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Mobility Robustness Optimization beyond Doppler Effect and WSS Assumption

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***Abstract*—Mobility robustness is often understood as making the radio link Doppler-resistent. However, guaranteeing proper cell changes, e.g. handovers, is another, as important and at least as challenging aspect beyond Doppler and wide sense stationarity (WSS) assumption. This paper tries to describe the complex optimization problem with scientific methods, in order to catalyze future academic work in the interesting field of minimizing handover problems. Simulation results will be presented for intra-frequency mobility robustness optimization (MRO) distinguishing network-wide, cell-specific and cell-pair specific optimization.**

I. Introduction

Robustness of mobility is a key objective of mobile communication. In the last decades a lot of scientific work was dedicated to the impact of Doppler effects on Layer 1 signal processing and Layer 2 MAC procedures, very often using wide sense stationary (WSS) assumptions [1]. However little scientific attention was paid to mechanisms leading to reliable and efficient cell changes [2][3]. Note that cell changes are a direct consequence of violated WSS assumptions. Connection problems such as call drops or radio link failures lead to dissatisfaction of subscribers, and too many or unnecessary handovers lead to dissatisfaction of the operator (and partly of the subscriber as well). In 3GPP terminology those aspects are summarized under the expression ”mobility robustness”. In the past, mobility robustness was improved in particular by manual procedures, i.e. human beings were monitoring mobility related performance indicators, correlating those with geographical maps and, not to be neglected, with their own experience, and finally changing mobility related parameters accordingly. 3GPP release 9 has explicitly addressed ”mobility robustness optimization” (MRO) [4] as one use case of ”self organizing networks” (SON) [5][6][7][8]. With the introduced new features the optimization of the mobility related parameters shall be done in an automated way having all the advantages well-known from SON.

So far, the MRO topic has been treated primarily in the 3GPP world using 3GPP terminology and 3GPP methods which are often heuristic and differ from scientific methods. In this work we try to describe the highly complicated optimization problem in scientific and mathematical ways, in order to catalyze future scientific work in the interesting area of MRO, beyond the 3GPP world.

After introducing the abstract system model, we will explain the handover procedures, including the mobility related parameters and the measurements leading to handover decisions. Furthermore, we will define the mobility problems, especially radio link failures and rapid handovers. Next we will discuss the optimization problem on different levels of the network (network-wide, cell-specific, cell-pair-specific, user-specific). Within this framework we will explain the heuristic 3GPP solution for the MRO problem. Finally we will present simulation results. Solutions and simulations are focussing on mobility from LTE cells towards other LTE cells of the same carrier frequency *(intra-frequency)*. However, the whole description of the optimization problems is general to cover mobility from LTE cells towards other LTE cells of different carrier frequency *(inter-frequency)*, as well as towards other cells of other radio access technologies *(inter-RAT)*. Solution are equivalent, details are found in [12].

II. Definitions

The system model which we will introduce in the following sections is based on the definitions used in [9].

A. Network: cells and users

We have a network consisting of C cells. Each cell c is described by a propagation map $L_c(\vec{p})$ which determines the attenuation from the antenna serving the cell c toward position $\vec{p}$. This includes antenna gains, antenna patterns, distance dependent pathloss as well as shadowing effects. Note that this is a deterministic function given by the environment. Fast fading is not considered here but later on when introducing the measurements. Furthermore every cell c has a transmit power P_c. Finally, we assume that cell c uses the frequency layer f_c, i.e. the cells may use different frequency layers. This work will focus on one or two frequency layers.

U users are moving through the network. The movement of user u is described by the location function $\vec{p}_u(t)$, which is the location of user u at time instance t. Note that the location function inherently expresses the velocity as well (derivative of $\vec{p}_u(t)$). The cell c serving user u at time instance t is given by the connection function $c = x_u(t)$. Later on we will define handovers to be changes in the connection function.

B. Received Powers and SINRs

The power which a user u receives from cell c at time instance t is given by

$$R_{u,c}(t) = P_c \cdot L_c\left(\vec{p}_u(t)\right). \tag{1}$$

Following the approach in [9] we approximate the SINR $\gamma_u(t)$ of user u at time instance t (in the serving cell) as

$$\gamma_u(t) = \frac{R_{u,x_u(t)}(t)}{\sum\limits_{\substack{\{c|f_c=f_{x_u(t)}\} \\ c\neq x_u(t)}} \rho_c(t) \cdot R_{u,c}(t) + N} \quad (2)$$

where the numerator represents the (desired) received signal from the serving cell, and the sum in the denominator covers all cells in the same frequency layer $f_{x_u(t)}$ excluding the serving cell leading to the intercell interference. $\rho_c(t)$ is the load in cell c at time t, i.e. a cell with small load produces small interference. N is the thermal noise.

C. Measurements

For the sake of simplicity we assume that a UE can measure the received power from all cells. In reality this certainly holds only for close cells. Fortunately those cells are the relevant cells for handover, so this assumption is uncritical as long as we do not look at the overhead induced by the measurements.

However, the signals impinging at the UE antennas are impacted by *small scale fading*, also called fast fading. Averaging has to be applied for stable estimates in order to avoid quick handovers following the small scale fading. This averaging will introduce latency to the estimates, and some signal fluctuations will still be left after averaging. Furthermore, due to complexity reasons, measurements are not done permanently, such that the measurements might be outdated. This is particularly the case for measurements done on another frequency layer, since the oscillators have to be changed for those measurements which should be done economically. In agreement with the LTE specifications we will use the dB domain for the UE measurements, since this eases the explanation of the handover procedures later on. Finally, we describe the measurements of the received signal powers at the UE u as

$$M_{u,c}(t) = 10 \cdot log_{10}\left(R_{u,c}(t - T_{lat})\right) + \mathbf{e}_{u,c}(t) \quad (3)$$

where T_{lat} approximates the latency due to the aforementioned averaging and the outdated availability. $\mathbf{e}_{u,c}(t)$ is a random process representing the residual signal fluctuations due to fast fading and other estimation errors. More averaging typically reduces the standard deviation of this error, however increases latency, and vice versa. In other words, T_{lat} can be invested into more stable estimates. This trade-off is illustrated in Figure 1 which is based on an example for LTE intra-frequency measurements. Short averaging leads to a large standard deviation of the error $\mathbf{e}_{u,c}(t)$, but to more immediate availability of the measurements. Averaging delays the measurements, but decreases the standard deviation. We can also observe that small velocities require longer averaging to reduce the signal fluctuations.

Note that initially we omit any subscripts for T_{lat} although different values per cell or even per UE could be applied.

D. Handover

In LTE and in 3G, a handover for user u is triggered by the base stations, typically when a corresponding measurement report from this user u is received. Such a report is sent if

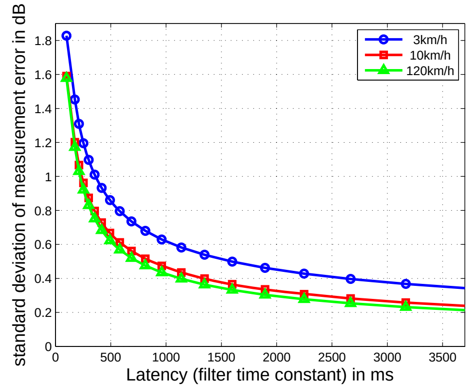

Fig. 1. Trade-off between latency and measurement error $\mathbf{e}_{u,c}(t)$

certain events expire at this terminal. The parameters for those events in turn are configured by the network. Therefore, these parameters are also called ”handover parameters” (although they do not necessarily lead to a handover). We will discuss the two most important of those events. The first expires at a time instance t_0 when a neighbor has significantly exceeded the serving cell for a certain amount of time T_T. With the introduced measurements we write:

$$M_{u,c}(t) > M_{u,x_u(t)}(t) + \omega \text{ for } t_0 - T_T < t < t_0 \quad (4)$$

where ω is the offset determining the aforementioned significance which is sometimes also called *hysteresis* or *margin*, and T_T is typically called *time to trigger*. Both parameters should guarantee the reliability for this event (and for the following handover decision). The other important event expires at t_0 when, again for a certain amount of time, the serving cell falls below a threshold τ_1 and a neighboring cell exceeds another threshold τ_2.

$$M_{u,x_u(t)}(t) < \tau_1 \wedge M_{u,c}(t) > \tau_2 \text{ for } t_0 - T_T < t < t_0 \quad (5)$$

Note that such an event is not appropriate to trigger the handover between cells using the same frequency layer. As soon as an intra-frequency neighbor becomes better than the serving cell, the user will start suffering from high interference, even if the own signal is still strong (above τ_1). Instead, this event is used for handovers to another frequency layer. Similar to the introduction of T_{lat} for the measurements, we again have omitted subscripts for the offset ω, the thresholds τ_1 and τ_2 as well as time to trigger T_T. After an event has triggered following steps are executed:

1) The user transmits a measurement report to the serving base station. This has some probability to fail in particular if the user is already far away from the serving cell.
2) The base station receiving the report will decide a handover to the strongest neighbor, will direct a handover request to this neighboring and will receive an acknowledgement (or a rejection). This induces an addition delay T_P which we typically call handover preparation time.
3) The base station will inform the user to connect to a neighbor. This so-called handover command again has

some probability to fail, since the user might already be inside the other cell.

4) The user will try to connect to the neighbor by sending a random access channel (RACH). This can fail as well, e.g. if the new cell disappears again.
5) Finally the neighbor will allow the user to enter the cell which is another message which can fail.

Hence the handover will be executed T_P after the event has expired (neglecting delays through the other steps), but only if none of the aforementioned messages has failed. As a simplification we assume that this is the case if the SINR after T_P is still above a certain threshold τ_{fail}. Otherwise the handover will not be executed and the user will stay with the old cell. In our mathematical framework handover execution at time t_{HO} to cell c_0 means a change of the connection function $x_u(t)$. So we can define the connection function in iteratively

$$\begin{aligned} & x_u(t) = c_0 \quad \text{for} \quad t > t_{HO} \\ \text{if} \quad & M_{u,c0}(t) > M_{u,x_u(t)}(t) + \omega \\ & \text{for} \quad t_{HO} - T_P - T_T < t < t_{HO} - T_P \\ \text{and} \quad & \gamma_u(t_{HO}) > \tau_{fail} \end{aligned} \tag{6}$$

i.e. whenever all those conditions are fulfilled, the connection function is changed at time instance t_{HO} to cell c_0 for the future, until the next handover is executed.

E. Radio Link Failure

It is obvious that if a handover is not executed in time due to whatever reason, a user may be in trouble due to high interference. Nevertheless, link problems are not in general directly associated with handover problems. If the terminal detects that a connection gets too bad such that communication is no longer possible, it will consider the connection to be failed, this is typically called "radio link failure" (RLF). From user perspective, this will lead to a call drop in many cases, or at least to some interruption. Mathematically, the RLF is detected at time instance t_0 if the SINR (in the serving cell) falls below a certain threshold τ_{rlf} for a certain amount of time T_{rlf}:

$$\gamma_u(t) < \tau_{rlf} \quad for \quad t_0 - T_{rlf} < t < t_0. \tag{7}$$

After detecting an RLF the user will connect to the next cell that he may find with sufficient quality. If the reason for the RLF was a coverage problem, it may take a while until the user finds a new cell. However, if the reason was a missed handover opportunity or a bad handover decision, it is very likely that a new cell is detected immediately.

It is obvious that RLFs are to be avoided as much as possible. RLFs will take an important role when defining cost functions for mobility robustness optimization.

F. Rapid Handover

Successful handovers which could have been avoided are another, however less severe problem since every handover produces overhead to the network. As long as proper packet forwarding is provided, the impact on user perception will be marginal. The most prominent example are so-called *pingpongs*, where one successful handover is followed by a handover back to the original cell within short time T_{RH}, e.g. 3 seconds. It is typically assumed that both handovers could potentially have been saved at all. Equivalently, if a successful handover is followed by another successful handover to a third cell within T_{RH}, one could assume that a single handover directly to this third cell would have served the purpose.

Those *rapid handovers* can be simply read from the connection function $x_u(t)$ as a short interval between two successful handovers. Avoiding those events is a secondary task of mobility robustness optimization.

III. Theoretical Optimization Problem

In this section we will describe the optimization task based on the definitions in the previous sections. We have already discussed that RLFs and rapid handovers will play a role in the target functions, but it is still unclear on which level and how exactly they are counted and optimized.

A. Parameters to be optimized

Let us first summarize the parameters address by MRO:

- the latency T_{lat} which trades delayed availability against stability/reliability of measurements
- the offset ω and the thresholds τ_1 , τ_2 which configure the reporting events (and thereby the handovers)
- the time to trigger T_T which avoids reactions based on measurement outliers.

However, it has to be discussed whether to optimize those parameters individually for every user, per cell boundary, per cell, or over the whole network.

For the sake of simplicity we will focus on intra-frequency scenarios where we only have a single frequency layer, and where handovers are triggered via the offset ω. We will not explicitly look at the thresholds τ_1 and τ_2 in and inter-frequency or inter-RAT scenario although the arguments are identical.

B. Illustration of mobility challenges - Gradients

Before discussing the levels of optimization we would like to illustrate the mobility challenges. It is obvious that the velocity plays an important role. However, we will show that the network layout given by the propagation maps $L_c(\vec{p})$, in combination with other details of the user movements $\vec{p}_u(t)$ such as angles and streets are as important. Figure 2 shows an excerpt of a network comprising 19 base stations with an inter site distance of 500m serving 57 cells [11]. Only one base station is visible in the excerpt. Each cell has a different grey scale. The crucial aspect for handover performance are obviously the gradients of the signal strength, i.e. how fast the serving signal degrades and how fast a neighbor gets stronger. To this end, we are overlaying with colors the location dependent *link imbalance* $\Delta(\vec{p})$ which is defined as the difference between the strongest signal and the second strongest signal for every position $\vec{p}$

$$\Delta(\vec{p}) = \max_c(P_c \cdot L_c(\vec{p})) - \overset{2}{\max_c}(P_c \cdot L_c(\vec{p})) \tag{8}$$

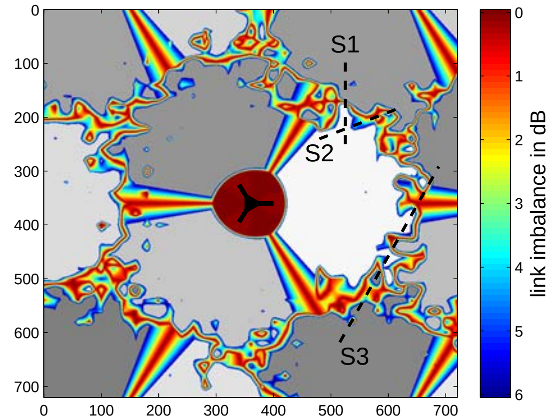

Fig. 2. Cell layout with link imbalances

where the $\overset{2}{\max}$ operator indicates the second strongest value. Only imbalances up to 6dB are shown. A quick change of the colors along a given path (thin colored areas) indicates a steep gradient, i.e. handovers on those paths are challenging. An example for such a path is the street S1. Handovers on those paths should be initiated early enough to guarantee the success, i.e. the latencies T_{lat} and T_T should be short, and the offset ω should be small.

On the other hand, thick colored areas indicate that signals are similar over a wider area, signal fluctuations may lead to unnecessary handovers. An example for such a user path is the street S2. On those paths it is more important to make sure that a handover is really necessary, i.e. T_{lat} should be invested into more stable measurements, T_T could be increased to exclude outliers and the offset ω can be increased.

Street S3 is another example for making rather well-thought-through handover decisions. Note that this path affects another cell boundary as S1 and S2, i.e. there might be a chance to solve the S3 challenge without affecting S1.

A typical simulation assumption for performance simulations is that users are uniformly distributed and go into random directions (*random walk*). In such a case some users would cross cell boundaries through steep gradients, and others through flat gradients, so that the user behavior would average out. Parameter optimization would be difficult since improving some users (e.g. walking on S1) will degrade others (e.g. walking on S2).

However, in reality the user behavior is very often much more quantized through streets, boardwalks, doors/gates, etc. In our model, this means that the location functions of the users $\vec{p}_u(t)$ are very similar for many users in a cell. So individual cell boundaries or whole cells might be dominated by a certain behavior which pronounces the occurrence of certain gradients. For instance, if the majority of the users leave the cell via S1 (and only few ones on S2), the cell could optimize for S1.

C. Network-wide optimization

With the above discussion it is quite clear that a network-wide optimization leads to very suboptimal results, since different paths with different gradients cannot be distinguished. However, the optimization problem seems feasible in this case. The primary cost function would be the total number K_{RLF} of RLFs over a longer time. The secondary cost function "rapid handovers" K_{RH} could be combined with the primary cost function via a weight w, e.g.

$$K_{overall} = K_{RLF} + w \cdot K_{RH}. \tag{9}$$

The operator can decide how severe he considers the rapid handovers compared to RLFs.

This would require some rough assumptions on the propagation maps $L_c(\vec{p})$ and the user movements $\vec{p}_u(t)$. As long as the statistical properties match, the optimization will lead to good results.

D. User-specific optimization

From a theoretical point of view, the best solution is certainly achieved if the parameters are optimized for every user u. However, this would not only require very precise knowledge of $L_c(\vec{p})$, but also a prediction of the user path $\vec{p}_u(t)$. Both are obviously unreasonable assumptions. Note that a single user behaves strongly non-stationary such that parameter decisions cannot be based on observations from the past. Hence, user specific optimization remains an academic (even though scientifically interesting) topic and will not be further elaborated.

However, we would like to mention that some user-specific properties, in particular velocity, can be measured and used to fine-tune some parameter decisions.

E. Cell-specific optimization

On the cell level, assuming that the traffic is similar over a certain time, we may exploit some stationarity, i.e. we can try to measure the user behavior and optimize cell-specific parameters $T_{lat,c}$, ω_c, $T_{T,c}$ from the observations. If the user behavior is fully random ("white"), there is not too much to benefit. However, we have previously discussed that cells are often dominated by a particular user behavior given by environmental characteristics, e.g. a street. In this case the user behavior can be considered as "colored" and there will be potential gains.

In principle the cost function can be the same as for the network-wide optimization. For a more convenient solution, it would be better to split this optimization problem comprising $3 \cdot C$ parameters into smaller problems. One option is to break the cost function down to a cell level, i.e. every cell counts its own RLFs and its own rapid handovers, and optimizes its own parameters. However, it is important to state that an RLF occurring in a certain cell c_0 is not necessarily caused by suboptimal handover parameters in this cell c_0, but the cause might be in another cell c_1. We will elaborate on this when discussing the practical solutions. Hence, a cell-specific cost function should be given by those RLFs (and rapid handovers) which have been *caused* by this cell.

F. Cell-pair specific optimization

A further improvement could be to allow a optimization per cell boundary leading to cell-pair specific parameters $T_{lat,c0,c1}$, $\omega_{c0,c1}$, $T_{T,c0,c1}$. Whereas the cell-specific optimization still needs to compromise one cell boundary against others (in the same cell), cell-pair specific optimization can do an individual optimization and thereby lead to more location specific solutions.

RLFs and rapid handovers can be further subdivided to obtain cell-pair specific cost functions. However we would like to emphasize again that RLFs would need to be assigned to the cells which have *caused* it, and not where they have occurred. This is not trivial at all.

G. Coupling of cells and cell-pairs

In the last two sections we have split the huge optimization problem into smaller parts. On one hand this is actually necessary, since a single cost function has the risk that some individual cells show exceptionally bad performance. This is typically not acceptable in the network. In many cases this will hit always the same users which may change the operator as a consequence, i.e. the problem is not well distributed.

On the other hand, in a strictly mathematical sense this requires that the sub-problems do not interact with each other. It is not obvious whether this is allowed. It may happen that solving mobility problems in one cell may create more mobility problems in another cell.

Nevertheless, the practical solutions in the next section will show that significant improvements can be achieved without affecting stability.

IV. Practical solutions for optimization problem

A mathematical solution would require precise a priori knowledge of the propagation maps $L_c(\vec{p})$ and, more critical, the user movements $\vec{p}_u(t)$, or at least of some properties thereof. Obviously both are totally unrealistic assumptions. In reality we have to use iterative solutions based on previous observations of the above cost functions, or maybe more elaborated ones. In the following we will describe a heuristic solution to this problem which has been enabled by 3GPP standardization. Note that the following procedures can in principle be applied at each optimization level (cell-pair-specific, cell-specific, or network-wide). Again we will focus on intra-frequency scenarios.

A. Root cause analysis

We have already mentioned that an RLF is not necessarily caused by the cell where it has occurred. So the occurrence of an RLF is too little information. The principle idea is that for every occurring radio link failure (and for every occurring rapid handover) we try to determine:

- which cell has caused this problem
- which parameter is responsible (e.g. $\omega_{c0,c1}$)
- how the parameter shall be tuned (up/down).

A single cell cannot do the aforementioned distinction. The cells need to communicate with each other, and furthermore some information from the terminals is required as well. This signalling has been specified in 3GPP [4]. This analysis is the core to any powerful MRO implementation in LTE.

B. Correction of parameters

The ups and downs are collected and counted over a long enough observation period. After that the collected ups and downs can be compared and the corresponding parameter is increased or decreased accordingly. Fixed stepsizes can be used, or the stepsize can be adapted, e.g. larger stepsize is applied if the ratio between ups and downs is very large or very small.

Let us look again at the example in Figure 2: if the middle cell is dominated by the street S1, problems will be ”too late handovers”, so the majority of mobility problems will vote for ω down. If dominated by S2, problems will be ”pingpongs” and ”too early handovers”, so the majority will vote for ω down.

V. Simulation Results

We will keep on focussing on intra-frequency scenarios. The observed effects are equivalent for inter-frequency and inter-RAT scenarios, cf. [12]. Figure 3 shows the network consisting of 12 base stations on a non-regular grid as proposed in [10], each serving 3 sectors. The propagation conditions $L_c(\vec{p})$ are given by the typical antenna, pathloss and shadowing models [11]. The user movements $\vec{p}_u(t)$ are restricted to streets shown by black lines. Users are uniformly distributed on these streets, move with 30km/h and randomly select the direction at every intersection. The measurement procedures are implemented according to the LTE specification.

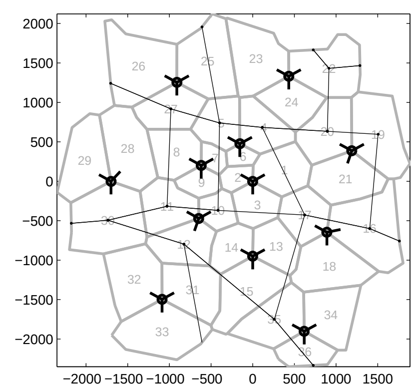

Fig. 3. Non-regular network layout with streets

We will separately evaluate the total number of RLFs and total number of pingpongs (we will ignore other rapid handovers), i.e. we show two different cost functions. We only modify the offset ω, for the sake of simplicity we leave the averaging latency T_{lat} and the time to trigger T_T constant. For network-wide optimization we do not apply the aforementioned method, we simply sweep the parameter ω (= exhaustive search). Cell-specific and cell-pair-specific optimization is done as described in the previous section. The optimization focusses on RLFs, pingpongs are not counted as mobility problem in those results.

The x-axis in figure 4 is a time axis in units of the collection period which is 90sec in this case (note that we are simulating in total 900 users which guarantees sufficient statistics in this interval). The y-axis represents the total number of RLFs (left plot) and pingpongs (right plot) occurred in each period.

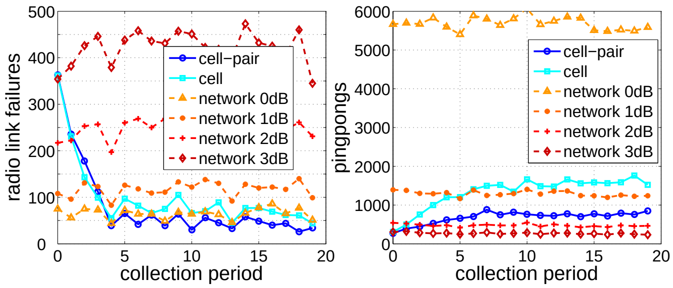

Fig. 4. Total number of RLFs and pingpongs

The dashed curves show the network-wide optimization where we have swept the ω parameter from 0dB to 3dB. No decisions are made during the simulation, the fluctuations of these curves over time are statistical fluctuations. The smaller the offset the smaller are the radio link failures. However, we can observe that the number of pingpongs explodes for 0dB and 1dB. So reasonable, network-wide parameters for this scenario are 2dB or 3dB, depending on operator's policy to trade RLFs against pingpongs.

For the cell- and cell-pair specific optimization cases we have set the initial values for all ω's to 3dB. The RLFs of the cell-specific optimization converge quickly against the 0dB solution, whereas the pingpongs stay much below that, since only critical cells are changing their ω. Finally, the cell-pair specific optimization outperforms even the RLFs of the 0dB solution whilst keeping the increase in pingpongs moderate. Recall that the algorithm does not even take pingpongs into account. However only the critical cell boundaries are adjusted in a selective way, only here pingpongs are risked.

This becomes more obvious when looking at the offsets after convergence. Figure 5 shows the histogram of the ω's in the last collection period (in logarithmic scale). The cell-specific optimization has to change the whole cell whenever there is a problem anywhere in the cell. So only 40% of the offsets stay with 3dB, many cells have to use a smaller value and thereby risk pingpongs. The cell-pair specific algorithm creates the significant RLF gain presented above by only changing very few selected offsets, more than 95% of all offsets are not touched at all. Furthermore, we observe extreme values: very small values down to -2dB, but, more surprisingly, also large values up to +5dB although we do not consider pingpongs in the optimization procedure. Nevertheless we have already mentioned that RLFs might be caused by too early handovers, i.e. in some cases RLFs can be avoided by larger offsets.

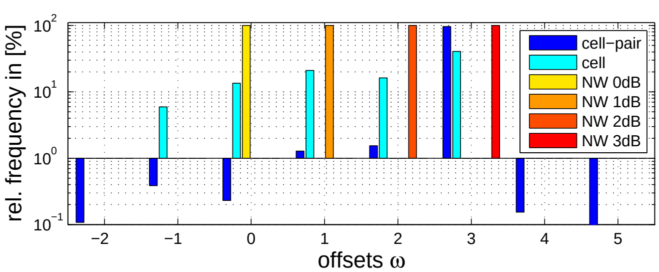

Fig. 5. Histogram of offsets ω

Although the algorithm is heuristic and simple, it seems to achieve very good performance. Unfortunately it seems impossible to compare this against an optimum, since the underlying optimization problem is so complicated. In [12] we compare it with numerical mathematical methods such as simulated annealing or Taguchi's method, none of the methods could even come close to the presented heuristic method. The proof that the performance is close to optimal is left for future studies.

VI. Conclusion

We have described the practical MRO problem with mathematical methods. We have explained the heuristic 3GPP solution within this framework, and we have shown that this solution can achieve significant gains, the more location-specific the parameters are defined. However, it is unclear how close the performance is to an optimal solution. It is often assumed that mobility parameters depend on velocity of the users, however the mathematical derivations have clearly shown the strong dependency on the combination of the propagation maps $L_c(\vec{p})$ and the user movement $\vec{p}_u(t)$. Even with a priori knowledge (which is obviously an unrealistic assumption) an optimal solution is more than challenging due to the huge number of parameters. We strongly believe that this optimization problem deserves more mathematical attention than in the past.

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