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Differential Signaling of Scheduling Information in Wireless Multiple Access Systems

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Abstract—This paper considers the control signaling on the downlink in wireless multiple access systems, with focus on the part of the control signaling that carries information on the user’s time/frequency scheduling assignments. A new idea is presented to reduce the amount of channel resources needed for this signaling. The idea is to exploit the fact that provided that only one single user is scheduled on each channel resource, then the different users’ scheduling assignments are correlated. This correlation can be exploited by encoding the scheduling information differentially. In order to recover the scheduling information, a user must then decode the scheduling information of some of the others. This is possible, because on the downlink, all users can hear the transmission by the base station so that users with a high SNR may decode the control signaling sent to users with a lower SNR. We present a practical scheme to exploit this idea. Both analytical analysis and numerical examples illustrate that the proposed technique can provide a substantial reduction in signaling traffic.

I. INTRODUCTION

A. Background and Motivation

Several state of the art wireless multiple access systems exploit multi-user diversity by adaptive scheduling of the different users on channel resources which are beneficial to them, given the current status of the fading radio channel. This opportunistic scheduling approach in combination with adaptive modulation and coding (AMC) and hybrid automated repeat request (HARQ) is essential for reaching the aggressive goals on peak throughput set up for modern mobile broadband multiple access systems. The multi-user scheduling is typically performed by the base station which given channel-state information (CSI) from the different mobile users, makes a scheduling decision according to more or less advanced scheduling algorithms. The price of opportunistic scheduling is that the scheduling decisions need to be propagated to the users over a control channel, which competes with payload data for channel resources. This process is typically referred to as *signaling* of the scheduling assignments. Keeping the amount of transmitted control data low allows for more efficient usage of the channel resources. Any improvements on the resource efficiency of representation and transmission of scheduling information on the control channel is therefore essential.

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Contributions: In this paper we present an idea to reduce the signaling traffic in wireless multiple access systems that contains the scheduling information. The idea is motivated by the fact that the scheduling assignments for different users are correlated. This correlation comes from the fact that no two users can be scheduled in the same channel resource. Therefore if a certain channel resource is assigned to user A, then provided that user B is allowed to overhear the scheduling information intended to user A, she knows a priori that she will not be scheduled on that channel resource. This correlation can be exploited by the source coding scheme that is used to compress the scheduling information for different users. One way of doing so is the scheme we propose in this paper.

B. Related Work

There are basically two approaches to combat the signaling overhead caused by the transmission of scheduling assignments. The first approach is to reduce the amount of control information that needs to be signaled to the users. A common technique for instance is to aggregate a couple of resources together into larger blocks and allocate each such block to one user. This technique is currently used in 3GPP Long Term Evolution (LTE). More specifically, the smallest possible scheduling granularity in LTE consists of 12 consecutive OFDM subcarriers in frequency and 14 consecutive OFDM symbols in time [1]. In [2], the authors proposed a compression scheme to encode the control information. The compression scheme therein consists of a run-length encoder, followed by a universal variable-length code (UVLC).

In the second approach, rather than reducing the amount of control information, the focus is on the actual transmission of the scheduling assignments. In other words, the second approach concerns finding efficient ways for transmission of the scheduling assignments. For instance a solution to improve the control signaling was proposed in [3]. The idea is to use adaptive modulation and coding for the transmission of control information based on a grouping of users into groups with similar channel qualities. In [4] another technique to reduce the control signaling was proposed. The idea therein is to use semi-persistent scheduling decisions and to change the scheduling assignments only if the gain in throughput is larger than the loss due to the signaling caused by transmission of the new assignments. In [5], two different ways for encoding and transmission of scheduling assignments were studied. The

performance of the two schemes in terms of the overall system throughput was evaluated for different scheduling granularities and strategies.

II. PRELIMINARIES

The scheduling decisions of the base station can in principle be envisioned as a *scheduling map* over the different channel resources. In this map the channel resources are marked with the identities of the users scheduled on them. We will restrict our discussion to scheduling maps that have an inherent one-dimensional structure. The scheduling map can then be reduced to a length N_s vector of integer numbers, where the integers are user identities and the positions in the vector corresponds to channel resources. This type of map we call a *joint map* since it displays the scheduling information of all users jointly. Scheduling maps can also be considered on an individual level in relation to a specific user. These maps corresponds to binary vectors with a “1” on those positions corresponding to channel resources the specific user is scheduled on and a “0” on all other positions. Such a map we call an *individual map*.

It is enlightening to consider two contrasting methods for the transmission of scheduling assignments: (i) joint compression, encoding and broadcast (JCEB), and (ii) separate compression, encoding and transmission (SCET). With JCEB, the joint scheduling map for all users is first compressed and then encoded using a single channel code, and broadcast to all the users. Here, the code rate must be chosen low enough so that all scheduled users, and in particular the user with the worst channel, can decode the information with a given (small) probability of error. The advantage of the JCEB scheme is that it exploits the correlation between the individual scheduling maps. This correlation comes from the fact that typically no two users can be scheduled on the same channel resource. The disadvantage of JCEB is that if the users SNRs are very different, then one may need a very low code rate to guarantee that all users can decode the scheduling information.

By contrast, with the SCET approach, an individual scheduling map is tagged with a user identity, compressed and transmitted to each scheduled user separately. Here the channel codes used for the error protection of the scheduling assignments can be chosen on a per-user basis. This ensures efficient usage of each separate user channel. However, the SCET scheme does not exploit the fact that the maps corresponding to different users are correlated. The SCET approach is the one favored by for instance the LTE standard [1].

In this paper we propose a new coding scheme that uses individual map transmission, with channel codes chosen on a per-user basis, but at the same time exploits the correlation among the individual scheduling maps. We will show analytically that on the average, the proposed scheme fully exploits the correlation among the individual scheduling maps. The new scheme could thus be adopted for LTE-like systems.

III. PROPOSED APPROACH

The motivation behind the proposed approach comes from the fact that a user with an SNR of γ in principle can decode

the scheduling information that is intended for all other users with an SNR smaller than γ . Furthermore, if a user overhears the scheduling information sent to a user with such a weaker channel, then she can deduce that she will not be scheduled on certain channel resources. This can be used to reduce the amount of information that must be transmitted to users with high SNR. In particular, there is no need to transmit a scheduling map at all to the scheduled user with the highest average SNR. It is enough to indicate that the user has indeed been scheduled, implying that the remaining resources are dedicated to her. In what follows we describe the proposed scheme in more detail.

Assume that there are N users that have been scheduled for reception of payload data. Let the integer vector \mathbf{v} represent the joint scheduling map¹. Without loss of generality, assume that the users are ordered according to their channel conditions. That is, user 1 has the worst channel and user N has the strongest channel. In the conventional SCET approach, for each user ℓ , we first find her individual scheduling map as a binary vector \mathbf{u}_ℓ according to,

$$\mathbf{u}_\ell(i) \triangleq \begin{cases} 1 & \text{if } \mathbf{v}(i) = \ell, \\ 0 & \text{otherwise,} \end{cases} \quad i = 1, 2, \dots, N_s,$$

where $\mathbf{u}_\ell(i)$ and $\mathbf{v}(i)$ denote the i th element of the vectors \mathbf{u}_ℓ and \mathbf{v} , respectively. Each individual map is compressed, encoded and transmitted separately. The channel codes used for the transmission of each such binary individual map, are chosen individually according to each users channel quality. More precisely, the channel code for user ℓ , is chosen based on her average receive SNR as signaled via the CSI report.

In the proposed method, the scheduling decisions are also transmitted to each user separately. The channel codes are chosen on a per-user basis and we exploit this to let the users overhear the transmissions intended for each other. Since user 1 has the weakest channel, it is possible for the other users (2 to N) to decode the data that is intended for her. Therefore, we start by transmitting the individual map $\mathbf{s}_1 = \mathbf{u}_1$ for user 1. Having decoded the incoming data, all users can locate the positions/resources that have been assigned to user 1. Therefore, we can safely remove these positions when encoding the scheduling vector for transmission to users 2 to N . Let vector $\mathbf{v}_2 = \mathbf{v} \setminus \mathbf{s}_1$ be the new shorter scheduling vector obtained by removing the positions assigned to user 1. We define an individual scheduling map as a binary vector \mathbf{s}_2 according to,

$$\mathbf{s}_2(i) \triangleq \begin{cases} 1 & \text{if } \mathbf{v}_2(i) = 2, \\ 0 & \text{otherwise.} \end{cases}$$

This vector should then be compressed, encoded and transmitted to the user with the second worst channel condition (user 2). Generally, \mathbf{s}_2 is much easier to compress (its representation requires less bits) than \mathbf{s}_1 .

¹This vector might be obtained from any scheduling strategy.

Using the same reasoning, for transmission of scheduling information to the j th user, we can omit the positions that have been assigned to user 1 to $(j - 1)$ from the scheduling vector \mathbf{v} , to obtain a new vector $\mathbf{v}_j = \mathbf{v} \setminus \{s_1, s_2 \dots s_{j-1}\}$. The individual scheduling map associated with the j th user, can now be obtained as the binary vector

$$\mathbf{s}_j(i) \triangleq \begin{cases} 1 & \text{if } \mathbf{v}_j(i) = j, \\ 0 & \text{otherwise,} \end{cases}$$

which is then compressed, encoded and transmitted. Finally for the last user (user N) by omitting the positions that have been assigned to the other user, the resulting vector $\mathbf{v}_N = \mathbf{v} \setminus \{s_1, s_2, \dots s_{N-1}\}$ only contains the positions that have been assigned to her. Therefore she finds her scheduling information by decoding all the data intended to the others. Figure 1 summarizes these procedures.

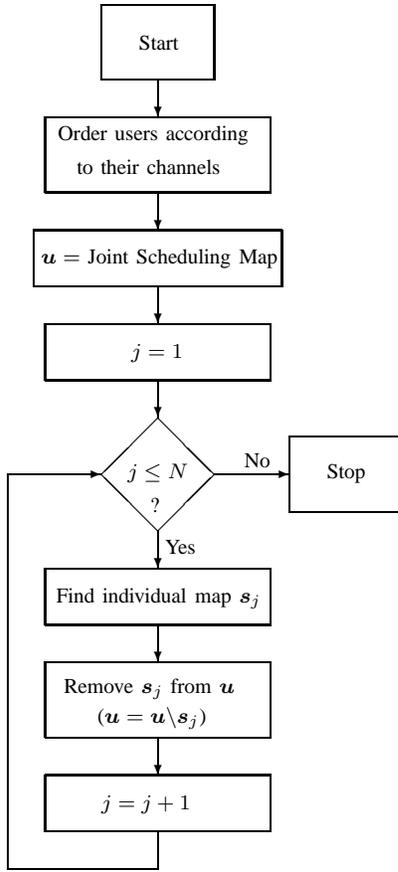


Fig. 1. Flowchart of the proposed scheme

We next provide an example to illustrate the proposed scheme. Assume that there are $N = 4$ scheduled users that are ordered according to their channel gains. (User 1 has the weakest while user 4 has the strongest channel.) Also assume that there are in total $N_s = 30$ channel resources that can be assigned to the users. Figure 2 illustrates the procedures that we used to find the binary maps for the two schemes. Herein, the joint scheduling map is assumed to be as Figure 2(a). The leftmost column shows the resulting joint scheduling maps

after removing the channel resources that have been successively assigned to users. In the middle column, the individual scheduling maps for the users according to the conventional approach are plotted. Finally, we see the individual scheduling maps for the users according to the proposed scheme in the rightmost column. We see that these maps have a less 'noisy' appearance and thus have lower entropy which means that they can be compressed more efficiently than the maps obtained from the conventional approach. We also see that in each step after removing the positions that have been assigned to the previous users, the length of the vectors decreases. This results in even more efficient compression of the binary maps.

IV. THEORETICAL JUSTIFICATION OF THE PROPOSED SCHEME

In this section we provide some more fundamental motivation for the proposed scheme. We derive the expected number of bits required for representation of the scheduling assignments according to the three schemes that we discussed. We show that under our assumptions, the proposed scheme can achieve the compression ratio equal to that of the JCEB scheme (whilst allowing for the use of higher average rate of channel codes). Let there be N users scheduled for reception of payload data and let there be N_s channel resources. Assume without loss of generality that the users are as usual ordered according to their channel gains, i.e. user 1 is the user with the worst channel while user N is the user with the best channel. We have the following:

Proposition 1: Assuming entropy achieving compression, the average number of required bits to represent the scheduling assignment according to the proposed scheme coincides with that of the JCEB approach and is less than or equal to the required number of bits with the SCET approach.

Proof: Let X_i be the scheduling information intended to user i , represented as a stochastic vector of length N_s . Using entropy achieving compression, to compress the joint scheduling map of length N_s , we need $N_s H(X_1, X_2, \dots, X_N)$ bits on the average. On the other hand according to the SCET approach, the scheduling information for each user is encoded separately. Therefore we need $N_s (H(X_1) + H(X_2) + \dots + H(X_N))$ bits on the average to represent the scheduling assignments according to SCET.

According to the proposed scheme, we first compress the scheduling information intended to the first user resulting in $N_s H(X_1)$ bits. Then we subtract the information associated with the first user and compress the scheduling information of the second user. Thus we need $N_s H(X_2|X_1)$ bits to represent the scheduling information intended to the second user. In general, for user i since we subtract the information associated to the users $1, 2, \dots, (i - 1)$ from the scheduling information intended to user i , we need $N_s H(X_i|X_{i-1}, \dots, X_1)$ bits on the average to represent the scheduling assignments for user i .

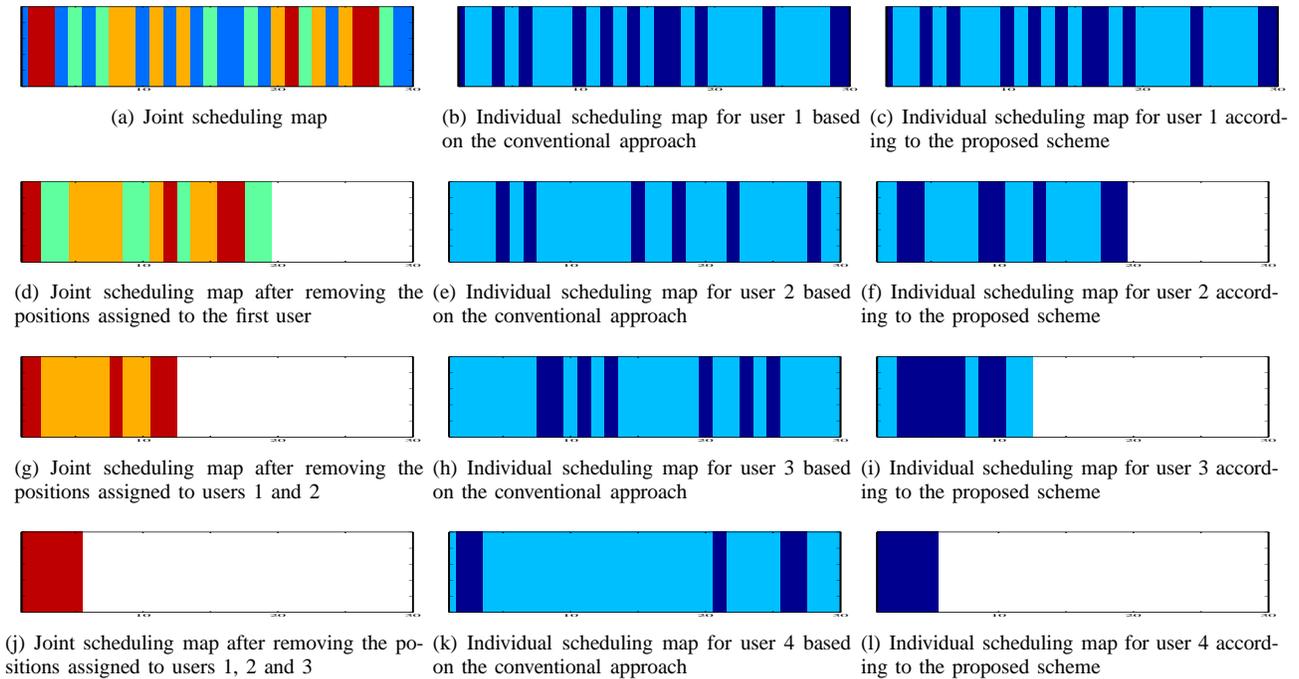


Fig. 2. Illustration of the conventional and proposed schemes. Note that according to the proposed scheme, not only the maps are easier to compress but also the length of the maps decreases in each step.

Now using the chain rule [6]

$$\begin{aligned}
 H(X_1, X_2, \dots, X_N) \\
 &= H(X_1) + H(X_2|X_1) + \dots + H(X_N|X_{N-1}, \dots, X_1) \quad (1) \\
 &\leq H(X_1) + H(X_2) + \dots + H(X_N) \quad (2)
 \end{aligned}$$

we see that the average number of required bits according to the proposed scheme is equal to that of the JCEB approach and is smaller or equal to that of the SCET approach and the proof is complete. ■

As an illustrative example, assume the scenario that all users are equally likely to “win” a certain channel resource. This means that for each resource all users are equally likely to be picked by the scheduler. We note that some schedulers such as the max C/I scheduler favor the users with good channel conditions [7]. However more relevant schedulers such as proportional fair schedulers typically schedule all the user [8]. Therefore the assumption that all users are equally likely to win a certain channel resource is not completely far fetched. Under this assumption it is anyway straightforward to show that the average number of required bits with the SCET approach with entropy achieving compression is

$$N_{\text{SCET}} = NN_s H_b(1/N) \quad [\text{bits}] \quad (3)$$

where $H_b(p)$ is the entropy of a binary source defined as

$$H_b(p) = -p \log_2(p) - (1-p) \log_2(1-p).$$

On the other hand, the average number of required bits with the JCEB and the proposed scheme is

$$N_{\text{PROP}} = N_{\text{JCEB}} = N_s \log_2 N \quad [\text{bits}] \quad (4)$$

Figure 3 illustrates the required number of bits normalized with the number of channel resources N_s , as a function of the number of users, N . As the graph shows, a significant improvement can be achieved when we exploit the correlation between individual scheduling maps using the proposed scheme (PROP). Note that the coinciding JCEB and PROP curves does not mean that the JCEB approach performs better than SCET. The reason is that with JCEB, the channel code used for the transmission of the scheduling assignments should be chosen according to the user with the worst channel, whereas with the SCET approach the channel codes can be chosen on a per user basis. However, according to the proposed scheme we not only exploit the correlation among individual maps but also we maintain the opportunity to choose a channel code for error protection of the signaling information on a per-user basis. Therefore the proposed scheme performs better than both JCEB and SCET approach.

V. SIMULATION MODEL

To demonstrate the gain with our new signaling scheme compared to the JCEB and the conventional SCET scheme, we have performed system simulations. The main reason is to show that with scheduling maps that are based on the correlated channel variations and scheduler operation the gain indicated in Figure 3 still remains substantial under more realistic conditions. We also want to illustrate the weakness of the JCEB approach by taking into account the varying channel qualities for the channels that are to convey the scheduling information to the different users.

We use a model for the distribution of supported rates and channel qualities over the different channel resources among the mobile users based on the following reasoning. Mobile

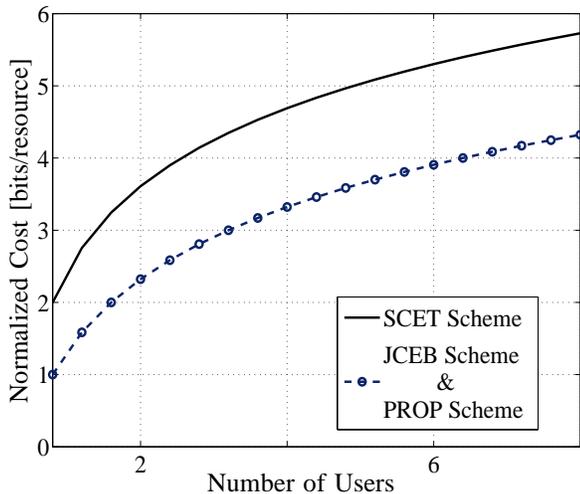


Fig. 3. Comparison of the schemes in terms of the representation cost of their associated maps for the case of uniform user distribution over the scheduling map.

users are assumed to be uniformly spread out in a donut shaped cell centered around the base station, with inner radius R_0 and outer radius R_c . This gives us a distribution $f_R(r)$ of user distances from the base station according to

$$f_R(r) = \frac{2r}{R_c^2 - R_0^2}, \quad R_0 \leq r \leq R_c.$$

This distance distribution is then translated into an average user receive SNR distribution using a simple path loss model and an SNR value at a reference distance (cell border). We do not include any shadow fading. Therefore, the average SNR received by a user at distance r from the base station is

$$\text{SNR}(r) = \text{SNR}(R_c) \left(\frac{R_c}{r} \right)^\alpha,$$

where α is the pathloss exponent. The resulting SNR distribution is then used to find a user rate distribution by assuming a supported rate according to a penalized channel capacity formula. Specifically, we say that a user i with average SNR γ_i can support a rate ρ_i of

$$\rho_i = \log_2(1 + \delta\gamma_i),$$

where δ is a penalty factor. The $\log(1 + \text{SNR})$ formula is often a useful measure of the system performance, since the throughput of most AMC schemes behaves as $\log(1 + \delta\text{SNR})$ for some δ where δ determines the performance gap to the capacity limit. For the presented simulation results we have used $\delta = 0.5$ which brings us to within 3 dB of channel capacity which arguably corresponds to a very good AMC for a control channel. However, our conclusions on the gain of our new signaling approach has shown not to be sensitive to this parameter value.

For user i , the ρ_i is used to calculate the number of channel bits required to transmit the scheduling assignments. In other words, we need $\lceil \frac{M}{\rho_i} \rceil$ channel bits to transmit M information bits to user i .

The distribution of SNRs and user rates are thus obtained, and used both as input to the generation of the scheduling

maps via a scheduler and as a cost measure for how much channel resources needs to be spent on each information bit of scheduling data to be transmitted to a user. For the input to the scheduler the SNR per resource element is taken as the average SNR value times a small scale fading factor from a normalized tapped delay line channel model with delay and power profiles adhering to standard channel models of the ITU (i.e. Vehicular/Pedestrian A and B).

As a relevant scheduler model we use a proportional fair scheduler [8]. After obtaining the joint scheduling map using proportional fair scheduling we find the individual scheduling maps for each user according to the conventional and proposed schemes. We then compress each of these maps individually using run-length encoding as the compression method [9]. However, in some cases run-length encoding can be more costly than sending uncompressed maps. This is typically the case when only a small number of channel resources are to be scheduled. Whenever this occurs, we send the data as an uncompressed binary map and we use run-length encoding only if it achieves compression. Thus an extra flag bit is necessary to indicate whether run-length encoding is used or not. We compare the conventional and the proposed schemes in terms of the total number of channel bits required to represent the collection of individual scheduling maps in each scheme.

VI. SIMULATION RESULTS

We have evaluated the JCEB, SCET and the proposed (PROP) schemes by performing Monte Carlo simulations using the model described in section V above for a varying number of users and cell border SNR.

Table I shows the simulation parameters that we used for the presented graphs.

δ	0.5
N_s	25
R_0	150 m
R_c	1500 m
α	4

TABLE I
SYSTEM SIMULATION PARAMETERS

The correlation between the channel coefficients associated with the different channel resources was for each user modeled to resemble those of an LTE system operating on a 5 MHz (25 resource blocks) system bandwidth subject to time and frequency fading according to the ITU Vehicular B channel model with 100 Hz maximum Doppler spread. The proportional fair scheduler used had a forgetting factor set to 200.

Figure 4 shows the comparison of the three schemes where the normalized costs to represent the scheduling information for the two schemes are plotted versus the number of users in the cell. We see that the proposed scheme performs better than the other two approaches. It is worth noting that the JCEB scheme in these simulations where the assumption of entropy achieving compression and uniformly distributed joint scheduling maps no longer holds, is slightly outperformed by our proposed scheme in terms of representation cost. Figure 5 shows the average number of channel bits required for the

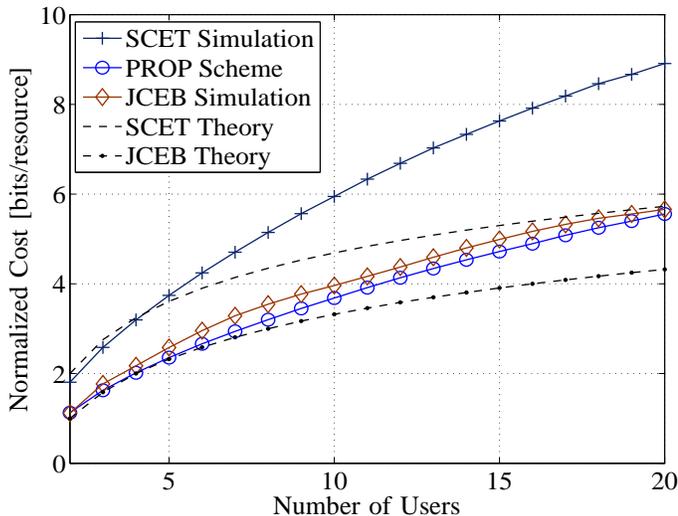


Fig. 4. Average number of required bits to represent the scheduling assignments according to the three schemes. The plots are normalized with the number of resources. For comparison the plots for the theoretical results (when assuming entropy reaching encoding and uniform user distribution over the scheduling map) are also included.

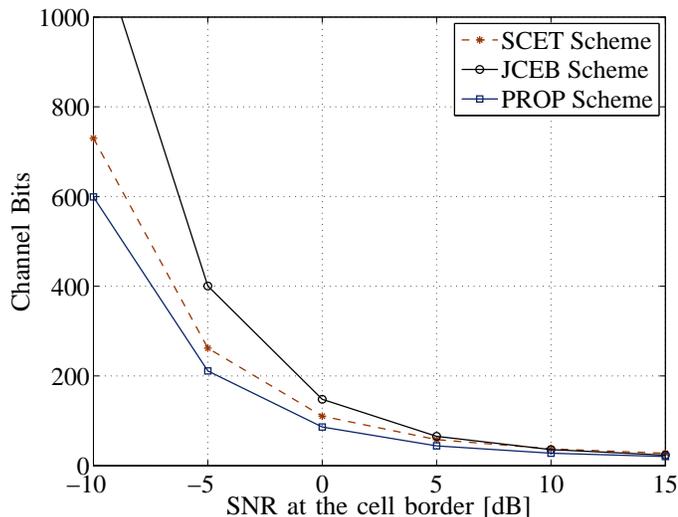


Fig. 5. Comparison of the three schemes in terms of average (over the number of scheduled users) number of channel bits required to signal the scheduling map.

transmission of the scheduling assignments as a function of SNR at the cell border. We see that the proposed scheme can improve the signaling overhead caused by the transmission of the scheduling assignments in terms of spent channel bits.

It is worth pointing out that the main concept in play in our new scheme is the fact that different mobile users are allowed to overhear the resource assignments of others than themselves. This is for instance prevented in the LTE standard today, since the control information (including resource allocations) aimed at a specific user is protected by a user specific cyclic redundancy check (CRC) [1]. This is used both for checking that the control information is not corrupt but also as an address tag. If the CRC fails then the user performing the check will deduce that either the control information is

corrupt or it was not meant for them. They have no means of telling the two events apart. Since the user specific CRCs are not known by all users they dare not use any overheard information since they cannot validate it.

The above approach of utilizing the correlation between the different scheduling maps can be extended into a more general form by using non-binary scheduling maps. In the above we have only considered single user binary scheduling maps. It is also possible to consider grouping users in groups with similar average SNR (as suggested in [3]) and broadcast to each such group a restricted multi-user scheduling map (using JCEB) containing a small number of users identities. In the same fashion as with the single-user maps the transmission is done in the order of worst channel conditions to best channel conditions for the groups (with a channel code adapted to the worst user in respective group) and user groups with better channels are assumed to be able to receive and interpret the scheduling maps of the preceding user-groups. Scheduling maps shall as above be interpreted in the context of all previously received/overheard scheduling maps.

VII. CONCLUSION

We have presented a new scheme for the signaling of scheduling assignments in multi-user mobile wireless access systems. We have shown, both via analytical arguments and via simulations, that our approach provides a substantial gain compared to the conventional SCET signaling approach used in the 3GPP LTE standard. We have also compared our new scheme to the alternative JCEB scheme. We have found that they on a theoretical level achieve the same compression of the scheduling maps, in that they fully exploit the correlation between the different users' resource allocations. We have also in simulations highlighted an important drawback of the JCEB scheme, namely that all information needs to be encoded with a low rate in order to reach the user with the weakest channel. This naturally proves to be detrimental to the performance of JCEB in terms of channel resources spent on the signaling.

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