Range Extension without Capacity Penalty in Cellular Networks with Digital Fixed Relays[1]

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Abstract – **The concept of relaying is a promising solution for the challenging throughput and high data rate coverage requirements of future wireless cellular networks. In this paper, we demonstrate that the area that a single BS (base station) can provide high data rate coverage can significantly be increased by the employment of digital fixed relays (deployed by the service provider) without any penalty in capacity. This network architecture which allows two-hop links (when necessary) is expected to facilitate cost-efficient high data rate coverage in beyond-3G cellular wireless networks. In particular we considered the downlink of a non-CDMA network where 6 digital fixed relays are placed around each BS in a hexagonal layout. A user equipment (UE) chooses to receive the transmitted signal either directly (in single hop) from the BS or via one of the relays (in two hops). Whenever a relay is used, a second channel is needed as the relays cannot receive and transmit at the same channel. We propose a "pre-configured" relaying channel selection algorithm which incurs minimal overhead due to its fixed nature. In this algorithm, relays further reuse the already used channels in the network; but this reusing is done in a controlled manner in order to prevent the co-channel interference from increasing to unacceptable levels. Therefore, the benefits of relaying are achieved without any loss in capacity (bandwidth). The improved two-hop links are exploited to yield higher throughput through the use of adaptive modulation and coding. We consistently observed that the throughput is increased and the outage is decreased in the relay-augmented network, which is converted to range extension without any capacity penalty, for the realistic range of values of the propagation and other system parameters investigated.**

I. INTRODUCTION

There are a number of reasons for the behind-schedule deployment of the 3G cellular networks. Here we would like to emphasize one critical factor related to the network architecture (deployment concept): 3G is not a very cost-effective technology; in other words, the cost per bit in 3G networks is relatively high. This is due to the inherent inefficiency of the conventional cellular architecture in the delivery of high data rates. The conventional cellular technology has been very successful for digital voice communications. This success can be measured by the subscription cost: the current monthly service rate for a cell phone is comparable to that of a wired phone. But when it comes to data, the wireless rates are much lower and the cost is much higher. The utilization of a network architecture which will enable the cost-efficient delivery of high data rates will be a key factor in the success of any beyond-3G network [2]. In this context, range extension in cellular networks through the use of digital fixed relays is considered in this paper.

Digital fixed relays are small, low-power, low-cost devices deployed by the service provider at locations where AC power is readily available (such as lamp posts). Since the relay locations can be chosen to be strategic, the BS-relay links can be made very reliable.

Throughput (average spectral efficiency) and outage are used in this paper as the performance metrics which are presented for varying cell sizes. It is assumed the network can track the channel variation, so that adaptive modulation and coding (AMC) can be applied.

II. CELLULAR LAYOUT & RELAYING CHANNEL PARTITION SCHEME

A network of seven clusters with four hexagonal cells in each cluster is considered in this paper. Fig. 1 shows this scenario, where cell clusters are outlined in bold. The bold letters A, B, C, D represent the BSs and the plain italic letters close to the cell boundary represent relays.

Similar to current cellular networks, the BS is located in the centre of the hexagonal cell. Six fixed relays are placed in each cell as new network elements enhancing the cellular infrastructure. Each relay is located on the line that connects the centre of the cell to one of the six cell vertices, and it is 2/3 away from the centre (BS).

In a relaying network, an extra channel, relaying channel (between relay and a UE), is needed by a relay to forward the signal between the BS and UE. In this paper, the assumptions are as follows: no channels are reserved for relaying purposes and the number of channels per cell equals to the number of UEs. In this case, the relaying channels have to be selected from the already used channels in that particular cluster. Therefore, there is no loss of capacity (bandwidth) in facilitating the two-hop links.

We present a novel "pre-configured" relaying channel selection algorithm which prevents any capacity loss due to

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relaying. The relaying channel partition scheme is based on the following: first of all, to avoid excessive interference, a relay is not allowed to reuse any channel in the same cell. For example, in a type A cell, all the relaying channels must be from type B, C, or D cells. Secondly, because a cell farthest from a relay most probably has the least co-channel interference to this relay, we decide to let a relay reuse the channel from the cell farthest from it. For example, let us take a look at the relay layout in Fig. 1; a relay marked as "A" indicates that that relay is reusing channels from the type A cells, because a type A cell is the farthest away cell from the relay in comparison to type B, C, and D cells.

Based on the above scheme, in each cluster, there will be twenty-four relays and every six relays will reuse a group of channels from type A, B, C, and D cells, respectively. In order to avoid the six relays reusing the channels from the same cell reuse the same channel, all channels belonging to a certain cell are divided into six disjoint groups with equal numbers of channels and each relay reuses channels only from one group. In Fig. 1, the plain italic letters (e.g., A_1, D_5) represent relays reusing a certain group of channels. A_1 reuses the first group of channels from type A cells, and D_5 reuses the fifth group of channels from type D cells.

The fixed relay position makes this relaying channel partition scheme a reality. The main advantage of this scheme is that it is a "preset" way of channel partition; there is no need for the complicated channel selection schemes and complicated channel measuring schemes, and there is no overhead calculation. Whenever a relay requires a relaying channel, it simply uses a channel from a set of channels allocated to it.

The aforementioned fixed relaying channel selection scheme not only applies to the cluster size $N = 4$ case, but works well for any cluster size (including the $N = 1$ case) [3].

III. RELAY SELECTION

In this network architecture, a UE has two choices to receive signals: either from the BS or from one of the six relays. A specific algorithm needs to be established to determine from which node (BS or one of the relays) a UE will receive its signal. An SINR-based relay selection algorithm is explained below which is used throughout this paper, with the exception of Fig. 5 (which will be explained later) where performance results are given for distance- and pathloss-based relay selection algorithms as well [3].

In our relay selection algorithms, we assume all six fixed relays are placed in strategic locations with good receiving signals from the BS. The AMC mode, to be detailed in the subsequent section, is decided based on the SINR (signal-to-interference-plus-noise ratio) of the relay-UE link. The BS-relay link is assumed to be good enough to support this mode of operation (due to strategic relay locations and high-gain antennas).

There are two steps to accomplish the SINR-based relay selection algorithm:

1. Out of the six relays in the cell in which the UE resides, select two that are the closest to the UE (R1, R2).
2. Compute the SINR between the two closest relays and the UE, and between the BS and the UE. The node (relay or BS) with the maximum SINR will be responsible for transmitting signals for the UE. In other words, the selected node will be $\arg\max \{ SINR_{R1}, SINR_{R2}, SINR_{BS} \}$.

IV. ADAPTIVE MODULATION AND CODING

To increase the throughput and to extend the high data rate coverage, AMC is employed in this study which allows using different combinations of constellation sizes and code rates based on the channel conditions (or received SINR values).

BICM (Bit-Interleaved Coded Modulation) [4] is applied in this paper as a coding scheme. BICM has a high performance in cases of high data rates and fading channels, mainly due to a bit-wise interleaving mechanism at the transmitting end and a soft-decision metric process at the receiving end.

The combinations of three modulation schemes (QPSK, 16-QAM, 64-QAM) and five code rates (1/2, 2/3, 3/4, 7/8 and 1) are considered. Table 1 depicts the relation between the received SINR value and throughput for all the fifteen combinations. The received SINR value determines which combination to use. For example, if the received SINR is greater than 21 dB, the threshold for "64-QAM, rate 7/8", but less than 26 dB, the threshold for "64-QAM, rate 1", the former combination will be employed.

Table 1. Relation of all combinations, required SINR and spectral efficiency

Combinations of modulation and code rates	Minimum Required SINR [dB]	Spectral Efficiency [bits/sec/Hz]
QPSK, rate: 1/2	4.0	1.0
QPSK, rate: 2/3	6.0	1.33
QPSK, rate: 3/4	6.8	1.5
QPSK, rate: 7/8	7.8	1.75
16-QAM, rate: 1/2	10.0	2.0
16-QAM, rate: 2/3	12.0	2.67
QPSK, rate: 1 (not used)	12.5	2.0
16-QAM, rate: 3/4	13.0	3.0
16-QAM, rate: 7/8	15.0	3.5
64-QAM, rate: 1/2 (not used)	15.1	3.0
64-QAM, rate: 2/3	17.7	4.0
64-QAM, rate: 3/4	19.0	4.5
16-QAM, rate: 1 (not used)	19.7	4.0
64-QAM, rate: 7/8	21.0	5.25
64-QAM, rate: 1	26.0	6.0

By looking up this table, we can find the system throughput based on the SINR value obtained from the simulation. Note that in Table 1 three combinations are not used as they lead inefficient results.

V. SIMULATION RESULTS

In our simulation the pathloss (in dB) is calculated as

$$20 \log_{10}(4\pi d_0/\lambda) + 35 \log_{10} (d/d_0) + X_\sigma,$$

which means that a propagation exponent of 3.5 is assumed. In the above, d_0 is the reference close-in distance (taken to be 10 meters) and X_σ is a lognormal random variable with a standard deviation of $\sigma = 8$ dB (which captures shadowing effects). The RF carrier frequency is assumed to be 2 GHz (which results in $\lambda = 0.15$ m). In addition to lognormal shadowing, flat Rayleigh fading is assumed to be present as well. The transmission bandwidth is taken to be 5 MHz. At the receiver, the thermal noise is considered with a noise figure of 8 dB.

The cluster size of the cellular network is taken to be equal to 4. Seven clusters are deployed, but the data is collected for the innermost cluster; i.e., the first tier co-channel interference is considered. Both the BSs and UEs are assumed to use omni-directional antennas with a gain of 6 dB. Power control is not considered in this simulation, because when AMC is used, power control does not contribute much towards the throughput increase. The BS transmit power is assumed to be 20 W. For the fixed relay transmit power, we consider a variety of values to compare the system throughput and performance: 0.1 W, 0.3 W or 1 W. Only the downlink scenario is considered. The UEs are placed randomly across the cluster with 72 UEs per cell.

In this simulation, we compare the with-relaying case with the without-relaying one. For the without-relaying case, all UEs will receive signals from the BS. In this case the interference comes from the other six BSs using the same channel. The calculation of SINR follows in a straightforward manner.

For the with-relaying case, as described above, six relays are placed in each cell. In this case, the received signal can be either from the BS or from a relay depending on which node the UE is communicating with. The interference structure in this case is different from that in the without-relaying case, because not only do we need to consider the interference generated by other BSs, but the interference from other relays using the same channel as well. Here the worst case scenario in interference calculation is considered; that is, we assume all the relays are using all channels allocated to them to transmit signals, though in fact sometimes some channels will not be used. After calculating the SINR for both cases, Table 1 is used to find out the throughput (spectral efficiency).

The simulation results are shown in Fig.s 2-7. Fig. 2 shows the CDF (cumulative distribution function) curves for SINR for various values of the cell radius, which give the coverage performance. This figure indicates that when there are relays in the system, the coverage can be greatly enhanced.

Fig.s 3 and 4 use two different metrics, average spectral efficiency and outage, to show the coverage extension benefit provided by digital fixed relays. We see a remarkable performance enhancement (spectral efficiency increase and outage decrease) due to relaying. For instance, from Fig. 3 we observe that the average spectral efficiency value achieved for no-relaying case in 2000-m cells is 2.4 b/s/Hz; when relaying is incorporated, on the other hand, the cell size (radius) can be increased up to 4000 meters while still achieving the same average spectral efficiency. This results in a cell area increase by a factor of $(4000/2000)^2 = 4$; i.e., a region which will necessitate 4 BSs (or access points), can be covered with only 1 BSs when fixed relaying is incorporated. That is, by installing 6 fixed relays, the service provider can save 3 BSs! Given that the BS to relay cost ratio is high (say, roughly 100:1), the remarkable deployment cost savings with relays becomes obvious. Similarly, it is observed from Fig. 4 that an outage constraint of 30% allows a cell size of 2000 meters when there are no relays, but with the same constraint the cell size can be increased up to 4500 meters when relays are used.

Although we described only an SINR-based relay selection algorithm in this paper, pathloss- and distance-based relay selection algorithms are considered as well in [3]. For comparison purposes, Fig. 5 shows the average throughput increase for the three relay selection algorithms for two different cell sizes, namely, 1000 and 2000 metres. We observe from this figure that whenever relays are used the throughput is increased in all the three cases. Note that in Fig. 5 the beginning of the horizontal axis ($P_{relay} = 0$ W) corresponds to the no-relaying case. The advantage and the disadvantage of the three relay selection algorithms are summarized as follow: the distance-based algorithm is the easiest to implement with the assistance of GPS (Global Positioning System) technology, but as expected, it brings in the least throughput increase; the SINR-based algorithm produces the greatest throughput improvement, however it involves more signalling overheads; the performance and complexity of the pathloss-based algorithm are in the middle.

Fig.s 6 and 7 show how often various combinations of the modulation and coding schemes are used when cell radius is 1000 metres. In the with-relaying case (Fig. 7), 64-QAM with different code rates is used more often in comparison to the without-relaying case (Fig. 6). In both figures, “% of failing links” means the percentage of UEs for which the received SINR is less than 4 dB that corresponds to zero spectral efficiency. This value can be viewed as the outage performance and it is 24.57% in the without-relaying case while it is decreased to 7.46% in the with-relaying case.

VI. CONCLUSIONS AND DISCUSSIONS

This paper studies the range extension potentials of the digital fixed relaying in future high data rate cellular networks.

A novel relaying channel assignment scheme is proposed in this paper in order to prevent potential capacity loss in facilitating two-hop links. With this scheme, the channel reuse becomes even denser since the relaying channels are acquired through the reuse of the existing channels, which will cause increased co-channel interference. However, simulation results show that there are still significant throughput improvements and outage reductions due to shorter links in the two-hop cases.

In this paper, we only show the simulation results for a particular set of parameters defined in Section V. We have done simulations for various sets of system parameters, including different values of cluster size, propagation exponent, shadowing standard deviation, antenna gain, BS transmit power, carrier frequency, and with or without multi-path fading. Obviously, the quantitative results depend very much on the values of these parameters; however, the encouraging trend is there for all cases: relaying results in significant range extension.

The demonstrated range extension potential (without any capacity loss) enabled by relays is the main result of this paper. It has to be stated that many issues that will work against the relaying case (including protocol overhead, etc.) have not been taken into account in this contribution. However, many other potential benefits of relaying (for instance, load balancing [1], and more sophisticated diversity and space-time processing that could be done by relays [5,6]) as well have not been incorporated. We expect that the overall benefits of relaying (especially its cost-effectiveness in the context of providing high data rate coverage) will legitimize the associated additional complexity in the network. If this expectation turns out to be true, relaying will become an essential component in beyond-3G cellular networks.

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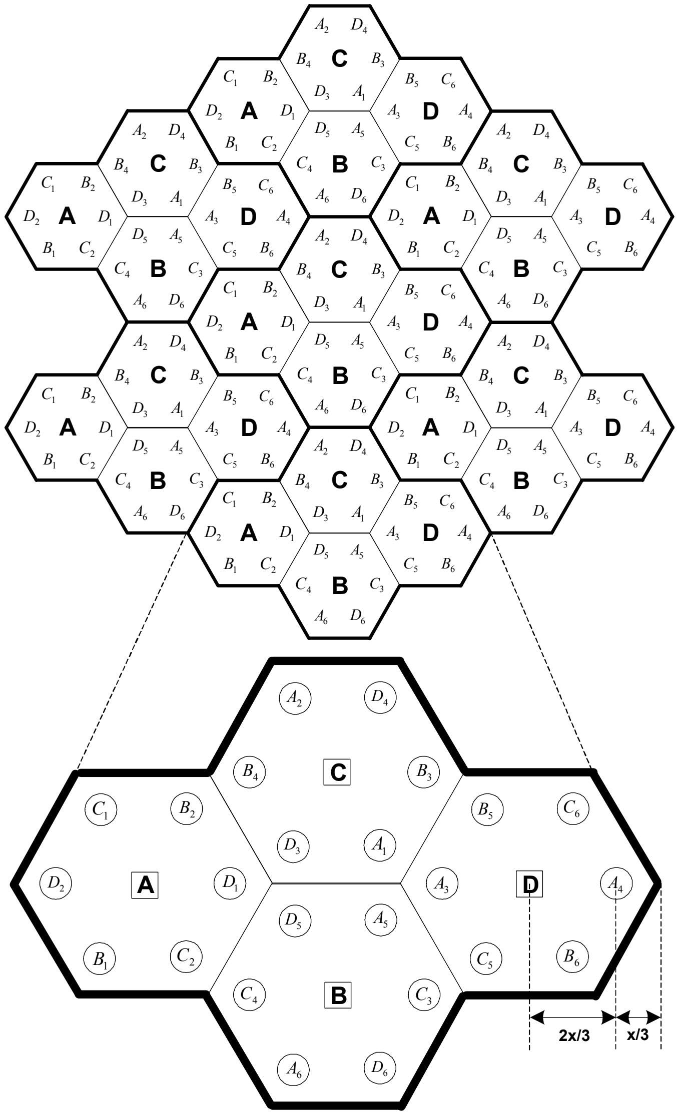

Fig. 1. Cellular layout and relaying channel partition scheme.

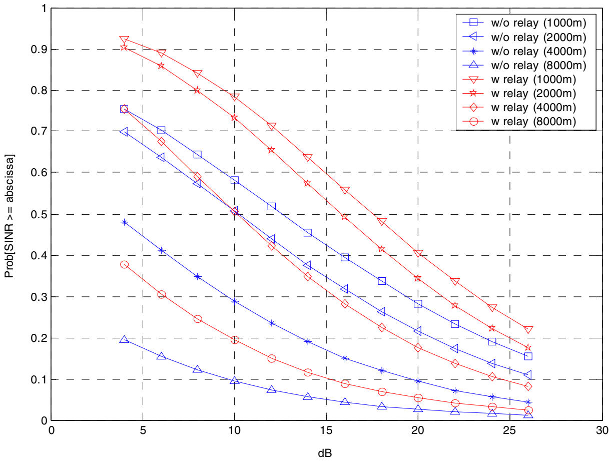

Fig. 2. Coverage at various *SINR* levels (SINR-based relay selection algorithm, $P_{relay} = 1$ W).

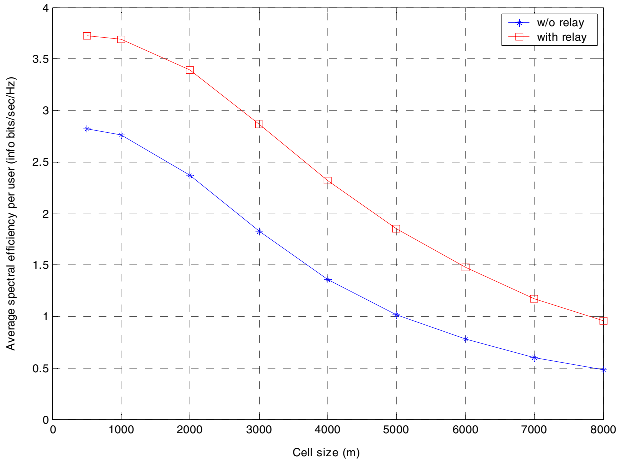

Fig. 3. Average spectral efficiency for various cell sizes (SINR-based relay selection algorithm, $P_{relay} = 1$ W).

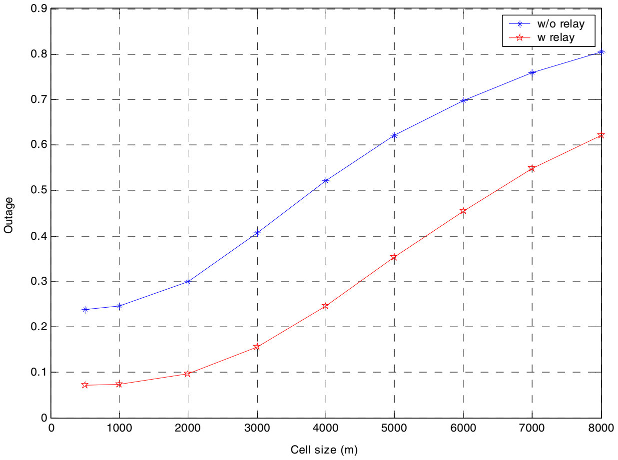

Fig. 4. Outage results for various cell sizes (SINR-based relay selection algorithm, $P_{relay} = 1$ W).

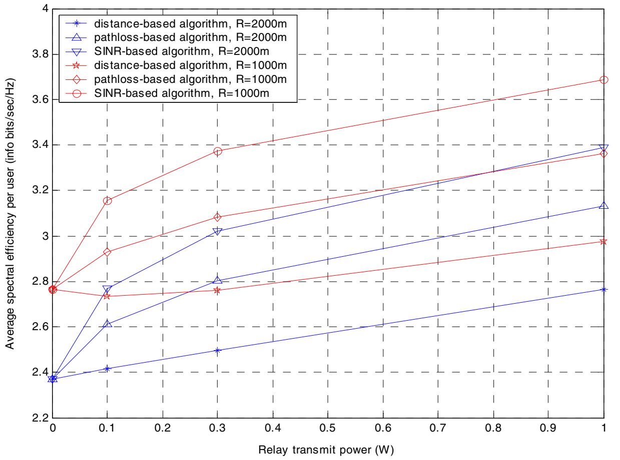

Fig. 5. Average spectral efficiency increase for distance-, pathloss- and SINR-based relay selection algorithms.

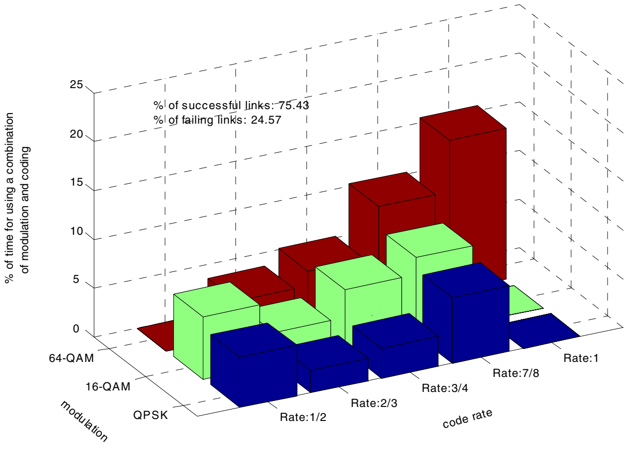

Fig. 6. 3-D histogram of adaptive modulation and coding usage (without relay, SINR-based relay selection algorithm, $P_{relay} = 1$ W, $R = 1000$ m).

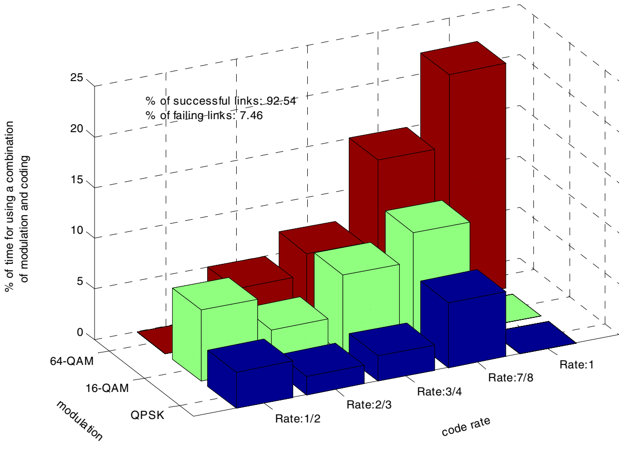

Fig. 7. 3-D histogram of adaptive modulation and coding usage (with relay, SINR-based relay selection algorithm, $P_{relay} = 1$ W, $R = 1000$ m).