Network Resource Trading: Locating the Contract Sweet Spot for the Case of Dynamic and Decentralized Non-broker Spectrum Sharing

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Abstract. This paper aims to present a framework for analysing network resource trading between operators. We present the results for the case of orthogonal inter-operator spectrum sharing as a sub-case of the network resource trading between operators.

A two-operator, two-cell scenario has been considered. Operators share bandwidth orthogonally using standard LTE technology, detailed in the paper. An operator can post resources to a local market (neighbouring cells) for trading them with other operators. We were interested in identifying the duration of the resource trading contracts for trading, which would provide throughput gains. Simulations show up to 30% increase of user throughput and a more efficient use of spectrum if we do not consider any monetary cost or value in the model. In a separate idealised scenario, throughput gains of up to 80% are reported.

Keywords: Resource trading · Spectrum sharing · Inter-operator Micro-trading · LTE

1 Introduction

During the last years, there has been a tremendous growth in mobile communications traffic. Alone in the period 2015–2020, mobile traffic is believed to multiply eightfold [3]. Spectrum scarcity is commonly seen as on of the main problems arising from this development. Recent reports [5] substantiate this perspective and explain countermeasures against the "mobile data crunch" that followed the success of data driven mobile services. Among those measures are improvement of spectral efficiency, network densification and increase of available bandwith. Such observations have led to technological developments and deployments like e.g. Long-Term Evolution (LTE) or LTE-Advanced [5,17]. Increasing numbers of network cells and the allocation of higher frequency bands introduce new

P. Marques et al. (Eds.): CROWNCOM 2017, LNICST 228, pp. 3–14, 2018.
https://doi.org/10.1007/978-3-319-76207-4_1

complications and opportunities since the coverage area of cells operated in these higher bands is reduced [16]. However, these developments and processes involve dealing with significant legal hurdles and require international harmonization. As a consequence of these multiple developments, the concept of spectrum sharing is on the verge of becoming a normality rather than the exception. This perspective is backed up by recent developments such as e.g. the decision of the British regulator Ofcom to allow spectrum sharing in the 3.8 and 4.2 GHz bands [13,14], and has been taken on by GSMA and operators as well [6,12]. The focus of this introduction is the European market, but the trends are identical on the entire globe.

Technically however a lot of the work still has to be done, and it seems due time to address some of the problems coming especially with dynamic spectrum trading in more detail. A number of previous works addressed open problems via extensive simulations. It was shown that high gains can be achieved and spectrum sharing is possible with state of the art technology [9]. Furthermore, fairness [7] and quality of service (QoS) improvements [11] are possible. Many of these simulations are performed with a varying degree of realism. For instance, the assignment of spectrum is often modeled unrealistically or with knowledge about user behavior that can never be matched in reality. We address this short-coming.

In this paper, we consider two operators serving their users in the same geographical area. Adjacent base stations use a market in the vicinity to trade resources. The market has no authority over the base stations. Many local markets might exist, but we omit the question of which base stations trade through which markets which poses its own technical challenges. Here we assume that base station have been already connected to the correct local market. The base stations measure the load that is caused by the users. The core idea is to sell resources when the base station has or predicts low load and buy resources otherwise for a certain duration and a certain price.

In a simulation campaign, we consider a single file download service and measure the time to empty the base station buffer as a load indicator. Using this simple model, we study the effect of the duration of spectrum trades. The duration of the trade is of special interest, as financial considerations and planning play a vital role in the dimensioning of a network. Spectrum sharing is a special case in which all prices of trades are set to zero, e.g. by agreements between operators. We don't consider any prices at this point to remove the effect of the operator's budget or other economical constraints and concentrate on the achievable gains when operators share for short durations. It is also assumed that both parties in the trade are honest and employ the same strategy for the trades. Apart from this technical restriction in the simulations, the approach that we lay out here marks a change from the classical approaches of spectrum sharing [18] towards a micro-trading approach [10]. In some classical approaches, the primary user can interrupt the secondary user which is not possible here. In the micro-trading approach, a central market is used to perform auctions; here, we envisage local markets for fast trades. We believe that even in the same busy hours, the traffic experienced at different base stations is not homogenous and thus short trades in the order of seconds or smaller will increase the data rates of the users.

We are aware that we only skim the surface for a true spectrum sharing architecture. In particular, the technical challenges of the suggested sub-system and its requirements need to be analysed in more detail. This however is out of the scope of this paper. We only show a first assessment of the gain using the proposed model and stress that there is a case for it.

The paper is structured as follows. In Sect. 2, the system definition is outlined and our architecture for a preliminary spectrum sharing implementation as well as an idealized system are introduced. Section 3 describes the heuristic trading algorithm and its parameter choice. Section 4 outlines our system-level simulation approach and Sect. 5 evaluates the performance of the realistic implementation and compares it to the results of the idealized system. Section 6 finally concludes the paper.

2 System Description and Definitions

The system is depicted in Fig. 1. In the following we consider two operators $i \in \{A, B\}$ with each operating one evolved Node B (eNodeB) serving some users UE_{ij}, $j = 1, \ldots, K_i$. The number of available resource blocks (RBs) in the Downlink (DL) is N. Each operator owns a part of the spectrum of n_i RBs, $n_i < N$, $n_i \in \mathbb{N}_+$. A gap of n_g RBs between both spectra is modeled as the guard band, i.e. the operators' operating bands are not necessarily adjacent. The whole spectrum satisfies:

$$n_A + n_B + n_\mathrm{g} = N. \tag{1}$$

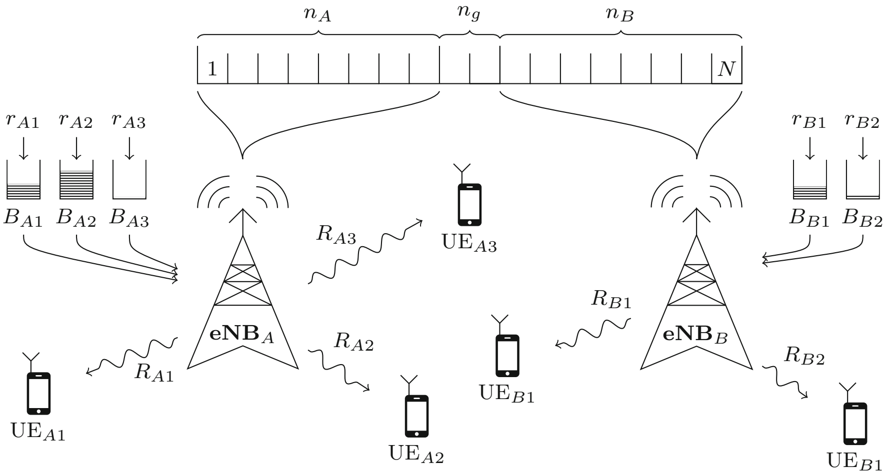

Fig. 1. The system model for the considered spectrum trading scenario.

At each time instant t, each operator serves a number of users $K_i(t) = K_i$ in its cell. For ease of notation and without loss of generality, the parameter t is omitted. The sum of all users in the system is $K = K_A + K_B$.

Data arrives at the eNodeB with a rate r_{ij} from a remote server (not displayed) and fills a buffer with buffer level B_{ij} and of finite size. The network between the eNodeBs and the remote server is assumed to be dimensioned such that it does not present a bottleneck in the simulations. The eNodeBs send this data to the corresponding User Equipment (UEs) with a rate $R_{ij} \ll r_{ij}$, as shown in Fig. 1.

More generally, let $\mathcal{M}_i \subset \mathbb{R}_{++}^{K_i \times M}$ be a set of measurements of one base station with M the number of measurements performed per user. For instance, the rates R_{ij} constitute the set $\mathcal{R}_i \subset \mathbb{R}_{+}^{K_i} \subset \mathcal{M}_i$ and $B_{ij} \in \mathcal{M}_i$.

We use a finite-buffer traffic model to model the user behaviour. In this model, users only have bursts of data when they access the system. This corresponds better to a real system than a typical full-buffer model, in which users constantly receive and send data. The considered performance metric is the DL throughput per user.

In the following, we only consider the DL. Two implementations for spectrum trading are investigated:

1. a practical spectrum trading implementation
2. a hypothetical implementation merging the operators.

The hypothetical implementation serves as an upper bound for our practical spectrum trading scenario.

In the considered practical implementation, two cells change the bandwidth on which they operate (cf. Fig. 2). Assume operator A to be in the need of additional spectrum. It might get this from operator B provided this one wants to trade its resources. If they exchange n RBs, $n \in \mathbb{N}$, operator A's bandwidth increases to $n'_A = n_A + n$ and B's bandwidth decreases to $n'_B = n_B - n$. This change happens for a previously determined duration t_D. During this time, (1) becomes

$$n_A + n_B + n_g = N = n'_A + n'_B + n_g. \tag{2}$$

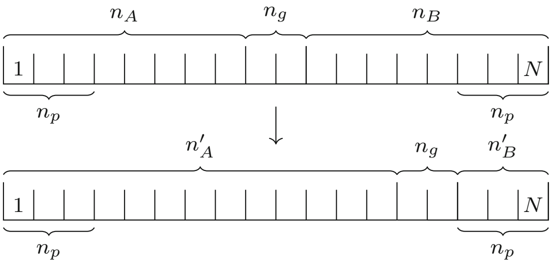

Fig. 2. A practical spectrum trading system: two operators exchange spectrum by increasing or decreasing their bandwidth.

Additionally, in Fig. 2, the extreme case of operator A buying as much spectrum from operator B as possible is shown. The latter gives all resources away except for some protected bands $n'_B = n_p$ which it maintains for QoS reasons.

The trading of resources happens on a market in the vicinity, shown in Fig. 3. An eNodeB tries to buy and sell spectrum according to its needs. Selling of spectrum is done via an "offer".

Definition 1 (Offer). *An offer* O *is a tuple* $(t_s, t_D, n, p_0, p_1, p_2)$ *including the start time* $t_s \in \mathbb{R}_+$ *of a potential spectrum trade, the duration* $t_D \in \mathbb{R}_+$*, and the number of exchanged resources* $n \in \mathbb{N}_+$*.* p_0 *is the posting price on the market,* p_1 *the consumption price (i.e. when buying) and* p_2 *the break-clause price. For spectrum sharing, we have* $p_0 = p_1 = p_2 = 0$*. The expiration time* $t_{ex} = t_s + t_D$ *is implicit.*

When a base station measures low load, it sends an offer of resources to the market. The functionality of selling and buying is ensured by a subsystem called the "negotiator", present in every base station that participates in the trading of resources.

Definition 2 (Negotiator). *Let* $D \in \{-1, 1, 0\}$ *be a choice to buy, sell or to not trade spectrum, respectively. Then, for some measurements* $\mathcal{M}_i$ *and offers* $\mathrm{O}_1, \dots, \mathrm{O}_L$*, the negotiator* N_i *of a base station of the operator* $i \in \{A, B\}$ *is a choice function* $\mathrm{N}_i : (\mathcal{M}_i, \mathrm{O}_1, \dots, \mathrm{O}_L) \rightarrow D$ *that decides whether resources need to be bought or sold on the market.*

Practically, it collects data from the eNodeB (like current data buffer level, DL throughput and so on), evaluates the current offers and decides about the acquisition or sale of resources. Communication is performed directly with the local market, as shown in Fig. 3.

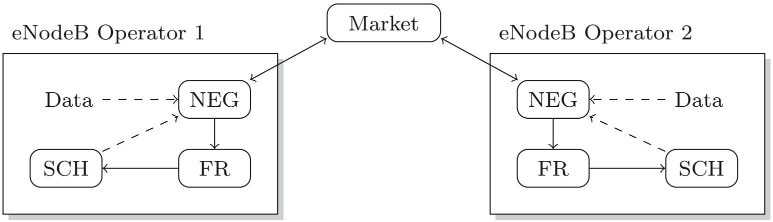

Fig. 3. The general structure of the spectrum trading architecture. NEG is the negotiator, FR the frequency reuse algorithm, and SCH the scheduler.

The market distributes a received offer O to the other negotiator. By applying the negotiator function, a buying decision can be made. In this case, it sends a message back to the market which then acknowledges this trade (if certain constraints like correct timing are met).

Definition 3 (Contract/Trade). *A contract or trade is an offer* O *by a negotiator of operator* $i \in \{A, B\}$ *that has been acknowledged by another operators's negotiator* $j \in \{A, B\}$*,* $j \neq i$*.*

At t_s, both eNodeBs change their used spectrum as indicated in the contract. It is assumed that both operators are fair. The sequence of events of a contract is shown in Fig. 4.

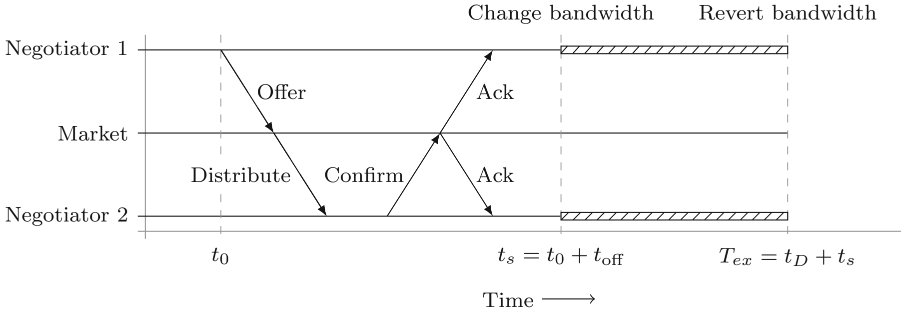

Fig. 4. The timeline of a trade, i.e. one negotiator puts resources on the market which the second accepts.

A negotiator can revoke a previously sent offer. In this case, the first reaction after the initial offer (own revocation or foreign confirmation) is determinant. The market acknowledges every event as well as the expiration of an offer.

Changes in the bandwidth on which to operate are applied via a modified Frequency Reuse (FR) algorithm. This in turn limits the scheduler of the LTE system to some of the available RBs.

Using a hypothetical spectrum sharing scenario (cf. Fig. 5), the maximum gain of spectrum sharing is investigated. Two cells share the spectrum orthogonally, each having the same amount of spectrum ($n_A = n_B$) and no guard bands are modeled ($n_{\text{g}} = 0$). This first scenario constitutes the no spectrum sharing scenario.

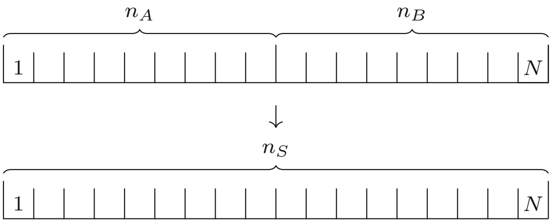

Fig. 5. Spectrum sharing in an ideal system using an single meta-operator (SMO).

The SMO constitutes the hypothetical spectrum sharing counterpart, using bandwidth n_S.

Definition 4 (Single Meta-operator). *Let A, B be two operators with users K_A, K_B and spectrum n_A, n_B. The SMO is the union of the operators, i.e. an operator serving all users $K = K_A + K_B$ on all resources $n_S = n_A + n_B$.*

Both operators A and B merge into one operator with one eNodeB. (1) becomes

$$n_A + n_B = n_S = N. \tag{3}$$

3 Trading Algorithm

The negotiator implements the driving trading algorithm. As already stated in Definition 2, a superset of the (practical) resource allocation can be the input of the choice function. An example of the (practical) resource allocation is the DL cell throughput. Additionally, the (theoretically) available resources can be taken into account. An example is the spectrum that might be bought. Moreover, the negotiator can use further knowledge at the base station, like priorities, buffer levels, historical data on user distribution, traffic demand, and so on.

Upon a decision, the negotiator communicates with the market. This was already shown in Fig. 3.

Our implementation is based on a simple heuristic. We use the buffered data of all users $B_i = B_i(k)$ at discrete time k as well as the current DL cell throughput $\tilde{R}_i = \tilde{R}_i(k)$

$$B_i = \sum_{j=1}^{N_i} B_{ij}, \quad \tilde{R}_i = \sum_{j=1}^{N_i} R_{ij}, \quad i \in \{A, B\}, \quad j = 1, \ldots, N_i \tag{4}$$

as eNodeB measurements $\mathcal{M}_i \supset \{B_{ij}, R_{ij}\}$. The throughput is smoothed using an exponential moving average of the form $R_i(k) = (1-\alpha)R_i(k-1) + \alpha\tilde{R}_i(k)$.

Then, it is possible to calculate an estimate of the time it takes to send all buffered data to all users, the Estimated Time to Empty Buffers (ETEB). It is, in seconds:

$$\mathrm{ETEB}_i = \frac{B_i}{R_i}, \quad i \in \{A, B\}. \tag{5}$$

Two thresholds t_{sell} and t_{buy} are used to parameterize the algorithm. If we have a low load such that $\mathrm{ETEB}_i < t_{\text{sell}} < t_{\text{buy}}$, the negotiator offers RBs on the market. If the load is very high, $t_{\text{sell}} < t_{\text{buy}} < \mathrm{ETEB}_i$, the negotiator should try to buy spectrum on the market. If $t_{\text{sell}} \leq \mathrm{ETEB}_i \leq t_{\text{buy}}$, the negotiator does nothing and revokes possibly sent offers that are still on the market.

The thresholds have been chosen by evaluating the ETEB in a no sharing case. The empirical probability of the load indicator depending on the user arrival process, we fixed it as described in Sect. 4.

The resulting histogram is shown in Fig. 6. Zeroes are suppressed to improve readability. The choice of the thresholds is arbitrary. We opted to "tolerate" the

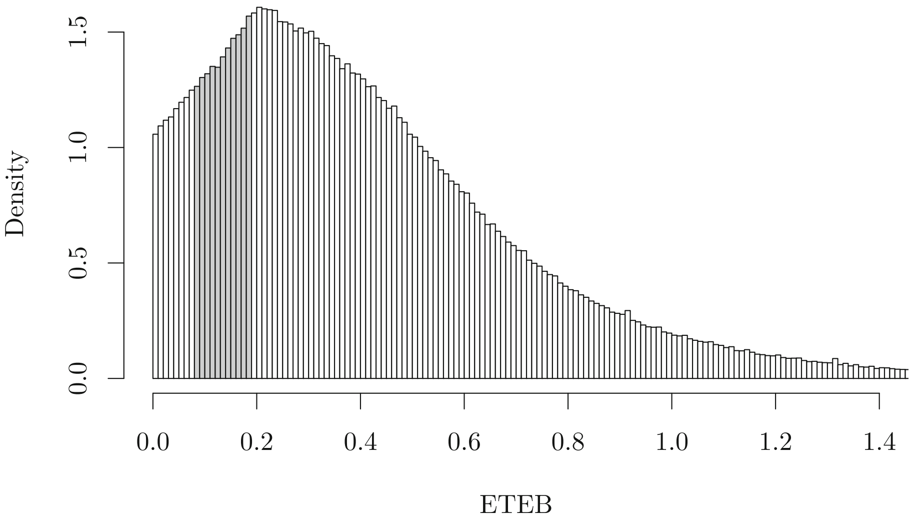

Fig. 6. The histogram of the ETEB of multiple simulation runs.

lower 10% of load during which the negotiator still tries to sell spectrum. For $t_{\text{sell}} < 0.09\,\text{s}$, we measure 10.5%. Another 15% of load above the selling threshold is "tolerated" without selling or buying spectrum (grayed region in Fig. 6). The upper 75% ($t_{\text{buy}} > 0.19\,\text{s}$) are defined as a load that could potentially be remedied by buying spectrum if possible.

The negotiator evaluates these thresholds on a periodic basis and performs the aforementioned actions depending on the outcome of the heuristic.

4 System-Level Simulation Description

For the evaluation of the described system, we used the simulator ns-3 [8] in version 3.26. ns-3 is a modular system-level simulator. It provides modules to simulate all layers from physical to application layer and also includes an LTE module [15]. We extended the simulator to support our architecture as described in Sect. 2 as well as the 3rd Generation Partnership Project (3GPP) FTP model 1, adapted from the publicly available ns-3 License-Assisted Access (LAA) Wi-Fi coexistence module[1].

The parameters of the considered scenario are listed in Table 1.

The scenario consists of two base stations located at the origin of the coordinate system. Ten mobile terminals are attached to each base station, initially uniformly distributed in the circular cell of radius $R = 800\,\text{m}$. They move within the cell according to a Random Waypoint Model that selects the next point by the same uniform distribution and to which they move with $3\,\text{km}\,\text{h}^{-1}$ without halting.

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[1] The source can be found at http://code.nsnam.org/laa/ns-3-lbt.

Table 1. General system parameters for the practical spectrum sharing case.

Parameter	Value
1st DL sub channel frequency	1805 MHz (EARFCN 1200)
Aggregate channel bandwidth	10 MHz (50 RBs)
Subcarrier bandwidth	15 kHz
Resource block bandwidth	180 kHz
eNOdeB DL transmit power	43 dBm over 50 RBs
Pathloss, in dB	$15.3 + 37.6 \log d$, d in m
Fading	Trace-based typical urban, $3\,\mathrm{km\,h^{-1}}$ [2, ETU]
Frame duration	10 ms
TTI (sub-frame duration)	1 ms
Scheduler	Proportional fair scheduler
FR algorithm	Modified hard frequency reuse
Radio link control (RLC) mode	Unacknowledged Mode (UM)
Traffic model	FTP model 1 [1]
User arrival rate λ	$1.5\,\mathrm{s^{-1}}$
Download file size S	550444 B
Cell radius r_o	800 m
Simulation duration	1100 s
Simulation runs	50 per campaign

Each cell operates on a bandwidth of 5 MHz, divided into 25 RBs. The used traffic model is derived from the 3GPP FTP 1 traffic model from 3GPP TR 36.814 [1]. In [1], files of size 512 kB are sent. In our simulations, we don't use retransmissions except for HARQ. In particular, we use the RLC UM mode and UDP as the transport protocol. Therefore, we chose to send files of size S = 550 444 B and calculate the statistics by only considering files which reach a threshold of received data $S_{\mathrm{rx,min}} = 512\,000\,\mathrm{B}$.

Furthermore, only the flows which started after 100 s simulated time, belonging to the "steady state", are used for further processing. We argue that after this time, every user has started to download at least one file and the simulation is not in an artificial start-up phase that does not directly stem from the user-arrival process. In fact, we have a Poisson process with intensity $\lambda = \frac{1}{\mathbb{E}[\tau]}$ with τ being the inter-arrival time (the same distribution for all inter-arrival times τ_i, $i = 1, 2, \ldots,$ is assumed). Then, the time so that all users started a download can be roughly estimated $T_{all} = n\mathbb{E}[\tau] = \frac{n}{\lambda}$. For the user arrival rate $\lambda = 1.5\,\mathrm{s}^{-1}$ and 10 users as used in the simulations, the last user can be expected to have started a download after on average 6.66 s. 100 s settling time is thus completely justified.

The user arrival rate λ is calculated as [1, A.2.1.3.4]:

$$\text{offered traffic} = \lambda \cdot S. \tag{6}$$

Considering that the peak rate of an LTE system is around 300 Mbps for a bandwidth of 20 MHz and 4 layers [4], a rate of 18.75 Mbps is the theoretical peak rate in the considered scenario per cell. We choose a user arrival rate of $\lambda = 1.5\ \mathrm{s}^{-1}$ resulting in an offered traffic of approx. 6.6 Mbps. This amounts to a reasonable average load while leaving some free capacity in the system.

The duration of a flow is defined as the time between sending the first packet $t_{1,\mathrm{tx}}$ and receiving the last packet m at time $t_{m,\mathrm{rx}}$. For a user receiving S_{rx} B of data, the DL user throughput, also called the User Perceived Throughput (UPT) [1] is calculated as

$$\mathrm{UPT} = \frac{S_{\mathrm{rx}}}{t_{m,\mathrm{rx}} - t_{1,\mathrm{tx}}}. \tag{7}$$

The time t_{off}, i.e. the duration between posting an offer and its expiration, is fixed to 5 ms, and we neglect any market communication time. The negotiator always proposes the maximum number of resources, i.e. 6 RBs are reserved as protected bands for QoS reasons and the rest is traded. No prices are considered.

5 System-Level Assessment

We are interested in the dependency of the throughput gain as a function of the contract length t_D. Furthermore, we compare the performance of the spectrum sharing implementation to the SMO. The results are shown in Fig. 7.

For the 95%-ile[2], we see clear gains. For the SMO implementation, we measure a gain of 80%, which is in line with previous works.

Depending on the contract duration, various gains are reported. Gains are higher for the shorter contract durations. This comes as no surprise as a base station will be able to get its resources back quickly. However, short contracts have the drawback of a more frequent reselling of resources, putting additional load on the backbone network through increased signaling, an effect which is not modeled here.

A contract duration decrease from 200 to 100 ms offers no significant advantage. In these cases, we find notable gains of 35%. The gains shrinks to the half for 660 ms. With increasing duration, the gains get smaller until eventually becoming negative for long durations. For the duration $t_D = 660\,\mathrm{ms} \approx \frac{1}{\lambda}$, equivalent to the average inter-arrival time, we still have a considerable gain.

For contract durations longer than $t_D = 1320\,\mathrm{ms} \approx \frac{2}{\lambda}$, losses for the 95%-ile start to emerge. For these contract durations, base stations are not able to adapt to changes in the system fast enough.

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[2] We use this 95%-ile similar to the 95%-ile of a full buffer traffic model, i.e. as a rate that every user achieves that is served by the base station in this cell.

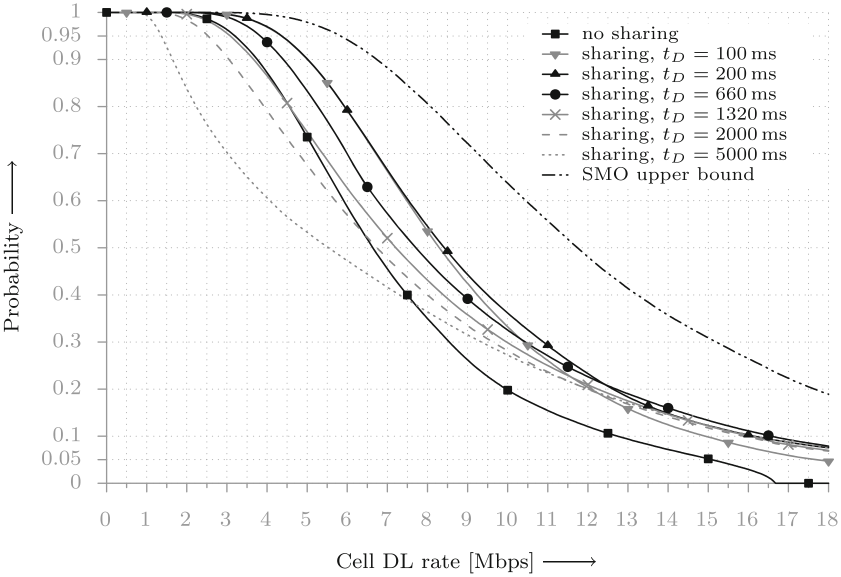

Fig. 7. UPT of a user depending on the duration of a contract t_D.

6 Conclusion

The contribution of this paper is two-fold. We first presented our generalized understanding of resource trading in a mobile communications network under the assumption of two co-primary network operators. Resource trading incorporates the notion of prices. Non-cooperative game theoretic frameworks could thus be used to model also the financial aspects of the different parties. We specialized this notion to a spectrum sharing scenario that makes no assumptions about the user behavior and trades resources on a local market and without common knowledge.

Second, we investigated the gains of this spectrum sharing system in presence of different contract durations. Simulations showed a hypothetical gain in throughput of 80%. Using a simple heuristic, gains of 30% are easily achieved. A trade duration of approximately the average inter-arrival time of the user arrival process shows high gains which incurs lower load in the backhaul network than a more frequent renegotiation.

Further work will concentrate on the following points. First, we want to investigate the QoS improvements of our spectrum sharing implementation. Second, an advanced trading algorithm making use of prediction and game theory is envisaged to improve the performance and incorporate prices.

Acknowledgements. This work was funded by the BMWi and ESF, grant 03EFHSN102 (AT, SN, JN).

We thank the Center for Information Services and High Performance Computing (ZIH) at TU Dresden for generous allocations of computer time.

References

1. 3GPP TR 36.814 Further advancements for E-UTRA physical layer aspects. Technical report, 3rd Generation Partnership Project (2010)
2. 3GPP TS 36.104 Base Station (BS) radio transmission and reception. Technical specification, 3rd Generation Partnership Project (2010)
3. Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2015–2020. White Paper, Cisco Inc. (2016)
4. Dahlman, E., Parkvall, S., Sköld, J.: 4G LTE/LTE-Advanced for Mobile Broadband. Elsevier, Oxford (2011)
5. GSMA-Mobile Spectrum - Data demand explained. GSM Association (2015)
6. Best practice in mobile spectrum licensing. GSM Association (2016)
7. Guidolin, F., Carpin, M., Badia, L., Zorzi, M.: Fairness evaluation of practical spectrum sharing techniques in LTE networks. In: 2014 IEEE Symposium on Computers and Communications, pp. 1–6. IEEE Press, New York (2014)
8. Henderson, T.R., Lacage, M., Riley, G.F.: Network simulations with the ns-3 simulator. SIGCOMM Demonstr. **14**, 527 (2008)
9. Jorswieck, E.A., Badia, L., Fahldieck, T., Karipidis, E., Luo, J.: Spectrum sharing improves the network efficiency for cellular operators. IEEE Commun. Mag. **52**(3), 129–136 (2014)
10. MacKenzie, R., Briggs, K., Gronsund, P., Lehne, P.H.: Spectrum micro-trading for mobile operators. IEEE Wirel. Commun. **20**(6), 6–13 (2013)
11. Middleton, G., Hooli, K., Tolli, A., Lilleberg, J.: Inter-operator spectrum sharing in a broadband cellular network. In: 2006 IEEE Ninth International Symposium on Spread Spectrum Techniques and Applications, pp. 376–380. IEEE Press, New York (2006)
12. Obiodu, E., Giles, M.: The 5G era: age of boundless connectivity and intelligent automation. GSM Assocation (2017)
13. The future role of spectrum sharing for mobile and wireless data services. Statement, Ofcom (2014)
14. 3.8 GHz to 4.2 GHz band: Opportunities for Innovation. Call for Input, Ofcom (2016)
15. Piro, G., Baldo, N., Miozzo, M.: An LTE module for the ns-3 network simulator. In: Proceedings of the 4th International ICST Conference on Simulation Tools and Techniques, pp. 415–422. ICST, Brussels (2011)
16. Ramsdale, P.A.: The Impact of New Spectrum Management Methods on Mobile Radio Engineering. Spectrum Trading Associates (2004)
17. Sesia, S., Toufik, I., Baker, M. (eds.): LTE – The UMTS Long Term Evolution: From Theory to Practice. Wiley, Hoboken (2009)
18. Tehrani, R.H., Vahid, S., Triantafyllopoulou, D., Lee, H., Moessner, K.: Licensed spectrum sharing schemes for mobile operators: a survey and outlook. IEEE Commun. Surv. Tutor. **18**(4), 2591–2623 (2016)