhaul/ABS subframe configuration condition.

II. System Design

A. System Model

The following describes the interference model used in this paper. During backhaul subframes, DeNBs may also schedule data for macro UEs (MUEs, UEs served by the DeNB) while relay nodes (RNs) are in receive mode. The interference in these backhaul subframes are from eNBs only. During access subframes, eNBs transmit to MUEs and RNs transmit to relay UEs (RUEs). The interference in these access subframes are from both eNBs and RNs. The interference model is better illustrated in Fig.2. The desired links and interference links are depicted for during backhaul and access subframes respectively. For the simplicity of illustration, backhaul subframe configurations are the same for both eNBs.

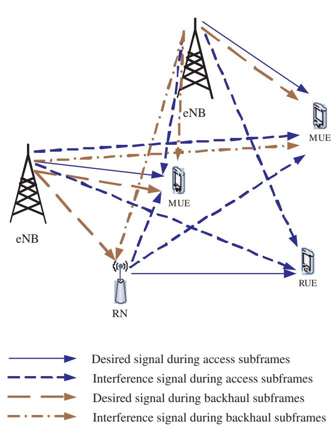


Fig. 2. Interference model for backhaul and access subframes

B. Protocol Design

We consider a relaying system with non-uniform backhaul/ABS subframe configurations. The procedure of the channel measurement and channel-state reporting scheme is as follows:

A relay is signaled by its DeNB about the backhaul/ABS subframe configurations of neighboring cells. This signaling can be done by RRC (Radio Resource Control) signaling or eNB broadcasting. After a UE is connected to a cell, it reports to its serving station (relay or eNB) the dominant interferers based on the received signal strength. Knowing UE's dominant interferers and the subframe configuration information, relay or eNB estimates the interference condition for each subframe. It then puts the subframes into groups with different interference levels. Since the subframe configuration has periodicity, each group of subframes can be represented by a bitmap with fixed length. The detailed algorithm will be given later. Relay or eNB then sends the bitmaps to each UE.

UE performs channel measurement and interference estimation with the use of downlink reference signal in subframes indicated by the received bitmaps. The measured results, for example, the signal-to-noise-and-interference ratio, are then averaged in each group according to the bitmaps. Each averaged result will be translated into one channel-state report, including a combination of RI (Rank Indication), PMI (Precoding Matrix Indicator), and CQI (Channel Quality Indicator). One may refer to [4] for details of the UE procedure for reporting CSI (Channel State Information). Next, multiple sets of channel-state reports are sent to the serving station.

Since interference level has periodicity, relay or eNB makes scheduling decision based on the CSI feedback for each subframe. Specifically, when doing scheduling at each subframe, the eNB or relay chooses the CSI feedback corresponding to the subframe position in the reporting period.

The purpose of this new channel measurement and channel quality reporting design is to match the interference condition in different subframes.

C. Algorithm

Here we use a general algorithm to further describe the subframe grouping method in this enhanced interference measurement and channel-state reporting scheme in a relaying system.

Assume each UE has 2 dominant interferers, namely I_1 and I_2. In this algorithm, only serving station and dominant interferers are concerned and indexed. We use notation $\mathrm{eNB_i}$ (i is the eNB ID, $0 \le i \le 2$) and $\mathrm{RN_{ij}}$ (i represents the DeNB ID, j is the RN ID inside the donor cell, $0 \le j \le 2$) to represent these nodes. The concerned UE can be classified into MUE or RUE depending on the type of its serving station. If it's MUE, assume the serving station is called $\mathrm{eNB_0}$. If it's RUE, assume this RUE is served by a relay named $\mathrm{RN_{00}}$ therefore the DeNB of this relay is $\mathrm{eNB_0}$. The dominant interfering nodes are possibly any combination of neighboring eNBs and RNs. Let $\mathbf{\Omega_b}$ and $\mathbf{\Omega_r}$ be the sets of dominant interfering eNBs and dominant interfering RNs respectively.

Let BM_i^B represent the bitmap of backhaul subframe configuration of $\mathrm{eNB_i}$ with bit '1' indicating a downlink backhaul subframe and '0' otherwise. BM_i^A represents the bitmap of ABS subframe configuration of $\mathrm{eNB_i}$ with bit '1' indicating an ABS subframe and '0' otherwise. Both bitmaps are valid across the macro cell and the relay cells that are managed by this DeNB. In any scenario, there will be at most three possibilities about the different interference levels at the UE, explained below.

By doing some calculations on the bitmaps at the serving station ($\mathrm{eNB_0}$ or $\mathrm{RN_{00}}$), the subframes where this UE experiences different interference levels can be given as follows:

- interfered by I_1 only: $\overline{BM_0^x}\&\overline{BM_k^y}\&BM_m^z$
- interfered by I_2 only: $\overline{BM_0^x}\&BM_k^y\&\overline{BM_m^z}$
- interfered by both I_1 and I_2: $\overline{BM_0^x}\&\overline{BM_k^y}\&\overline{BM_m^z}$

where $\bar{\cdot}$ means the bitwise NOT of $\cdot$;

"&" means bitwise AND;

k is the index of I_1 if $I_1 \in \mathbf{\Omega_b}$, or the index of the DeNB of I_1 if $I_1 \in \mathbf{\Omega_r}$;

m is the index of I_2 if $I_2 \in \mathbf{\Omega_b}$, or the index of the DeNB of I_2 if $I_2 \in \mathbf{\Omega_r}$;

$$x \rightarrow \begin{cases} A, \text{if concerned UE is MUE} \\ B, \text{if concerned UE is RUE} \end{cases}$$

$$y \rightarrow \begin{cases} A, \text{if } I_1 \in \mathbf{\Omega_b} \\ B, \text{if } I_1 \in \mathbf{\Omega_r} \end{cases}$$

$$z \rightarrow \begin{cases} A, \text{if } I_2 \in \mathbf{\Omega_b} \\ B, \text{if } I_2 \in \mathbf{\Omega_r} \end{cases}$$

Afterwards the serving station ($\mathrm{eNB_0}$ or $\mathrm{RN_{00}}$) sends 3 calculated bitmaps, namely $\overline{BM_0^x}\&\overline{BM_k^y}\&BM_m^z$, $\overline{BM_0^x}\&BM_k^y\&\overline{BM_m^z}$, and $\overline{BM_0^x}\&\overline{BM_k^y}\&\overline{BM_m^z}$, to the UE. In the above algorithm, $\rightarrow$ means "is replaced by".

For UE, one bitmap indicates one group of subframes during which the CSI values are averaged. UE needs to measure interference at subframes covered by all bitmaps. It then feedbacks three averaged CSI reports for three group of subframes corresponding to the received bitmaps, to the serving station over the reporting period. If feedback overhead is a concern, two groups can be combined into one to reduce the number of feedback groups.

In some cases, some of the bitmap results calculated above will be all zeros. In this case, there is no need for the serving station to send out this bitmap and the number of groups of subframes for measurement and reporting is reduced.

For TDD (Time Division Duplexing) systems, the bitmap length is the number of down link subframes in backhaul/ABS subframe configuration periodicity (10ms), which varies from different TDD UL-DL (uplink-downlink) configurations.

III. Case Study

In this section we give a case study of the channel measurement and CSI reporting procedure of an RUE for scenario where $I_1 = \mathrm{eNB_0}$ and $I_2 = \mathrm{eNB_1}$, in FDD (Frequency Division Duplexing) mode. Fig.3 shows the deployment of this scenario. In the 8ms downlink subframe structure, "B" represents downlink backhaul subframe, and "A" represents ABS subframe.

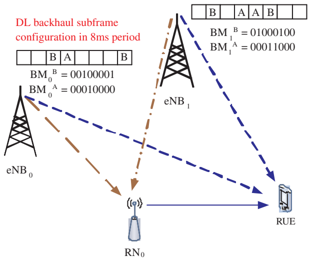


Fig. 3. Scenario where dominant interferers are DeNB and one neighboring eNB

As described in previous section by doing some calculations on the bitmaps at $\mathrm{RN_{00}}$, the subframe sets where RUE experiences different interference levels can be given as follows:

$\overline{BM_0^B}\&\overline{BM_0^A}\&BM_1^A = 00001000$, so RUE experiences interference which comes only from $\mathrm{eNB_0}$ at subframe 4.

$\overline{BM_0^B}\&BM_0^A\&\overline{BM_1^A} = 00000000$, so there is no subframe where RUE experiences interference from $\mathrm{eNB_1}$ only. This is a special case.

$\overline{BM_0^B}\&\overline{BM_0^A}\&\overline{BM_1^A} = 11000110$, so RUE experiences interference from both $\mathrm{eNB_0}$ and $\mathrm{eNB_1}$ at subframe 0,1,5,6.

$\mathrm{RN_{00}}$ sends 2 bitmaps (00001000 and 11000110) to RUE. RUE measures channel at two groups of subframes (4) and (0, 1, 5, 6), then sends two averaged CSI values to $\mathrm{RN_{00}}$.

Relay scheduler chooses the correct CSI feedback at each subframe from the group of CSI feedbacks based on the subframe position it schedules for. In this way the grouped CSI feedbacks help the relay scheduler have a better estimation on the interference level thus choose suitable transmission parameters.

If two dominant interferers are considered, there are at most three groups of CSI feedback during one CSI reporting period. If assuming more than two dominant interferers, similar approach can be applied, only the number of bitmaps for channel measurement and channel-state reporting will be increased. From a practical point of view, assuming more than two dominant interferers seems unnecessary.

IV. Simulations

To evaluate our proposed relay channel measurement and channel quality reporting scheme, numerous C++ based system level simulations are carried out against the related art for comparison. In each scenario, two different schemes are simulated and results are compared. One scheme is the one in [3] where UE assumes each cell has the same backhaul/ABS subframe configuration. The measurement method then treats each neighboring cell in a uniform manner. We call this scheme "Uniform" scheme. The other scheme is our proposed scheme based on subframe grouping. This scheme is called "Grouped" scheme.

We have evaluated downlink performance of in-band Type 1 relay with frequency reuse factor 1. The cellular layout in simulation is a hexagonal grid with 7 sites, 3 sectors per site, wrap around. We simulate scenarios where there are 1, 2, 4 relays per sector, respectively. In each simulation drop 15 UEs are randomly distributed geographically in every sector. A UE is associated to macro eNB or relay with the highest received signal strength. The RN placement method is shown in Fig.4 assuming there are 4 RNs in each sector. Relays are placed close to eNB antenna boresight. From some preliminary simulation tests, it is found that when the eNB-to-relay distance is about 0.4-0.45ISD (inter-site distance), the performance gain of deploying relays over a non-relay system is more significant. Therefore we choose 0.45ISD as the eNB-RN distance in our simulations. Relay site planning is realized by adding bonus to path loss formula [2].

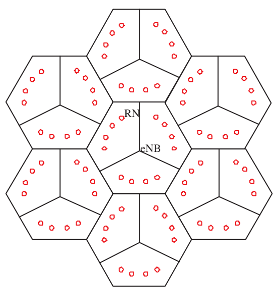


Fig. 4. Relay placement

The traffic model used are full buffer and FTP traffic at eNB side. In FTP traffic model, FTP file size of 500KB is used and the poisson arrival rate is 2.5 per cell. When a file arrives, a user in this cell is randomly chosen to download this file. A relay only forwards correctly decoded packets to its RUEs. The duplex method in simulation is TDD with configuration 1. There are two downlink backhaul/ABS configurations (configuration 1a and configuration 1b) for all the cells. The detailed subframe configurations are described in Table I[5]. Each cell randomly picks one relay subframe configuration between 1a and 1b with some probability. More simulation parameters are shown in Table II. Due to limited space, other parameters like path loss, shadowing, antenna pattern and so on are not listed here and they can be found in [2].

TABLE I
TDD BACKHAUL/ABS SUBFRAME CONFIGURATIONS

subframe:	0	1	2	3	4	5	6	7	8	9
config 1a:	D	S	U	UB	DB	A	S	U	UB	DB
config 1b:	D	S	U	UB	DB	D	S	U	UB	DB

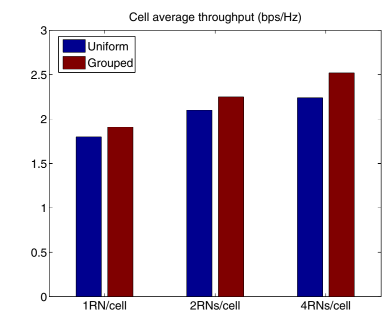
D - DL access; U - UL access; DB - DL backhaul;
UB - UL backhaul; S - special subframe; A - ABS

We have simulated two different scenarios. In scenario 1, full buffer traffic model is used. The ratio of cells with configuration 1a to those with configuration 1b is 4:1. Subband CQI feedback is used. The average cell spectrum efficiency and cell-edge spectrum efficiency represented by 5%ile user throughput are shown in Fig.5.

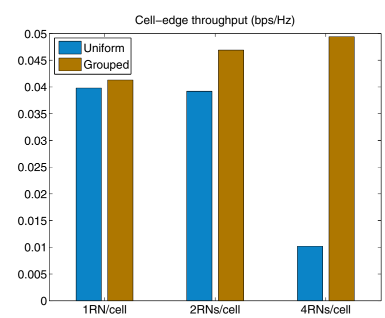
In scenario 2, FTP traffic model is used. The ratio of cells with configuration 1a to those with configuration 1b is 1:1. Wideband CQI feedback is used. The average cell spectrum efficiency and cell-edge spectrum efficiency represented by 5%ile user throughput are shown in Fig.6.

TABLE II
SIMULATION PARAMETERS

Parameter	Assumption/Value
Simulation case	3GPP Case 1 (ISD=500m)
Channel model	SCM
Total eNB TX power	46dBm
Total relay TX power	30dBm
Carrier frequency	2GHz
Bandwidth	10MHz
Thermal noise density	-174dBm/Hz
Antenna gain	eNB: 14dBi; RN: 5dBi; UE: 0dBi
Number of antennas	eNB: 2TX; RN: 2TX, 2RX; UE: 2RX
UE speed	3km/h
Control channel overhead	3 symbols
HARQ	IR, maximum retransmission times: 6
CQI feedback delay	6ms
Scheduling algorithm	PF
Link to system level interface	MIESM



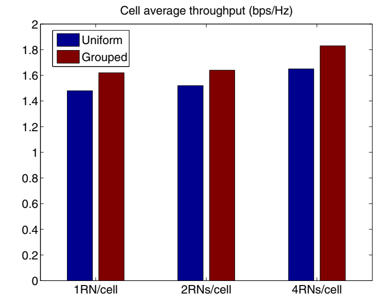
(a) Cell average throughput



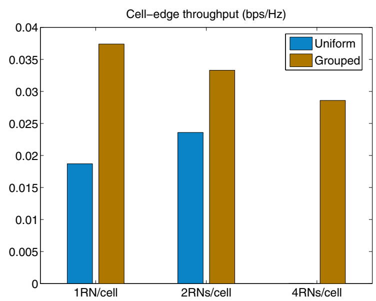
(b) Cell-edge user throughput

Fig. 5. Performance results of scenario 1

In each scenario, the cell average throughput of both schemes increases as the number of the relay nodes increase in a cell. In addition, the cell average throughput gain of the “Grouped” scheme over “Uniform” scheme becomes more obvious as the number of relay nodes increases in a cell. This is due to the fact that multiple relays in a donor cell lead to more interfering nodes. The effect of the unevenness of the

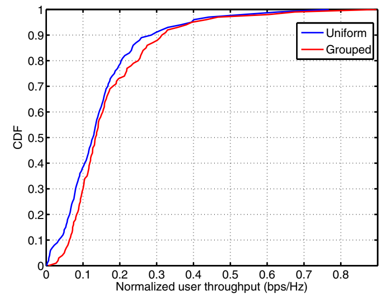


(a) Cell average throughput

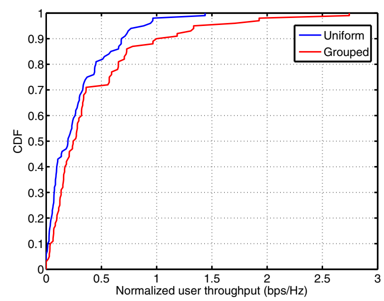


(b) Cell-edge user throughput

Fig. 6. Performance results of scenario 2



(a) Full-buffer traffic



(b) FTP traffic

Fig. 7. CDF of the normalized user throughput for different channel measurement schemes

interference level of neighboring cells becomes more obvious. Therefore the interference measurement based on subframe grouping method can be more effective. With regard to cell-edge user throughput, “Grouped” scheme has substantial gain over the “Uniform” scheme. The “Grouped” scheme has a relatively constant performance with the increase of relay nodes in a cell, while the performance of “Uniform” scheme is very unstable. In “Uniform” scheme, edge UEs suffer most from the inaccurate estimation of interference, so the edge UEs have very low throughput (even zero).

The CDF of the normalized user throughput for two different relay interference measurement schemes are also plotted for 4RNs/cell with full-buffer traffic and FTP traffic, respectively in Fig.7. In these figures, the “Grouped” scheme has a relatively better performance. “Uniform” scheme has relatively much poorer performance for lower percentile users especially when traffic load gets large (full-buffer traffic). In heavy load traffic condition, the proposed interference estimation scheme matches the actual interference situation better than a lightly-loaded situation.

Simulation results from both scenario 1 and scenario 2 indicate that the performance of average user throughput and cell-edge user throughput of “Grouped” scheme has large gain over the “Uniform” scheme. Results show that this “Grouped” scheme will give benefit especially under heavy traffic load condition.

V. Conclusion

Relaying provides an attractive means of coverage extension and throughput improvement. Support of Type 1 relay in LTE-Advanced has been agreed and defined in 3GPP standard. In this paper, we propose a novel channel measurement and channel quality reporting scheme based on subframe grouping. Detailed description of simulation setting and results on system level evaluations for relay downlink performance are provided. We also compare with other channel measurement and CSI feedback scheme showing that our proposed scheme has large performance gain over the other scheme. The relevant interference information may also provide support for interference management to increase the Quality of Service in a heterogeneous network. Furthermore, the proposed scheme has very low computation complexity and the protocol design is compatible with the current LTE standard.

References

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