Multi-RAT Scheduling for Heterogeneous Networks

Pawel Kryszkiewicz
Poznan University of Technology
Poznan, Poland
Email: pawel.kryszkiewicz@put.poznan.pl

***Abstract*—Mobile network operators are required to support a number of users utilizing various Radio Access Technologies (RATs). While operating in a costly, licensed spectrum, the efficiency of its utilization is of crucial importance. This will promote newer RATs, supporting higher spectral efficiency. On the other hand, the quality of service for older RATs' users has to be maintained. This paper proposes a scheduling algorithm, dynamically distributing time-frequency resources between two or more RATs. Interference between RATs is modeled and considered while allocating resources. The algorithm is presented and validated by means of simulations for a coexistence of GSM and LTE systems. This solution is proved to be spectrally efficient in dynamic resource distribution, especially for traffic demand varying in time among different RATs.**

I. INTRODUCTION

It is commonly known that limited, licensed radio frequency resources have to be efficiently utilized by mobile network operators facing rapid growth in user data volume [1]. There are numerous solutions to this problem, e.g., network densification, higher spectral efficiency of the modulation technology applied or data offloading to unlicensed frequency bands. However, older, less spectrally efficient Radio Access Technologies (RATs) cannot be rapidly deactivated as some users may still use the older technologies. Commonly, slow refarming of frequency bands is utilized. Recently, trials of LTE introduction in band adjacent to GSM carriers in the 900 MHz band were reported [2]. However, this approach is neither dynamic, nor automatic. Daily changes of traffic demand between different RATs cannot be reflected in the resource allocation scheme. Additionally, worst case inter-RAT interference has to be assumed while designing such a coexistence.

This paper proposes a dynamic approach to sharing time-frequency resources in a heterogenous network composed of various RATs. A real time scheduler is proposed that distributes available resources among users. For simplicity, only downlink traffic is considered. However, the same algorithm can be applied in the uplink as well. While in a given RAT resources allocated to different users are orthogonal, e.g., Resources Blocks (RBs) in LTE or timeslots in GSM, it is no longer true in multi-RAT scheduling. The inter-system interference is modeled based on the methodology presented in [3] and taken into account during scheduling. Various RATs have different spectral efficiency, so that *max-rate* scheduling will typically cause *starvation* of one's RAT users. A proportional fair (PF) scheduler is considered in the paper as a mechanism providing fairness among different RATs users. It is based on a state-of-the-art, low computationally complex algorithm proposed for LTE in [4]. This approach requires control information exchange between both RATs' Base Stations (BSs), as it is foreseen that both BSs will be collocated at the same transmission site. Not only it is the case in real networks, but it simplifies the interference calculation procedure as well. Most importantly, the proposed scheduler is RAT-agnostic, i.e., can be used with various RATs. In the simulations it is used for resources scheduling among LTE and GSM users. Observe that the proposed allocation is short-term, low-layer in contrast to the long-term, higher-layer approach proposed in [5].

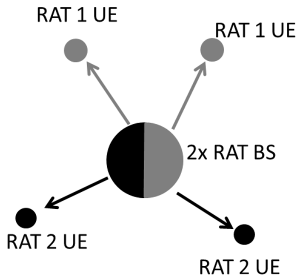

Fig. 1. Diagram of the considered network: 2 RATs collocated.

The paper is organized as follows. Sec. II presents a system model, followed by the method for inter-RAT interference calculation. Next the proposed PF scheduler is presented. Sec. III shows a simulation scenario and results. The paper is concluded in Sec. IV.

II. SYSTEM MODEL

The considered system is composed of a base station (BS) utilizing 2 RATs. Although a higher number of RATs is possible, this assumption will simplify the description with no loss in generality. It is foreseen that the proposed scheduler operates in a single BS, utilizing two RATs, or two tightly connected BSs, operating at the same transmission site. These assumptions allow for real-time channel quality information reporting (low delay) and simpler interference calculation (the propagation channel of the wanted and interference signals can be assumed to be the same). The proposed scheme is graphically presented in Fig. 1.

From the perspective of available resources on the time-frequency grid, both systems are assumed to be non-orthogonal, as it is visible in Fig. 2. On the other hand,

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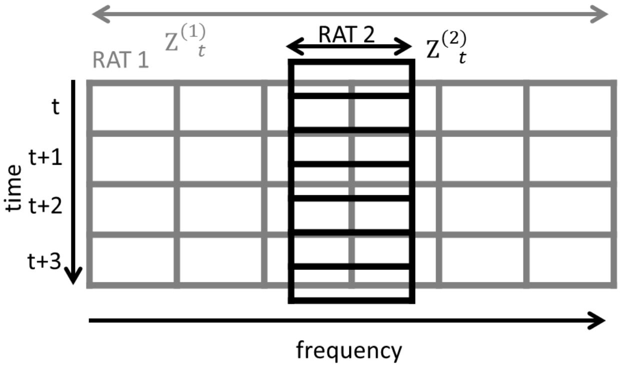

Fig. 2. Example of time-frequency grid used for scheduling.

resources used in a given RAT are assumed to be orthogonal as it is typically done, e.g., with Resource Blocks in LTE or timeslots in GSM. Obviously both RATs can have different timeslot/subframe duration. As such, for a single resource allocation in one RAT (a single timeslot), none or many resource allocations can be carried out in the other RAT. In Fig. 2 the basic timescale is associated with RAT 1. During one timeslot in RAT 1, one or two resource allocations (collocated with the beginning of a RAT 2 timeslot) have to be carried out in RAT 2. The vector of total available resources in RAT 1 in timeslot t is denoted as Z_t^1. For RAT 2 this vector is denoted as Z_t^2. The channel capacity depends on propagation channel conditions, allowed bandwidth, power, noise floor and interference power. Additionally, depending on modulation and coding schemes (MCS) implemented in a given RAT, a limited number of discrete throughput values can be achieved. Function f^1 or f^2 (specific for a given RAT) maps the vector Z_t^1 or Z_t^2 of all available resources to $j-th$ user maximal achievable throughput $R_t(j)$. It is is defined as

$$\left[R_t(j), \Delta Z_t^{\alpha(j)}(j)\right] = f^{\alpha(j)}\left(Z_t^{\alpha(j)}, I_t^{\alpha(j)}\right), \tag{1}$$

where $\alpha(j)$ maps index of user j to index of its RAT, $I_t^{\alpha(j)}$ is the vector of interference power caused in timeslot t to RAT $\alpha(j)$ and $\Delta Z_t^{\alpha(j)}(j)$ is the vector of resources actually utilized by the user. Utilization of these resources introduces some interference to the other RAT. The function mapping these resources in RAT $\alpha(j)$ to interference power in the other RAT, denoted as $\widetilde{\alpha(j)}$, is defined as

$$\left[\Delta I_{t-1}^{\widetilde{\alpha(j)}}(j), \Delta I_t^{\widetilde{\alpha(j)}}(j), \Delta I_{t+1}^{\widetilde{\alpha(j)}}(j)\right] = g^{\alpha(j)}\left(\Delta Z_t^{\alpha(j)}(j)\right), \tag{2}$$

where $\Delta I_{t-1}^{\widetilde{\alpha(j)}}(j)$, $\Delta I_t^{\widetilde{\alpha(j)}}(j)$ and $\Delta I_{t+1}^{\widetilde{\alpha(j)}}(j)$ are the interference power vectors caused to the previous, current and next timeslots. As mentioned before, the interference within a given RAT is not modeled, as typically resource allocation is orthogonal[1]. The function calculating this interference is specific for a given RATs pair. It is elaborated in the next subsection.

A. Interference power calculation

The interference power observed by a receiver of RAT A from a transmitter of RAT B depends on many factors, as it has been presented in [3] between the Filter Bank Multicarrier or OFDM and UMTS or GSM. The interference calculation between two OFDM-based systems is presented in [7]. In general, the received interference power in band Δf around frequency f_0 can be calculated as

$$P_I = \int_{f_0-\Delta f/2}^{f_0+\Delta f/2} P^{TX}(f)|H_{TX-RX}(f)|^2 |H^{RX}(f)|^2 df, \tag{3}$$

where $P^{TX}(f)$ is the Power Spectral Density (PSD) of the transmitter signal (dependent on the currently allocated resources $\Delta Z_t^{\alpha(j)}(j)$, e.g., knowing that each LTE subcarrier has a sinc-like PSD shape as shown in [7]), $H_{TX-RX}(f)$ is the channel frequency response and $H^{RX}(f)$ is the receiver frequency response (depending on the internal filtering and demodulator implemented). While the first component can be modeled analytically, based on the Spectrum Emission Mask or on-line measurements, the second can be estimated based on users' channel quality reports. The third component is partially dependent on the RAT standard, e.g., in LTE, the minimal Adjacent Channel Selectivity is specified, but mostly it depends on a vendor design. Typically, a set of standard receivers has to be measured. Please refer to the discussion in [3].

The above formulas assume both systems occupy their transmission channels continuously in time. However, the scheduling scheme proposed in this paper makes use of timeslots. As such, time-continuous interference power calculated according to (3) transfers to interference power defined in (2) as

$$\Delta I_t^{\widetilde{\alpha(j)}}(j) = \Psi P_I, \tag{4}$$

where $\Psi \in \langle 0; 1 \rangle$ is a duty cycle of time when the interfering signal (occupied timeslot of interfering RAT) is present in timeslot t of the RX RAT.

B. Proposed PF scheduler

As explained in the introduction, joint scheduling of both RATs users with the same priority excludes, e.g., *max-rate* algorithms from consideration. However, the Proportional Fair (PF) algorithm allows both systems' users to transmit. The baseline is a suboptimal algorithm proposed for LTE in [4]. The suboptimality of the algorithm reduces the computational complexity of the solution. It is important, as interference calculation will add many extra computations to this algorithm.

A block diagram of the proposed algorithm is shown in Fig. 3. For each RAT, the maximal rate achievable by each user is calculated, i.e., (1) is evaluated for users $j = 1, ..., N1$ belonging to RAT 1, and for users $j = N1+1, ..., N1+N2$ belonging to RAT 2. At this time, the interference vectors are populated only by interference generated by resources

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[1] In the future, inter-RAT interference can be considered as well, after the introduction of some new technologies like Non-Orthogonal Multiple Access (NOMA) [6].

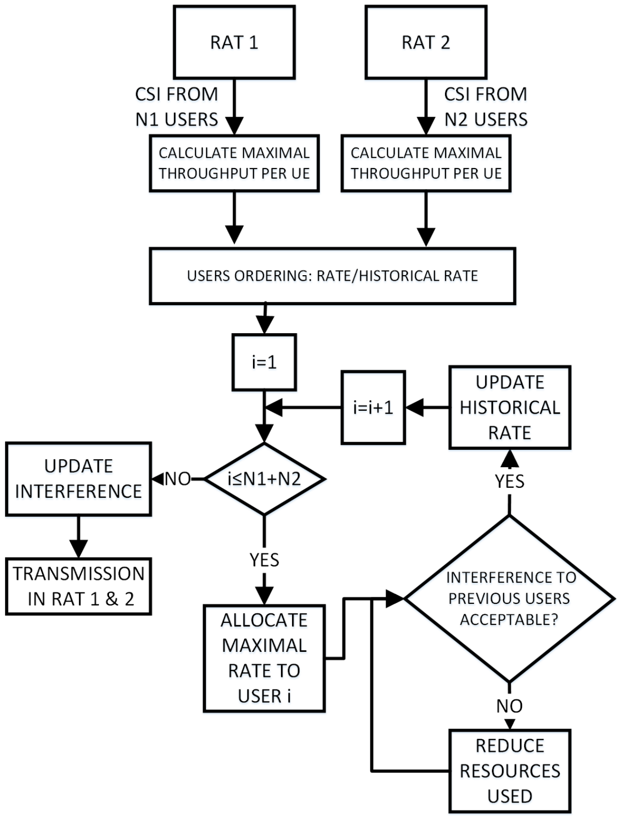

Fig. 3. Block diagram of the proposed multi-RAT scheduling algorithm.

allocated in the previous timeslot. Let us denote the mean historical rate of the j-th user at timeslot t as $\overline{R_t(j)}$ (its update procedure will be presented at a further step of the algorithm). The proportional fairness of resource allocation is achieved by *USERS ORDERING*, i.e., sorting all users' relative rates $R_t(j)/\overline{R_t(j)}$ in descending order. Let us denote as $\beta_t(i)$ a function mapping the i-th user index after ordering to the j-th user index before ordering in timeslot t. This results in $R_t(\beta_t(1))/\overline{R_t(\beta_t(1))} \geq ... \geq R_t(\beta_t(N1+N2))/\overline{R_t(\beta_t(N1+N2))}$ [2].

For each user i, the proposed algorithm recalculates the maximal possible rate considering a possibly limited resources vector (by previously allocated users utilizing the same RAT) and increased interference (by previously allocated users using the other RAT) as

$$\Big[R_t(\beta_t(i)), \Delta Z_t^{\alpha(\beta_t(i))}(\beta_t(i))\Big] = f^{\alpha(\beta_t(i))}\Big(Z_t^{\alpha(\beta_t(i))} \tag{5}$$
$$- \sum_{\substack{k=1\\ \alpha(\beta_t(k))=\alpha(\beta_t(i))}}^{i-1} \Delta Z_t^{\alpha(\beta_t(k))}(\beta_t(k)), I_t^{\alpha(\beta_t(i))} + \sum_{\substack{k=1\\ \alpha(\beta_t(k))\neq\alpha(\beta_t(i))}}^{i-1} \Delta I_t^{\alpha(\beta_t(i))}(k)\Big).$$

Based on the potential resource utilization $\Delta Z_t^{\alpha(\beta_t(i))}(\beta_t(i))$ the potential interference vectors to the other RAT in timeslots t-1, t and t+1 are calculated according to (2). Obviously, any additional interference introduced to the other RAT's users allocated in timeslot t-1 and previously allocated users in timeslot t, i.e., users indexed $\beta_t(k)$ for $k = 1, ..., i-1$ and $\alpha(\beta_t(k)) \neq \alpha(\beta_t(i))$, can deteriorate their transmissions. However, some degradation of a single user bitrate has to be accepted in order to increase the global throughput. One of the simple solutions (tested later via simulations) is to check all these users if the same modulation & coding scheme is retained, assuming the maximal acceptable Block-Error Rate, e.g., 10%. An other approach is to allow the user throughput to be degraded by a maximum of Γ percent. For the k-th allocated user in timeslot t, the following condition has to be met

$$f^{\alpha(\beta_t(k))}\left(\Delta Z_t^{\alpha(\beta_t(k))}(\beta_t(k)), I_t^{\alpha(\beta_t(k))} + \sum_{\substack{n=1\\ \alpha(\beta_t(k))\neq\alpha(\beta_t(n))}}^{i} \Delta I_t^{\alpha(\beta_t(k))}(n)\right)$$
$$\geq \frac{100-\Gamma}{100} f^{\alpha(\beta_t(k))}\left(\Delta Z_t^{\alpha(\beta_t(k))}(\beta_t(k)), I_t^{\alpha(\beta_t(k))}\right). \tag{6}$$

If it is not met, the amount of resources available to user $\beta_t(i)$ has to be reduced, e.g., some resource blocks have to be turned off in LTE, or a timeslot has to be deactivated in GSM. This should reduce the interference observed by user $\beta_t(k)$. Although in general any resource deactivation scheme is possible, typically the resources closest in the time-frequency grid to the interfered resources cause the strongest interference, i.e., they should be deactivated [8]. As a result, (5) has to be recalculated followed by interference vectors calculation in (2). Depending on RAT granularity (e.g., the number of resource blocks in LTE), the reduction of utilized resources can be enforced many times, till the interference constraint, e.g., (6) is met. In the worst case the amount of resources available to user $\beta_t(i)$ will reduce to 0, resulting in no transmission to this user and no interference to the other RAT.

Finally, for the $\beta_t(i)$ user the algorithm goes to block *UPDATE HISTORICAL RATE*. The allocation for user $\beta_t(i)$ is fixed and its mean historical rate is calculated according to the exponential moving average formula as

$$\overline{R_{t+1}(\beta_t(i))} = (1-\gamma)\overline{R_t(\beta_t(i))} + \gamma R_t(\beta_t(i)), \tag{7}$$

where $\gamma \in \langle 0; 1\rangle$ is a smoothing parameter.

After allocating all users, transmission in both RATs can be carried out. It has to be preceded by updating the interference vectors. The vector of interference power leaking to timeslot t+1 is calculated for RAT 1 as

$$I_{t+1}^1 = \sum_{\substack{i=1\\ \alpha(i)\neq 1}}^{N1+N2} \Delta I_{t+1}^1(i). \tag{8}$$

Similar calculations are carried out for RAT 2. Observe that the proposed algorithm is RAT-agnostic. Only functions f and g and *reduction of used resources* have to be specific for a given RAT.

III. SIMULATION RESULTS

The proposed scheduler is evaluated by means of simulations assuming a coexistence of GSM and LTE systems. Most

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[2] Any potential control channel signaling should be prioritized at this point.

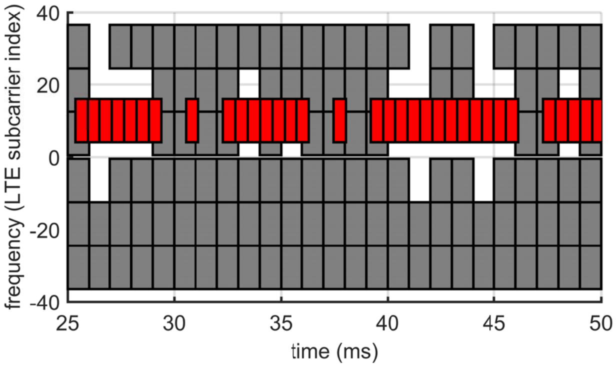

Fig. 4. Example of time-frequency grid. Red rectangle - GSM timeslot utilized. Grey rectangle - LTE RB utilized.

parameters are taken from [9]. Both BSs operate at the 43 dBm transmit power in the 900 MHz band. The GSM carrier frequency is arbitrarily chosen to be higher by 150 kHz than the LTE carrier frequency. LTE uses a 1.4 MHz bandwidth, i.e., a maximum of 6 resource blocks. Both base stations utilize an antenna of a 12 dBi gain mounted 15 m above the ground. All users, i.e., 16 for LTE and 4 for GSM if not stated otherwise, are equally distributed in a cell of the radius of 1000 m. Each user equipment uses a 0 dBi-gain antenna and is characterized by a noise figure of 9 dB. A full buffer traffic model is used. The path loss is calculated according to the macro cell propagation model for urban areas [9]. In each simulation 1000 random user locations are considered. Each iteration is composed of 100 timeslots, 1 ms duration each. In each timeslot, an independent Rayleigh-fading channel instant is generated following the 9-path Extended Vehicular A channel model defined in [10]. Full channel knowledge at the BS is assumed similarly as in [4].

While a single resource chunk in GSM is a timeslot (200 kHz bandwidth, about 0.58 ms duration), LTE uses Resource Blocks and subframes (180 kHz bandwidth, 1 ms duration). As the PF scheduler considers the mean historical rate, the first 10 ms of each iteration are excluded from statistical calculations. In the case of LTE 15 MCS are considered with the exponential effective signal-to-interference-plus-noise ratio calculated according to [11] and the required coefficients taken from [12], [13]. In the case of GSM, data transmission is carried out using the General Packet Radio Service (GPRS) with 4 available coding schemes. Mapping between SINR, Block Error Rate (BLER) and the obtained bitrate is taken from [14].

The interference power vectors are calculated according to the methodology presented in [3] with the GSM spectrum emission mask taken from [15] and GSM receiver selectivity taken from [16].

First, simulations are carried out for the smoothing parameter γ equal to 0.1. An example of a time-frequency grid with resources used by GSM (red rectangles) and LTE (grey rectangles) is shown in Fig. 4. It is visible that in many cases LTE RBs close to an utilized GSM timeslot are turned off. This reduces the mutual interference between both systems. In nother timeslots GSM transmission is turned off in order to allow for LTE transmission with higher quality. The balance depends on the current channel conditions and the historical rate, i.e., $R_t(j)/\overline{R_t(j)}$, as explained in the previous section.

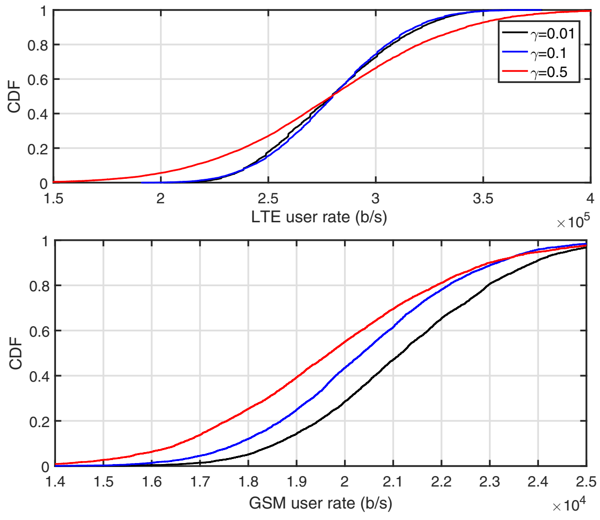

Fig. 5. Cumulative density function of LTE and GSM users for varying mean historical rate smoothing parameter γ.

Next, the system was tested for various historical rate smoothing parameters, i.e., γ equal to 0.01, 0.1 and 0.5. Cumulative Density Functions (CDFs) of mean user rates are shown in Fig. 5. In the case of LTE users it is visible that a lower γ value enforces fairness between users. For instance, there are more than 25% of users having a mean rate below 250 kbps for $\gamma = 0.5$. For $\gamma = 0.1$ there are fewer than 15% of them. On the other hand, a relatively low γ value reduces the number of users with a high rate as well. The mean LTE user rate is equal to about 280 kbps in all the cases. For GSM users it is visible that a lower γ value allows all the GSM users to obtain a higher rate. However, the gain in the mean rate is relatively low, from 18.8 kbps for $\gamma = 0.5$ to 21.2 kbps for $\gamma = 0.01$. In all the cases the time-frequency resource utilization (calculated as the ratio of the cumulative area of both red and gray rectangles to the total area of time-frequency grid in Fig. 4) equals about 0.97. Only 3% of the available time-frequency resources are unused in order to decrease inter-system interference.

In order to observe how the proposed algorithm adjusts to changing traffic balance between both RATs, simulations were carried out for the ratio of GSM:LTE users changing from 1:19 to 19:1, for the total number of 20 users. γ equals 0.01. In the top plot in Fig. 6 it is visible how the mean GSM and LTE user rate changes with the number of GSM users. As expected, the higher the number of GSM users, the lower the possible rate a single user can achieve. The resources available in a given RAT have to be divided among all connected users. A similar phenomenon is observed for LTE users. However, in

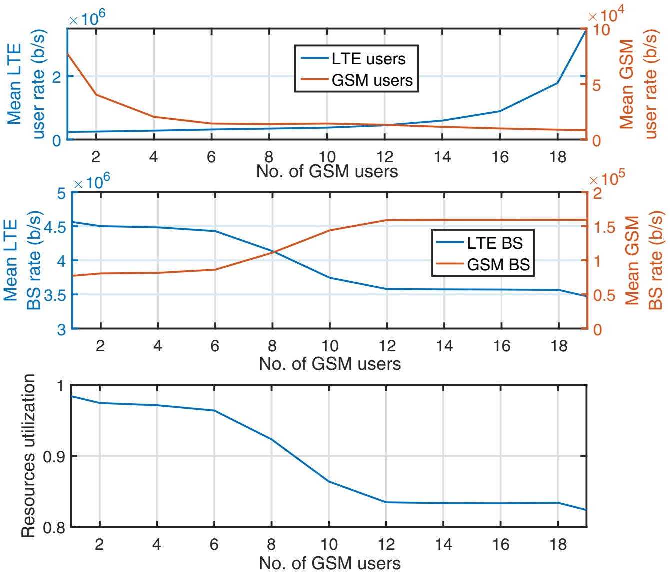

Fig. 6. Mean rate and time-frequency resources utilization for varying number of GSM/LTE users.

the middle plot, the mean LTE and GSM BS rate is shown. The higher the number of GSM users, the higher the rate obtained in this RAT and the lower in LTE. This proves that the proposed algorithm adjusts to changing traffic conditions. Finally, in the bottom plot, the mean time-frequency resources utilization is shown. It is the highest for a low number of GSM users. In this case there are many timeslots where only LTE is transmitting, obtaining instantaneous resource utilization equal to 1. For a higher number of GSM users, many RBs in LTE, close in frequency to the GSM band, have to be turned off. However, the resource utilization is still higher than 80%.

IV. CONCLUSION

The proposed inter-RAT scheduling algorithm allows for dynamic allocation of resources among users utilizing different RATs operating in the same spectrum while controlling the inter-system interference. In the worst case the time-frequency resources utilization is higher than 80% with no need for additional filtering of static guard bands between RATs.

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