Performance comparison between DF relay and RF repeaters in the cellular system

Miao Qingyu1,3, Afif Osseiran2
1 Ericsson Research, Beijing, China,
2 Ericsson Research, Stockholm, Sweden,
3 Beijing University of Posts and Telecommunications, Beijing, China
qingyu.miao@ericsson.com

Abstract—This paper compares the system level performance of Decode-and Forward (DF) relay and a RF repeater in a cellular system. The results show that for small cell sizes, the repeater system can bring higher cell spectrum efficiency gain than the relay system since repeaters in contrast to the relays are assumed to be able to receive and transmit at the same time. However, for larger cell sizes, the relay system can bring higher cell spectrum efficiency gain than the repeater system thanks to the possibility of simultaneous transmission by both the access point and relay node through employment of channel reuse. Irrespectively of cell size, simultaneous transmission by access point and relay node also implies that relays can provide higher system and user throughput than RF repeaters.

I. Introduction
Increasing the system capacity becomes one of the key goals in the wireless system design, but increasing the system capacity may lead the coverage to decrease. The concept of relaying and repeater has recently emerged as a viable option for challenging the trade-off between the transmission range and the end-to-end data rate.

Relay is not only efficient in eliminating dead spots throughout the coverage region, but more importantly, it may extend the high data rate coverage range of a single access point (AP) [1][2][3][4]. Relay Nodes (RN) do not have a wired connection to the backhaul. Instead, they store the data received wirelessly from the AP and forward to the user terminals, and vice versa. There are two typical types of relay, decode-and-forward (DF) relay, and the amplify-and-forward (AF) relay.

Employment of RF repeaters (RP) for extending the coverage of cellular systems, has been investigated for rural and suburban systems [5] and indoor systems [6]. An RF repeater receives the signal and amplifies the entire signal almost at the same time. The delay between the transmission and reception is so small that it is not noticeable at the user terminal (UT), i.e., the repeaters only introduces artificial multi-paths. It is common belief that the repeater will increase the system coverage and it will increase the system capacity in some cases [5][6].

The main difference between the RN and the RP is that the relay systems require no less than two hops in order to transmit the data to user, whereas the reception and transmission in RP are at the same time.

Both relay systems and repeater systems can improve the coverage, especially for the high data rate coverage. For relay systems, since it is possible to have simultaneous transmission by both the AP and RN, capacity gains may also be achieved by either exploiting reuse efficiency or spatial diversity. The additional signalling is needed for routing in relay systems, which will cost part of capacity, while for the repeater system, there is no need for the additional signalling. However, the repeater brings more interference.

There are a lot of papers dealing with the performance on the relay performance [3], which includes DF and AF relays, and a few papers investigated the RF repeater performance [5][6]. Most of the relay studies focus on the single link performance and few of them investigate the system level performance. The purpose of the paper is to compare the system level performance of the DF relay and the RF repeaters in a cellular system.

The rest of the paper is organized as follows. In section II, the system models for DF relay and RF repeaters are presented separately. The simulation assumption and parameters can be seen in section III. Results are given in section IV and section V concludes the paper.

II. System Models
A. System model for the DF relay system
The working assumptions for the DF relay system in [1] are reused in this paper. In the network, RNs and APs are assumed fixed while UTs are considered mobile. UTs are here assumed not to act as relays. APs act as traffic ingress/egress point. Only DF relay is taken into account in this paper. For the relay systems, the data from the source to the RN is transmitted in the first hop and the data transmitted from RN to destination is on the second hop.

The system adopts time division multiplexing (TDD) and time division multiple access (TDMA). Orthogonal frequency division multiplexing (OFDM) transmission is employed in the down links (i.e. AP to UT, AP to RN and RN to UT). The whole network is purely TDMA based and it is assumed
coordinated and synchronized, which avoids AP to AP, RN to RN, and UT to UT interference. A 2-phase protocol is adopted which is specified as follows (see Fig. 1):

- **Phase 1**: AP transmits to either RN or UT
- **Phase 2**: both AP and RN transmit to UTs

![Fig. 1 System structure for the 2-hop relay](image)

A routing algorithm determining a suitable path to forward the data from the source (transmitter) to the destination (receiver) is one of the fundamental algorithms in multi-hop networks. In this paper routing is performed based on end to end delay. The delay for each link is calculated as the reciprocal of the average Shannon capacity of that link. For the two hop path, the end to end delay is the sum of the link delay of each hop. The path (one hop or two hop) providing the lowest delay is always selected.

### B. RF Repeaters

There are three types of RF repeaters available, Off Air Repeaters, Frequency Translating Repeaters and Optical Repeaters. The normal and widely used Off Air Repeaters is investigated in this paper. The RF repeater amplifies and retransmits all the received signal, including interference (the inter-cell interference) and noise (the thermal noise in repeaters).

![Fig. 2 Off air repeaters.](image)

The off air repeater in Fig. 2 has a donor antenna and a subscriber antenna. The donor antenna receives the signal from AP and the subscriber antenna transmits the signal to UT. Since they transmit and receive at the same time a high isolation between the donor and subscriber antennas is required. A 15 dB gain-to-isolation backoff is recommended [7] to prevent the repeater from oscillating (i.e. Isolation - Gain = 15dB). Failure to provide a large enough isolation-to-gain backoff causes the repeater to oscillate rendering the repeated signals unusable.

Assume that there are \(N\) repeaters and \(M\) APs. Here the RF repeaters amplify the signal from all the APs and the UT receives the signal from all the RF repeaters. It is assumed that there is large isolation between a donor antenna and a subscriber antenna. The received signal at the UT is given by:

\[
y = \sum_{j=1}^{M} h_{j}^{(0)} \cdot \sqrt{P_j} \cdot s_j + \sum_{i=1}^{N} h_{i}^{(2)} \cdot \sqrt{G_i} \cdot a_i \left( \sum_{j=1}^{M} h_{i,j}^{(0)} \cdot \sqrt{P_j} \cdot s_j + \sqrt{N_{RP,j}} \cdot z_{RP,j} \right) + \sqrt{N_{UT,j}} \cdot z_{UT,j} \tag{1}
\]

Where

- \(P_j\) is the power of the \(j\)th AP,
- \(s_j^{(0)}\) is the transmitted complex data symbol from \(j\)th AP,
- \(h_{j}^{(0)}\) is the complex channel gain between the \(j\)th AP and the UT,
- \(h_{i,j}^{(1)}\) is the complex channel gain between the \(i\)th repeater and the \(j\)th AP,
- \(h_{i}^{(2)}\) is the complex channel gain between the \(j\)th AP and the \(i\)th repeater,
- \(N_{RP,j}\) and \(N_{UT,j}\) are the thermal noise at the \(i\)th repeater and the UT, respectively.
- \(a_i\) is the amplitude gain factor applied at the \(i\)th repeater.

The received signal can be further written as:

\[
y = \left(h_{0}^{(0)} + \sum_{i=1}^{N} h_{i}^{(0)} \cdot \sqrt{G_i} \cdot a_i \right) \cdot \sqrt{P} \cdot s_j + \sum_{j=1}^{M} h_{i,j}^{(0)} \cdot \sqrt{P_j} \cdot s_j + \sum_{j=1}^{M} h_{i,j}^{(0)} \cdot \sqrt{P_j} \cdot s_j + \sum_{j=1}^{M} h_{i,j}^{(0)} \cdot \sqrt{P_j} \cdot s_j + \sqrt{N_{RP,j}} \cdot z_{RP,j} + \sqrt{N_{UT,j}} \cdot z_{UT,j} \tag{2}
\]

It can easily shown the the Signal to Interference and Noise Ratio (SINR) at the UT can expressed as:

\[
\text{SINR}_{RP} = \frac{\left(h_{0}^{(0)} + \sum_{i=1}^{N} h_{i}^{(0)} \cdot \sqrt{G_i} \cdot a_i \right) \cdot P_t}{\sum_{j=1}^{M} h_{i,j}^{(0)} \cdot \sqrt{P_j} \cdot s_j + \sum_{j=1}^{M} h_{i,j}^{(0)} \cdot \sqrt{P_j} \cdot s_j + \sqrt{N_{RP,j}} \cdot z_{RP,j} + \sqrt{N_{UT,j}} \cdot z_{UT,j}} \tag{3}
\]

### III. SIMULATION ASSUMPTIONS

The following simulation assumptions have been used for the relay system and the repeater system.

#### A. Deployment of relays and repeaters
The deployment of relays [1] and repeaters [5] will affect the performance substantially. Fig. 3 depicts the assumed deployment. Three-sector site APs are assumed, each one surrounded by either 3 or 6 relays/repeaters (6 shown in the figure). Wrap around is used in the simulations such that all cells are surrounded by neighbours.

B. Propagation model

The Spatial Channel Model Extended (SCME) model [7] is implemented in the simulation. Both APs and RNs (RPs) are assumed fixed and mounted on high buildings so that they have line-of-sight (LOS) transmission to each other. There is no LOS between AP and UT. Distance dependent probability of LOS is assumed between RN/RP and UT. Other types of links, such as AP to AP, RN/RP to RN/RP, and UT to UT, are disregarded since the resource allocation is performed in such a way that this type of interference never occurs. APs are assumed to employ 3-sector antennas, while both RN(RP) and UT have the omni-directional antennas. The detailed propagation parameters are listed in Table 1.

<table>
<thead>
<tr>
<th>Link</th>
<th>AP - UT</th>
<th>AP - RN/RP</th>
<th>RN/RP-UT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel</td>
<td>'suburban macro'</td>
<td>'suburban macro'</td>
<td>'urban micro'</td>
</tr>
<tr>
<td>pathgain constant for LOS</td>
<td>N/A</td>
<td>-62.4</td>
<td>-30.18</td>
</tr>
<tr>
<td>pathgain slope for LOS</td>
<td>N/A</td>
<td>2.0</td>
<td>2.6</td>
</tr>
<tr>
<td>shadowfading standard deviation when in LOS</td>
<td>N/A</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>pathgain constant for non LOS</td>
<td>-31.5</td>
<td>-32.4</td>
<td>-34.53</td>
</tr>
<tr>
<td>pathgain slope for non LOS</td>
<td>3.5</td>
<td>3.8</td>
<td>3.8</td>
</tr>
<tr>
<td>shadowfading standard deviation when in non LOS</td>
<td>8.0</td>
<td>8.0</td>
<td>10.0</td>
</tr>
</tbody>
</table>

C. Traffic model

A full queue traffic without modelling higher layers is assumed in the simulations. In the full queue user traffic model, all the users in the system always have data to send or receive. In other words, there is always an infinite amount of data that needs to be transferred, in contrast to bursts of data that follow an arrival process. This model allows the assessment of the spectral efficiency of the system independent of actual user traffic distribution type.

However, at the RNs the traffic availability depends on the forwarded traffic from either APs, or UTs even in the full queue model.

D. Link adaptation & power control

Link adaptation is employed in the time domain, selecting the combination of modulation and coding rates that provide the highest data rate while meeting the block error rate (BLER) requirement (1%).

The available coding rates include 1/3, 1/2, 2/3, 3/4 and 8/9. All modulation schemes from BPSK to 64QAM are available.

All nodes transmit with maximum power when active and the power is evenly allocated in the whole bandwidth.

E. Quality Model

This paper adopts a mutual-information based link quality model[9]. The model maps SINR to mutual information based on which link throughput and BLER is calculated. Then the link adaptation is performed using the estimated link throughput and BLER.

F. Other simulation assumptions

The other system and simulation parameters can be found in Table 2.

<table>
<thead>
<tr>
<th>TABLE 2 SIMULATION PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SYSTEM PARAMETERS</td>
</tr>
<tr>
<td>carrier frequency [Hz] 2e9</td>
</tr>
<tr>
<td>Sub-carrier bandwidth [Hz] 15000</td>
</tr>
<tr>
<td>number of OFDM sub-carriers (tones) in the system 1280</td>
</tr>
<tr>
<td>number of chunks in frequency domain (frequency sub-bands) 80</td>
</tr>
<tr>
<td>length of cyclic prefix extension [s] 0.000004</td>
</tr>
<tr>
<td>number of OFDM symbols in frame 8</td>
</tr>
<tr>
<td>number of frames per superframe 8</td>
</tr>
<tr>
<td>AP power [dBm] 43</td>
</tr>
<tr>
<td>RN/RP power [dBm] 37</td>
</tr>
<tr>
<td>RN/RP receiver noise figure [dB] 5</td>
</tr>
<tr>
<td>UT receiver noise figure [dB] 7</td>
</tr>
<tr>
<td>SIMULATION PARAMETERS</td>
</tr>
<tr>
<td>cell radius [m] 500, 1500, 3000</td>
</tr>
<tr>
<td>Site type 3-sector</td>
</tr>
<tr>
<td>average number of offered calls to a cell 20</td>
</tr>
<tr>
<td>mean speed [m/s] 10</td>
</tr>
</tbody>
</table>
IV. SIMULATION RESULTS

Both the performance from the user point of view and the performance from the system point of view are compared. In order to compare the performance with traditional single-hop cellular systems, the performance is normalized and the throughput in the traditional cellular system is regarded as 100%. In the figures the x-axis ("rpos") means the RN/RP positions relative to the cell radius. A value of 0.4 means the relay is deployed 0.4 times the cell radius from the AP. Note that the site-to-site distance is 3*R due to the assumption of 3-sector antennas. The red line is the result without relay (the traditional cellular), which is always 100%. Either 3 or 6 RN/RPs are deployed in each cell. In each figure, different subfigures represent the results for different cell sizes.

A. User throughput

Here the 5th percentile user throughput is provided. The user throughput is defined as the ratio of the number of information bits that the user successfully receives during the simulation time. The normalized user throughput, the user throughput divided by the total bandwidth, is presented.

![Fig. 4 Downlink 5th percentile user throughput, 2-hop relay.](image)

From the relay performance in Fig. 4, the gain of 5th percentile user throughput can be increased substantially with relays. It can be seen that for the most favourable relay position the gain of 5th percentile user throughput is more than 70% when there are 3 relays in each cell, and 150% gain with 6 relays for small cell size (500m). The gain is larger with 6 relays than with 3 relays. The most favourable relay position is about 1.1-1.4 times the cell radius from the AP.

From the RF repeater performance in Fig. 5 it can be seen that there is a clear gain only for the small cell size. An explanation to this is that the coverage of a repeater is rather limited, so for the large cell size, there is little gain. However, in a relay system, simultaneous transmission by both the AP and RN is possible due to frequency/channel reuse. This leads to a wider coverage as explained in the following.

From a pure propagation model point of view, the area covered by repeater and relay should be similar since the same propagation model is used. In the repeater system, the user throughput is limited by the SINR (see Eq. (3)). For the relay system, the user throughput is limited by the throughput in the first hop and the throughput in the second hop. Neglecting the possibility for channel reuse the throughput in the first hop reaches the peak rate (limited by the 64QAM) and the user throughput is limited by the second hop.

\[
\text{tpu}_{2\text{hop}} = \min(\text{tpu}_{1\text{st-hop}}, \text{tpu}_{2\text{nd-hop}})
\]

However, by employing channel reuse in the relay system the AP and RN can transmit simultaneously, which means there are more channel resources (such as time slots) for the 2nd-hop link than the channel resource for the 1st-hop link. Assuming that 2nd-hop has N times more channel resource than one 1st-hop, the throughput is changed to

\[
\text{tpu}_{2\text{hop}} = \min(\text{tpu}_{1\text{st-hop}}, N \times \text{tpu}_{2\text{nd-hop}})
\]

Eq. (5) shows that even with low throughput in 2nd-hop, the total throughput can still reach a high value, which results in that a relay gets a wider coverage area than a repeater.

As in the relaying case the result shows that the gain is larger with 6 repeaters than with 3. The most favourable repeater position is around 1.1 times the cell radius from the AP.

B. Cell spectrum efficiency

We measure system performance through the Cell Spectral Efficiency, defined as,

\[
\text{Cell\_Spectral\_Efficiency} = \frac{\text{total\_system\_throughput}}{\text{num\_of\_cells}\times\text{total\_bandwidth}}
\]

Where, 

- \(\text{total\_system\_throughput}\) is the total system throughput in the whole system.
- \(\text{num\_of\_cells}\) is the number of the cells in the whole system.
- \(\text{total\_bandwidth}\) is the total bandwidth used in the system.
Fig. 6 Downlink cell spectrum efficiency, 2-hop relay.

Fig. 7 Downlink cell spectrum efficiency, RF repeaters.

Fig. 6 shows the cell spectrum efficiency for the 2-hop relay system. The downlink cell spectrum efficiency can increase more than 50% when there are 3 relays per cell and about 70% when there are 6 relays per cell for small cell size (500m). The gain is even larger for large cell size. There are two main reasons for the capacity gain. The first one is that the 2 hop link provides a better link budgets. The other reason for the capacity gain is due to the simultaneous transmission by both the AP and relays. The most favourable relay position from a spectrum efficiency point of view is the same as from a throughput perspective (Section V-A), i.e. about 1.1-1.4 times the cell radius from the AP for large cell size.

Once again the result shows that the gain is larger with 6 than with 3 repeaters, and that the favourable repeater position is around 1.1 times the cell radius from the AP.

V. CONCLUSIONS

We compared the performance of DF relay and the RF repeater in the cellular system.

The cell size turns out to be a determining factor for which of the solutions is most favourable from a spectrum efficiency perspective. For the small cell size, the repeater system can bring up to 200% cell spectrum efficiency gain compared to up to 175% in case of a relaying system. However, for a larger cell size, the relay system can bring up to 250% cell spectrum efficiency gain compared to 20% provided by the repeater system.

The investigated relay system provided much higher user throughput (up to 350%) compared to 150% offered by the repeater system, thanks to the possibility for simultaneous transmission by both the AP and relays through channel reuse.

The most favourable RP/RN position is around 1.1 to 1.4 times the cell radius from the AP, assuming 3-sector sites.

REFERENCES

[4] IST-4-027756 WINNER II, D3.5.1 v1.0, “Relaying concepts and supporting actions in the context of CGs”.