On Increasing the Spectral Efficiency More Than 100% by User-In-The-Control-Loop

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***Abstract*—OFDMA has become the key technology for future cellular wireless networks like the IMT-Advanced systems IEEE 802.16m and 3GPP LTE-A. The advantage of allowing different modulation&coding schemes (PhyModes) adaptively for each radio resource is at the same time a new disadvantage because the performance is now distance-dependent from the base station (BS) and the total spectral efficiency depends on how user terminals (UTs) are provided with service opportunities. Instead of increasing the effort to support cell-edge users with high data rates this paper investigates the chances of letting the user participate in the process such that his mobility becomes utility-driven, in a similar way the user behaves in 802.11 hotspot areas. The user's willingness to move to regions of higher SINR must be supported by a display of the current situation (and indications where to move) plus a utility model (lower cost or higher data rate) which motivates moving a distance monotonic in the utility value. By giving input to the user and utilizing the output of his behavior the user becomes a member of the control loop, in a system theoretic sense. The paper shows numeric results of common scenarios and compares the old and new paradigms.**

***Index Terms*—IMT-Advanced, LTE, Relays, User-in-the-loop**

I. Introduction

THE demand for higher data rates is ever increasing. Cellular wireless networks try to keep up with this demand in order to oversize the capacity, so that in busy hours the network is still operational. Technologies to increase the spectral efficiency are highly sophisticated already, so it is unclear if and how an advancement after IMT-Advanced will look like [1]. Multi antenna techniques can multiply the achievable rate, but SU-MIMO only works well in regions of high signal-to-(noise+interference) ratio ($SINR$), i.e. when the user terminal (UT) is located in the cell center around a base station (BS). Coordinated transmission schemes can improve the capacity near the cell edge, however at the expense of more radio resources used (e.g., 2-3 BS transmitting) and a signaling overhead and less scheduling freedom of choice, so the outcome is questionable. Multihop techniques (using decode-and-forward relay nodes, RN) are reasonable to increase cell edge capacity or coverage [2], [3] but with (low) additional cost and gains typically below 50% [4].

The near-far dilemma is illustrated in Fig. 1. Due to high pathloss and interference, the offered data rate is one order of magnitude lower at the cell border than close to the base station. Even worse is the situation that the same data rate for a UT occupies almost eight times the amount of resources. This is exactly the ratio between the supported rates [bit/s/Hz] between the highest and the lowest PhyMode (Fig. 2, Table I).

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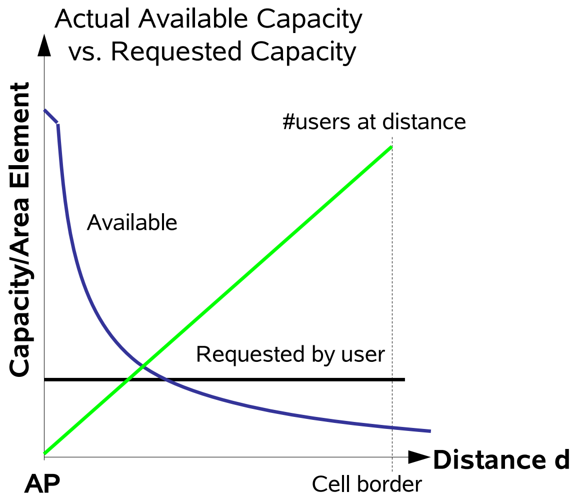

Fig. 1. The near-far problem: With a constant user density the number of users increases with d, so the cell capacity offered per area element differs from the capacity requested by users

In this paper a novel approach is proposed to increase the spectral efficiency. In its uttermost consequence it reflects the user behavior observed very commonly in IEEE 802.11 WiFi hotspot areas. Assuming the UT devices show the current signal quality at the UT position $\vec{p_1} = (x_1, y_1)$ (related to the mutual information MI_1 in bit/s/Hz [5]) and the user has a benefit b of moving towards a location of higher MI_2 at $\vec{p_2} = (x_2, y_2)$, and knows where to go from $\vec{p_1}$ to $\vec{p_2}$, then a certain fraction p_M of users will be motivated to do this move.

In a globalized individualistic world the motivation of people to act with reason for the prosperity of the total population is rather limited [6]. But the global challenges demand a rethinking. The current cellular tariff plans (pay per minute, pay per $Kbit/s$, flatrate), of which the first two at least lead to reasonable thriftiness, have no element to reflect the different effort (and therefore cost) to support a given data rate. In the present paradigm the network is expected to support the demand anywhere with the same QoS [7]. Therefore the usual cell spectral efficiency is just an average value of all possible $MI(x, y)$, for SISO typically in the interval $[1; 2]$ bit/s/Hz.

In this paper the previous assumption is canceled. The user becomes involved in the cost process and so the mobility becomes utility-driven. The user is influenced to adjust his location by a noticable incentive for him, so he becomes a part of a closed control loop [8]. Positive user experience and

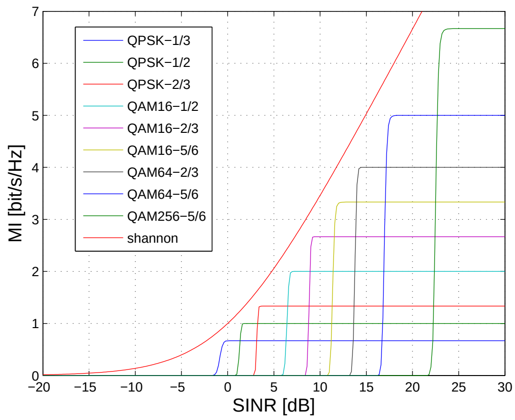

Fig. 2. Link level performance (net MI) for different modulation&coding schemes (PhyModes). QAM256 is not used here.

Fig. 3. Example of feedback (input) to user at his UT display. If the benefit for the user is attractive, he will move to a different location with higher spectral efficiency with probability p_M.

not punishment are important for success. Also, an immediate feedback to the user is a psychological advantage. Long delays like not having this until the next phone bill will by far not work as good. Power supply companies recently started to investigate into similar approaches [9].

The initial proposal is to keep tariffs as currently known, but allow savings or payback options on voice calls for those who move to a location of better MI, e.g., at certain times of the day (busy hour). Pricing models for traffic become more and more important for engineers anyway [10]. For data traffic the suggestion is a different utility proposal: Let the data rate to/from to a user be proportional to the MI, i.e., the scheduler provides a resource fair instead of a rate fair assignment. Not only resource efficiency is an advantage of this approach, but also the green aspect of consuming less energy per bit.

This is one of the popular adcantages of WiFi (802.11) hotspots. The user knows that he can interact and move for improving his performance. This new approach is beneficial for both the user and the operator by means of a better utility (price, rate or QoS) and a higher spectral efficiency.

The paper is organized as follows. The first section defines the utility and mobility models. Then the scenarios of investigation are defined. The last section shows performance results achieved in scenarios based on the IMT-Advanced evaluation [11]. The conclusion summarizes the key contributions.

II. Utility-driven mobility

In this paper it is assumed that a UT can observe the current signal quality $MI(\vec{p_1})$ at position $\vec{p_1} = (x_1, y_1)$. Plus, the user has a tariff model that encourages him to change his position to another location $\vec{p_2} = (x_2, y_2)$ if he has a utility advantage of $\Delta u_{1,2} = u(\vec{p_2}) - u(\vec{p_1})$. This utility u can be either financial ($\$ \propto u$) or an increased data rate. Assume also that the user has all information to make his decision and a suitable UT device (e.g., with GPS[1] built in), so he knows which direction to move for an improvement and what distance $d_{1,2}$ is required for each improvement step. Figure 3 shows an example how this may look like. The user now becomes a part of the closed loop system, which is a hybrid of technical and human system blocks. System theory including human elements is not new [12]. Figure 4 shows the system diagram. There is an input to the user block given by $d(m)$ and $u(m)$, meaning the distance and utility for the MI levels m (Table I).

The user itself is expected to decide whether he follows the suggestion or not. There is no coercion to behave according to the proposal, but there must be a motivation to do so. When he is not subscribed to the proposed plan, this is counted as No. The output of the user block is a (movement to a) new location $\vec{p_2}$, which is a random process which can be anywhere between 0 and $d_{1,2}$ meters. For simplicity, but without loss of generality, it is assumed as a Bernoulli random process with p_M being the probability of a move to $\vec{p_2}$, where the highest $MI \geq MI_{thresh}$ is nearby, and $(1 - p_M)$ for no movement at all. MI_{thresh} is the least MI to achieve after the movement (index m_{thresh} correspondingly). These are expected to be the main parameters describing the user behavior. The motivation aspect itself (from financial or rate benefit to p_M) is not treated in this paper. A more elaborate model would be a probability mass function $M(m_2|m_1)$ for the probability to go to a location with MI index $m_2 \geq m_{thresh}$ when the user is currently at m_1. Also, in a further step, there can be a 'motivation probability density distribution' $Pr\{d_{1,2}|m_2, m_1)\}$ which describes the probability of a user to move a distance $d_{1,2}$ to obtain his utility, because there might be less motivation to move more than $100m$. In this paper the first model p_M is analyzed and the analysis provides probabilities of average $\bar{d}$ made by the $(100 \cdot p_M)\%$ users who follow the suggestion.

[1] without GPS, the network operators can still support ranging by BS-based triangulation and give hints for movement

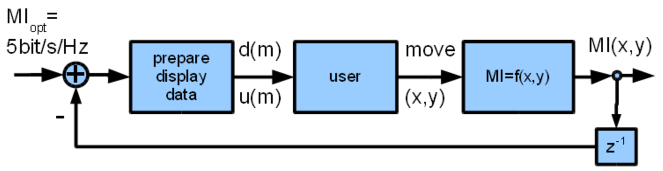

Fig. 4. The user becomes a part of the system (in the loop)

TABLE I
PHYMODES AND SINR INTERVALS

Index m	1	2	3	4	5	6	7	8
SINR	0.9	2.1	3.8	7.7	9.8	12.6	15.0	18.2
Mod.	QPSK			QAM16			QAM64	
Cod.	$1/3$	$1/2$	$2/3$	$1/2$	$2/3$	$5/6$	$2/3$	$5/6$
MI	$2/3$	1	$4/3$	2	$8/3$	$10/3$	4	5

III. Performance Models and Scenarios

For the analysis the IMT-Advanced scenarios were taken as reference [11]. Table III shows the main parameters and Table II gives the technology parameters according to LTE-Advanced. The analysis takes into account the two-pathloss model (LOS,NLOS) with probability p_{LOS} [13], [14] and calculates the steps given in the sequence below. For the *intentional* user movement it is assumed that the LOS properties hold at the destination location $\vec{p_2}$, with a linear increase of p_{LOS} to 1.0 from distance $0m$ to d_{LOS} (here $d_{LOS} = 10m$ assumed).

- *Transmit Power P_{Tx}:* see Table III,
- *Pathloss:* see Table III and [11] [14],
- *Interference I:* neighbor cell BSs and neighbor sectors interfere (100% load, cluster order 1)
- *Noise N:* accounted for but not serious (I-limited),
- *SINR:* $SINR = S/(N + I)$,
- *MI:* mutual information $MI = f(SINR, mod)$ [15],
- *BER:* bit error ratio, depends on MI,
- *PER:* packet error ratio, the result after channel decoding,
- *Throughput:* determined by bandwidth, PhyMode (modulation and code rate), ARQ overhead,
- *Cell Spectral Efficiency:* net spectral efficiency MI [bit/s/Hz] is throughput per bandwidth averaged over the cell (sector) area [15],
- *Relays:* least resources[2] BS/RN association [15],

In addition to the cellular layout with neighbor interference as in the model above, a particular realistic city scenario [16] (shown in Figure 5, with 13 relays) has also been investigated. It will be referred to as the Jersey scenario. Here we can see the effects of shadowing and how easy it is for a user to move to a point of better coverage. The initial user density is assumed constant in the area bounded by the green polygon. The population density after movement is expected to be higher close to the streets and in the city center.

IV. Numerical Results

Numeric results based on analysis have been obtained. The cell spectral efficiency is the calculated $MI(x, y)$, averaged

[2]the decision of single or multihop (relayed) route is taken by considering which option uses less resources, not by $max(SINR)$

TABLE II
TECHNOLOGY PARAMETERS ACCORDING TO LTE-A

Bandwidth [MHz]	FDD: 20DL,20UL
Traffic	full load; best effort
Antenna gain (boresight)	$17dBi$
Antenna aperture horizontal θ_{3dB}	$70°$
Antenna aperture vertical ϕ_{3dB}	$15°$
Thermal noise	$-174dBm/Hz$
UT noise figure	$5dB$

TABLE III
IMT-ADVANCED SCENARIO SPECIFICATIONS

Scenario	Urban micro UMi	Urban macro UMa	Suburban macro SMa	Rural macro RMa
d_{BS-BS}	200 m	500 m	1299 m	1732 m
h_{BS}	10 m	25 m	35 m	35 m
r_{min}	10 m	25 m	35 m	35 m
Ant. tilt ϕ_t	$-12°$	$-12°$	$-6°$	$-6°$
$f_C[GHz]$	2.5	2.0	2.0	0.8
P_{Tx}	44 dBm	49 dBm	49 dBm	49 dBm

over all points (x, y) of the cell area. The user movement is modeled by circularly searching for each point $\vec{p_1}$ the nearest point $\vec{p_2}$ where $MI(\vec{p_2}) \geq MI_{thresh}$ and assuming this $MI(\vec{p_2})$ as the new $MI'(\vec{p_1})$. At the same point the distance $d_{1,2}$ is recorded. Both increases of ΔMI and d are weighted with p_M, because $(1 - p_M)$ of the users are not willing to move. Users who don't need to move because they're already at a good position account with $d = 0$. In the following, HUD means homogeneous user distribution (conservative model) and UIL means user-in-the-loop (progressive model) with anisotropic user density.

Table IV shows the spectral efficiency and distance results for the IMT-Advanced scenarios defined in table III and [11] (HUD part from [14]). For these results rather moderate values for the parameters have been chosen: $p_M = \frac{1}{2}$ and $MI_{thresh} = 2.5bit/s/Hz$. With an effective movement

Fig. 5. Scenario map of Jersey [16]: One BS (middle) and a hierarchical RN placement as well as the polygon of interest (green)

TABLE IV
GROSS SPECTRAL EFFICIENCY RESULTS FOR THE IMT SCENARIO EVALUATION [BIT/S/HZ/SECTOR] WITH $p_M = \frac{1}{2}$ AND $MI_{thresh} = 2.5bit/s/Hz$

Scenario	UMi	UMa	SMa	RMa
3S,0RN,HUD	1.567	1.254	1.234	1.974
3S,0RN,UIL	2.170	1.995	2.836	2.509
$\bar{d} =$	4.4 m	4.7 m	7.8 m	30.7 m
3S,3RN,HUD	1.945	1.804	1.825	2.310
3S,3RN,UIL	2.333	2.239	2.858	2.654
$\bar{d} =$	1.9 m	1.7 m	5.0 m	12.0 m

TABLE V
GROSS SPECTRAL EFFICIENCY RESULTS FOR THE JERSEY SCENARIO EVALUATION $[bit/s/Hz/Sector]$ AND AVERAGE MOBILITY $\bar{d}/[m]$

Scenario	SpecEff	coverage	$\bar{d}$
Jersey,0RN,HUD	1.516	69.9%	0m
Jersey,0RN,UIL	2.350	(100%)	11.9m
Jersey,13RN,HUD	2.358	99,1%	0m
Jersey,13RN,UIL	2.771	(100%)	11.9m

of just a few meters the total spectral efficiency could be increased by 25% to more than 100%, depending on the IMT scenario. It can also be observed that relays reduce the effort for the user to move, because a RN might be closer to his position. Figure 7 shows from where the users need to move and how far, if they want to achieve the benefit.

Figure 10 and Table V show the results over the cell area of the Jersey scenario of Figure 5 (HUD part see [16]). A significant improvement can be achieved while the average movement is quite "convenient" for the user.

Next the influence of the parameters p_M and MI_{thresh} is studied. We have a look at the total cell spectral efficiency MI and the distance of movement $\bar{d}$. Figure 8 shows the increase of spectral efficiency we can really achieve by user-in-the-control-loop. As we can see, a factor of 3 or an increase of 200% is possible and even a moderate gain is easy to achieve with just a minority of people involved. Obviously the dependency on p_M is linear, which appears natural given how it is incorporated. MI_{thresh} has a nonlinear (piecewise linear) influence, simply because of the switching points of Table I. In Figure 9 we observe that the distance $\bar{d}$ is not so high, taken absolutely. With less MI_{thresh} it is more convenient for the user to find the next best location but at the same time the total spectral efficiency is less compared to, e.g., moving to a place where $MI(x,y) = 5bit/s/Hz$.

Comparing 0 and 3 relays in Figure 9 we observe only a difference where $MI_{thresh} \leq 2.5bit/s/Hz$. This is reasonable, because a two-hop transmission can never achieve more than half of the capacity of the highest PhyMode in Table I. If this is acceptable (MI_{thresh}), the user saves effort ($\bar{d}$); otherwise the relay cannot be taken by those users. In the end, when more users cooperate (higher p_M), the highest spectral efficiency is not only a theoretical goal.

V. CONCLUSION

This paper presents a new paradigm to let the user actively participate in the process of optimizing the resource usage. For him this is motivated by a utility, either financial or higher data rate. This cancels the conservative paradigm of constant user density and equal service provisioning regardless of different costs. The method was then applied to the IMT-Advanced evaluation scenarios and a realistic city scenario to find out the gain in spectral efficiency and the typical effort required for a user. The obtained results show huge gains up to 200% without any effort in the physical or MAC layer. Just a slow location-dependent database and a GUI application is required. Also the distances to move are easy to reach on foot. For the motivation, a promising tariff contract or a resource-fair data rate assignment is advised. Future work will take more elaborate user statistics into account. Also the financial aspect of tariff income and reduced infrastructure investment costs can be studied.

The author recommends not to promise the customers ubiquitous equal service quality anymore. Instead, announce that it is location dependent and let him contribute to the common benefit. In the future this may even be extended to the time domain (not only space), in order to reduce the load at busy hours and to improve the overprovisioning (in)efficiency.

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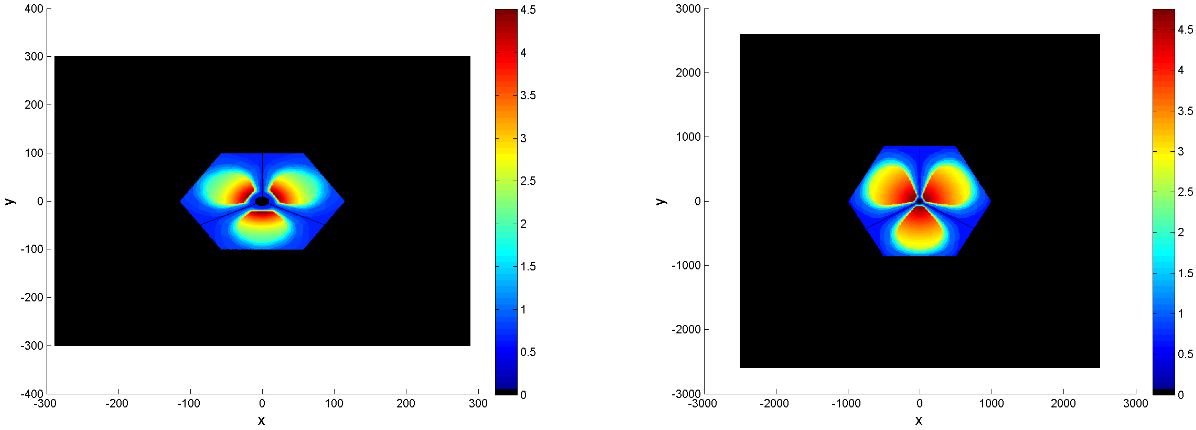
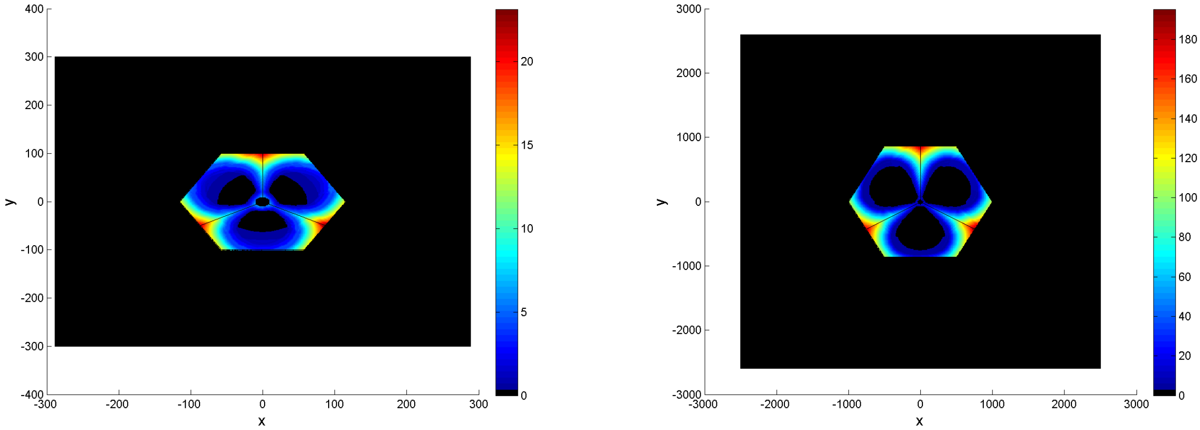


(a) MI of IMT-A scenario UMi

(b) MI of IMT-A scenario RMa

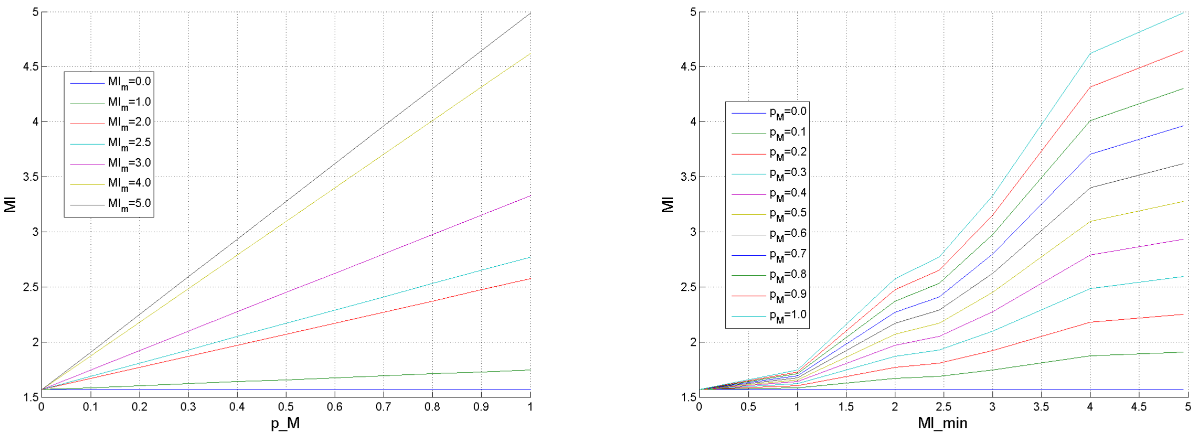
Fig. 6. Example Scenarios (RMa,UMi) of the IMT-Advanced evaluation without our proposed method. The color indicates the MI [bit/s/Hz].



(a) UMi scenario

(b) RMa scenario

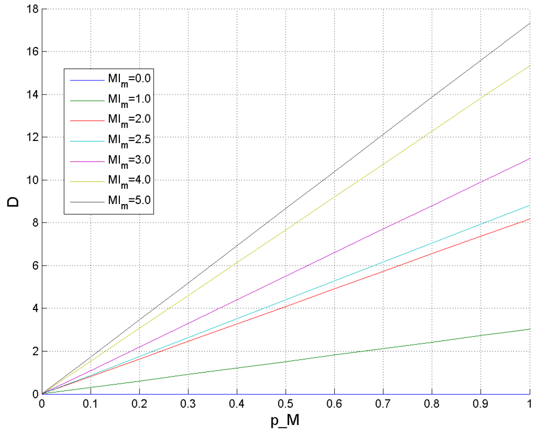
Fig. 7. Distance of movement $\bar{d}/[m]$ (indicated by color) to achieve best MI with 0 relays, $p_M = \frac{1}{2}$ and $MI_{thresh} = 2.5$ bit/s/Hz. In most cases(UMi), a move of the UE of about $5m$ will already result in achieving the best MI



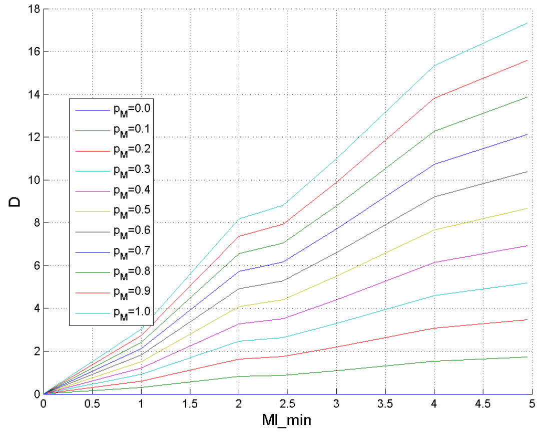
(a) Dependency on p_M

(b) Dependency on MI_{thresh}

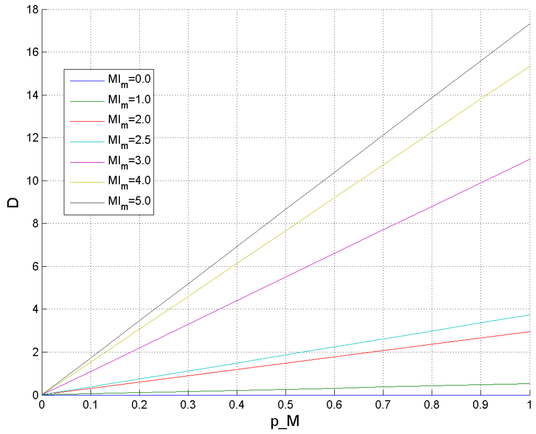
Fig. 8. Observed Spectral Efficiency $\bar{MI}/[bit/s/Hz]$ with given parameters in UMi scenario. Obviously a factor of more than three can be achieved.



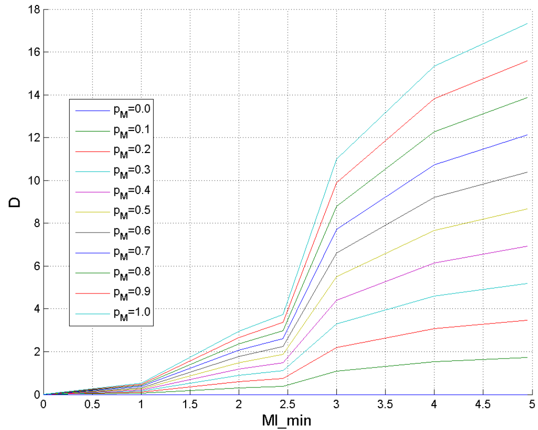
(a) Dependency on p_M



(b) Dependency on MI_{thresh}

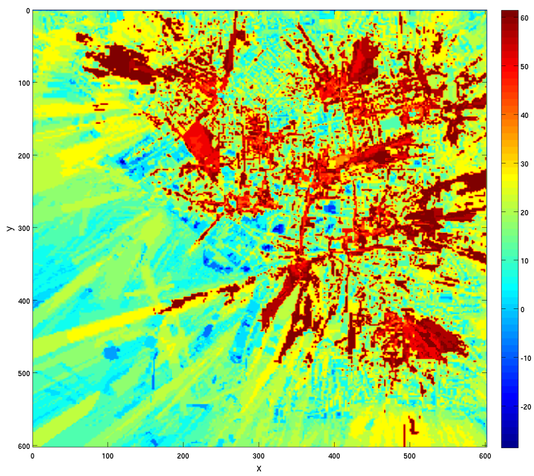


(c) Dependency on p_M

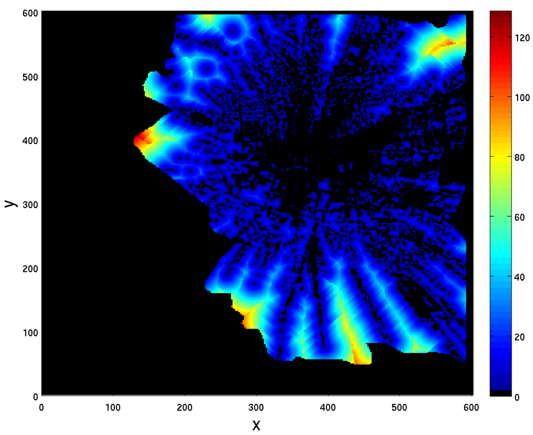


(d) Dependency on MI_{thresh}

Fig. 9. Average distance of user movement $\bar{d}$ to achieve best $MI \geq MI_{thresh}$ in UMi scenario without (top) or with relays (bottom)



(a) $SINR/dB$ of region using all 13 relays



(b) Distance of movement $\bar{d}/m$ to achieve best MI

Fig. 10. Jersey scenario results (one step in x,y direction is $3.5m$). The required movement is only huge at the cell border, as expected.