On PHY and MAC performance of 3G-LTE in a multi-hop cellular environment

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***Abstract*— Next generation cellular radio systems will exceed the limitations of UMTS. The convergence of data and voice traffic will be supported by a flexible OFDM-based PHY layer and an OFDMA-capable MAC layer. The long term evolution (LTE) successor of the 3G systems incorporates this. But problems concerning coverage and capacity at the cell border still remain for the classical cellular layout. Relaying or Multihop operation is an option to massively improve the coverage as well as the capacity issue at low cost, without the need of a cable or fibre access. For the performance analysis of such cellular systems models for ISO-OSI layers 1+2 (PHY+MAC) are needed. In this paper an analytic modelling framework and results are presented for the cellular LTE performance in two multihop scenarios.**

***Index Terms*— OFDMA, LTE, FDD, Multihop, Relaying**

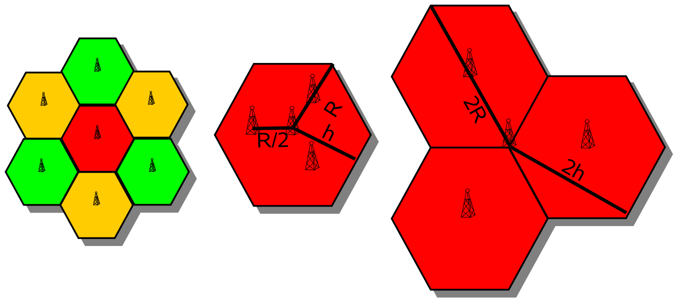

Fig. 1. Left: Conventional cellular geometry, Middle: Best geometry to increase capacity, Right: Best geometry to increase coverage

I. Introduction

THE demand for constantly high data rates all over a large covered area is user-driven. The conventional cellular architecture cannot match this demand for some reasons. First, due to a given limited transmit power level (EIRP limited), the higher transmission rates lead to a lower energy per bit. Second, the radio propagation above $2GHz$ is more vulnerable to bad non-line-of-sight conditions, which happens frequently in densly populated areas. In effect, the path loss is higher between base station and mobile. Third, non-constant rate offer: The maximum data rate offered by a base station depends on the distance between mobile and base station. Close to the base station, the higher received $SINR$ value allows the highest Modulation&Coding scheme (PhyMode), which offers the highest data rate. Near the cell border the offered data rate is one order of magnitude lower. Even worse is that the same data rate occupies ten times the resources when using the lowest PhyMode (cell border) instead of the highest PhyMode near the base station (BS). That means the average cell capacity is overproportionally determined by the maximum possible rate at the outer regions.

To overcome this problem, more base stations (BS) can be placed per area, but this comes with much higher deployment costs, since every base station needs its own access to the fiber backbone network.

Another solution is the deployment of Fixed Relay Stations (FRS), also called Relay Nodes (RN), that are feeded over the same wireless technology. Such a Multihop architecture [1] has the advantage of cheap and easy deployment, and serves like a BS for a cell area where capacity and coverage is increased. For these *relay enhanced cell (REC)*, the base station coordinates the partitioning of radio resources. The goal of the described multihop-augmented infrastructure-based networks is the almost ubiquitous provision of coverage [2] and throughput with very high data rates for any user terminal (UT) within the cell. Figure 1 shows the two ways from a conventional cellular layout to multihop-augmented cells for both goals.

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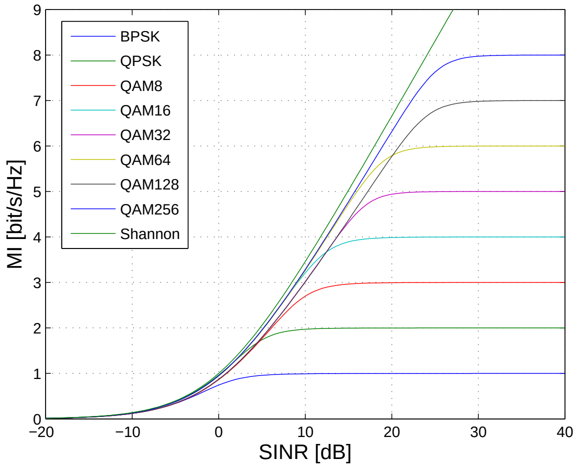
The optimum use of radio resources is a key advantage of OFDM. OFDMA scheduling [3] decides on PhyModes based on expected SINR levels at the receivers. For that purpose and also for performance evaluation, the link level function between $SINR$ and sustainable rate needs to be known for each PhyMode [4]. Formerly these had to be known in a tabular way [6] but here we show a closed formula for the modulation performance. This paper addresses the required analytical layer-1+2 performance modelling and performance results for the upcoming long term evolution (LTE) technology [5] discussed in the 3GPP.

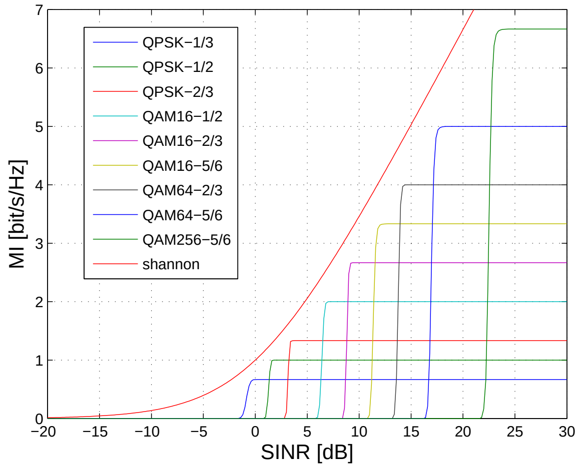
The paper is organized as follows. The first section gives an overview of layer-1 (PHY) performance models for orthogonal frequency division multiple access (OFDMA). Then, the performance models for layer-2 (MAC) are presented. The last section deals with performance results in the multihop case. A concluding summary contains statements to the key contributions in this paper.

II. PHY layer performance models

Determining the suitable PhyMode within each OFDMA subchannel (group of carriers in a chunk) is the task of a resource scheduler in the BS. This adaptive modulation and coding (AMC) is a key feature of OFDM schedulers. The decision is based upon the SINR level expected at the receiver. It requires channel state information (CSI) which it can obtain by channel quality indication (CQI). Dynamic subcarrier assignment (DSA) also requires this information to choose the right subfrequency for each UT.



(a) Mutual information (MI) depending on $SINR$ and PhyMode



(b) resulting net rate taking PER and ARQ into account

Fig. 2. Link level results for different modulation&coding schemes (PhyMode). They are calculated analytically, not by simulation.

For determining the required link level results we build upon the mutual information (MI) method [6]. This works by applying the steps $SINR \rightarrow MI$, $MI \rightarrow BER$ and $BER \rightarrow PER$ to get the packet error probability. For the first step the performance data of modulation schemes typically comes from link level simulations. MI has the meaning of the number of effective bits that can be transported at a certain $SINR$ level. It is always below the Shannon bound

$$MI_{shannon}(SINR) = log_2(1 + 10^{SINR/10dB}) \quad (1)$$

For the $SINR \rightarrow MI$ we have developed an analytic expression by fitting the link level result data with a suitable function. Figure 2(a) shows the result graph. In low $SINR$ regions, MI is limited by the Shannon bound. In high $SINR$ regions it is saturated and limited by the number of bits the modulation scheme supports (m). The region in between is influenced by both effects and handled by this new formula:

$$MI(SINR, m) = \frac{1}{([s \cdot MI_{shannon}(SINR)]^{-w} + m^{-w})^{1/w}} \quad (2)$$

using the following abbreviations

$$s = s(m) = 0.95 - 0.08 \cdot (m \bmod 2) \quad (3)$$

$$w = w(m) = 2 \cdot m + 1 \quad (4)$$

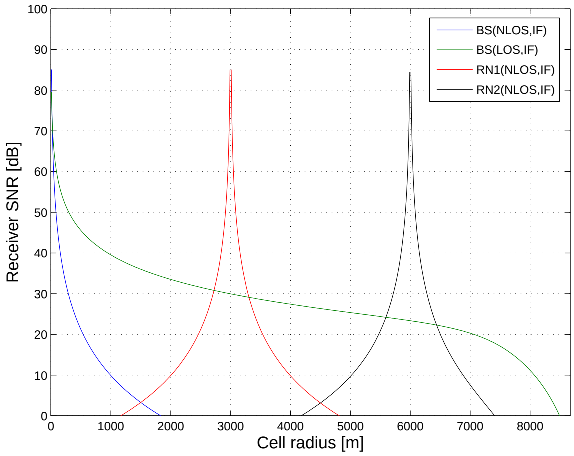
m is the modulation index, i.e. the number of bits per symbol (1=QPSK,...8=QAM256). The scale factor $s(m)$ reveals the remarkable fact that square-shaped modulaton constellations (m=2,4,6,8) perform slightly better than the other I/Q-asymmetric constellations. The MI value has the unit of $[Mbit/s/Hz]$, so we can derive the data rate by multiplying with the bandwidth of the subchannel. The net bit rate of the PHY layer is less than this value because of channel coding. The net PHY throughput is obtained by multiplying with the coding rate. For LTE, coders have $1/3, 1/2, 2/3$ and $5/6$ [7]. The approximation formula in eq. 2 has been validated with tabular simulation results and differs from the simulation-measured data by at most $0.2dB$.

III. MAC LAYER PERFORMANCE MODEL

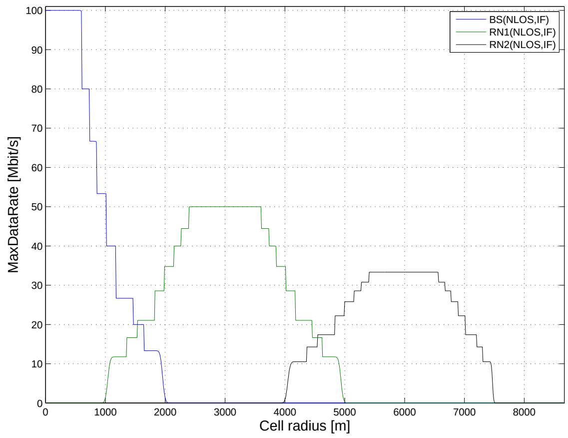
In the MAC layer, bit trains become packets. The CRC unit detects packets with errors. The probability of a packet error is PER. It depends on the type of channel coder used, the coding rate, and the packet length. This mapping must be taken from tabular results of simulations. With ARQ, these dropped packets are retransmitted again. Retransmission produces an overhead, since capacity is wasted. The resulting net rate is given by $r_{aboveARQ} = r_{belowARQ} \cdot (1 - PER)$. Taking these effects into account, the result $r_{MAC} = f(SINR)$ can be derived. Figure 2(b) shows this rate function for the 3G-LTE PhyModes. The mode $QAM256 - 5/6$ was added, because it can be used for the quasi-static BS-to-RN links to improve the relaying performance.

From link level to MAC throughput, the performance of the example system is now evaluated by calculating the following steps.

- *Transmit Power:* $40W_{peak}$ at the BS,
- *Pathloss I:* non-line-of-sight propagation,
- *Pathloss II:* slow and fast fading effects,
- *Interference:* neighbor cell BSs interfere (100% load, cluster order 7),
- *Noise:* accounted for but not serious in interference-limited systems,
- *SINR:* the first performance measure below PHY layer,
- *MI:* mutual information determined from $SINR$ and modulation,
- *BER:* bit error ratio, the PHY performance result,
- *PER:* packet error ratio, the result after channel decoding,
- *Delay:* determined by PER (ARQ retransmissions) and roundtrip times,
- *Throughput:* determined by bandwidth, PhyMode (modulation and code rate), ARQ overhead,



(a) Signal-to-Interference ratio (SINR)



(b) Supported data rate

Fig. 3. Analytical analysis of a coverage extension scenario with one BS and two relays. A line-of-sight link or antennas with gain between BS and relays is assumed. An interferer is positioned at $9000m$

IV. Multihop Operation and Performance

Typical scenarios for cellular multihop operation are shown in figure 1. In the coverage extension scenarion, the supported area (regarding sufficient $SINR$) around relay nodes is of same size as the singlehop area around the base station. The inner hexagon is typically served by BS within its range, while the outer regions are served by one of the three RNs respectively. For capacity extension, the whole hexagonal area can be served by the BS, but in regions closer to the cell border and near the RN, the RN offer a much higher data rate to user terminals than the BS would.

Being served by a RN means that an intra-cell handover has been performed, where the decision has been taken that the UT is better supported by the RN than by the BS. Better not only means that the UT receives a higher $SINR$ at its current position, but additionally that the total amount of resources needed for $hop1$ (BS-RN) and $hop2$ (RN-UT) is less than what would be required if it was a single hop transmission between BS and UT. That means, relaying is the most efficient way to handle the UT traffic, both locally for the UT, and globally for the spectral efficiency of the cell. Figure 3 shows typical $SINR$ conditions and the resulting supported rate around BS and RNs for a three-hop scenario (BS,RN1,RN2,UT). We observe the high benefit beyond the BS coverage range in figure 3(b). The results are based on the calculation, not from simulation.

A. Analytical Results

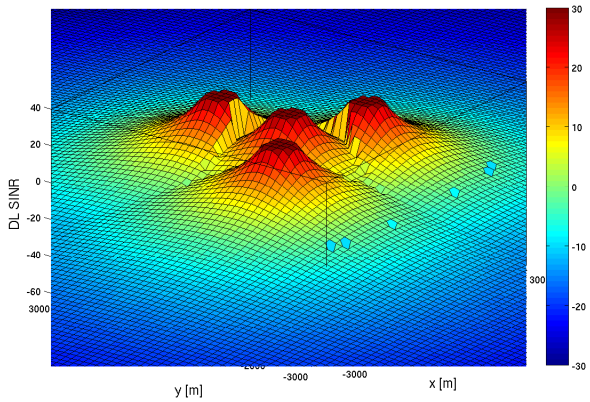
Figure 4 shows results for the coverage (above) and capacity (below) extension scenarios defined in fig. 1. The results use the analytic model of section II and did not use any simulation. The interference of neighbour cells with similar layout is properly taken into account with a frequency reuse of C=7. The DL SINR results plotted over the cell area show the $SINR$ of the best station (BS,RN), not the maximum $SINR$. The important difference is that the *best station* is determined by the highest rate any of the stations can offer. The rate/throughput results contain the maximum achievable rate at a certain position within the cell, taking also the required first hop resources into account. Therefore, the second hop maximum rate near the relay cannot be as much as near the BS. The relay is chosen as the serving station (association) if this is an advantage in less resources used, which is here the same as the maximum rate. In both scenarios there are huge areas where the relay offers an advantage over the singlehop case. So there is more than just high $SINR$ around RNs.

B. Coverage Extension Scenario

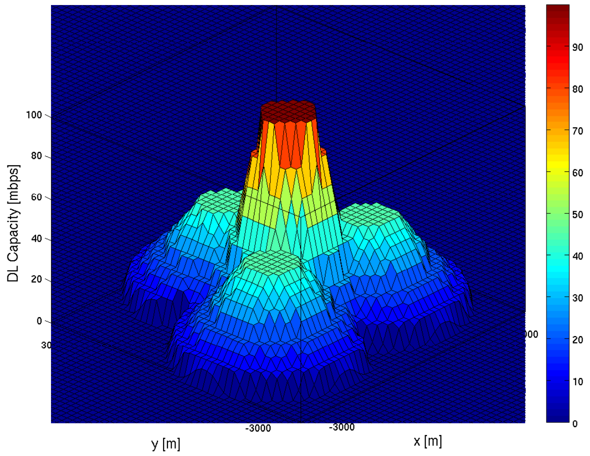
The cell geometry is extended as shown in figure 1 so that the covered area is three times the original area ($+200\%$). In figure 4(a) the area served by the BS is small compared to the coverage achieved by the relays. Figure 4(b) shows that the maximum rate around the RNs is only half of the BS rate, but in areas the BS would never cover. So while the inner cell still has capacity to offer, it can be used to extend the coverage very economically. Note that the extra throughput around the relays already accounts for the resources taken on the first hop, so it is really a net gain here.

C. Capacity Extension Scenario

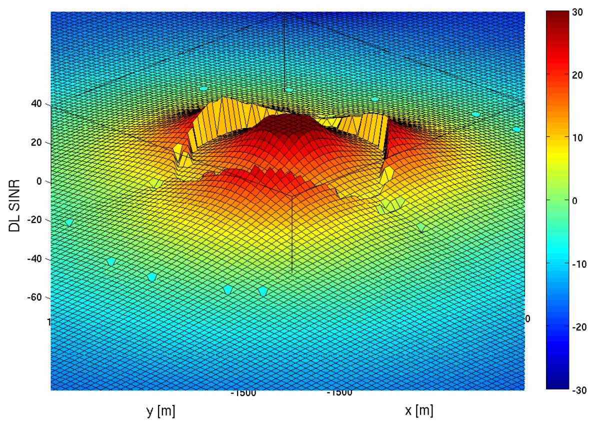
Relays placed within the normal radius of the single-hop cell mean that the BS is able to provide coverage for all UTs in the cell. But there are areas near the cell border where a RN provides much better service, not only in terms of $SINR$ (fig. 4(c)) but regarding the offered capacity for the UT (fig. 4(d)). So the cell border is no longer an area of the worst PhyMode, the highest (transmit) power consumption and the worst performance. So this scenario makes sense for urban scenarios where the capacity demand per area at the border is the same as near the BS.



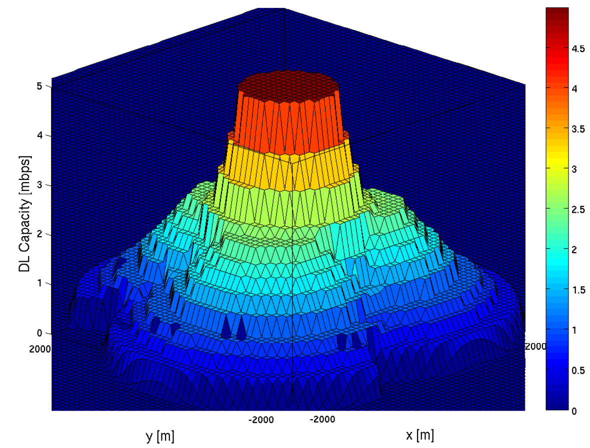
(a) Coverage Extension Scenario: SINR(area)



(b) Coverage Extension Scenario: Rate(area)



(c) Capacity Extension Scenario: SINR(area)



(d) Capacity Extension Scenario: Rate(area)

Fig. 4. Results for the two basic relaying scenarios. Values are for 3GPP-LTE, but the principles are the same for other technologies. In the graphs, a DL capacity close to $100 Mbit/s$ in the center is achieved in both scenarios. See [8] for similar WiMax related results.

V. Conclusion

This paper shows an analytic modelling framework to obtain performance results on the MAC layer. A new formula was presented to calculate the mutual information MI from $SINR$ for any known PhyMode. The method was then applied in multihop cellular scenarions where all calculations were done analytically using Matlab.

For the Coverage Extension Scenario and the Capacity Extension Scenario it is shown that the multihop communications can provide an remarkable increase in link and network capacity. Especially in areas suffering from high path loss relays can be successfully applied. The benefit is also that the high capacity of future cellular networks (near the BS) can be traded against coverage or better capacity at the outer regions.

References

[1] R. Pabst, B. Walke, D. C. Schultz, and et al, "Relay-Based Deployment Concepts for Wireless and Mobile Broadband Radio," *IEEE Communications Magazine*, pp. 80–89, Sep 2004.

[2] V. Sreng, H. Yanikomeroglu, and D. Falconer, "Coverage enhancement through two-hop relaying in cellular radio systems," in *Proc. IEEE Wireless Communications and Networking Conference(WCNC'02)*, 2002.

[3] G. Song and Y. Li, "Utility-based resource allocation and scheduling in OFDM-based wireless broadband networks," *IEEE Communications Magazine*, pp. 127–134, Dec 2005.

[4] M. Ahmed, H. Yanikomeroglu, and S. Mahmoud, "Fairness enhancement of link adaptation techniques in wireless access networks," in *Proc. Vehic. Technol. Conf.-Fall*, 6–9 Oct. 2003, pp. 1554–1557.

[5] http://www.3gpp.org/Highlights/LTE/LTE.htm.

[6] K. Brueninghaus and D. e. a. Astely, "Link performance models for system level simulations of broadband radio access systems," in *Proceedings of the 17th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Sep 2005, pp. 2306–2311.

[7] K. J. e. a. Ekstrom H., Furuskar A., "Technical solutions for the 3G long-term evolution," *IEEE Communications Magazine*, pp. 38–45, Mar 2006.

[8] C. Hoymann, M. Dittrich, and S. Goebbels, "Dimensioning cellular WiMAX: Multihop networks," in *Proceedings of European Wireless*, 2007. [Online]. Available: http://www.comnets.rwth-aachen.de