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The Use of Intelligently Deployed Fixed Relays to Improve the Performance of a UTRA-TDD System

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***Abstract*— This paper examines the use of intelligently deployed fixed relays to improve the performance of a UTRA-TDD 3G system. In this study, the benefits of intelligent relaying in the form of enhanced capacity and/or coverage and reduced RF emissions relative to a traditional cellular network are quantified. Simulations are carried out in a microcellular environment using propagation data from a site-specific model and an optimisation algorithm to determine the locations of base stations (BSs) and relay nodes in the system. A system level simulation of a UTRA-TDD system is used to quantify the benefits of the relayed over the non-relayed system. Results show significant improvements in capacity, spectrum efficiency and reductions in mean terminal transmit power in the relayed system over conventional cellular BS-only operation. The effects of different code allocation strategies for the relay nodes are also investigated, revealing that benefits in relaying will only be realised if code re-use between the BSs and relay nodes is enabled or if relay nodes are allocated their own pool of spreading codes.**

I. INTRODUCTION

The gradual evolution of 3G-and-beyond mobile networks will allow for the parallel development of new techniques and technologies to enhance the performance of the core 3G network. The concept of intelligent relaying as an enhancement to cellular networks has been considered for inclusion in 3rd Generation Specifications [1]. Relaying allows the forwarding of data in the cellular environment using either other user terminals (UE) in an adhoc manner (as in ODMA [2]), or using intelligently located fixed relay nodes i.e. wireless routers. This can potentially improve the network coverage by providing connections for users in shadowed locations as well as extending the base station (BS) coverage beyond the regular boundaries of the cell. By only transmitting a short distance to the best (in terms of path loss) relay node, the required transmit power is reduced compared to direct transmission to the BS or mobile. The reduction in path loss (and hence transmit power) due to relaying can be illustrated by examining the scenario depicted in Figure 1. The total path loss between two points A and B separated by a distance D is given by:

$$P\_direct = k\,D^{n} \qquad (1)$$

where k is a frequency dependent constant and n is the path loss exponent.

If a relay R is introduced between A and B, at a distance d_a from A and d_b from B, then the combined path loss in the two paths AR and RB is given by:

$$P\_relay = k\,d_a^{\,n} + k\,d_b^{\,n} \qquad (2)$$

Since $D = d_a + d_b$,

$$P\_direct = k\,(d_a + d_b)^{n} > P\_relay \qquad (3)$$

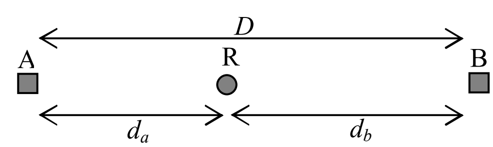

Figure 1: Path loss reduction by relaying

Hence the total path loss is reduced by breaking the initial distance into two smaller distances. This analysis can be extended to cases with more than one relay; however in this contribution we only consider single-hop relaying to reduce routing complexity. Particularly in CDMA systems where capacity is interference limited, the reduction in terminal transmit power will lead to a reduction in interference and hence an improvement in capacity and spectrum efficiency. Additional benefits in terms of battery saving can also be realised.

This work focuses on quantifying the benefits of intelligently located fixed relay nodes on the performance (in terms of capacity and coverage) of a UTRA-TDD 3G system. Location optimisation algorithms for cellular planning have been investigated by many authors, e.g. [3]; however these methods are restricted to the optimization of BSs in a cellular environment. In this paper we use an enhancement of a well known optimization algorithm (the Combination Algorithm for Total optimisation - CAT [4]) in order to optimize the number and location of BSs and relay nodes. Additionally, a state of the art 3D propagation prediction model [5] is utilised to obtain channel information in the required area, and a system level Monte-Carlo simulation of a UTRA-TDD system is then used to quantify the capacity and spectrum efficiency enhancements offered to the 3G network by the use of fixed relays.

II. APPROACH

As mentioned previously, the use of relay nodes can lead to increased coverage as well as reducing interference by reducing the terminal transmit powers in the network. To quantify these benefits several studies were carried out in a dense urban environment in Bristol where capacity requirements are at their highest. The studies which assume the use of UMTS like technology at 2 GHz, include the deployment of a high capacity 3G cellular network as well as the deployment of a mixed network that combines the use of fixed relay nodes and conventional BSs. A relay node is a simple repeater-type structure which communicates with mobiles as well as BSs. Each relay node is dedicated to a single BS and communicates with the BS via a high gain directional antenna in order to reduce interference. Downlink communication to mobile terminals is through a conventional omni-directional antenna. The complexity and cost of a relay node is intended to be small relative to that of a BS.

Using propagation data from the propagation modelling tool, the number and locations of the BSs and relay nodes are optimized to meet defined coverage and capacity targets. The propagation modelling and site optimisation tools are described in the following subsections.

A. Propagation Model

A state of the art propagation model has been used to provide channel data for evaluating 2GHz cellular outdoor networks. The deterministic model uses geographic data (terrain, building, foliage and ground cover) to predict power as well as time, frequency and spatial dispersion in the radio channel [5]. It is optimised for intracellular coverage as well as inter-cellular predictions (interference) between different cells in a mixed-cell network. Propagation data is supplied for each base site in a list of potential base site locations as well as for each potential relay. This data is then passed on to the optimisation module (in the next section) and is used to optimise the number and locations of cellular BSs and fixed relay nodes.

B. Site Optimisation

A novel optimisation algorithm that allows the optimum positioning of cellular sites and fixed relay nodes has been implemented. This algorithm is based on a combinatorial approach previously developed for cellular planning [4]. The new optimisation method has been re-designed to solve the problem of optimising the locations and density of cellular BSs and/or relay nodes for different environments. To solve the optimisation/placement problem, the algorithm uses an over specified user defined group of possible BSs and relay nodes. A complex analysis, based on combinatorial theory, is then performed before the final set of BS and relay node sites is chosen. To implement this analysis, the algorithm uses data from the propagation model described in the previous section. The final group of BSs and relay nodes required to fulfil the target requirements is selected among the initial group of over specified sites. The specification for user supplied sites is used as a matter of practicality, due to the fact that network operators cannot deploy sites in arbitrary locations, such as protected buildings, difficult geographical locations and so on.

The algorithm has been used to deploy a number of cellular BSs and relay nodes to meet coverage and capacity requirements over a 1km x 1km area of the city of Bristol. For the deployment of relay nodes, the potential locations have been selected among street lamppost locations, while conventional locations have been used for the deployment of 3G type base stations. The study has been performed at 2GHz, assuming BS omni-directional antennas located at a height of 5m, and relay nodes at a height of 3m. The relays use a 20dBi gain 20^0 HPBW directional antenna in the uplink and an omni-directional antenna in the downlink.

Three different scenarios have been produced based on network requirements. A first scenario has been produced containing only 7BSs, representing a conventional network deployment. In the second scenario, 8 relay nodes are chosen and added to the 7 BSs. Finally, assuming that higher network requirements for the area are needed, a third case containing the 7 BSs and 21 relay nodes has been produced. This will also allow an analysis of the effect of number of relay nodes on the system performance. Figure 2 shows the locations of the 3G base stations (denoted '*BS') and the 21 relay nodes (denoted '*RN') on an aerial photograph of Bristol.

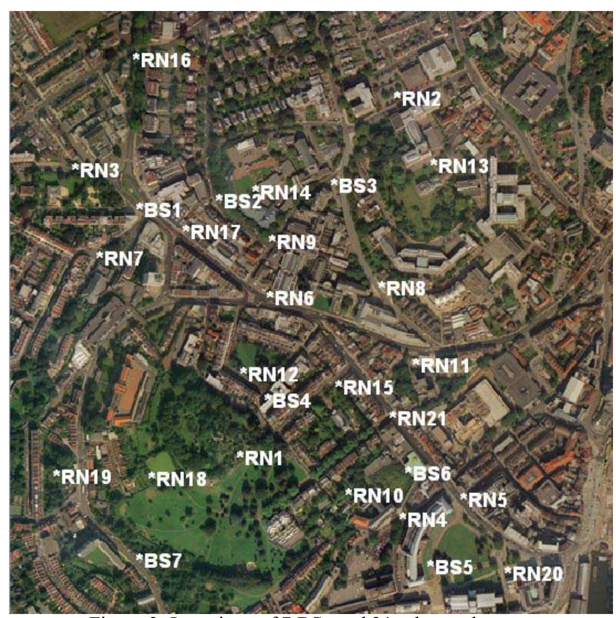

Figure 2: Locations of 7 BSs and 21 relay nodes

III. SYSTEM LEVEL SIMULATION

A system level Monte-Carlo simulation is used to determine the interference, transmit power, capacity and spectrum efficiency benefits of the mixed cellular – relaying network over the conventional cellular network. The simulation is static i.e. it considers snapshots of the system at particular time instants, and does not consider signalling or other network overheads. The 3G simulation assumes a 3.84Mcps UTRA TDD type system [6], with a fixed and ordered time-slot allocation, but with asymmetric sharing of slots between the uplink (UL) and downlink (DL). 3 classes of user are considered: Class A users support voice at 15kbps, Class B users support data at 144kbps and Class C users support data at 384kbps. The traffic mix is specified as: 60% Class A: 30% Class B: 10% Class C. Users are uniformly deployed in the 1km x 1km area of Bristol, and the propagation model is used to determine path losses to the various BSs (BS-UE) and relay nodes (RN-UE) as well as losses between BSs and relay nodes (BS-RN) and between different relay nodes (RN-RN) for interference calculations. The optimal transmission path from user to BS is then determined as the path with the minimum total path loss. The main features of the simulation are summarised in the proceeding subsections.

A. Admission Control

Each class of user has predefined quality targets (Eb/No) in the UL and DL. These Eb/No targets are obtained from acceptable BER and PER thresholds for various services [6] and are assumed to remain constant during the simulation.

For a given user location, the simulation calculates the required UL and DL transmit powers to meet the Eb/No targets at the user terminal, relay node and BS, using the path loss and interference information from the propagation model. The UL interference at a BS or relay node includes received transmissions from users in (intracell) and outside (intercell) the desired cell and UL transmissions from relay nodes. The DL interference at a user terminal or relay node is a summation of received DL transmissions from relay nodes and BSs. The received powers are weighted by a code orthogonality factor (COF) for intracellular as well as intercellular interference calculations. Additionally, the noise rise (*NR*) which is defined as the level of interference relative to the noise power at the BS or relay node as a result of the new user, is also evaluated.

$$NR = \frac{I_{new}}{N} \tag{4}$$

where I_{new} is the new total interference power at the BS/relay node and N is the noise power.

The user is 'admitted' into the network if and only if:

i) all the transmit powers in the UL and DL required to meet the Eb/No targets are below specified maximum transmit power levels for the UE, relay node and BS
ii) there are enough resources (spreading codes and time slots) to meet the desired data rate
iii) the resulting noise rise does not exceed a specified maximum NR_{max}

B. Resource Allocation

The 15 timeslots (TS) in a 10ms UTRA-TDD frame are shared asymmetrically between the uplink (UL) and downlink (DL) depending on the type of application required. Internet download for example, will require more DL than UL resources and can therefore be adequately catered for by selecting a switching point in favour of DL slots. In our simulation, the switching point is calculated from the ratio of UL to DL resources required. In the UL, different data rates are handled by selection of an adequate spreading code from an OVSF code tree [7] (multi-rate operation), whereas in the DL, multiple spreading codes all with a single spreading factor of 16 can be used (multi-code operation).

If a user is connected directly to the BS, then only one set of UL and DL resource units (RUs) are allocated. However, if the connection is by way of a relay node, then 2 consecutive sets of RUs in the UL and DL are allocated as illustrated in Figure 3. Where possible, consecutive TSs are used in relaying to minimise delay and improve on latency. All TSs are allocated on the basis of minimum interference i.e. the UL TS with the least interference at the relay/BS and the DL TS with the least interference at the relay/user.

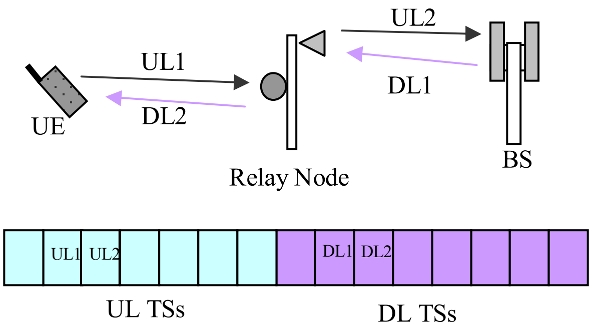

Figure 3: TS allocation with relaying.

Clearly, relayed users require twice the resources (spreading codes and slots) of non-relayed users. In order to determine the optimum spreading code allocation strategy for relaying, 2 options have been implemented in the simulation:

i) relay nodes use spreading codes belonging to associated BS (code sharing)
ii) relay nodes re-use BS codes (code re-use) or use codes from their own code pool

For channelisation code (CH_B) re-use to be possible, the downlinks from BS-UE, BS-RN and RN-UE are allocated different *scrambling* codes (SC_M, SC_B, SC_R) as illustrated in Figure 4.

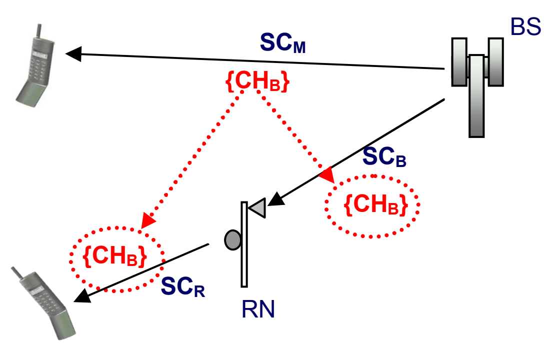

Figure 4: Channelisation code re-use through scrambling code allocation

The effects of these code allocation strategies will be examined in Section IV.

C. Power Control

After admitting a new user, a power control algorithm is applied to ensure that all other users sharing the same TSs still have acceptable quality of service. Initially, the interference information at all BSs, relay nodes and UEs on the same TSs is updated. The new Eb/No values for all BSs, relay nodes and UEs are calculated using the new interference, and compared to the target Eb/No values. The UL and DL transmit powers are then increased or decreased in steps of 0.5dB depending on whether the calculated Eb/No values are below or above the target thresholds. The power control loops are repeated a number of times after which any users still not meeting the quality targets are dropped from the network.

D. Joint Detection

Joint detection (JD) in the UL can be used to reduce intracell interference in 3G and beyond networks [8]. In this simulation, joint detection is modelled as an efficiency value of the UL interference cancellation. Hence a 50% (JD) efficiency translates to cancellation of 50% of all UL interference. JD is only considered to be implemented at the BSs and not at the relay nodes in order to keep the complexity and cost of the relays to a minimum.

IV. RESULTS

A. Coverage Extension

Figures 5 and 6 show the coverage levels in the modelled Bristol area with BSs only and with a combination of BSs and 21 relay nodes respectively. The coverage extension brought about by the addition of the relay nodes is clearly visible in Figure 5. As might be expected the 8 relay scenario produces a slightly lower coverage enhancement compared to the 21 relays.

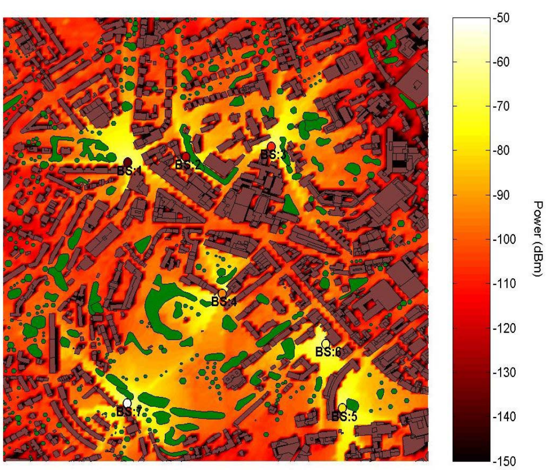

Figure 5: Coverage levels with BSs only

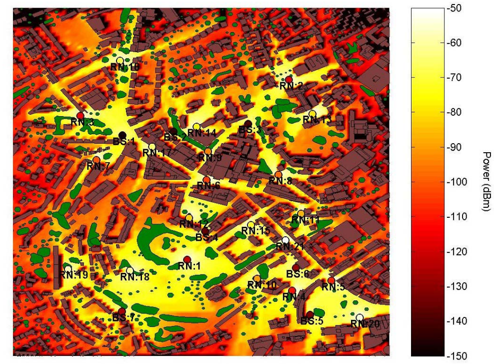

Figure 6: Coverage levels with BSs and 21 relay nodes

These results also suggest that the number of BSs can be reduced at the expense of a number of relatively cheaper relay nodes whilst still maintaining the desired coverage levels.

B. Capacity and Spectrum Efficiency Results

The simulation described in Section III above was carried out for the Bristol area, initially with the 7 BSs only, then with a combined network of 7 BSs and 21 relay nodes, and finally with the 7 BSs but only 8 relay nodes. The main simulation parameters are presented in Table 1.

Max UE transmit power:	20dBm
Max relay transmit power:	30dBm
Max BS transmit power:	40dBm
NR_{max}:	5dB
Intracell COF:	0.6
Intercell COF:	0.4
Bandwidth:	3.84Mcps
JD Efficiency:	50%

Table 1: System Level Simulation Parameters

Each study is terminated when the grade of service (GoS) drops to 95% (maximum blocking probability of 5%). The results presented in Figures 7, 8 and 9 are averaged over 500 independent studies or snapshots, and compare the capacity, spectrum efficiency (SE) and the mean UE transmit power respectively, for the 3 scenarios described above. The effects of the different code allocation strategies for the relay nodes are also shown in the results.

The capacity results in Figure 7 clearly show that a substantial improvement in the number of supported users (up to 75% increase with 21 relay nodes) is achieved when relay nodes are added to the cellular system. This improvement can however only be obtained when the relay nodes re-use the BS spreading codes. When the relay nodes share the codes allocated to their associated BSs, then the capacity becomes limited by the number of codes. Since relayed users need twice the number of codes compared to non-relayed users, this actually leads to a decrease in the overall system capacity compared to the non-relaying scenario. Decreasing the number of relay nodes from 21 to 8 still gives a significant (though much smaller) capacity increase (8%) in the case where relays re-use BS spreading codes. Again in this case, code sharing between BSs and relay nodes leads to a lower capacity than in the non-relaying case as a result of code 'shortage'. This is confirmed by the fact that the capacity is higher for 8 relays than for 21 relays when code sharing with BSs is used. With more relay nodes, a higher proportion of users are relayed (due to increased coverage) and they then compete for the even fewer codes available to each BS/relay node.

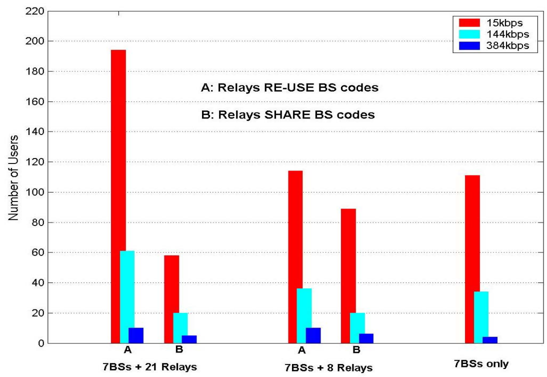

Figure 7: Capacity results for relaying versus non-relaying

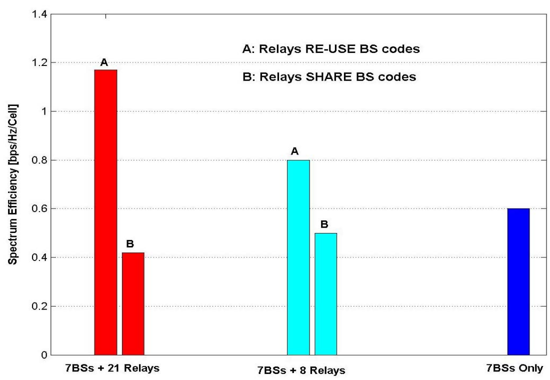

Figure 8: SE results for relaying versus non-relaying

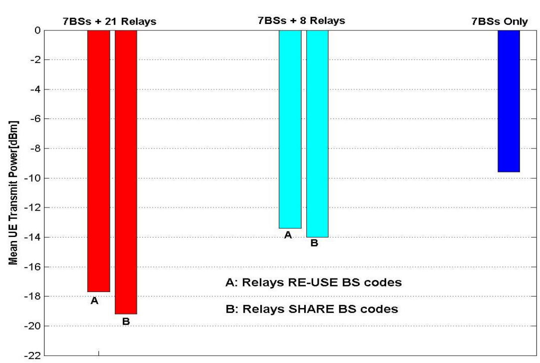

Figure 9: UE transmit power comparison

The spectrum efficiency results in Figure 8 show a similar trend. There is an increase in spectrum efficiency when relaying is used (up to 1.2 bps/Hz/BS with 21 relays) but again only if relays do not share spreading codes with BSs. Figure 9 shows that the mean UE transmit power decreases by 8dB when 21 relays are added to the BSs, each relay re-using the BS spreading codes. This decrease is actually greater (15dB) if only relayed UEs are considered in the comparison. This decrease is lowered to 4dB when only 8 relays are used, as fewer users have access to the power-saving relayed routes. The slightly lower mean UE transmit powers observed when code sharing between BSs and relays is used is attributable to the smaller number of users who are connected directly to the BSs due to code shortage at the BSs. Since these direct connections are the most power inefficient, the mean UE transmit power falls.

V. CONCLUSIONS

In this paper, it has been shown that the use of intelligently deployed low cost fixed relay units can yield significant improvements in the performance of a conventional 3G cellular network. Using a site deployment optimisation algorithm together with a site-specific propagation modelling tool, a number of BSs and fixed relay units were deployed in an urban microcellular environment. A system level Monte-Carlo simulation of a UTRA-TDD system was then implemented to quantify the benefits of relaying. The results obtained indicate that a significant improvement in the number of supported users (up to 75% increase in our study) can be achieved when intelligently deployed relay units using high-gain directional antennas in the UL are used to complement the 3G cellular system. The capacity improvements can however only be achieved if relay nodes re-use BS spreading codes instead of sharing codes with its associated BS. Corresponding increases in spectrum efficiency have also been demonstrated (increase of 0.6bps/Hz/cell in our test case). The capacity and spectrum efficiency gains are accompanied by a mean UE transmit power saving (up to 8dB for the maximum capacity scenario), which will lead to an increase in battery lifetime. Coverage extension using relay nodes has also been demonstrated. Further work will address different traffic mixes and quantify the financial benefits of replacing some BSs with relays whilst still maintaining the desired GoS.

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