A Simple Speed Estimation Algorithm for Mobility-Aware SON RRM Strategies in LTE

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***Abstract*— Mobility management in so-called heterogeneous networks (HetNets) becomes a complicated issue due to the increased complexity of inter-layer radio resource management (RRM) techniques. Frequent inter-layer reselections and handovers should be minimized when dealing with high-speed users by taking into account both user speeds and relative cell sizes. In this paper we propose a simple speed estimation algorithm for application in mobility-aware cell reselection and handover strategies in Long Term Evolution (LTE) wireless networks. The suitability of mobility-aware RRM strategies based on the exchange of speed and cell size information between terminals and base stations is analyzed. A simple receiver structure for speed detection is proposed that relies on the analysis of the downlink Doppler power spectrum. Simulations show that the proposed algorithm is accurate enough for performing advanced RRM techniques based on user speed.**

Keywords*— *SON, HetNet, speed detection, Doppler power spectrum

I. Introduction

As the spectral efficiency of a point-to-point link in cellular networks approaches its theoretical limits, there is a growing need for an increase in the node density to further improve network capacity. However, in already dense deployments in today's networks, cell splitting gains can be severely limited by high inter-cell interference. An alternative approach involves the deployment of low power nodes overlaid within a macro network, creating what is referred to as a heterogeneous network (commonly known as "HetNet"). Increasing the proximity between the access network elements and the end users has the potential to dramatically increase overall throughput and spectrum efficiency per square km. However major technical challenges appear when dealing with inter-layer mobility.

Mobility management becomes a complicated issue in HetNets due to several reasons. When the layers are deployed in different frequencies, appropriate gaps are required for inter-frequency measurements which cause interruptions and make the handover process more costly [1]. If the layers are deployed in the same frequency, mobility is easier to manage but interference problems may appear, making it important to carefully control the point at which handovers and reselections take place. It is thus of vital importance to control mobility so that inter-layer handovers are performed only when strictly needed.

Additionally, the existence of a large number of small cells (micro, pico or femto cells) in the coverage region of a macro cell may originate a high amount of signaling exchange due to mobility procedures (such as Location/Routing/Tracking Area updates), even if the users are in Idle state.

One possible solution is to keep fast moving users in connected mode in the macro layer whenever possible, being handed over to the small cells layer only if the radio conditions force to do so. Fast moving users in Idle mode should also be kept under control of the macro layer in order to avoid an excessive amount of idle mode signaling exchange in the form of Tracking Area updates. Both solutions involve appropriate velocity estimations for idle and connected mode users, as well as RRM strategies that incorporate velocity estimations for mobility decisions.

This paper explores the possibility of performing mobility-aware RRM strategies in HetNets based on User Equipment (UE) speed, and proposes a simple algorithm for speed estimation in LTE based on downlink signal analysis.

The rest of the paper is organized as follows. Section II describes suitable mobility-aware RRM strategies based on UE speed. Section III describes a simple algorithm for speed detection by the UE. Section IV describes simulation results about the performance of the proposed algorithm, and finally section V is devoted to conclusions.

II. Mobility-Aware RRM Strategies

A number of RRM strategies can be proposed for cell reselection and handover in wireless mobile networks. Fig. 1 depicts the global scenario for application of mobility-aware RRM techniques. A heterogeneous network comprises several cells with different sizes, frequencies and/or Radio Access Technologies (RATs), with large macro cells including the coverage regions of several micro/pico/femto cells. Different types of users may be considered according to mobility: high-speed users (UE1 in the figure), static users (UE2 and UE4), and low-speed users (UE3). UE1 crosses several cell boundaries but enjoys full coverage of the macro cell; hence it should be kept in the macro if frequent cell reselections and handovers are to be avoided.

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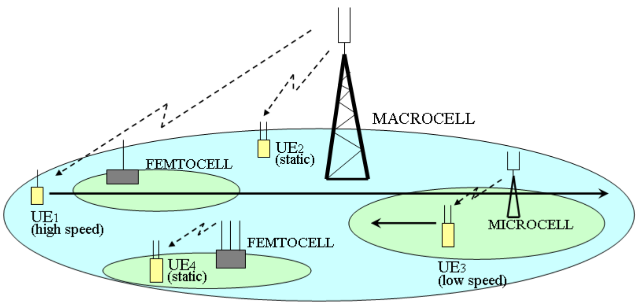

Fig. 1. Scenario for application of mobility-aware RRM strategies.

UE2 is a static macro user and UE4 is a static femto user; both of them should be kept in their best serving cells (the macro and the femto respectively). Finally UE3 is a low-speed user located under the coverage of a micro cell; as the user moves slowly several cell changes may be needed in order to keep it within the best radio conditions.

The following general mobility-aware strategy is proposed in this scenario:

- Base stations shall broadcast a new parameter (denoted as "CELL_SIZE" in what follows) in any suitable broadcast control channel, such as Broadcast Control Channel (BCCH) in LTE. This parameter represents a relative measure of the effective cell size taking into account transmission power and carrier frequency.
- Idle mode users, upon evaluating neighbour cells for eventual reselections, shall read the corresponding broadcast control channels and decode the cell size indications. Additionally, the UE shall estimate its own speed based on any suitable means.
- According to the estimated velocity and the relative sizes of the neighbour cells, idle mode UEs can perform suitable cell reselection strategies taking user speed into account. As an example, the UE may not reselect to a small sized cell when the speed is above a certain threshold, and inversely the UE may reselect to a small cell whenever the speed is considered to be low.
- Connected mode users shall also read and decode the neighbour cell size indications and estimate speed. Both speed and neighbour cell sizes shall then be reported to the serving base station in a periodic or aperiodic way by means of any suitable uplink control/data channel. The serving base station can thus take this extra information into account in order to perform mobility-aware handover decisions.

CELL_SIZE may be one of a discrete set of possibilities (such as "macro", "micro", "pico" and "femto"), or an integer expressing the approximate cell radius according to the operational frequency. Cell size indications may be broadcast as part of any suitable Information Element (IE) contained within the broadcast control channel, or in a separate IE.

Velocity, on the other hand, should be dynamically reported by UEs in connected mode. The network can therefore trigger periodic or aperiodic velocity reports to be sent by the UE in a suitable uplink control or data channel. Velocity indications should not be sent much frequently, hence time periods of the order of several seconds should suffice for periodic velocity reporting.

A. Mobility-based reselection in Idle mode

An idle mode user can read a neighbour cell size indication from the corresponding broadcast channel, as well as estimate its velocity from the serving cell's pilot channel. According to the resulting velocity estimation, usual cell reselection rules can be modified in order to avoid reselecting to a small sized cell when velocity is above a certain threshold. Conversely, users with sufficiently slow velocity can camp on any cell disregarding its size. This is schematically illustrated in Fig. 2.

B. Mobility-based handover in connected mode

In connected mode the network is in charge of steering the user to the best suitable cell. Speed information should be an important criterion for moving users in heterogeneous scenarios. The network may estimate the user's velocity in some cases, when uplink transmissions are sufficiently continuous so as to enable accurate calculations at the base stations. However this cannot always be assumed as bursty traffic is the most typical data pattern in connected mode.

Velocity indications are thus proposed to be measured and reported by the UE as depicted in Fig. 3. This information may be carried by any suitable uplink control or data channel, with a granularity and periodicity to be defined by actual implementations. The network may instruct the UE to report velocity on a periodic or aperiodic basis, e.g. through a suitable scheduling indication. As velocity cannot vary very quickly, this information may be reported over large time periods (of the order of several seconds) and the overhead would be low. The periodicity for velocity estimations should be related to the actual time required by the UE to derive the estimations, as shown in the proposed algorithm of Section III.

The network should be aware of the neighbour cell sizes in addition to the user's velocity for eventual application of velocity-based handovers. This is also illustrated in Fig. 3

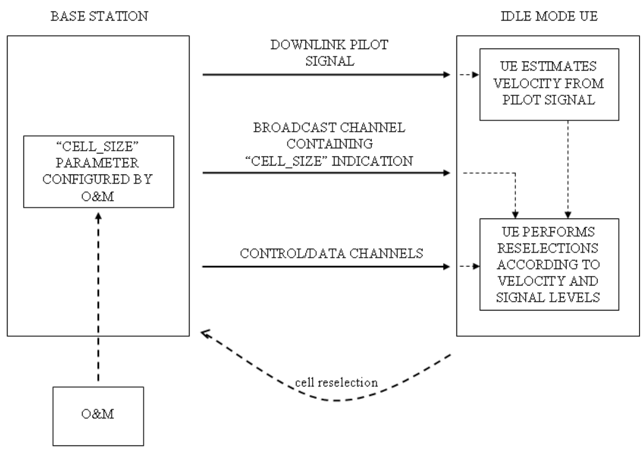

Fig. 2. Mobility-aware reselection strategy based on cell size and UE speed.

where the measurement reports contain suitable indications on the neighbour cell sizes as obtained from their corresponding broadcast channels.

III. Speed Estimation Based on Doppler Spectrum

In this paper we propose a simple speed estimation mechanism that can be performed by LTE UEs with any desired accuracy that is a trade-off between processing capabilities, time required for velocity estimation and battery drain.

It will be assumed that the UE is able to track the LTE cell reference signals (CRS) employed for channel estimation. With the aid of CRS the UE is able to obtain and store the relevant channel transfer functions. If more than one antenna is employed for transmission or reception, it would be sufficient to store only one of the available transfer functions as the algorithm should bring identical velocity estimations for all of them. It is also possible that the UE has to modify its Discontinuous Reception (DRX) parameters in order to wake up its receiver with the periodicity required by the proposed algorithm (which can be parameterized as explained below).

A. Theoretical background

In what follows the time-variant impulse response will be denoted as $h(\tau;t)$, being defined as the output obtained as a response to a Dirac delta at time *t*. By taking the Fourier transform with respect to τ we can obtain the time-variant channel transfer function:

$$H(f;t) = FT_{\tau}\{h(\tau;t)\}. \tag{1}$$

It is usually assumed that the impulse response is wide-sense stationary, and that the attenuation and phase shifts of the individual multipath components are uncorrelated (assumption of uncorrelated scattering [2]). Under these conditions, the autocorrelation function of the time-variant channel transfer function only depends on the frequency and time differences Δf and Δt:

$$R(\Delta f;\Delta t) = E\left[H^{*}(f;t)H(f+\Delta f;t+\Delta t)\right]. \tag{2}$$

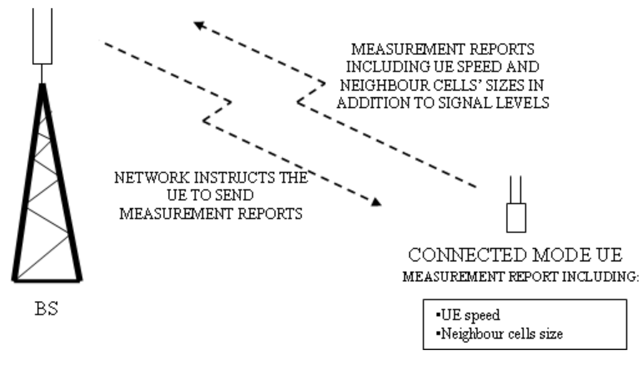

Fig. 3. Mobility-aware handover strategy based on neighbour cell sizes and UE speed.

Setting $\Delta f = 0$, we obtain $R(0;\Delta t) \equiv R(\Delta t)$. By taking the Fourier transform with respect to Δt it is possible to obtain the Doppler power spectrum of the channel:

$$S(f_d) = \int_{-\infty}^{\infty} R(\Delta t) e^{-j2\pi f_d \Delta t} d\Delta t. \tag{3}$$

The width of the Doppler power spectrum gives a measure of the maximum Doppler shift due to velocity, which happens when the velocity vector is collinear with the imaginary line connecting the UE and the base station [3] [4]:

$$f_{d,\max} = \frac{v}{c} f_c, \tag{4}$$

where *v* is the user's velocity, *c* is the speed of light and f_c is the carrier frequency. The coherence time is a measure of the time over which consecutive samples of the channel are sufficiently correlated. A useful rule of thumb for calculation of the coherence time is [5]:

$$T_c \approx \frac{0.423}{f_{d,\max}}. \tag{5}$$

B. Proposed receiver structure for speed estimation

With this theoretical framework, the structure in Fig. 4 is proposed for estimation of the Doppler power spectrum and hence the user's velocity.

The sampling period for the channel transfer function is denoted as ΔT and represents the time periodicity for successive collection of channel values. This magnitude must be carefully chosen so as to account for the desired range of minimum and maximum velocity values to be estimated. Some design rules are proposed in Section III.C for the choice of the best values in a given scenario. The inputs to the circular buffer should be the channel transfer function values $H_0[n]...H_{L-1}[n]$ at time instant *n*.

Fig. 5 represents graphically the proposed structure for the circular buffer in Fig. 4. The channel transfer function values are denoted as $H_l[i]$, where the subscript *l* refers to the frequency domain and the index *i* to the time domain. The buffer stores a total amount of *L* possible frequencies and *N* time intervals, hence giving a total of *LxN* elements. Both *L* and *N* are configurable parameters depending on real needs; some values are proposed in section III.C according to a

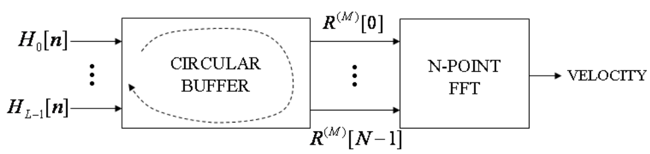

Fig. 4. Proposed structure for velocity estimation.

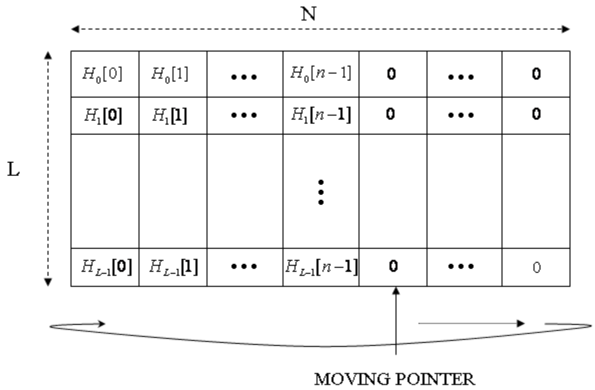

Fig. 5. Contents of the circular buffer in Fig. 4.

specific scenario. A moving pointer marks the next free position in the buffer, moving from left to right in the figure and coming back to the first position after reaching the last possible index value (N-1). In the figure it is depicted a case where only the first n positions are filled, the other N-n positions being still empty (and marked with zeros).

This buffer structure facilitates the calculation of the desired correlations between channel values. The expectation operator should act on both frequency and time dimensions, as correlations only depend on the relative time difference. We can calculate a first set of correlations denoted as $R^{(0)}[0], R^{(0)}[1] \ldots R^{(0)}[N-1]$ where:

$$R^{(0)}[\Delta k] = E\{H_l^*[k] H_l[k+\Delta k]\}, \Delta k = 0,1,..., N-1 . \quad (6)$$

The correlation for Δk = 0 is simply the average channel power and will be of no interest. Appropriate averaging over time and frequency should be applied for calculation of these values. Hence the following partial products may be defined:

$$P_{ijl}[k] = H_l^*[i] H_l[j], \text{such that } j - i = k , \quad (7)$$

where $k = 0,1,..., N-1$. Correlations are then calculated by averaging over all possible values of indices i, j and l:

$$\begin{aligned} R^{(0)}[0] &= \frac{1}{Ln_0} \sum_{i,j,l} P_{ijl}[0], \\ R^{(0)}[1] &= \frac{1}{Ln_1} \sum_{i,j,l} P_{ijl}[1], \\ &\vdots \\ R^{(0)}[N-1] &= \frac{1}{Ln_{N-1}} \sum_{i,j,l} P_{ijl}[N-1]. \end{aligned} \quad (8)$$

The quantities $n_0, n_1,..., n_{N-1}$ denote the number of possible i, j combinations in P_{ijl}. It is clear that:

$$n_0 = N, n_1 = N-1, \ldots, n_{N-1} = 1 . \quad (9)$$

Neglecting $R^{(0)}[0]$, it is apparent that while there are $L(N-1)$ partial products for calculation of $R^{(0)}[1]$, there are only L products for calculation of $R^{(0)}[N-1]$. In order to avoid this difference in accuracy, we can enhance the correlation estimations by successively calculating new R values as more and more values enter the buffer, as explained below.

After $L{\cdot}N$ channel values the buffer is full and the above correlations $R^{(0)}[k]$ can be calculated. After that, subsequent channel values will overwrite existing positions in the buffer and correlations can be successively enhanced. Denoting m as an index starting with 0 when the buffer is full and incremented by one at each sampling period, new correlation values $R^{(m+1)}[k]$ can be calculated from previous ones $R^{(m)}[k]$ by adding L new partial products $P_{ijl}[k]$ in the following way:

$$R^{(m+1)}[k] = \frac{L(n_k + m) R^{(m)}[k] + \sum_l P_{ijl}[k]}{L(n_k + m + 1)} . \quad (10)$$

The indices i, j in the above equation are such that $j - i = k$ and j is the position of the last stored values in the buffer. After a number M of iterations (M corresponding to the maximum value of m), the calculation stops and final correlation values $R^{(M)}[k]$ can be obtained. A total amount of $L{\cdot}(N{+}M)$ channel values will have been used for the correlations, but always keeping N-1 as the maximum time difference due to the buffer size.

The Doppler spectrum can finally be obtained after performing an N-point DFT/FFT of the obtained correlation function, given by:

$$F[p] = \sum_{k=0}^{N-1} R^{(M)}[k] e^{-j2\pi \frac{k}{N} p} . \quad (11)$$

It is to note that the correlation is a hermitian function, i.e. $R[-k] = R^*[k]$, and its Fourier transform is thus real. As the above summation does not cover the negative k indices, the Doppler spectrum will be given by:

$$S[p] = \sum_{k=-N}^{N-1} R^{(M)}[k] e^{-j2\pi \frac{k}{N} p} = 2 \operatorname{Re}\{F[p]\} . \quad (12)$$

The p indices span from 0 to N-1 and are related to the Doppler frequencies f_d by the relation $f_d = p \cdot \Delta f$. Δf is the minimum resolvable frequency interval, which is a function of the sampling period and the length of the buffer by the relation $\Delta f = 1/(N{\cdot}\Delta T)$.

Denoting $p_{\max}$ as the maximum index p for which an appreciable Doppler spectrum is obtained (distinguishable from the perceived noise level), the estimated velocity will be:

$$v = \frac{c p_{\max} \Delta f}{f_c} . \quad (13)$$

In practice some threshold may be applied for estimation of the maximum Doppler bandwidth, such as a given power density level (in dB) below the maximum.

The effect of a finite size DFT/FFT has implications on the resulting Doppler spectrum. Given that the theoretical continuous-time Fourier transform is by definition bandwidth-limited (the bandwidth given by the maximum Doppler frequency), a finite-size DFT gives rise to a Gibbs phenomenon similar to that appearing when trying to approximate a discontinuous function with a truncated Fourier series. An edge-enhancement method could then be applied for accurate determination of the Doppler width, such as e.g. a median filter.

Fig. 6 depicts the simplified block diagram for velocity estimation. At each sampling period Δ*T*, *L* new channel values $H_l[i]$ are stored in the circular buffer. After a total amount of *L·N* channel values the buffer is full and partial products $P_{ijl}[0]...P_{ijl}[N-1]$ can be calculated, as well as initial correlations $R^{(0)}[0]...R^{(0)}[N-1]$. Then a process starts where, at each sampling period, *L* new channel values enter the circular buffer and enable updating the correlation values $R^{(m)}[0]...R^{(m)}[N-1]$, for m = 1, 2…, *M*. After *M* iterations, final values $R^{(M)}[0]...R^{(M)}[N-1]$ are obtained and the Doppler power spectrum is calculated by means of a suitable discrete Fourier transform (DFT or FFT). The Doppler bandwidth measurement gives an estimation of the user's velocity. The above process takes a total time of $(N+M)\Delta T$ seconds, and can be repeated any number of times thus resulting in a periodical velocity estimation process. Such continuous estimation can be enhanced by appropriate filtering in order to remove estimation errors.

C. *Design rules for N, M, L and ΔT*

The minimum resolvable Doppler frequency is given by $\Delta f = 1/(N\Delta T)$. This gives a minimum value of the resolvable velocity, which in turn determines *N* through the expression:

$$v_{\min} = \frac{c\Delta f}{f_c} = \frac{c}{f_c N \Delta T} \Rightarrow N = \frac{c}{v_{\min} f_c \Delta T} . \quad (14)$$

The sampling period Δ*T* is related to the maximum velocity to be estimated:

$$f_{d,\max} = \frac{N}{2}\Delta f = \frac{1}{2\Delta T} = \frac{v_{\max}}{c} f_c \Rightarrow \Delta T = \frac{c}{2 v_{\max} f_c} . \quad (15)$$

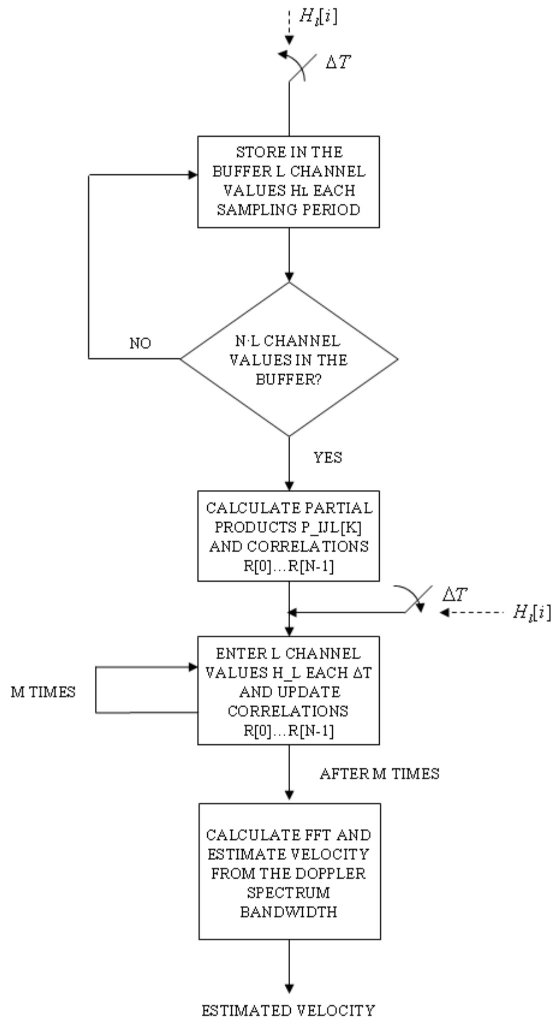

Fig. 6. Flow diagram for the proposed speed estimation algorithm.

The value of Δ*T* thus calculated should also be greater than the coherence time of the channel given by (5). It is clear that in this case the design condition $\Delta T = 1/(2 f_{d,\max})$ ensures that the sampling period is greater than the coherence time of the channel.

The value of *M* is related to the difference in precision between the number of partial products for calculation of $R^{(M)}[1]$ and $R^{(M)}[N-1]$. As explained in section III.B, the number of partial products for calculation of the correlation values $R^{(M)}[k]$ is $L(n_k + M)$. The ratio between the minimum and maximum number of partial products is thus:

$$\frac{L(n_{k,\min} + M)}{L(n_{k,\max} + M)} = \frac{1+M}{N-1+M} . \quad (16)$$

This ratio can be regarded as the relative difference between the number of partial products for the minimum and maximum time difference. If a relative error lower than ε is sought, *M* can be calculated in the following way:

$$\frac{1+M}{N-1+M} > 1-\varepsilon \Rightarrow M > \frac{(N-1)(1-\varepsilon)-1}{\varepsilon}. \qquad (17)$$

This gives an estimation of the value M for which correlations $R^{(M)}[1]$ and $R^{(M)}[N-1]$ have a difference in relative accuracy less than ε.

It is also important to note that the total estimation time is $(N+M)\Delta T$, and that this time should not be very large in order to keep the shadowing properties of the channel relatively unchanged. Hence the distance covered at the minimum resolvable velocity should not be higher than the shadowing correlation distance, to avoid distortion for the highest time difference $N \cdot \Delta T$.

Finally, the number L of channel samples in the frequency dimension may be obtained considering the minimum required number of partial products in the correlation calculations. This minimum number is $L(1+M)$, from which it is possible to derive L after having obtained M.

IV. Simulation Results

The performance of the proposed algorithm was assessed with the aid of an LTE link level simulator. Table 1 summarizes the main parameters and assumptions. Figures 7 and 8 contain the average estimated speed values for channel models ITU EPA and ITU EVA respectively, including also the standard deviations. It is apparent that the proposed algorithm yields very good results for both channel models, with slightly higher errors in the EVA case. Very little dependence on the SNR was observed, as the accuracy was mainly determined by the choice of M, N and ΔT. The velocity estimation can therefore be applied for mobility-aware RRM strategies based on speed measurements from the UE.

V. Conclusions

In this paper we explore mobility-based RRM strategies in LTE Idle and connected modes that exploit speed measurements reported by the terminal to the base station, and propose a simple algorithm for speed estimation based on the Doppler power spectrum. We show that the proposed algorithm provides sufficiently precise velocity values for application in RRM strategies even in low SNR conditions. Design rules have been given for speed estimation over a range of velocities of interest with a relative difference in precision between the correlation terms lower than a given value. Future work can be focused on filtering of the resulting values for higher precision.

TABLE I. Parameters for Calculation of the Compression Ratio in Downlink

Parameter	Setting
Carrier frequency	2.6 GHz
System bandwidth	20 MHz
Power delay profile	ITU EPA, ITU EVA
Channel estimation	Ideal
N	128
M	1280
L	10
ΔT	2 ms
Bandwidth detection	–6 dB power level below the maximum
SNR	0, 5, 10, 15, 20, 25, 30 dB
UE speed	3, 30, 50, 70 and 100 km/h
No. realizations	50 channel realizations per SNR value

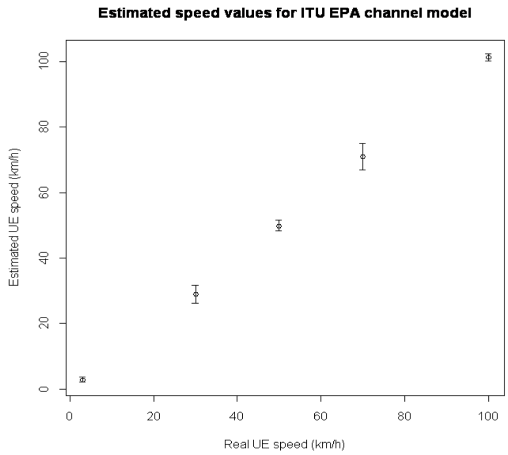

Fig. 7. Simulation results for ITU EPA channel model.

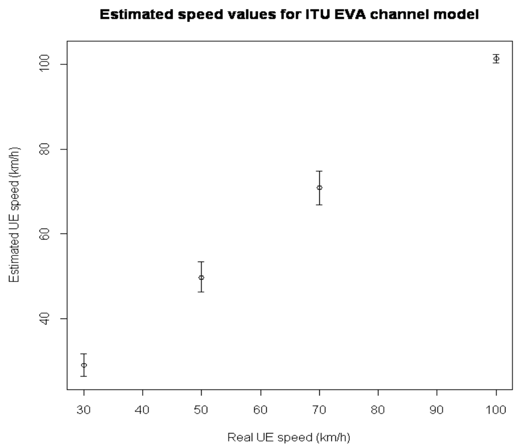

Fig. 8. Simulation results for ITU EVA channel model.

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