Capacity and Coverage Analysis of a 3GPP-LTE Multihop Deployment Scenario

Rainer Schoenen, Wolfgang Zirwas, and Bernhard H. Walke

***Abstract*— Broadband wireless access will be deployed in a cellular way with 3GPP-LTE [1]. For the first rollout the main demand is a huge area coverage. With only few available base station sites that are connected to an access fiber, multihop (relaying) techniques can be used well to fill the coverage gaps. Later with increasing offered traffic, the demand shifts to higher capacity over the area. Even for this purpose relays are beneficial. There is an area around relays where they provide better overall capacity to the user terminal, taking into account all resources used for the first and second hop (the relaying overhead). Relaying or Multihop operation therefore massively improves the coverage as well as the capacity goals at low cost, without the need of a cable or fiber access.**

This paper analyzes a realistic urban scenario on the island of Jersey. We study the coverage and capacity over the area in three cases. One base station (BS) only, one BS with four relay nodes (RNs), and the latter plus another ring of nine RNs. The BS has fiber access for rates beyond 100 Mbit/s, while the first hop of Relays (H1) is fed over the air from BS using shared resources in the same LTE band. The second hop H2 is fed by the relays of group H1. In this paper we provide the results from numeric analysis based on models we explain here. It is shown that huge gains in coverage and capacity are obtained by relaying.

***Index Terms*— Multihop, Relaying, LTE, Coverage, Capacity**

I. Introduction

MULTIHOP techniques are an elegant method to improve coverage and capacity in relay enhanced radio cells [2]. This is possible at much lower cost than providing more base stations (BS) with their need for high-rate fixed network access at every location. Due to the limited power of transmitters and the high path loss in non-line-of-sight conditions the received signal strength is not sufficient in many urban areas. To improve the coverage we therefore need more sending stations, which can be full BS or relay nodes (RNs of store-and-forward type). In this paper we study the realistic scenario of the city of Jersey. Compared to abstract and regular cellular scenarios, where the benefit of relaying can be shown easily [3], this provides a good proof-of-concept.

The OFDMA-based transmission scheme of 3GPP-LTE [1] allows to coordinate the radio resources used in time and frequency domain. In any relay enhanced cell we assume a full coordination, so that there is no intra-cell interference. Therefore, a resource block can only be used by one of the actors, either BS or one of the four $RN_1 \in H1$ or one of the nine $RN_2 \in H2$. For this reason, any traffic PDU that goes from BS to a user terminal (UT) associated to RN_2 consumes three resource blocks R_0, R_1, R_2, one on each hop $0, 1, 2$. The size of R_i in bits shall be the same, but the size in terms of time and frequency bandwidth ($T \times F$) depends on the modulation&coding scheme ($PhyMode$) on this subchannel.

Close to the sender, the higher received $SINR$ value allows the highest $PhyMode$, i.e. the highest data rate. At the cell border the offered data rate is one order of magnitude lower ($QPSK-1/3$ compared to $QAM64-5/6$ for LTE [1]). What is bad in this situation is that a terminal operating at the lowest PhyMode occupies a ten times higher part of the spectrum than a terminal operating at the highest PhyMode. That means the average cell capacity is overproportionally determined by the maximum possible rate at the outer regions.

Related work in this area mostly analyzes regular cellular geometries without considering realistic pathloss due to obstructions [4] [5] [6].

The paper is organized as follows. The first section defines the scenario. Next, the used layer 1 (PHY) and layer 2 (DLC) models are explained. Numerical results and 2D graphs are presented in the next section. The paper ends with a summary.

II. Urban Scenario (city of Jersey)

The urban scenario of Jersey has been chosen because the area of approx. $4.439 km^2$ is a typical cell size. A radio network planning has been done to place the base station and all relay nodes at best possible locations. See figure 1 for the geographic positions. The topology (building placement) was known in advance and raytracing tools have been used to obtain the received signal power $P_{R,i}$ at each location from each possible transmitter site. The physical parameters and calculation steps are given in section III. In the end we obtain a coverage map which shows for each point on the map which serving station a terminal is best associated to (best server). This can be the base station, if this is the rate optimal association, but it can also be one of the relays $RN \in H1$ or $RN \in H2$. The maximum achievable rate at a certain point is then determined. From these matrix (2D) results we calculate scalar performance measures to show that the overall coverage and capacity is increased compared to using only one BS. Therefore we compare the scenario with 1) one BS only, 2) the BS plus a ring of four $RN \in H1$ and 3) the BS plus a ring of four $RN \in H1$ plus a second ring of the nine $RN_2 \in H2$.

III. Layer 1 and 2 models

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

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Fig. 1. The Scenario map of Jersey showing the BS (middle) and RN placement

- *Transmit Power:* $37dBm$ at the BS, $34dBm$ at the RN,
- *Bandwidth:* $b = 18$MHz net (20MHz system),
- *Frequency:* $2.5GHz$ apropriate for LTE or WiMAX,
- *Scenario Geometry:* Cell Radius $R = 1600m$,
- *Pathloss I:* 3D model of the city scenario (walls of buildings),
- *Pathloss II:* ray tracing to capture multi-path propagation,
- *Noise:* Thermal noise power is $N = -96.4dBm$,
- *SINR:* the first performance measure below PHY layer,
- *MI:* mutual information determined from $SINR$ and modulation (Eq. 2),
- *BER:* bit error ratio, the PHY performance result,
- *PER:* packet error ratio, the result after channel decoding,
- *Throughput:* determined by bandwidth, PhyMode (modulation and code rate), ARQ overhead (Eq. 5),
- *Second Hop Throughput:* reduced by resources required on first hop (Eq. 6).
- *Third Hop Throughput:* reduced by resources required on first and second hop (Eq. 7).

A. PHY layer

The received power $P_{R,i}$ on every location is the output of software tools for raytracing. The next steps were analyzed analytically-numerically using Matlab. With $SINR = P_{R,i}/(N+I)$ the signal to noise ratio is easily determined. For each $SINR$ level between around 0 and 20 there in another $PhyMode$ chosen, depending on the estimated performance of this $PhyMode$ in terms of $bis/s/Hz$. For determining the required link level results we build upon the mutual information (MI) method [7]. We apply the steps $SINR \rightarrow MI$, $MI \rightarrow BER$ and $BER \rightarrow PER$ to get the packet error probability. For the $SINR \rightarrow MI$ we use [3]:

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

PhyMode	modulation	code rate	$SINR_{min}$ in $[dB]$
1	QPSK	1/3	0.9
2	QPSK	1/2	2.1
3	QPSK	2/3	3.8
4	QAM16	1/2	7.7
5	QAM16	2/3	9.8
6	QAM16	5/6	12.6
7	QAM64	2/3	15.0
8	QAM64	5/6	18.2

TABLE I

LTE $PhyModes$ AND THEIR REQUIRED $SINR_{min}$

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

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

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

m is the modulation index, i.e. the number of bits per symbol (1=QPSK,...8=QAM256). Figure 2(a) shows the result graph. The net PHY throughput is obtained by multiplying with the coding rate. For LTE, coders have rates $1/3, 1/2, 2/3$ and $5/6$ [8]. So the results in Figure 2(b) were obtained. The $PhyModes$ in this figure are given in Table I. Within this cell, all RNs are coordinated by the BS, so there is no intra-cell interference.

B. DLC layer

On DLC (MAC) layer, there is an overhead due to framing, signaling and ARQ retransmissions. The latter depends on PER, which can be taken into account when assuming selective repeat ARQ by equation 5.

$$r_{aboveARQ} = r_{belowARQ} \cdot (1 - PER) \qquad (5)$$

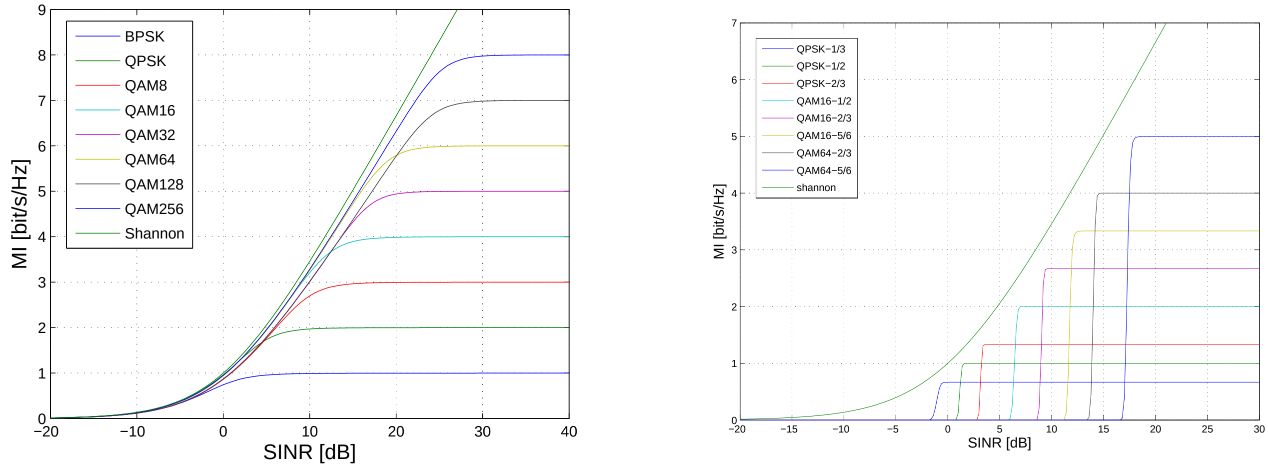
In total we obtain a MAC overhead of $MAC/PHY = 132.3\%$. The PHY overhead of $PHY/RAW = 107.1\%$ comes from OFDM cyclic prefix duration. Under multihop operation there are individual resources needed on every hop. The constant packet length requires a different resource share depending on the used $PhyMode$ which determines the maximum rate $r_{i,max}$ usable on each hop. Therefore we can get the maximum rate on the second hop to be

$$r_2 = (r_{1,max}^{-1} + r_{2,max}^{-1})^{-1} \qquad (6)$$

and on the third hop

$$r_3 = (r_{1,max}^{-1} + r_{2,max}^{-1} + r_{3,max}^{-1})^{-1} \qquad (7)$$

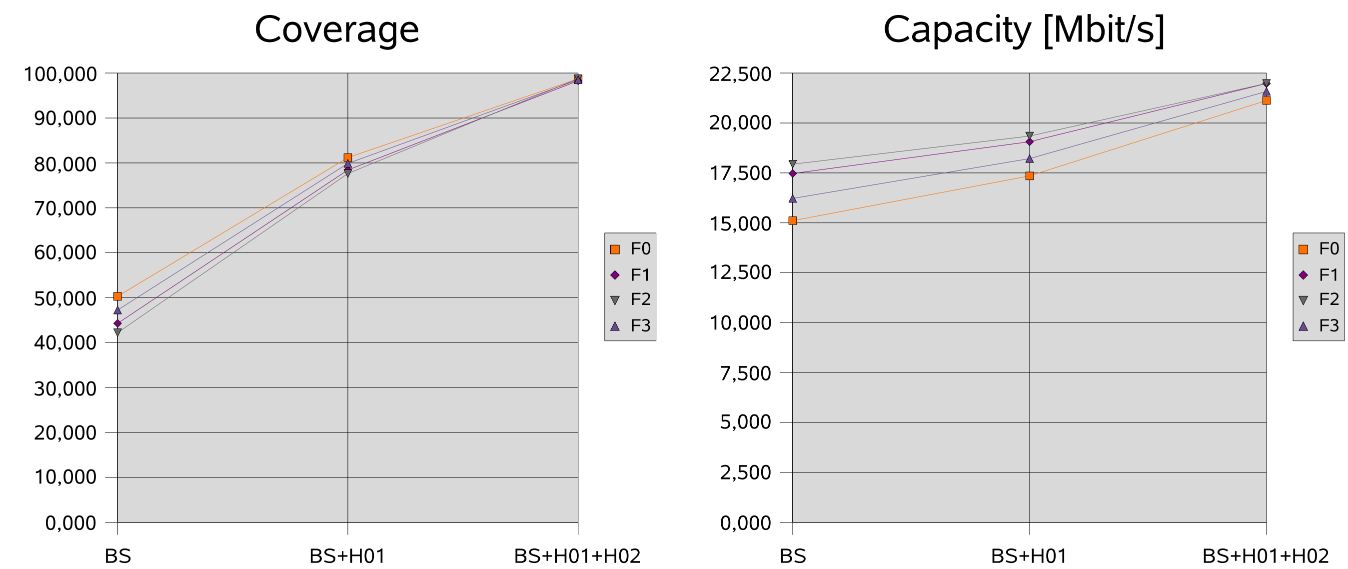
For every location (x, y) we can now determine the best rate out of r_1, r_2, r_3 which gives us the result in Figure 7. One of the three rates is maximum and the index i of the maximum r_i determines the “best server”, i.e. it shows which station the UT at that location should be associated with. Note that we can also determine the best server by choosing the highest $SINR$. But in the case of relaying, this would neglect the overhead due to the resources used in the hops before. Figure 7(f) shows the best server determined by rate (optimum) and for comparison Figure 5 shows the best server determined by $SINR$.



(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 ($PhyMode$).



(a) coverage using relays

(b) capacity increase using relays

Fig. 3. Coverage and capacity compared for three scenarios: BS (one BS only), BS+H01 (with one tier of relays), BS+H01+H02 (BS with two relay hops H1+H2). $F0..F3$ are 2D FIR data filters.

IV. Numerical Results

The analysis using our own numerical code in Matlab has been carried out to generate the two-dimensional data in fig. 6 and 7. Here we show the downlink only that also applies to the uplink if the uplink pathloss is the same (FDD). But the benefit in terms of capacity reveals if we derive scalar performance measures from it. The coverage (in % of the area) of the scenarios differing by the number of relays involved is determined by counting all locations with $SINR > SINR_{min}$. For LTE $SINR_{min} = 0.9dB$ holds. Figure 3(a) shows the coverage of each scenario. The system capacity is determined by assuming equal traffic load for each user terminal and a homogeneous user density over the area. This means that a UT far outside, having a low $PhyMode$, requires more share of the resources than a UT close to the BS. The following equation [9] for the capacity C considers this:

$$\frac{1}{C} = \int_{cellarea} \frac{1}{Capacity(x,y)} dxdy \tag{8}$$

Figure 3(b) shows the capacity of each scenario. Two-dimensional FIR filters have been applied to upsample the original quantized data from raytracing engine. Figure 4 shows that in a multihop scenario, more and more of the coverage area of BS is taken over by RNs. The capacity C in bit/s can be used to calculate the spectral efficiency $e = C/b$ using the used bandwidth b. As result we get the performance metrics in Table II. According to this, two tiers of relays, compared to the BS only scenario, increase the coverage by a factor of 2.08, and both the capacity and spectral efficiency by a factor

Scenario	coverage $[\%]$	capacity $[Mbit/s]$	spec.eff.$[bit/s/Hz]$
BS only	47.257	16.223	0.901
BS+H1	79.891	18.217	1.012
BS+H1+H2	98.519	21.583	1.199

TABLE II
SCALAR RESULTS FOR THE RELAY SCENARIOS

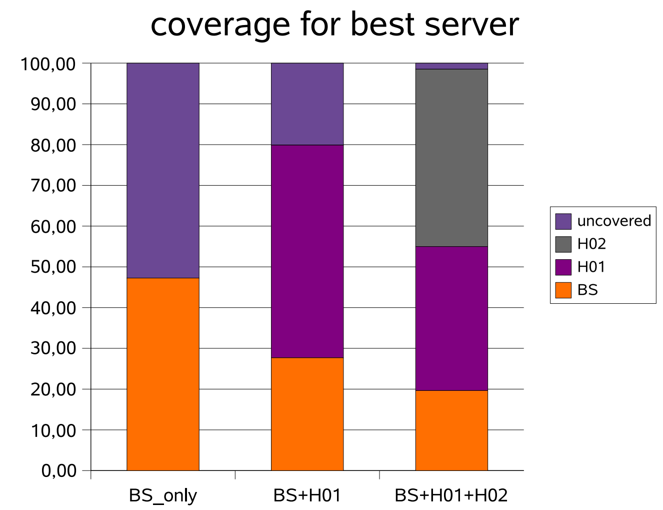


Fig. 4. The fraction of area served by each group of servers

of 1.33.

V. CONCLUSION

This paper treats the numeric coverage and capacity analysis of a real city scenario. We analyzed the topologic structure of the city to get the path loss, $SINR$ and data rate values for every location in that area. From that we derive the coverage (in %) and capacity (in $Mbit/s$) as well as the spectral efficiency calculated for the whole system. Doing this analysis for three scenarios, one with a base station only, one with two hops (one tier of relays) and one with three hops (two tiers of relays), we observed remarkable gains when using relays. Since relays are served via radio by the BS, the number of interfaces to the fixed network remains the same in all three scenarios. But the relays help to cover areas behind obstructions or other locations where the path loss from the BS is too large. Even in terms of capacity the multihop techniques improve the spectrum efficiency, because for all covered areas there is only one radio channel needed. In contrast, having several BSs to serve the same area tends to require more channels, since a reuse factor of one would result in too high interference. It would be interesting to perform an economic comparison of the CAPEX and OPEX related to the scenarions considered, e.g. [10]. In addition to abstract and regular cellular scenarios [3], this provides a realistic view on the application of relays.

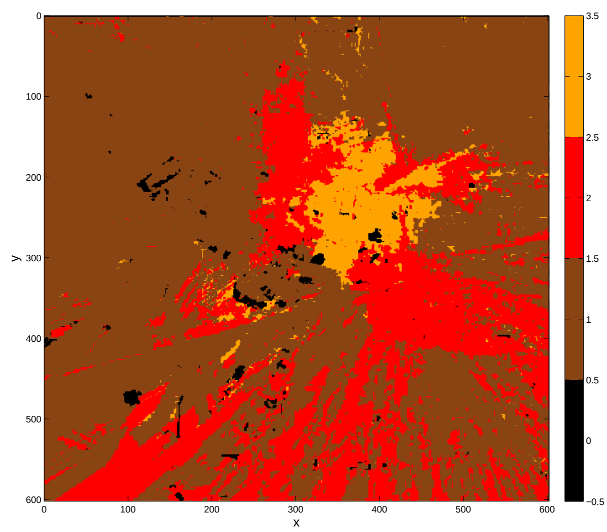


Fig. 5. Best server of BS+H1+H2 determined by SINR instead of net rate

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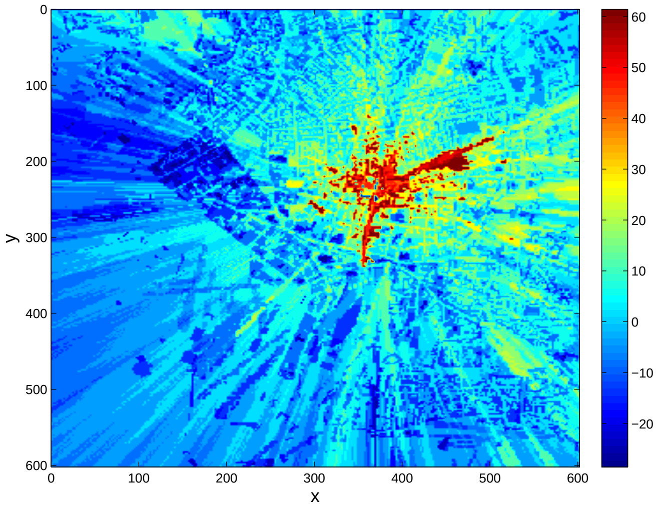
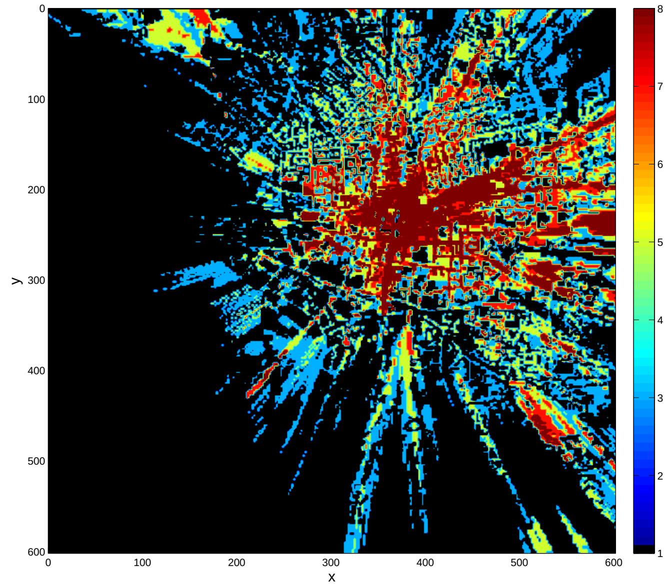
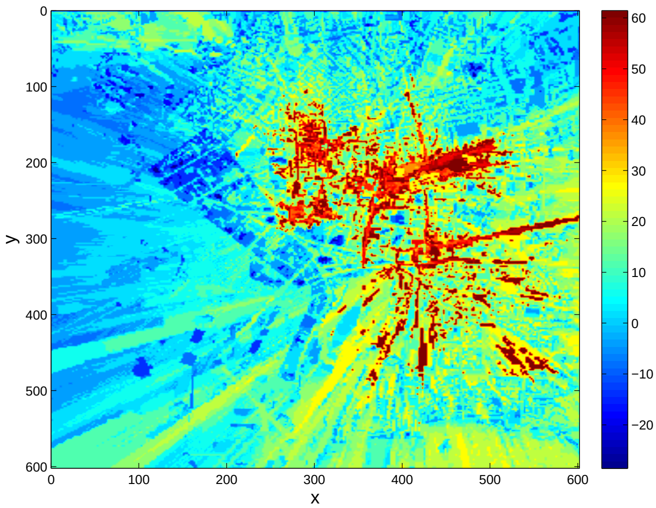


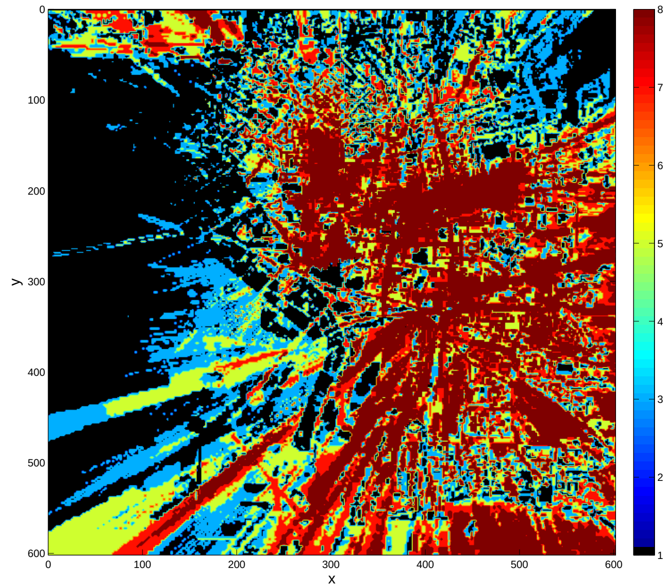
(a) SINR of BS only (in dB)



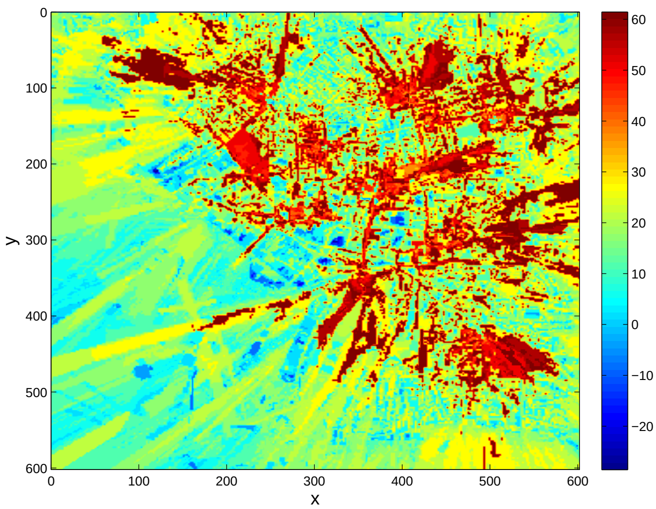
(b) PhyMode of BS only



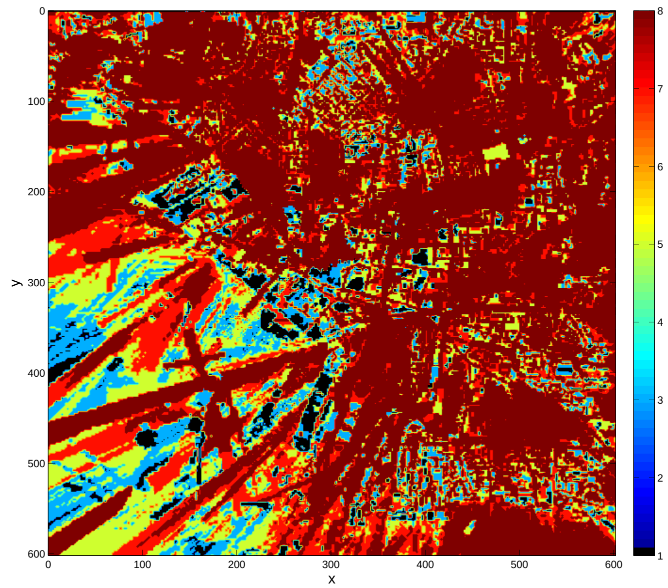
(c) SINR of BS with H1 (in dB)



(d) PhyMode of BS with H1

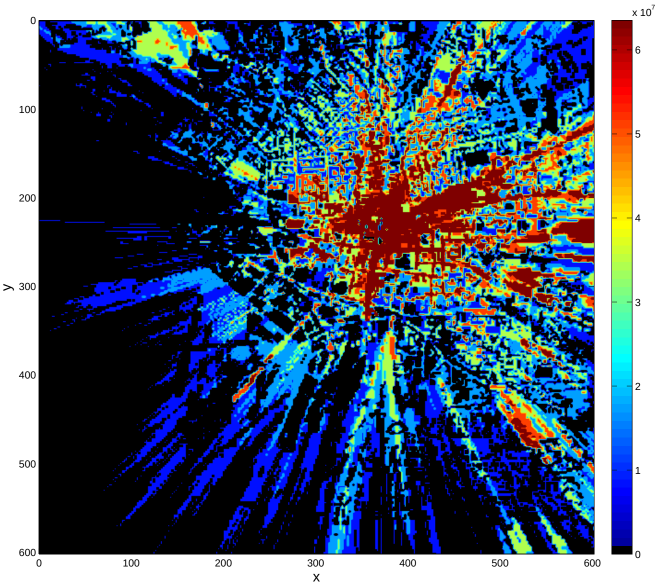


(e) SINR of BS with H1 and H2 (in dB)

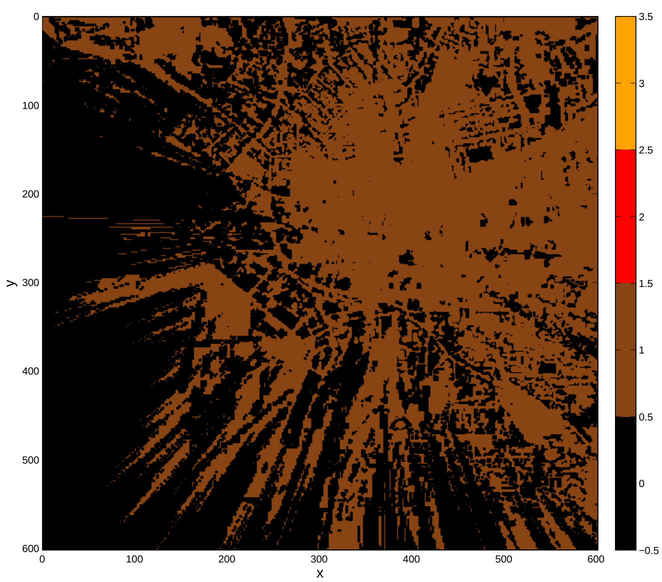


(f) PhyMode of BS with H1 and H2

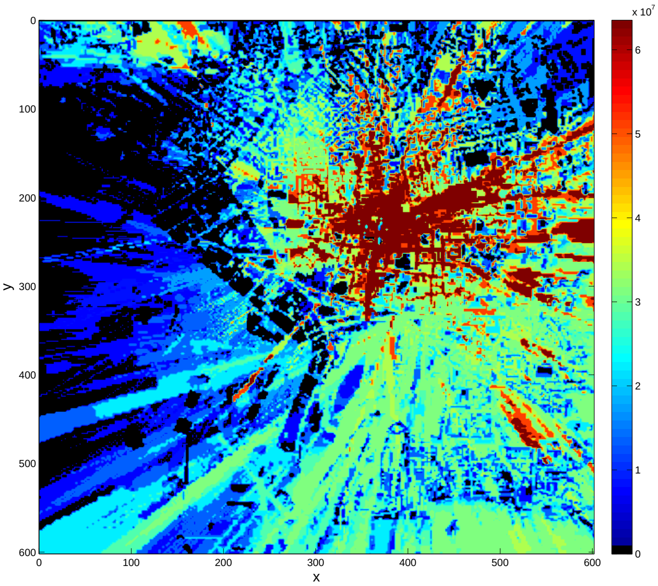
Fig. 6. On the area map of Jersey, these figures show the SINR [dB] and PhyMode [1..8] for a scenario with BS only, with one tier of relays H1, and with two relay hops H1+H2



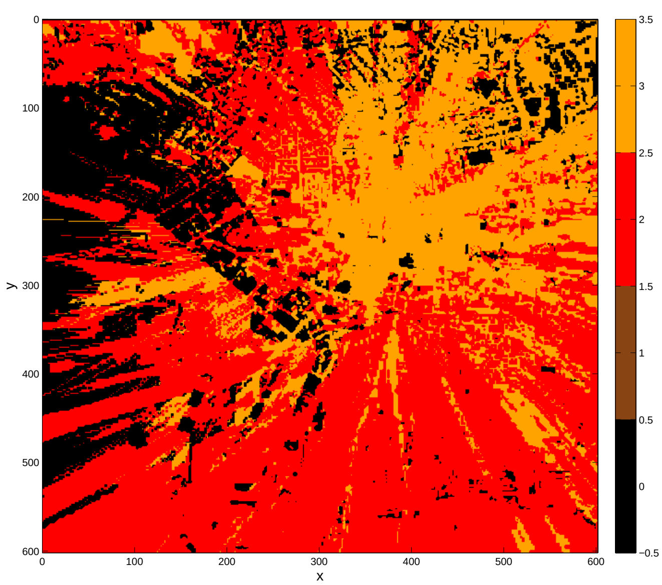
(a) Rate of BS only



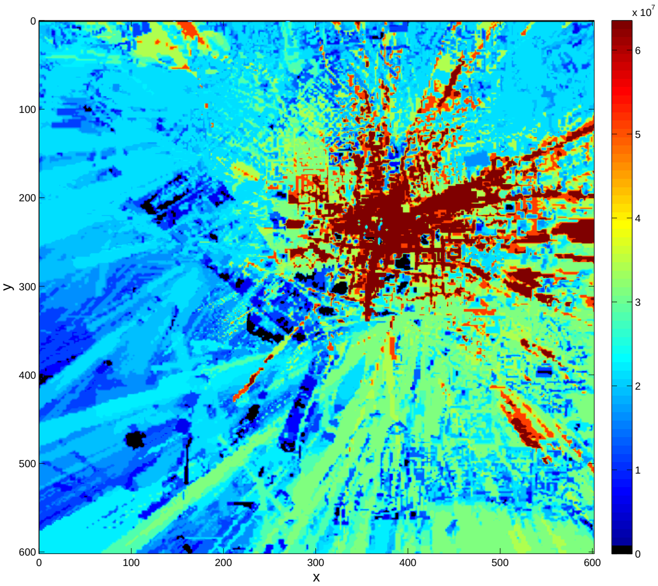
(b) Best server (coverage) of BS only



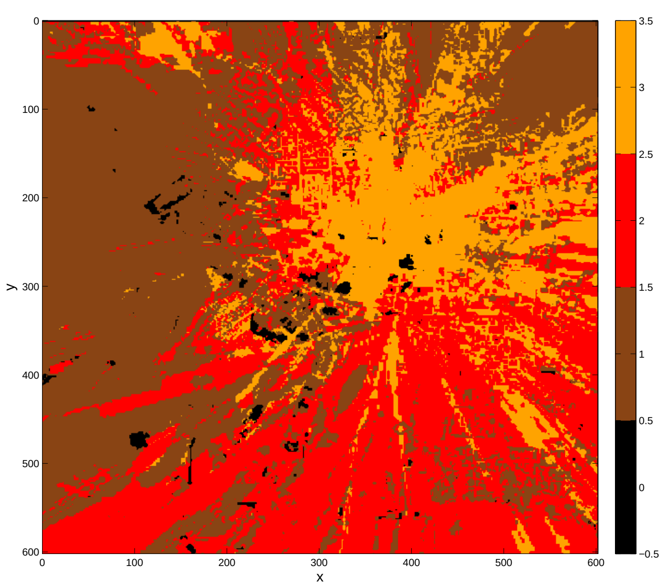
(c) Rate of BS with H1



(d) Best server (coverage) of BS with H1



(e) Rate of BS with H1 and H2



(f) Best server (coverage) BS with H1 and H2

Fig. 7. On the area map of Jersey, these figures show the available rate capacity [bit/s] and best server (middle=3=BS, 2=H1, 1=H2) for a scenario with BS only, with one tier of relays H1, and with two relay hops H1+H2