Interaction of Transmit Diversity and Proportional Fair Scheduling

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Abstract— **In evolving 3G systems, the proportional fair packet scheduling algorithm promises an attractive trade-off between average cell capacity and user fairness by exploiting multi-user selection diversity in time-shared channels. However, in these systems the option of antenna transmit diversity already exist, whose performance benefit is dependent on the considered scheduling strategy.**

This study focusses on the interaction between proportional fair packet scheduling and open or closed-loop transmit diversity techniques. The basic interaction is studied by using an analytical model. Additionally, Monte Carlo simulations are conducted to study the effect of scheduling delays.

In the low mobility Rayleigh fading case, the potential average cell capacity gain with proportional fair scheduling, compared to a simple round robin in time approach, is on the order of 60% for single-antenna transmission. It reduces, however, to around 35% when dual antenna transmit diversity is additionally deployed. Comparing the performance of the different transmit diversity schemes to single-antenna transmission, conditioned on proportional fair scheduling, it is found that the closed-loop schemes provide a benefit over a wide range of terminal speeds, whereas open-loop space-time block coding exhibits limited performance and in some cases even a loss.

Index Terms— **Transmit diversity, multi-user diversity, STBC, proportional fair scheduling, 1xEv-Do, HSDPA.**

I. INTRODUCTION

IN [1] it was shown that wireless system capacity can be increased if the radio channel resources are allocated to a single user at a time, depending on the user's instantaneous channel conditions. Assuming a limited amount of flexibility to delay transmissions until a user's conditions are improved, the option of devoting the majority of system resources to a single user at a time has recently been adopted for the downlink of CDMA2000 and WCDMA systems; i.e. 1xEV-DO [2] and *high speed downlink packet access* (HSDPA) [3]. In this context, different packet scheduling algorithms have been studied [4]. Here, the main focus is on the *proportional fair resource* (P-FR) scheduler [5], which promises an attractive trade-off between cell capacity and user fairness by exploiting channel quality feedback from all users in the cell.

The P-FR principle is to allocate resources to the user whose radio channel is experiencing a constructive multipath fade and to avoid transmitting to a user that is temporally in a destructive multipath fade. Furthermore, instead of stabilizing every user's received *signal to interference plus noise ratio* (SINR) through power control [3], the philosophy is to transmit packet data with fixed transmit power and to utilize every encountered SINR as efficiently as possible. For this purpose, the dynamic range of the systems is extended through the introduction of *adaptive modulation and forward error correction coding* (AMC) and the possibility to allocate multiple orthogonal spreading codes to a single user [2], [3], [6]. As for the packet scheduling algorithm, the transmission scheme adaptation is based on every users' *channel quality indication* (CQI) feedback.

Other diversity techniques considered for 3G systems include *open-loop* (OL) and *closed-loop* (CL) *transmit diversity* (TD) schemes [7], which can also be deployed to improve circuit switched traffic connections. CL TD techniques utilize user-feedback to maximize every user's received signal power [7], whereas OL techniques (i.e. STS, STTD) employ *space-time block coding* (STBC) [8]. Their achievable diversity order is comparable. The closed-loop techniques, however, have the additional potential to benefit from an antenna combining (array) gain.

In this paper, an analytical system model is formulated to study the interaction of P-FR and TD for the case where instantaneous CQI is used to adapt the downlink transmission data rate. Furthermore, a Monte Carlo simulation strategy is introduced to study the effect of scheduling delays. Results are presented using HSDPA as a general framework.

II. SYSTEM MODEL

A. SINR Definitions

Table I provides a summary of the SINR definitions that will be used throughout the paper. Furthermore, the expression 'normalised' refers to normalisation to the long-term average, received SINR of user i per transmit diversity branch ($\overline{y}_i$). The average is taken over small scale multipath fading, and it is assumed that the long-term average SINR does not change over time (e.g. neither shadowing variation nor changes in path loss).

B. Simplified Model of the P-FR Scheduling Algorithm

In the system under investigation it is assumed that scheduling can be conducted without consideration of any minimum service requirements (i.e. delay-tolerant, best effort data services). It is further assumed that the *base station* (BS) has an infinite stream of data to be transmitted to each of the M queued users in the cell. Through an uplink data rate request all users inform the BS about their instantaneous channel quality (CQI).

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TABLE I

EMPLOYED SINR NOTATION

Symbol	Definition
y_i	Instantaneous, received SINR of user *i* per transmit diversity branch.
$\bar{y}_i$	Average, received SINR of user *i* per transmit diversity branch.
$y_{TD,i}$	Instantaneous, post transmit diversity combining SINR of user *i*.
$\bar{y}_{TD,i}$	Average, post transmit diversity combining SINR of user *i*.
$y_{TD,PFR,i}$	Instantaneous, post transmit diversity combining SINR of user *i* when scheduled.
$\bar{y}_{TD,PFR,i}$	Average, post transmit diversity combining SINR of user *i* only averaged when scheduled.
$\frac{y_{TD,i}}{\bar{y}_i} = \tilde{y}_{TD,i}$	Instantaneous, normalised, post transmit diversity combining SINR of user *i*.
$\frac{\bar{y}_{TD,i}}{\bar{y}_i} = \bar{\bar{y}}_{TD}$	Average, normalised, post transmit diversity combining SINR of user *i*, (assumed) as a fixed constant for all the users and equivalent to the mean gain of the employed transmit diversity scheme.

The P-FR scheduling algorithm time multiplexes the downlink data transmission between the M users on a per *transmit time interval* (TTI) basis which for HSDPA is of 2 ms duration.

Commonly, scheduling priority is allocated to the user with the highest data rate request relative to its received data rate averaged over a certain time window [4]. However, as in [5] some simplifying assumptions are adopted to enable a simple analytical model:

- The fading statistics of all users are *independent and identically distributed* (i.i.d.). Users move with the same speed and have equal access probability.
- A user's achievable data rate is (approximately) linearly related to its instantaneous, post transmit diversity combining SINR ($y_{TD,i}$).
- A sufficiently long averaging window is used, so that the average received data rate of a user is stationary.

While these conditions are unlikely to be fulfilled in a real dynamic system, they suffice to extract the fundamental relationship between P-FR and TD. Under the above assumptions, the P-FR decision metric can be approximated by

$$\max_i \left(\frac{y_{TD,i}}{\bar{y}_{TD,PFR,i}} \right) = \max_i \left(\frac{y_{TD,i}}{\bar{y}_{TD,i}} \right), \; i = 1 \ldots M \; . \qquad (1)$$

Seen from a system perspective, the P-FR approach introduces selection diversity [9], which in this case is not used to stabilise a single BS-user connection, but rather to assure that the BS utilizes the instantaneous, proportionally best connection to any user. This kind of diversity is therefore also known as multi-user diversity.

To adopt an SINR-related statistical model, a single BS-user connection can be described via the probability that user *i*'s instantaneous, normalised, post transmit diversity combining SINR $\tilde{y}_{TD,i}$ drops below a fixed level $\tilde{y}$. Here, this probability is represented by the *cumulative probability density function* (CDF) $\mathrm{P}\left[\tilde{y}_{TD,i} \leq \tilde{y}\right]$. Under the aforementioned iid assumption, the probability that all users' signal powers fade simultaneously below $\tilde{y}$ can be described by the product of their fading CDFs [9], e.g.

$$\mathrm{P}\left[\bigcup_{i=1}^{M} \tilde{y}_{TD,i} \leq \tilde{y} \right] = \mathrm{P}\left[\tilde{y}_{TD,i} \leq \tilde{y}\right]^M \; . \qquad (2)$$

The round robin in time or *fair resource* (FR) scheduler also gives equal access probability to all users, but schedules independently of the instantaneous channel quality. Hence, FR does not provide any multi-user diversity, and the FR reference case is modelled by setting the exponent M in (2) to 1, independent of the actual number of queued users in the cell.

C. Transmit Diversity

The CDF of a flat Rician fading TD combined connection is based on a non-central chi-square distribution with n degrees of freedom and can for an even number of transmit diversity branches be conveniently described with the help of the generalised Marcum Q-function $Q_{\frac{n}{2}}(a,b)$ [10]

$$\mathrm{P}\left[\tilde{y}_{TD,i} \leq \tilde{y}\right] = 1 - Q_{\frac{n}{2}} \left(\frac{s}{\sigma}, \frac{\sqrt{\tilde{y}}}{\sigma} \right) , \qquad (3)$$

where s^2 is the non-centrality parameter and σ denotes the standard deviation of the n underlying Gaussian random processes.

The normalised mean power of the specular multipath component is $\frac{2 \cdot s^2}{n}$, and the normalised mean power of the scattered multipath components is $2 \cdot \sigma^2$. Their ratio forms the Rician K-factor

$$K = \frac{s^2}{n \cdot \sigma^2} \; . \qquad (4)$$

Furthermore, the first moment of the non-central chi-square distribution is [10]

$$\bar{\bar{y}}_{TD} = n \cdot \sigma^2 + s^2 \; , \qquad (5)$$

which is equivalent to the mean gain of the employed transmit diversity scheme. Solving (4) and (5) for σ and s and inserting the results in (3) delivers

$$\mathrm{P}\left[\tilde{y}_{TD,i} \leq \tilde{y}\right] = 1 - Q_{\frac{n}{2}} \left(\sqrt{n \cdot K}, \sqrt{\frac{\tilde{y} \cdot \mathrm{n} \cdot (\mathrm{K}+1)}{\bar{\bar{y}}_{TD}}} \right) . \qquad (6)$$

(6) can now be used to describe a simple single antenna connection (1-Tx), a 2 tx to 1 rx antenna STBC connection (2-Tx-STBC), and an ideal CL 2 tx 1 rx TD connection (2-Tx-CLTDi), where perfect knowledge of the radio channel at the BS is used to perform transmit maximum ratio combining.

The parameter settings for the three transmission schemes are summarized in Table II.

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TABLE II

TRANSMISSION SCHEME PARAMETERS

TD scheme	$\overline{\tilde{\gamma}}_{TD}$	n
1-Tx	1	2
2-Tx-STBC	1	4
2-Tx-CLTDi	2	4

D. Simulation Strategy

The presented analytical model assumes that scheduling of a BS-user connection can instantly be triggered by the corresponding CQI. However, in a practical system there exists a delay between the channel quality measurements at the user terminals and the downlink transmission to the scheduled user. Furthermore, closed loop TD schemes rely on antenna weight feedback and are therefore in itself delay sensitive. In the following, a three-step Monte Carlo simulation strategy is developed to analyse delay sensitivity.

In the first step, M uncorrelated flat Rician fading traces are produced with an extended version of the I-METRA MIMO channel simulator [11]. The simulator extension is related to the fact that these traces incorporate the delay sensitive combining effects of any applicable TD scheme. For the non-ideal CL TD simulations (2-Tx-CLTD1 , 2-Tx-CLTD2) the same discrete sets of weights are applied as specified for WCDMA FDD Rel'99 [3], [7][1]. In a second step, scheduling decisions are taken every 2 ms according to (1). They are applied with a 4 ms delay and remain valid for the whole TTI of 2 ms duration. The final simulation step extracts the fading *probability density functions* (PDFs) and CDFs based on the selected fading values.

Table III summarises the simulation parameters.

TABLE III

SIMULATION PARAMETERS

Parameter/scheme	Setting
Carrier frequency	2.15 GHz.
BS antenna correlation	Uncorrelated.
Fading type	Flat Rayleigh.
2-Tx-CLTDi	Ideal transmit maximum ratio combining (no delay).
2-Tx-CLTD1	Power evenly split between antennas. Discrete phase weights applied with 90°granularity. Weight application delay of $2 \cdot 0.67$ ms.
2-Tx-CLTD2	Power unevenly split (0.8/0.2) between antennas. Discrete phase weights applied with 45°granularity. Weight application delay of $4 \cdot 0.67$ ms.
2-Tx-STBC	Ideal transmit maximum ratio combining (no delay) excluding array gain.
P-FR scheduling delay	4 ms equivalent to 2 TTI.

E. Post Processing of Fading Statistics

Both the analytical and simulation-based models produce multi-user channel fading CDFs reflecting the concatenation of TD and P-FR. To study the results in more generally 'measurable' terms, this section presents a method for mapping fading statistics into capacity.

As mentioned previously, the 3G evolutions use AMC as well as multi-code transmission to extend the dynamic range of the communication system. Here, these mechanisms are simplified using the assumption of *optimal transmission rate adaptation* (ora) and constant transmit power [12]. With this assumption, the capacity at a certain average SINR ($\overline{\gamma_i}$) is given by

$$C_{ora} = B \cdot \int_{0}^{+\infty} \log_2\left(1 + \tilde{\gamma} \cdot \overline{\gamma}_i\right) \cdot p_{\tilde{\gamma},M}(\tilde{\gamma}) \cdot d\tilde{\gamma}\,, \qquad (7)$$

where B denotes the bandwidth, and $p_{\tilde{\gamma},M}(\tilde{\gamma})$ represents the concatenated fading PDF.

Although the selection strategy in (1) assumed a linear relation ship between a user's achievable data rate and the instantaneous, post transmit diversity combining SINR, (7) is regarded as reasonable approximation to visualise the effect of P-FR-TD interaction. Link adaptation inaccuracies, as well as dynamic range limitations are not taken into account, and the presented numbers should be understood as indicative showing just the main trends. To obtain more detailed system simulation results the interested reader is referred to [13].

The ratio of own cell transmitted power to other cell transmitted power is commonly described by the G-factor [3]. Its distribution, $p_{G_i}(G_i)$, depends among others on cell geometry and propagation loss. Under the assumption that other cell interference plus background noise can be modelled as AWGN, and that in flat fading own cell interference can be avoided with the help of orthogonal spreading codes, the average, received SINR of user i per transmit diversity branch is given by

$$\overline{\gamma_i} = G_i \cdot \eta\,, \qquad (8)$$

where η is the fraction of the own cell transmitted power assigned to the considered packet data channel. The average cell capacity with optimal transmission rate adaptation can then be calculated as

$$C_{\overline{cell}} = B \cdot \int_{0}^{+\infty}\int_{0}^{+\infty} \log_2\left(1 + \tilde{\gamma} \cdot \eta \cdot G_i\right) \cdot p_{\tilde{\gamma},M}(\tilde{\gamma}) \cdot p_{G_i}(G_i) d\tilde{\gamma} dG_i\,. \qquad (9)$$

The following cell capacity results are generated using the microcell G-factor distribution from [14] and setting η to 0.5.

III. DISCUSSION OF RESULTS

The combined fading CDFs from analytical and simulation method are compared in Fig. 1 for two different user diversity orders and the three different antenna transmission schemes. A good match is achieved as simulation results are generated for the low mobile speed of 3 kmph, in which case the scheduling delay only has a minimal impact. It can be seen that in this case,

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[1] Currently, only CL TD mode 1 is specified for HSDPA operation.

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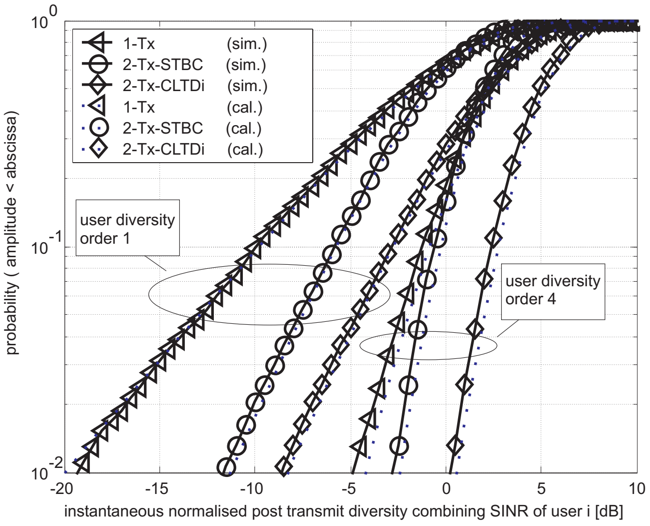

Fig. 1. Simulated and calculated channel fading CDFs

P-FR scheduling increases the overall system diversity order by a factor equal to the multi-user diversity order. This is reflected by the slope increase of the CDFs in Fig. 1. Furthermore, due to increased space diversity the slopes of the 2-Tx-CLTDi and the 2-Tx-STBC schemes are steeper than the corresponding slopes of the 1-Tx schemes. It should be noted that with increased user diversity order, the difference between the schemes decreases, which shows the interdependence between the different diversity mechanisms.

A more detailed consideration of the results in Fig. 1 reveals that the CDFs of 1-Tx and 2-Tx-STBC cross for a user diversity order of 4. This means that for this user diversity order, the probability of having high SINR peaks (e.g. 4 dB above the average) is higher for the 1-Tx scheme than for the 2-Tx-STBC scheme. The reason is that 2-Tx-STBC not only reduces the severity of destructive fades, but also the probability of encountering very high constructive fading peaks, by effectively averaging over two transmit diversity branches. This is not attractive in conjunction with P-FR scheduling, which can more clearly be seen in Fig. 2, where the fading statistics are mapped into capacity curves using (7). At a user diversity order of 4, the capacity of 1-Tx is slightly higher than the capacity of 2-Tx-STBC.

The 1-Tx results in Fig. 2 match closely the selection diversity results in [12]. The capacity of an AWGN channel [12] is used for performance comparison. Comparing single user 1-Tx and 2-Tx-STBC to the capacity of an AWGN channel with identical average SINR shows that the STBC scheme comes closer to this upper bound due to a second order transmit diversity. Going to a user diversity order of 4, both schemes outperform the AWGN channel, which clearly shows the benefit of multi-user diversity. It has to be said, however, that the selection process from (1) changes the average, post transmit diversity combining SINR of all users. For the 1-Tx scheme in Rayleigh fading, this average is given by [9]

$$\bar{y}_{TD,PFR,i} = \bar{y}_{TD,i} \cdot \sum_{i=1}^{M} \frac{1}{i} , \qquad (10)$$

and the average adjusted AWGN capacity (cal. av. adj.) for a user diversity order of 4 is plotted as an upper bound.

Fig. 3 displays the simulation results for $C_{\overline{cell}}$ versus the user diversity order at a fixed speed of 3 kmph. Generally, it is seen that the CL TD schemes outperform the 1-Tx and 2-Tx-STBC schemes. Moreover, 1-Tx outperforms 2-Tx-STBC when the user diversity order exceeds 2. Generally, the benefit of increasing the multi-user diversity order is highest for low absolute system diversity numbers. As the user diversity order increases beyond 6-10, capacity gains become marginal.

In Fig. 4 $C_{\overline{cell}}$ simulation results are plotted for various terminal velocities. If the speed in a system with 10 users is increased from 0 to 60 kmph, it can be seen that the performance of all transmission schemes degrades. With increased terminal speed, the distance travelled during the scheduling delay is larger, which decreases the correlation between the SINR at the channel measurement instant and the SINR at the data transmission instant. At 60 kmph the traveled distance during the 4 ms scheduling delay is around 0.48 wavelengths. This causes the channel to becomes almost decorrelated over the scheduling delay period, in which case P-FR scheduling no longer provides

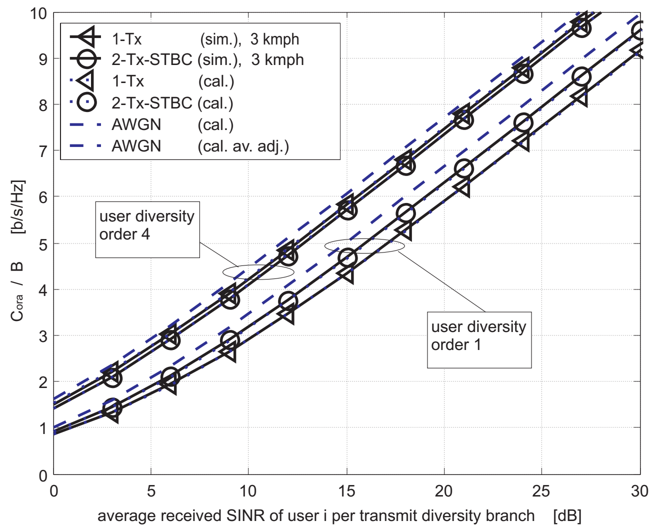

Fig. 2. Optimal rate adaptation capacity

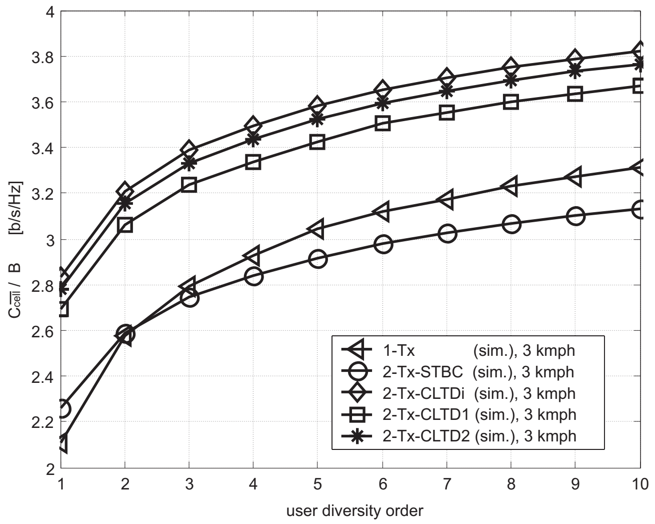

Fig. 3. Average cell capacity versus user diversity order

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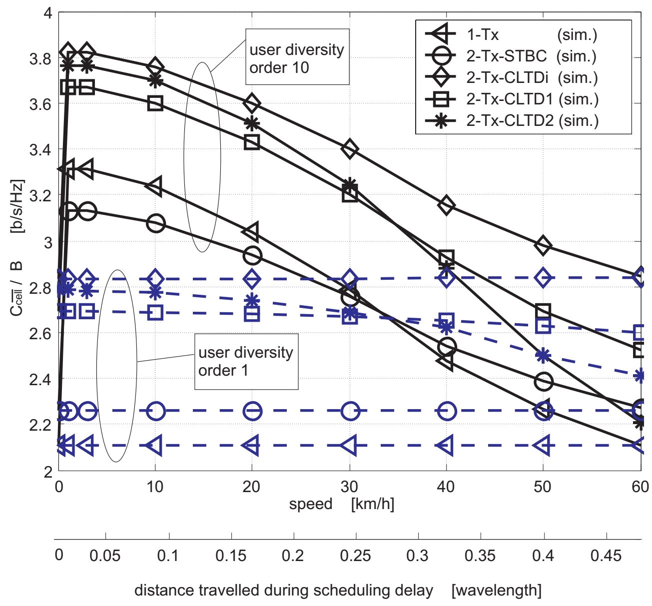

Fig. 4. Average cell capacity versus terminal speed

a benefit due to channel tracking problems. Therefore, Fig. 4 clearly shows that in a system with scheduling delays and terminal mobility, the effective user diversity order is not simply determined by the number of potential connections M, but also wether scheduling decisions are applied within the channel's coherence time.

Comparing the slope of 2-Tx-STBC with the slope of 1-Tx and the delay sensitive 2-Tx-CLTD schemes, it can be seen that it is less steep. This can be interpreted as a sign of increased robustness of the 2-Tx-STBC scheme towards an increase in terminal mobility. This is one of the inherent advantages of OL schemes, and with P-FR there is a terminal speed from which on one type of diversity becomes more suitable than another. Here, all presented capacity results have been generated assuming optimal rate adaptation. As can be seen in [13], the notion of increased mobility robustness of the 2-Tx-STBC scheme is even amplified when the assumption of optimal rate adaptation is replaced by a more detailed link adaptation model.

As a special case, Fig. 4 also suggests that no multi-user diversity can be exploited by any scheme at an effective terminal speed of 0 kmph, corresponding to a perfectly static situation, in which case the P-FR method yields the same results as the FR scheduler. In reality, power fluctuations of owncell and other-cell interference as well as movement of scatterers in the vicinity of the user terminals will create some SINR variation, which can be utilized by the P-FR scheduler provided that the SINR changes fast enough to satisfy packet traffic delay constraints.

IV. CONCLUSION

Based on simplifying assumptions the P-FR scheduling algorithm was transformed into a simple selection diversity mechanism suitable for analytical studies. Furthermore, the fading statistics of a single BS to user connection in flat Rician fading were presented for different TD strategies. With these models the interaction of P-FR and TD was studied showing general results regarding their combined performance.

It was shown that P-FR scheduling offers a significant gain over FR for a wide range of terminal speeds and for all transmission schemes. Under the given assumptions, the 1-Tx scheme with no inherent diversity benefits the most from P-FR. At a multi-user diversity order exceeding two, 1-Tx performance is improved to the point where it outperforms the 2-Tx-STBC scheme. Looking at absolute, average capacity numbers the CL TD schemes outperform both 1-Tx and 2-Tx-STBC up to speeds exceeding 55 kmph. Moreover, at very high speeds, where the BS loses the ability to track the fading channel, the link stabilization available with the open-loop 2-Tx-STBC scheme gains attractiveness.

Frequency selectivity, abrupt other cell interference power variation, packet data delay constraints, delay sensitive link adaptation, as well as uplink feedback errors will alter the presented results and are subject of future work.

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