Enhanced Fractional Frequency Reuse to Increase Capacity of OFDMA Systems

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***Abstract*—Inter-cell interference (ICI) mitigation is always a big challenge issue in cellular systems. In this work we propose an Enhanced Fractional Frequency Reuse (EFFR) scheme combined with power allocation and an interference-aware reuse mechanism to achieve not only ICI limitation at cell edge but also enhancement of overall cell capacity in orthogonal frequency division multiple access (OFDMA) based communication networks. The EFFR scheme divides the whole available bandwidth into a Primary Segment and a Secondary Segment. The exclusive reuse-3 subchannels in the Primary Segment will be prior used by cell-edge users with higher transmission power, whereas the remaining subchannels are all reuse-1 subchannels allowing to be used with lower power. In addition, the resources in the Secondary Segment will be occupied by means of signal-to-interference-ratio (SINR) estimation. We implement the proposed EFFR scheme in a system-level simulator and compare its performance with the well-known Soft Frequency Reuse (SFR) scheme and the classical reuse-1 scheme. In order to investigate the impact on the performance by power allocation, schemes are simulated with various power masks, and using a scenario with surrounding cells up to 2nd-tier. Simulation results show that the EFFR scheme is more flexible and robust than the SFR scheme, and can gain substantial improvements in terms of both, the overall cell capacity as well as the cell-edge user performance.**

***Index Terms*—Cellular system, frequency reuse, inter-cell interference mitigation, LTE, OFDMA, WiMAX.**

I. Introduction

THE expected convergence of fixed and mobile Internet services, the emergence of new applications and the growth of wireless subscribers will lead to an ever increasing demand for bandwidth in wireless access. With the Orthogonal frequency division multiple access (OFDMA) transmission technique, great benefits in handling inter-symbol interference, inter-carrier interference and high flexibility in the resource allocation can be reaped. Nevertheless, a big challenge issue with OFDMA still remained is co-channel interference (CCI) or so-called inter-cell interference (ICI).

It is known that effective reuse of resources in a cellular system can highly enhance the system capacity. With a smaller frequency reuse factor (FRF), more available bandwidth can be obtained by each cell. So, in this sense the classical FRF of 1 is desirable. However, with the usage of FRF-1, the most user terminals (UTs) are seriously afflicted with heavy ICI, especially near the cell edge. And that causes severe connect outages and consequently low system capacity. The conventional method to figure out this problem is through increasing the cluster-order, which can mitigate the ICI efficiently, nonetheless at the cost of a decrease on available bandwidth for each cell. This leads to restricted data transmissions and lower system spectrum efficiency.

To take aim at improving cell-edge performance while retaining system spectrum efficiency of reuse-1, several solutions [1]-[5] have been proposed recently. Among them, the most representative approaches are the Soft Frequency Reuse (SFR) scheme [2], [4]-[5] and the Incremental Frequency Reuse (IFR) scheme [3]. These two methods concentrate on the high system spectrum efficiency with FRF-1 and efficient reduction of ICI (especially near the cell edge) simultaneously. However, the IFR scheme does not perform better than the classical reuse-1 scheme in full-load or overload situation. The performance with the usage of the SFR scheme might be advanced, compared to the classical reuse-1 system, but the resources are still underutilized. Based on a thorough analyzing of the SFR approach, in this paper we will put forward a new design referred as Enhanced Fractional Frequency Reuse (EFFR) scheme for a better fulfillment of the goals, namely, to enhance the mean system capacity while restraining the ICI at cell edge. Moreover, since solutions with low system complexity and flexible spectrum usage are desirable, we will take systems with distributed radio resource management into account.

The remainder of this paper is organized as follows. In section II the noted SFR approach for ICI mitigation in cellular OFDMA networks is outlined. Based on a discussion of its advantages and limitations, a novel Enhanced Fractional Frequency Reuse (EFFR) scheme is contributed in section III, which intends to further improve the overall cell capacity while retaining a better cell-edge performance with the usage of FRF of 3 to the cell-edge users. Then, in section IV, simulation results of three different frequency schemes with distinctive power masks are compared. Finally, the paper ends with some concluding remarks.

II. Soft Frequency Reuse

The Soft Frequency Reuse (SFR) scheme, which has been adopted in the 3GPP-LTE system [1]-[2], addresses the

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challenge by increasing FRF and transmission power for cell-edge users, so that the ICI from contiguous cells to those users can be alleviated, and thereby to improve their performance.

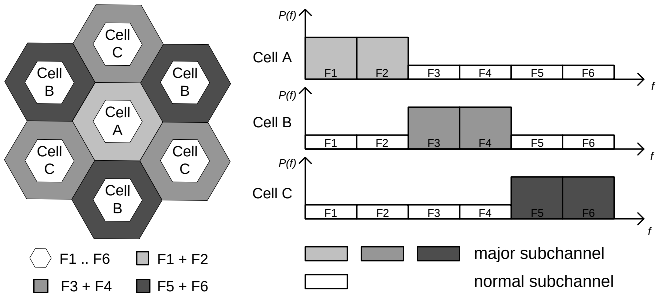


Fig. 1. Concept of the SFR scheme in a cellular system based on FRF =3 for CEUs and FRF =1 for CCUs.

The basic idea of the SFR scheme is apply FRF of 1 to cell-centre users (CCU) and FRF of 3 to cell-edge users (CEU) as illustrated in Fig. 1. Simply one third of the whole available bandwidth named *Major Segment* can be used by CEUs, yet on this Major Segment, packets are sent with higher power. To realize FRF of 3 for CEUs, Major Segments among directly neighboring cells should be orthogonal. In opposite to the CEUs, the CCUs can access the entire frequency resources, however, with lower transmission power. The power allocation for each type of users can be calculated as

$$P_{CCU} = \frac{S \cdot p}{(\alpha - 1)\cdot T + S} = \frac{3p}{\alpha + 2}, \tag{1a}$$

$$P_{CEU} = \alpha \cdot P_{CCU} \tag{1b}$$

, in which S, T stand for the total number of subchannels in a system and the available subchannels for the CEUs, respectively. α denotes the power ratio of a subchannel used by a CEU to which used by a CCU. p is used as a reference power, which signifies the uniform transmit power used on each subchannel in a classical reuse-1 system. When α equals 1, P_{CCU} is equal to P_{CEU}. The SFR system is a reuse-1 system. When $\alpha \to \infty$, P_{CCU}, P_{CEU} will converges at 0 and $3p$, respectively. The SFR system is now a reuse-3 system, but using a scheduling with Min-Throughput strategy.

Taking a view of the SFR design, some intrinsic limitations are exposed. For one thing, generally, there are more CEUs than CCUs in a cellular system, since the outer surface area is much larger than the inner part. However, with the SFR scheme CEUs have maximum one third of the entire bandwidth to utilize, which results in lower spectrum efficiency. Next, more CCI could happen even in a low traffic load situation, while there are still subchannels in idle and underutilized in the system. This is because the resource allocation of all cells via the SFR scheme starts always from the first subchannel up. Lastly, in consequence of the inherent susceptibleness of the CEUs, they still will be grievously interfered by the CCU transmissions in the adjoining cells, in spite of using higher power.

III. Enhanced Fractional Frequency Reuse

Aiming at the limitations of the SFR scheme mentioned above, we came up with a new design named the Enhanced Fractional Frequency Reuse (EFFR) scheme, which intends to retain the advantages of the SFR approach while avoiding its limitations, and seeks to further enhance the system capacity especially in overload situations.

A. *Design Requirements*

The EFFR scheme is designed to meet the following requirements:

- Support flexibility with non-uniform user or traffic distribution
- Support adaptation to time varying traffic conditions
- Exploit possibility for self-setting up preferable reuse combinations
- No need for the resource coordination among different base stations (BS) in radio network controller (RNC) in the fixed resource allocation method
- Applicable for high FRF systems
- Low system complexity

B. *Concept of the Enhanced Fractional Frequency Reuse Scheme*

The objective of the proposed EFFR architecture is to improve system capacity while bettering spectrum efficiency at the cell edge. This can be achieved by basing on effectual mitigation of unwanted co-channel collisions for CEUs, maximizing the opportunities for the other users to choose suitable resources (time share and frequency share respectively) to reuse.

1) Reuse Partition

Just like the SFR scheme, the EFFR scheme defines 3 cell-types for directly neighboring cells in a cellular system, and reserves for each cell-type a part of the whole frequency band named *Primary Segment*, which is indicated in the right part of Fig. 2 with thick border. The Primary Segments among different type cells should be orthogonal. Apart from the Primary Segment, the remaining subchannels constitute the *Secondary Segment*. The Primary Segment of a cell-type is at the same time a part of the Secondary Segments belonging to the other two cell-types. Each cell can occupy all subchannels of its Primary

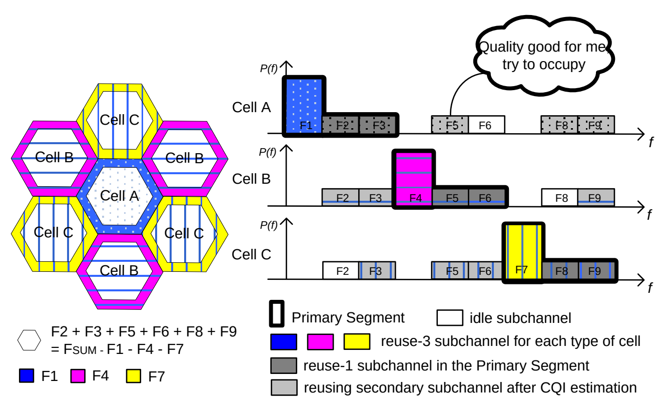


Fig. 2. Concept of the EFFR scheme in a cellular system based on partition of exclusively reuse-3 subchannels and reuse-1 subchannels in the Primary Segment, as well as interference-aware reuse on the Secondary Segment.

Segment at will, whereas only a part of subchannels in the Secondary Segment can be used by this cell in an interference-aware manner.

The Primary Segment of each cell will be further divided into a reuse-3 part and reuse-1 part. The reuse-1 part can be reused by all types of cells in the system, whereas reuse-3 part can only be exclusively reused by other same type cells. To be precise, the reuse-3 subchannels cannot be reused by directly neighboring cells, which attenuates the ICIs among them and therefore it is stipulated for the vulnerable CEUs to take priority of using these subchannels over CCUs.

2) Power Loading

As we have the constant total power assumption, the power allocation on each type of subchannel can be calculated as

$$P_{reuse-1\_subchannel} = \frac{S \cdot p}{\alpha \cdot M + 3 \cdot N}, \tag{2a}$$

$$P_{reuse-3\_subchannel} = \alpha \cdot P_{reuse-1\_subchannels} \tag{2b}$$

, in which *M*, *N* stand for the number of available reuse-3 subchannels and reuse-1 subchannels in the Primary Segment, respectively. α denotes the power ratio employed on a reuse-3 subchannel to a reuse-1 subchannel. And *p*, *S* have the same meanings as in (1a). Since in the EFFR scheme, any cell-type (e.g., cell-type-A in Fig. 2) cannot use the reuse-3 subchannels dedicated to the other two cell-types (e.g., cell-type-B and -C in Fig. 2), the $P_{reuse\text{-}3\_subchannel}$ can be tripled (α equals 3) without decreasing the $P_{reuse\text{-}1\_subchannel}$ for other available reuse-1 subchannels. Otherwise, the $P_{reuse\text{-}1\_subchannel}$ will vary with different values of the $P_{reuse\text{-}3\_subchannel}$. Note that with SFR, it is impossible that CEUs transmit or receive packets with power larger than 3 times of *p*, whereas using EFFR they can. Hence, the EFFR scheme seems more flexible than the SFR to adapt to various wireless environments.

3) Signal-to-Interference-Ratio (SINR) Estimation

Since a cell acts on the Secondary Segment as a *guest*, and occupying secondary subchannels is actually *reuse* the primary subchannels belonging to the directly neighboring cells, thus reuse on the Secondary Segment by each cell should conform to two rules:

- *monitor before use* and
- *resource reuse based on SINR estimation*.

Each cell listens on every secondary subchannel all the time. And before occupation, it makes SINR evaluation according to the gathered channel quality information (CQI) and chooses resources with best estimation values for reuse. If all available secondary resources are either occupied or not good enough to a link, it will give up reusing for this link. This will not lead to a resource wasting, which means some resources maybe not reusable for this link, but can be reused by other links. And another thereby gained merit is that it will not generate excessive interferences for the neighboring cells which would degrade their performances. So, an upgrade of spectrum efficiency is expected by using the interference-aware-reuse mechanism on the Secondary Segment.

On the other hand, all above elucidation is based on a precise SINR estimation. However, an improper modulation and coding scheme (PHY-mode) selection due to a bad SINR estimation would cause to either higher packet loss rate or lower spectral efficiency, and thereupon wastes precious resources. Hence, to have a reliable SINR estimation is a crucial factor for maximizing system spectrum efficiency.

4) Resource Allocation

The algorithm works as follows:

1. The reuse-3 subchannels will be assigned to CEUs with the usage of the proportional faire scheduling strategy. If there are still resources remained after all CEUs are served, they will be continuing allotted to such CCUs with relatively poor SINR values.
2. When the reuse-3 subchannels are exhausted, the remaining reuse-1 subchannels in the Primary Segment are allocated to residual unsatisfied users using maximum throughput strategy until demands of all users are met or the entire Primary Segment is occupied.
3. If still resources are requested, available reuse-1 subchannels in the Secondary Segment will be scheduled to adequate users by applying interference-aware-operation.

C. Distinctions between the EFFR Scheme and the SFR Scheme

The EFFR scheme owns mainly the following salient features, which are typically different to the SFR scheme:

- Since the users at cell edge are very weak at resisting ICIs, the reuse-3 subchannels in the Primary Segment for each cell are exclusively available for the users in the same type cell. This means *real* reuse-3 is applied on these subchannels, and for each cell not the whole bandwidth is available.
- In order to advance spectral efficiency, users which are allotted shares of the reuse-3 subchannels, should send packets with higher transmission power, whether they are CCUs or CEUs. In contrast, to reduce excessive interferences to the neighboring cells and avoid unwanted power wasting, packets will be sent on a reuse-1 subchannel in lower strength.
- Allocation of reuse-1 subchannels in the Secondary Segment is *not blindly* carried out, but in an interference-aware way according to the SINR estimation.
- In the Primary Segment unsatisfied users, whether they are CCUs or CEUs, have the same chance to get resources in the Secondary Segment, if they can find usable resource in accordance with the SINR estimation.

With the above introduced EFFR design, we can notice that several relevant factors play paramount roles in the realization and could influence the system performance severely, such as: 1) the ratio of *M* to *N* in the Primary Segment; 2) the power ratio α; 3) range definition for partition of CCUs and CEUs; 4) SINR threshold for reuse etc.. In what follows, we will focus on the effects on performances by using the EFFR scheme with varying ratios of *M* to *N* and different power ratios.

IV. Evaluation

The Open Wireless Network Simulator (OpenWNS) is a framework for the implementation of event driven wireless network protocol simulators. It has been developed at the Chair of Communication Networks RWTH Aachen University, and is used for the implementation of several wireless network protocols like GSM, UMTS, IEEE 802.11, IEEE 802.16 [6]. We have integrated the SFR scheme and the proposed EFFR scheme into the so-called WiMAC module, which is an implementation of the IEEE 802.16 standard in the OpenWNS.

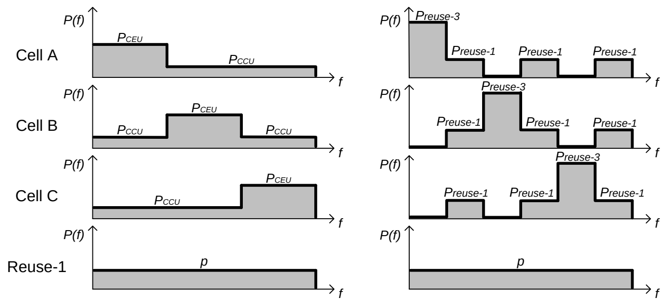


Fig. 3. Cell-specific power masks over system bandwidth for the SFR scheme and the EFFR scheme.

TABLE I
Simulation Parameters

Parameter	Value
System bandwidth	20 MHz
Center frequency	5470 MHz
Subcarriers (FFT size)	2048
OFDMA symbol duration	102.858 µs
Number of subchannels	30
Frame length	10 ms
DL-subframe : UL-subframe	1:1
Noise figure at [BS, UT]	[5, 7] dB
Cell radius	1100 m
Range for CEUs	550 m - 1100 m
Number of interfering cells	18 (up to 2nd tier)
Pass loss exponent	2.9
UT thermal noise density	-174 dBm/Hz
Traffic model	symmetric, neg. exp IAT

With simulations we aim to demonstrate the effectiveness of the proposed EFFR scheme in terms of improvement of CEU throughput as well as mean cell capacity. We will compare the performance of the devised EFFR scheme with three *M* to *N* combinations (8:2 | 7:3 | 6:4) to the performances of the SFR scheme and the classical reuse-1 scheme. An OFDMA uplink cellular system in an omni-cell case for simulations is considered. UTs are uniformly distributed within each hexagonal cell. We assume the total system transmission power is kept constant, and each UT has a maximal transmission power of 200mW. Fig. 3 instantiates the corresponding used cell-specific power masks in response to diverse spectrum usage for studied approaches. The other main relevant parameters used in simulations are shown in Table I. And switching thresholds for the PHY-modes in [7] are adopted.

Fig. 4 displays the average cell throughput as a function of the number of users in each cell. Both SFR scheme and EFFR

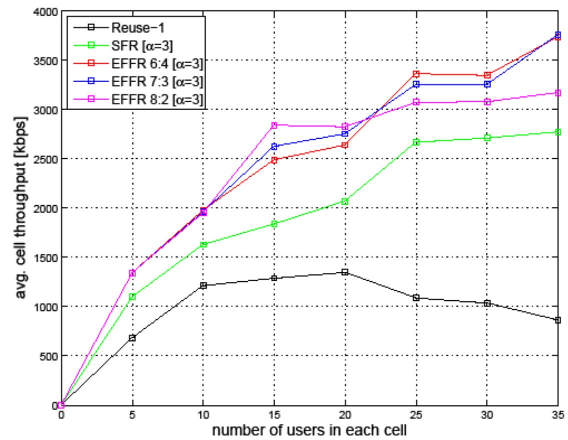


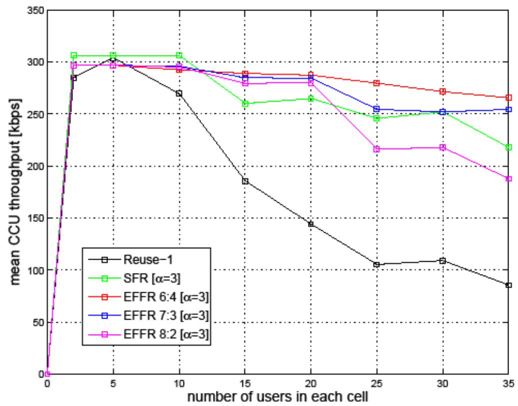
Fig. 4. Mean uplink cell capacity of three frequency reuse schemes as a function of the number of users in each cell, with 333 kbps offered traffic for each user and power ratio α = 3 for the both SFR and EFFR schemes.

scheme use a power ratio α for high to low power level of 3. The results show that the EFFR scheme can provide a remarkable improvement on the overall cell capacity. And it outperforms the other two schemes in every situation, regardless of with which *M* to *N* combination. Moreover, the EFFR with *M*:*N* = 8:2 combination performs better than it with other combinations till the number of users increases to 20. Then, with a further increase of the user numbers, the advantage of EFFR with *M*:*N* = 6:4 becomes significantly. In general, the EFFR with *M*:*N* = 6:4 is able to obtain around 30% gain over the SFR scheme.

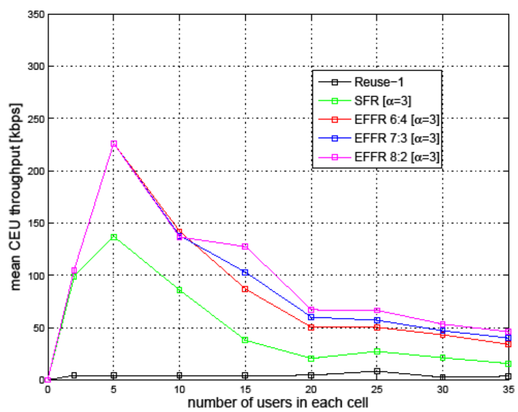
Detailed observations in terms of mean throughput of a CEU and a CCU are presented in Fig. 5. Fig. 5a shows that for the CCUs the SFR scheme has a close performance to the EFFR scheme, and performs significantly better than the classical reuse-1 scheme. However, Fig. 5b exposes that the SFR works much inferior to our proposed EFFR scheme for the CEUs, although it can provide more available bandwidth to the CEUs than the EFFR scheme. This is mainly due to the facts that CEUs using the SFR scheme transmit packets with lower power than those using the EFFR scheme, and simultaneously they are interfered by the near CCUs in the directly neighboring cells. The Bandwidth advantage of the SFR scheme cannot pay off the effects of these limitations.

The merit of the EFFR scheme compared to the other schemes can also be verified by Fig. 6, which shows the cell-edge outage probabilities of the three schemes. Again the performance of the EFFR scheme gains a noteworthy advantage over the SFR scheme and the conventional reuse-1 scheme.

To disclose the impact on the system performance by the power allocation, Fig. 7 exhibits the average cell capacity as a function of the offered traffic per user for different schemes with various power ratio values. 25 users are uniformly distributed in each cell in the system. From the results, we came to the following conclusions: Firstly, the EFFR scheme performs better the SFR and the classical reuse-1 scheme. Secondly, both the EFFR scheme and the SFR scheme with a power ratio α of 3 surpass which with other power ratios. Lastly, the power masks



(a) Mean uplink throughput of CCU



(b) Mean uplink throughput of CEU

Fig. 5. Mean uplink throughput of each type of users as a function of the number is users in each cell, having the same environment as in Fig. 4.

have severe impacts on performances of the SFR scheme, whereas using the EFFR scheme the cell capacities are similar under different power ratios. With an inappropriate power allocation, the performance of the SFR scheme will be strongly deteriorated. As a consequence, the proposed EFFR design can gain more robustness than the SFR scheme.

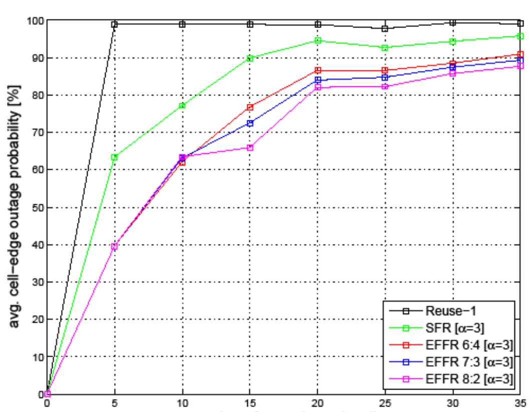


Fig. 6. Cell-edge average outage probability of three frequency reuse schemes as a function of the number of users in each cell, having the same environment as in Fig. 4.

V. Conclusion

In this paper an enhanced frequency reuse scheme, the EFFR scheme, for ICI mitigation in OFDMA networks is developed and evaluated. It designs a resource allocation-and-reuse mechanism and can provide a considerable improvement with the help of the CQI estimation. In terms of the inherent vulnerability of CEUs, the EFFR scheme reserves resources for them with two emphasizes: 1) using *dedicated* FRF-3; 2) with more flexible power allocation. Taking advantage of the geographic predominance of CCUs, the EFFR scheme allows them to occupy resources with FRF-1 and interference awareness.

A detailed performance evaluation by means of event driven stochastic simulations is presented, whereby the EFFR scheme is compared with the conventional reuse-1 scheme and the in the 3GPP-LTE system adopted SFR scheme. The presented results show that significant cell capacity gains and increases at cell edge can be achieved with the deployment of the proposed EFFR scheme. Furthermore, with respect to the power allocation, the EFFR scheme can provide more flexibility and robustness than the SFR scheme. In conclusion, with the usage of the EFFR scheme the medium is able to be more effectively utilized, and the performance of all users including both CEUs and CCUs are advanced.

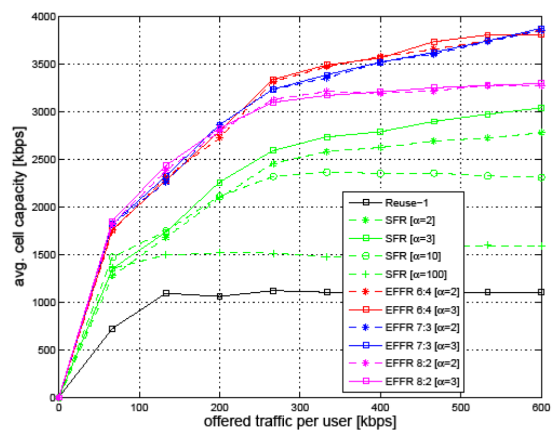


Fig. 7. Mean uplink cell capacity of three frequency reuse schemes with different power ratios as a function of offered traffic per user, 25 users are uniformly distributed in each cell in the system.

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