FIXED RELAYS FOR COST EFFICIENT 4G NETWORK DEPLOYMENTS: AN EVALUATION

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ABSTRACT

The paper provides a qualitative performance assessment of relay based deployment concepts in comparison to single-hop deployment. The results in this paper prove the general assumption that the deployment of Relay Nodes (RNs) provide a strong opportunity to reduce the network deployment cost substantially. It is shown how low power RNs have to be applied in cellular scenarios with high power Base Stations (BSs) and what cost benefits can be expected. The qualitative results show that the low power relays do have the potential to decrease the deployment cost. It is further shown that a parallelization of the relay link between the RNs and the serving BS will help to improve the cost efficiency of the relay based deployment concept.

I. INTRODUCTION

Fourth-Generation (4G) radio system such as investigated in the EU funded IST project WWI New Radio (WINNER) [1] aim at the provision of ubiquitous broadband access for nomadic users.

It is well known that the range of a 4G broadband radio interface will be limited by the high attenuation at the envisaged carrier frequencies beyond 3.4 GHz, a limited transmission power (Effictive Isotropically Radiated Power (EIRP)) owing to regulatory constraints and unfavorable radio propagation conditions, e.g., in densely populated urban areas. Thus, conventional (single-hop) cellular radio network deployment concepts would require a very high Base Stations (BSs) density to achieve sufficient radio coverage. As a consequence, the system deployment cost in terms of Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) for broadband radio system would increase dramatically, resulting in high costs per bit transmitted. Further, the available maximum throughput is depending on the distance from the BS. The highest capacity is available in the small area close to the BS and decreases with increasing distance. On the other hand most users can be expected in areas more far away from the BS due to the increased coverage area with increasing distance [2]. Fixed layer-2 Relay Node (RN) based appear to be the most promising technology to bring the capacity available at the BS into the area [3][4].

Thus, the evaluation of RN based deployments has to take the deployment cost into consideration [5]. To achieve a fair comparison the cost have to measured against a required service level[6], which means the relay based deployment should provide the same service level at less cost compared to the single-hop BS deployment.

In this paper it is shown under what cost conditions a RN based deployment can be more cost efficient compared to a conventional single-hop deployment for two different deployment scenarios.

The paper is structured as follows: in the next section the expected cost factors of a RN in comparison to the BS cost are introduced and the deployment strategies investigated in this paper are motivated. Sec. III. provides details about the underlying models, scenarios and the assessment methodology taken from [6].

The results in terms of indifference curves for different types of scenarios are presented in Sec. IV.. A final discussion of the results is provided in the concluding section.

II. RN TYPES AND DEPLOYMENT STRATEGIES

Cost is the main argument for relay-based deployments. The RN is assumed to be more cost efficient compared to a respective BS as they don't need an extra (wired, fibre or micro wave) backbone access, which leads to reduced deployment costs (CAPEX and OPEX). Thus they are cheaper in terms of hardware cost as well as more flexible in positioning than a BS. A fact which allows a fast network roll out and adaptive traffic capacity engineering.

In today's cellular networks it can be differentiated between different types of BS ranging from macro BS mounted on extra towers over micro BS to small pico BS, e.g. home BS as foreseen in future Third-Generation (3G) networks.

In general high Tx power will result in high cost for power supply, transmitter hardware and cooling. E.g., macro BS operating with Tx power $\geq 40\,\mathrm{dBm}$ need extra air conditioning. Thus it will be much more appropriate to install low power RNs without expensive cooling mechanism. RNs in the size of macro BS would also loose their deployment flexibility, which means the backbone connection might be only a minor point in the overall cost structure of a macro nodes.

Thus, the investigations shown in this paper focus on adding micro RNs to macro BS. The exact definition of the used node types is shown in Table 1. In the following the term RN refers to a micro RN and the term BS is used synonymously for a macro BS if not specified differently.

Table 1: Node Type in Wide Area Cellular Networks

Node Type	Tx Power	Bandwidth
Macro BS	46 dBm	100 MHz
Micro BS	37 dBm	100 MHz
Micro RN	37 dBm	100 MHz

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III. Simulation Model and Scenarios

In order to achieve iso performance curves as introduced in the next subsection, the system level simulation tool developed at the Chair of Communication Networks (ComNets) at RWTH Aachen University, called Wireless Network Simulator (WNS), was used to calculate the Downlink (DL) Signal to Interference plus Noise Ratio (SINR) for different BS to BS distances and different RN scenarios with different distances between the BS and the RNs and different numbers of RNs within the coverage area of one BS.

A. *Iso performance cost comparison*

To compare relay based deployments against single-hop solutions the method of *"iso cost performance"* as presented in [7] was used. Area Spectral Efficiency (ASE) $[bps/MHz/km^2]$ was chosen as iso performance level. The target performance can be provided by different deployment concepts with different constellations of macro BS and RN densities (ρ_{BS}, ρ_{RN}) resulting in different deployment cost to achieve the same network performance. The relay enhanced BS increases its capacity compared to a single-hop BS. At the same time the relay enhanced BS increases its coverage area, thus, the ASE remains the same.

If the cost ratio between RN cost, c_{RN}, and BS cost, c_{BS} fulfils the following inequity the relay based system is more efficient than the single hop one [7]:

$$\frac{c_{RN}}{c_{BS}} < \frac{\rho_{BS,single-hop} - \rho_{BS,multi-hop}}{\rho_{RN}} \quad (1)$$

The optimum mix between BS and RN is reached at the point where the *Equal Cost Line* is tangent to the *Iso Performance Curve*. According to linear cost model [8] the slope of the *Equal Cost Line* can be expressed as

$$cr_{ECL} = c_{BS}/c_{RN} = \frac{\rho_{RN,opt}}{\rho'_{BS} - \rho BS, opt} \quad (2)$$

ρ'_{BS}, where the *Equal Cost Line* tangent to the iso performance curve intersects the x-axis, is a virtual point of operation of a single-hop BS that provides a cost adjusted site spectral efficiency. Further, ρ'_{BS} denotes the BS density one can afford for the prize of an optimized relay enhanced deployment.

Eq. 1 compares the multi-hop system against a single-hop system. This can also be expressed as gain factor

$$\begin{aligned} g_{cost} &= \frac{\rho_{BS,0} * c_{BS}}{\rho_{BS,opt} * c_{BS} + \rho_{RN,opt} * c_{RN}} \quad (3) \\ &= \frac{\rho_{BS,0}}{\rho_{BS,opt} + \rho_{RN,opt} * cr_{ECL}} \\ &= \rho_{BS,0}/\rho'_{BS} \end{aligned}$$

B. *Physical Layer and Propagation Model*

For all access links, i.e. the link between the Radio Access Point (RAP) (either BS or RN) and the User Terminal (UT), the pathloss model *"C2"* as defined in [9] is used:

$$\begin{aligned} PL_{C2} = & \quad (4) \\ & [44.9 - 6.55 * \log_{10}(h_{BS})] * \log_{10}(d[m]) + 34.46 \\ & +5.83 * log_{10}(h_{BS}[m]) + 20 * \log_{10}(f[GHz]/5) \end{aligned}$$

with the RAP height $h_{BS} = 25m$ and the UT height $h_{UT} = 1.5m$. An Orthogonal Frequency Division Multiple Access (OFDMA) system was assumed operating with 100 MHz bandwidth subdivided in 104 subcarrier at $f = 3.95GHz$.

The Relay Link (RL) between the BS and the RN is assumed to be line of sight and does not suffer from interference.

The link level mapping is based on Low Density Parity Check (LDPC) coding results with code word size of 288 bit. Further a perfect link adaptation is assumed.

C. *Relaying and Radio Resource Management (RRM)*

A simple relaying scheme where relaying is performed in the time domain is assumed. Thereby only one RAP is active per time. Further, the paper is limited to a two-hop system.

The capacity of a multi-hop link without any protocol implications can be written as

$$\phi_{MH} = \frac{1}{\sum_{i=1}^{N_{tier}} \frac{1}{\phi_{RL_i}} + \frac{1}{\phi_{AL}}} \quad (5)$$

where ϕ_{RL_i} denotes the capacity achieved on the i^{th} RL and ϕ_{AL} is the capacity achieved on the access link.

Thus a single 2-hop link capacity can be written as follows

$$\phi_{2Hop} = \frac{1}{\frac{1}{\phi_{RL_1}} + \frac{1}{\phi_{AL}}} \quad (6)$$

The underlying multiple access scheme is Time Division Multiple Access (TDMA), which meand the resources are shared among all active nodes in the time domain. Further, it is assumed that all RNs are active at the same time, but not in parallel to the BSs, which means the RNs don't experience interference form the BS. This scheme allows that, e.g., two RN of a two RN Relay Enhanced Cell (REC) can serve two UTs at the same time while the BS can serve only one UT at one time.

The BSs are assumed to operate with a reuse of three, whereby for the sake of simplicity the reuse is also assumed to happen in the time domain. The resources for the RLs between the RNs and the serving BS are coupled to the BS resources, i.e. reuse of three. The RL is separated in the time domain.

The capacity experienced by N UTs each connected to one RN within a REC comprising N relays can therefore be calculated as:

$$\phi_{RUT_N} = \frac{N}{\sum_{i=1}^{K} \frac{1}{\phi_{RL_i}} + \frac{1}{\phi_{AL}}} \quad (7)$$

with $K = N$ without parallelization on the RL and $K = \lceil N/3 \rceil$ if up to three RLs can be operated in parallel. Thus the RRM scheme is reuse one for the micro nodes and reuse three for the macro BS. This effect is expressed in the quantitative throughput calculation by a reduction of factor three of the BS spectral efficiency.

In the model the UT is always connected to the best serving RAP, which can be either the BS or a RN, from the system load point of view. This means if the UT achieves a higher throughput connected to a RN under consideration of the parallelization gain and RL then it will connect to the RN.

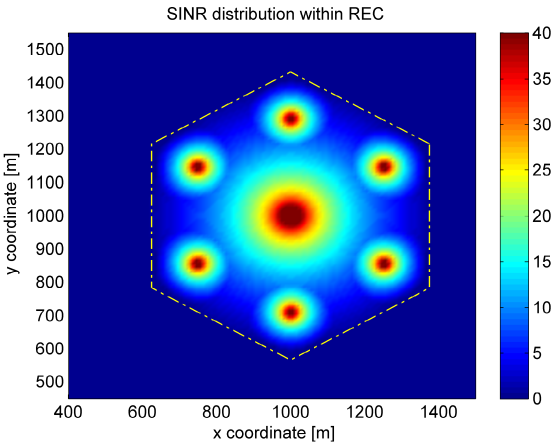

Figure 1: SINR within a REC of six RN fed by macro BS with omnidirectional antenna

D. Scenario

Table 2 summarizes the two different scenarios based on two type of macro BS. The BSs are placed in different regular scenarios with and without micro RAPs. Depending on the inter BS distance the micro RAPs have been placed in four distances to the serving BS in order to get the best point of operation.

Table 2: Node Type in Wide Area Cellular Networks

BS Antenna	micro Nodes per BS	BS - BS distance
3 Sectors	3, 6, 9	500 - 1500 m
Omnidirectional	2, 3, 6	500 - 1000 m

Fig. 1 shows the REC cell shape and SINR distribution within the REC for a BS with omnidirectional antenna feeding six RNs. Obviously the SINR at the cell edge is improved.

Fig. 2 shows the REC cell shape and the SINR distribution within a three sector cell applying two RNs per sector. Also here a benefit in SINR can be noted.

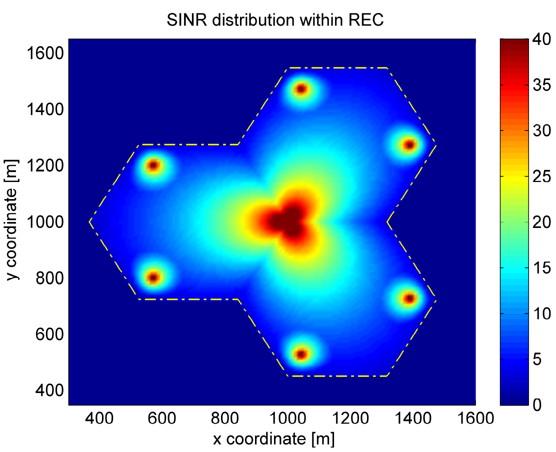

Figure 2: SINR within a REC of six RN fed by a macro BS with three sectorized antennas (two RN per sector)

IV. Results

In this section the results in form of iso performance curves are presented showing the potential cost gain of relay based systems compared to single hop deployments. The densities of the iso performance curve have been normalized to the required single hop BS densities. As target performance an ASE of $2\,\mathrm{bps/MHz/km}^2$ has been chosen. Further, a minimum throughput of 2 Mbps has to be available in the whole cell.

To get a feeling of the upper bound performance of a relay-based system a RN scenario with unlimited capacity on the RL has been investigated, too. As these type of RN is very similar to micro BS the scenario is further referred to as micro BS. Please note, that the increased cost of micro BS compared to RN have not been considered for the evaluation. Further a scenario allowing up to 3 parallel RLs has been investigated.

A. RN performance in scenarios based on BS with omni directional antennas

Fig. 3 shows the iso performance curve for the scenarios based on a macro BS with omni directional antenna. The solid iso performance curve is for the REC, the dashed curve shows the results for the micro BS deployment.

For the cost comparison a equal cost line with the slope of

$$cr_{ECLomni} = c_{omniBS}/c_{RN} = 10/1$$

was chosen. It is shown that, under the given assumptions in terms of cost ratio and target performance, the total deployment cost can be reduced by more than 10 %. The equivalent micro BS deployment shows that the a more sophisticated RL can further reduce the cost down to half of the cost of a pure macro BS scenario.

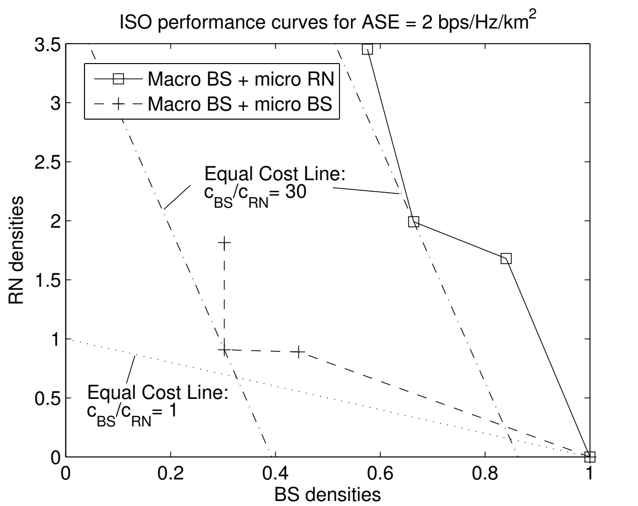

Figure 3: Iso performance curve for macro BS with omnidirectional antenna enhanced by micro RAP; target performance to achieve: $2\,\mathrm{bps/MHz/km}^2$

Fig. 4 shows the minimum achievable throughput of a BS with (REC) and without RN. It is shown that RNs can be used to extend the range of BSs with omnidirectional antennas if enough are deployed or if the range should be extended only to certain regions, e.g. shadowed from the BS.

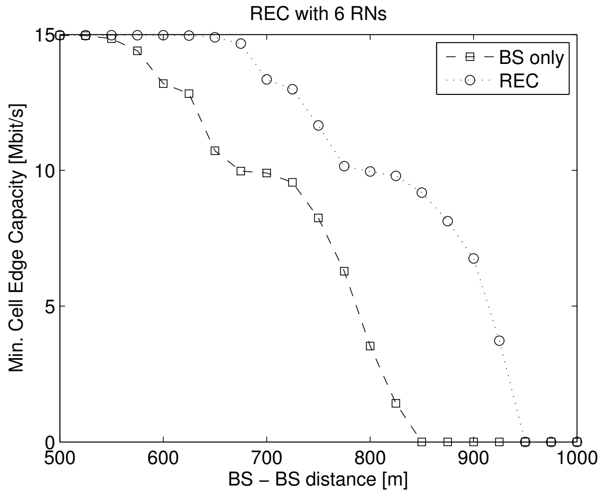

Figure 4: Minimum achievable throughput at the cell edge of BS with and without RN

B. *RN performance in scenarios based on three sector BS*

Fig. 5 shows the iso performance curve for the scenario with the macro BS equipped with a three sector antenna.

For the cost comparison a equal cost line with the slope of

$$cr_{ECL3Sect} = c_{3SectBS}/c_{RN} = 20/1$$

was chosen under the assumption that the BS with a three sectorized antenna is more expensive than one with an omni directional antenna. Fig. 5 shows that the gain of the RN is less than in the omni directional case. More surprising is the big difference between the micro BS and the RN deployment. This means that the potential of having more advanced technologies on the RL is much higher in this scenario than in the one with the omni directional antennas.

Fig. 6 shows the minimum cell edge throughput for the scenarios with a three sector BS with two RNs per sector. Compared to the omni directional scenarios increase of coverage due to the RNs is rather low. Three RNs per sector would also increase the interference in the cell edge regions and are therefore less helpful in terms of coverage extension.

C. *Summary*

In Table 3 the results are summarized. The table contains in addition the results for the scenario with three parallel RLs. The minimum cost ratio cr_{min}, i.e. the cost ratio which is required to deploy the relay based system at the same cost as a single-hop system, is rather high for relay-based scenario with the serial RLs, especially in the scenario with 3 sectors at the BS. But if three RLs can be operated in parallel the minimum required cost ratio is decreased substantially.

Fig. 7 shows the cost gain over the target ASE for the two different macro BS scenarios with RN with serial RL, with 3 parallel RLs and with infinite capacity (e.g. fixed backbone access) on the RL. The gains are for the cost ratios as described

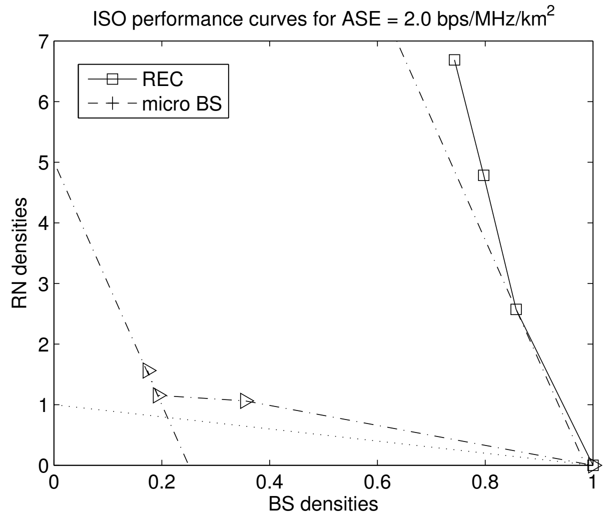

Figure 5: Iso performance curve for macro BS with three sector antenna enhanced by micro RAP; target performance to achieve: $2\,\mathrm{bps/MHz/km^2}$

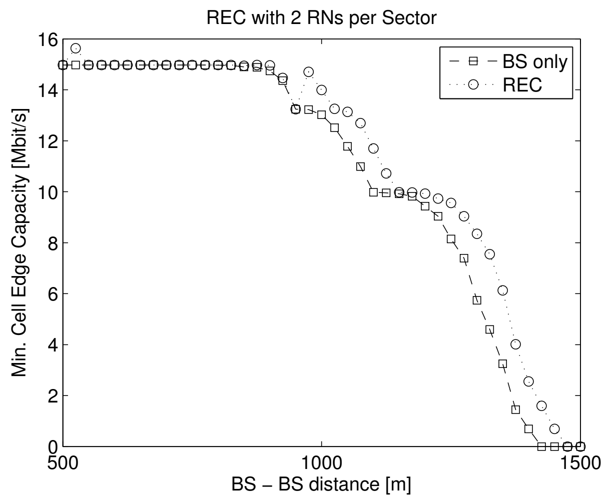

Figure 6: Minimum achievable throughput at the cell edge of a 3 sector BS with and without RNs

Table 3: Results of iso performance curves for a target performance of $2\,bps/MHz/km^2$

BS Type	Omnidirectional	3 Sectors
min. $c_{mac.BS}/c_{RN}$	cr_{min} = 5.9	cr_{min} = 18.0
Parallel RLs	cr_{min} = 2.7	cr_{min} = 4.7
min. $c_{mac.BS}/c_{mic.BS}$	cr_{min} = 1.3	cr_{min} = 1.4
cost gain (CG) RN	14 %	1 %
CG with parallel RLs	46 %	41 %
CG micro BS	61 %	75 %
max. RN CG	19 %	20 %
max. CG (para. RLs)	46 %	47 %
single hop BS density	3.82 BS/km^2	3.21 BS/km^2

above. It is shown that the cost gain of the system with more advanced RLs is going into saturation at very high level, with slightly more than 45% for three parallel RLs (see also Table 3). In case of serial RLs the gain decreases with higher target performance after a first peak as the resource consumption on the RL is too high to operate the RNs efficiently. It is further shown that below a certain ASE threshold no gain can be expected from the RN for the investigated scenarios.

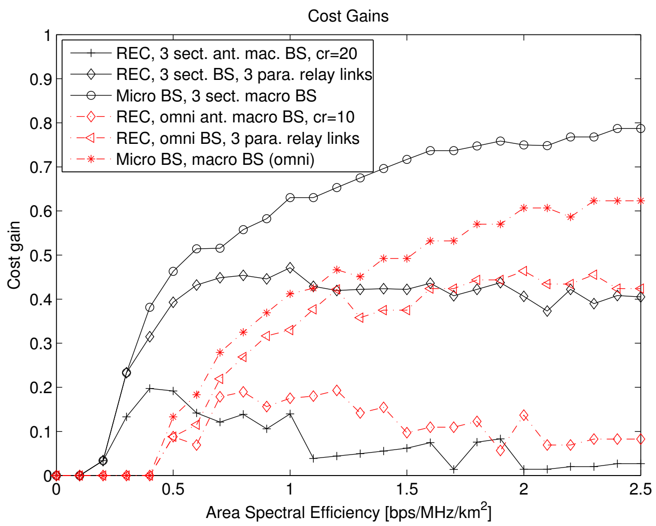

Figure 7: Comparison of cost gain vs. target Area Spectral Efficiency (ASE)

V. Conclusion

The results shown in this paper prove that Relay Nodes (RNs) can help to reduce the deployment cost of the investigated wide area scenario substantially. It is further shown that the benefit of RN is depending on the deployment scenario. In case of more sophisticated BS the benefit of simple RN is less than in the scenario where simple BS are enhanced with RNs, even if the cost ratio was adapted. The results of the RN deployment in conjunction with the sectorized macro BS is a first indicator of the performance of RNs in scenarios with even more sophisticated BS, e.g. with multiple antennas for multiuser beamforming (Space Division Multiple Access (SDMA)) or Multiple Input Multiple Output (MIMO) technologies. But the results also show that through exploitation of the advanced BS technologies for the Relay Link (RL), e.g. parallel transmission of several RLs, the efficiency of RN based deployments can improve a lot.

It was shown that RNs provide good benefits to enlarge the coverage area of BSs with omni directional antennas. According to the shown results this benefit is rather limited for BS with directed antennas. On the other hand RNs are the only technology to extend the range of a BS towards otherwise shadowed areas.

The paper touched only a very limited field of the huge parameter space which opens up when starting to deploy RNs. Therefore it remains to further study how the capacity of RN based deployment can be improved by dedicated RN based RRM schemes, better technologies on the RL, e.g. MIMO or parallel feeding of several relays. The micro BS results have also proven that there is a lot of room for improvement on the RL. In real scenarios where the deployment is not equally distributed the benefit of RN-based deployment might be increased as they can serve as cheap "hot spot" enlargements for a macro BS. Further, only the downlink has been investigated, whereas the uplink of macro BSs is assumed to be more range critical, as the UT will operate with much lower Tx power, which means the system can benefit a lot from the deployment of RNs in terms of range.

Finally the design of the RN will be a trade off between the complexity required to achieve the desired performance and the related cost.

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