Inter-operator Dynamic Spectrum Sharing (Analysis, Cost and Implications)

Gbenga Salami g.salami@surrey.ac.uk
Center for Communication Systems Research
University of Surrey,
Guildford, GU2 7XH, United Kingdom

Rahim Tafazolli r.tafazolli@surrey.ac.uk
Center for Communication Systems Research
University of Surrey,
Guildford, GU2 7XH, United Kingdom

Abstract

This paper addresses Dynamic Spectrum Sharing (DSS) between two wireless operators. The Universal Mobile Telecommunication System (UMTS) network is used as a case study. The proposed protocol is evaluated under the uniform and non-uniform traffic conditions. The underlying principles of the algorithm can be deployed in the UMTS extension Band (2500MHz-2690MHz) which is yet to be allocated or the re-farmed GSM spectrum (900MHz/1800MHz). The simulation results for the proposed protocol shows that significant spectrum sharing gains can be obtained. However such spectrum efficiency gain need to be carefully balanced with the complexity in terms of latency (delays) and additional overhead it brings to the network. The results show that significant spectrum sharing gain of 4.0 % and 2.0 % can be obtained under uniform and non-uniform traffic conditions.

Keywords: Dynamic spectrum sharing, fixed spectrum allocation, call setup, queuing.

1. INTRODUCTION

Several measurement studies have indicated that the finite spectrum resource is not efficiently utilized [1] [2]. When the scarce spectrum resource is viewed dynamically as a function of time (temporal variations) and space (spatial variation) or a combination of both, there exists “spectrum opportunities or holes” that require more efficient techniques in order to be exploited. The traditional spectrum management method is known as Fixed Spectrum Allocation (FSA). FSA is simple and effectively controls interference through the use of a guard band. However, it has three main deficiencies; it is static, inefficient and it limits innovation or rapid deployment of new technologies [3]. This is because spectrum licenses and hence chunks of spectrum blocks are issued in an exclusive manner to the network provider/operator. Therefore a new network provider/operator is not allowed to use this spectrum during the idle or less busy periods.

The future/next generation wireless network will consist of a plethora of heterogeneous networks. In order to satisfy the service demands of these complex networks, Dynamic Spectrum Access (DSA) provides a very promising solution to address the problem of spectrum underutilization [4] [5]. The DSA solutions can be centralized [6] [7], distributed [8] or a combination of both. A classification of these solutions according to the intelligent decision maker together with the advantages and disadvantages of each approach is presented in [9].

The successful realization of DSA schemes will depend on the elimination of a number of technical, economic and regulatory barriers. These barriers are highlighted in [5]. A detailed survey on the challenges to be addressed within the context of opportunistic spectrum access is presented in [4] [5] [10]. These papers have outlined the key requirements involved in the design of DSA schemes for next generation wireless systems. The requirements include: architectural design requirements, techniques to effectively identify reuse opportunities (spectrum sensing), efficient exploitation of detected opportunities through adaptive transmission and modulation waveforms, reconfigurability, the release of the resource once communication has ended (spectrum mobility) and interference mitigation mechanisms [10]. A framework for hierarchical spectrum management in a heterogeneous network is presented in [11]. The successful management of DSA networks involves specialized “protocols” and “policies”. An example of such a policy is discussed in [12]. The goals of these spectrum sharing protocols are usually multi-objective in nature. The protocols should ensure efficient and fair use of the spectrum in a stable manner by allowing secondary users into the white spaces, while at the same time minimizing harmful interference to the licensed primary users of the spectrum.

The main contributions of this paper are as follows; the paper describes a spectrum access framework for the evaluation of spectrum sharing algorithms. The proposed protocol takes into account the fact that although the peak period may coincide, the differential loading during the peak hour between two operator’s traffic pattern provides sufficient gain which can be exploited to improve system capacity and hence spectrum efficiency gain. The characterization depicted here represents the lower bound conditions (worst case scenario). It has been shown in [22] that the spectrum efficiency gain increases significantly in un-correlated traffic situations. The simulated performance takes into account soft handover and Inter-operator interference in the form of Adjacent Channel Interference (ACI). The impact of ACI is particularly important if the operator base stations are non-co-located and displaced by distance *(d)*. This effect serves to reduce the achievable capacity gain for DSS, since in the real world base stations belonging to different operators are more likely to be displaced.
Secondly, the paper has evaluated the call setup latency associated with the proposed algorithm, since longer call setup times will be expected if the User Equipment (UE) is unable to seek connection on its initial network. Furthermore the overhead cost in the form of call setup messages is also presented. The overall aim is to provide a guideline for wireless operators in the selection of an appropriate scheme, taking into account the spectrum efficiency gains and the associated penalty or complexity resulting from the use of such DSS schemes.
Similarly, the algorithm takes into account uniform and non-uniform traffic cases. In the non-uniform traffic case, hotspots cell areas have been included in the model. Hotspots are areas of temporarily high call volume occurring statically or dynamically, due to specific events such as campaign rallies, sporting events, airports etc.
The work presented in this paper addresses a case study involving two UMTS operators sharing spectrum and may be deployed in any band as stated earlier. Furthermore, this paper proposes the architecture for enabling co-operative spectrum sharing between two UMTS operators. A major component of any DSA scheme is the signaling cost and control information overhead associated with it. Therefore central to the implementation of any spectrum sharing algorithm is the determination of the cross-over point at which spectrum sharing may be detrimental to the network. This paper gives an insight into the signaling overhead (call setup delays) involved in the proposed schemes.
The remainder of this paper is structured as follows. Section II introduces the spectrum access framework and the cases investigated. Section III and Section IV gives the details of the system model and algorithm description respectively. Section V analyses the call setup delays. The simulation metrics and DSA performance results are presented in Section VI. This section also gives a discussion of the results. The conclusions and future work plans are outlined in Section VII.

2. RELATED WORK

DARPA Next Generation (XG) [13] has initially investigated dynamic spectrum access with the aim of developing new technologies and system concepts (including new waveforms) to intelligently redistribute the spectrum through opportunistic access. Since the early 1990s, DSA has been formerly studied under the heading of Dynamic Channel Allocation (DCA) [14]. In 2000, the European projects such as the DRIVE [15] and its successor OVERDRIVE [16] have proposed network centric algorithms such as contiguous and fragmented schemes for addressing dynamic spectrum access. This investigation quantifies the spectrum efficiency gain in UMTS-DVB-T sharing scenario to be about twenty nine percent. More recently in 2008, the work in [17] under the E^2R II (End to End Reconfigurability) project applies genetic algorithm to solve the optimization problem involved in cell-by-cell DSA. This work reported a spectrum efficiency gain of 38 % and 41 % respectively under uniform and non-uniform traffic conditions. Reconfigurability is an important practical enabler of DSA systems. The European project E^2R project, and its follow up E^2RII [18], have focused on different aspects of radio reconfigurability, spectrum sharing, and CR implementation in a test-bed. In [18], the factors for achieving this are captured in three-dimensional spaces: technical, economic and regulatory. The technical requirements (radio segment and network segment) can further be broken into a multi-dimensional space composed of service *(s),* time *(t),* space *(sp)* (i.e. location), frequency *(f),* and RAT dimensions. In 2009, the End to End Efficiency (E^3) project [19] funded by the European Union aims to address the integration of Cognitive Wireless networks into beyond 3G network. A further manifestation of the intense interest within the research community in this area is demonstrated by the numerous publications in the IEEE conferences DySPAN [20], CROWNCOM [21].

2.1 Spectrum Access Framework

In order to adequately develop a Spectrum Access Framework, it is important to understand the variety of spectrum sharing models available in literature. The authors in [4] [23] have provided a detailed classification of the different types of sharing options. This paper focuses on a centralized mechanism for spectrum sharing between two operators using the same technology. The traffic demand of Network Operator A is given by (D_{1A}, D_{2A}, D_{3A}, ...,D_{NA}) at time intervals (t_1, t_2, t_3, t_4........., t_n), similarly for Network Operator B, the traffic demand is given by (D_{1B}, D_{2B}, D_{3B},......,D_{NB}) at time intervals (t_1, t_2, t_3, t_4,........, t_n). It can be seen that although the operator may have the same peak hour periods, this does not necessarily mean that the two operators have exactly the same peak load.

The traffic profile for the two operators is exactly the same. The peaks coincide as shown in Fig.1. A realistic traffic model inspired by [1] [24] is used in this paper. Fig. 1 shows the normalized traffic profile of the two operators (initially measured in calls/cell/hour), with similar peak periods occurring at 8-10 am (morning) and 4-6 pm (evening).

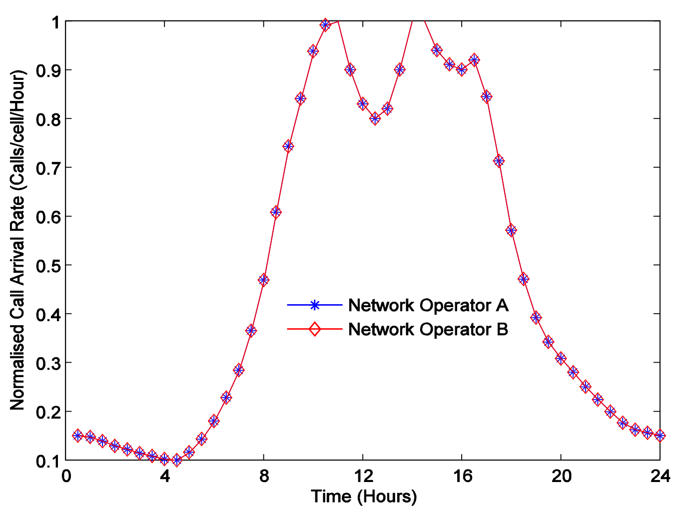

FIGURE 1: Showing normalized traffic profile for two networks

A closer look at the Fig. 1 indicate that although the peaks coincide there are instantaneous opportunities that could be exploited during the peak hour due to statistical multiplexing of call arrivals. This represents the worst case scenario and it gives the lower bound on the spectrum efficiency gain. These instantaneous fluctuations are captured in Fig. 2.

.

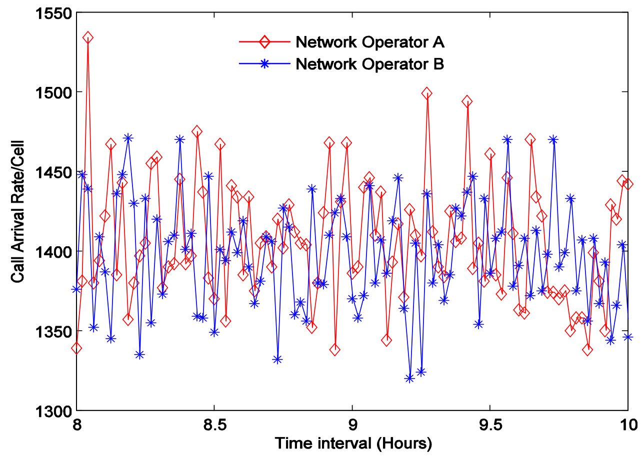

FIGURE 2: Instantaneous variation in peak hour load for two networks with similar traffic profile.

In order to properly address spectrum sharing, the papers in [8], [17] have proposed a hierarchical solution. Fig. 3 presents an architectural enabler to facilitate spectrum sharing between two operators. The Spectrum Management Entity (SME) controls all spectrum related activity such as user migration between networks, carrier allocation and release. The architecture allows resource optimization to occur at different levels from intra-network to inter-network.

.

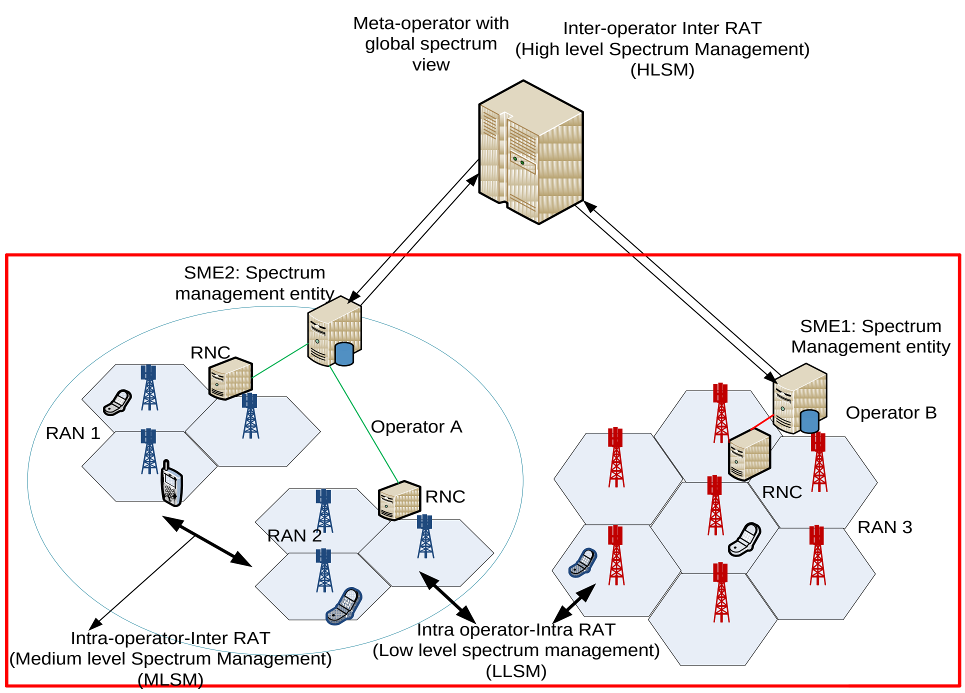

FIGURE 3: Architectural enabler for UMTS spectrum sharing showing interfaces and network elements.

This paper presents an algorithm description of the component required at the different levels of the spectrum access framework. It is important to note that at each level, resource optimization is required using a combination of legacy and new techniques (power control, call admission control, load balancing and inter-operator resource scheduling etc) in order to achieve the desired overall spectrum efficiency gain.

Based on Fig. 4, a resource allocation request in the network triggers the low level spectrum management functionality (LLSM). The specific techniques at this level will encompass intra-operator intra-RAT resource management strategies. The time scale for this operation is also considered to be of the order of milliseconds. If the resource optimization criteria can be met at this level no further interaction with the MLSM entity is necessary and the resource is granted to the user. The inability of the system to satisfy the UE at the lower level triggers the Medium Level Spectrum Management (MLSM) subsystem. This subsystem includes a number of intra-operator inter-RAT resource management techniques. The time scale for the MLSM operation is longer compared to the LLSM but shorter compared to the HLSM. This will be of the order of few minutes. The failure of MLSM to address the spectrum needs of the user triggers the HLSM functionality.

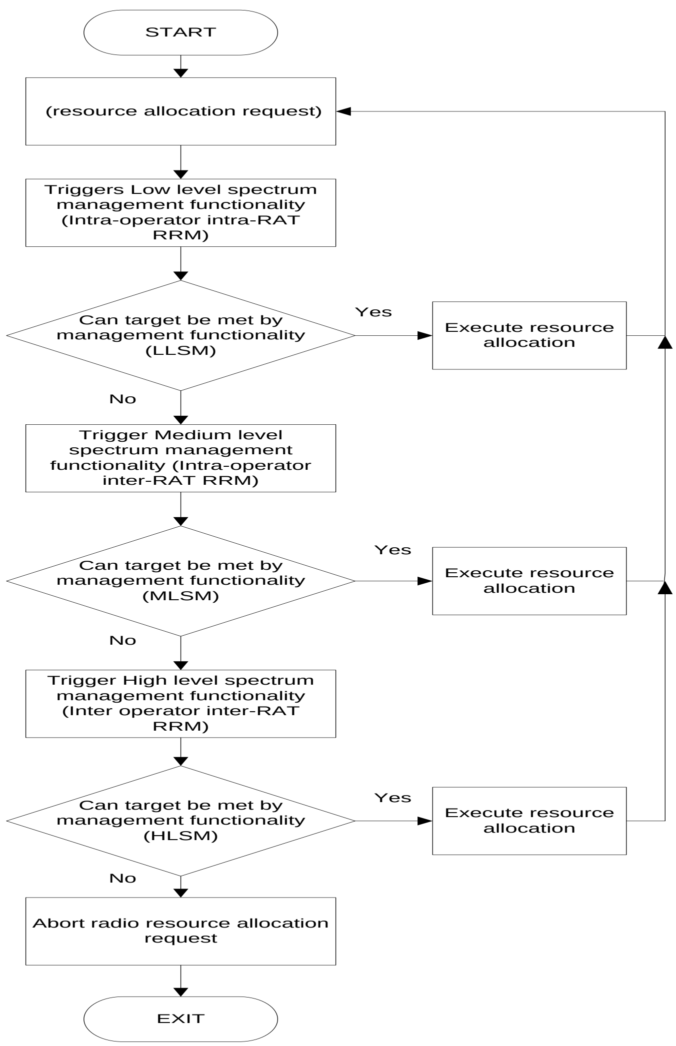

FIGURE 4: Flowchart description of the UMTS spectrum management framework

2.2 System Model

Consider the following model, in which two operators share the spectrum. The traffic profile of the two networks (T_a and T_b) is as described in Fig. 2. Two cases have been identified. In the first case, whole carriers may be exchanged by the operator depending on their traffic and hence carrier requirement. In the second case, the users from one operator may be migrated to another operator's network based on pre-establishment agreement between the two operators. The second is more likely in the case of Wideband Code Division Multiple Access (WCDMA) system where the release of whole carrier is highly unlikely due to the wideband nature of CDMA.

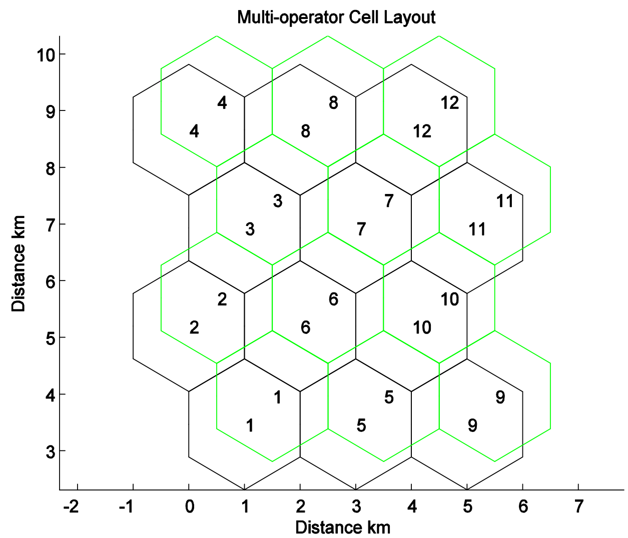

FIGURE 5: Cell deployment for two operators covering same geographic area with displaced BS

In the model, the operators are assumed to have the cell grid deployment shown in Fig. 5 with wraparound mobility to maintain constant user density. It is an important assumption that both operators cover the same geographical area and the cell radius is 1km. The displaced cell model means the impact of ACI needs to be taken into account. ACI primarily due to imperfection in transmit and receive filter characteristics, is modeled as a reduction in the network capacity [25]. Soft handover gain is modeled according to [26] [27]. Perfect power control is also assumed. Two traffic models are used in the simulation. The first is the uniform traffic case in which the average cell load in all the different cells is approximately the same. In the non-uniform traffic case, three hotspots cells with 10% higher call volume are included. According to [28], the same cell interference (I_{sc}) is given in (1) for mobiles in the same cell as;

$$\mathrm{I_{sc}} = (\mathrm{M}-1)\times \mathrm{S}\times \alpha_{\mathrm{r}} \qquad (1)$$

Where S is the power of each mobile at the receiver, α_r is the average reverse link voice activity factor. The other cell interference (I_{oc}) is given in (2) as

$$\mathrm{I_{oc}} = (\mathrm{M}\times \alpha_{\mathrm{r}} \times \mathrm{S})\times \xi \qquad (2)$$

Where ζ is the reuse fraction given by;

$$\xi = \frac{\text{total other cell received power}}{\text{total same cell received power}} = \text{reuse fraction}$$

The UMTS capacity equation used in the simulation is given in [29-30] by (3)

$$M = 1 + \frac{1}{\alpha_r}\left(\frac{B_w}{R_b}\right)\left(\frac{N_o}{E_b}\right) \times \frac{1}{1+i} \qquad (3)$$

Where "*i*" is the ratio of other cell to own cell interference.

2.3 Algorithm Description

In the algorithm description, there is a primary and secondary operator. The primary operator (PO) is defined as the operator which has instantaneous spare capacity to support the secondary operator (SO) during a capacity crisis. The secondary operator suffers capacity problems and requires additional resources from another network for a given period of time. It is important to note that the process is dynamic in time (i.e op A and op B may interchangeably be PO or SO) based on traffic demand. In FSA, the operators maintain their carrier allocations and no spectrum sharing takes place. In Fig. 6, no further effort is made to admit dropped calls and the right hand side of the flow chart is ignored.

In DSA, the operators are able to support their user requests on another network. Furthermore, queuing is introduced to minimize inter-network signaling. The priority is to support the connection request of the users on its own network initially. If the users are unable to find a free channel, then the calls are queued for a short period of time (2 - 3 seconds) respectively. The connection request times due to queuing introduces increased spectrum efficiency gain at the expense of delays. This process termed "DSA with queuing" helps to minimize the inter-network signaling overhead involved in the process. This is because the user is initially queued on its home network before inter-network signaling occurs. A flow chart of the DSA algorithm is shown in Fig. 6.

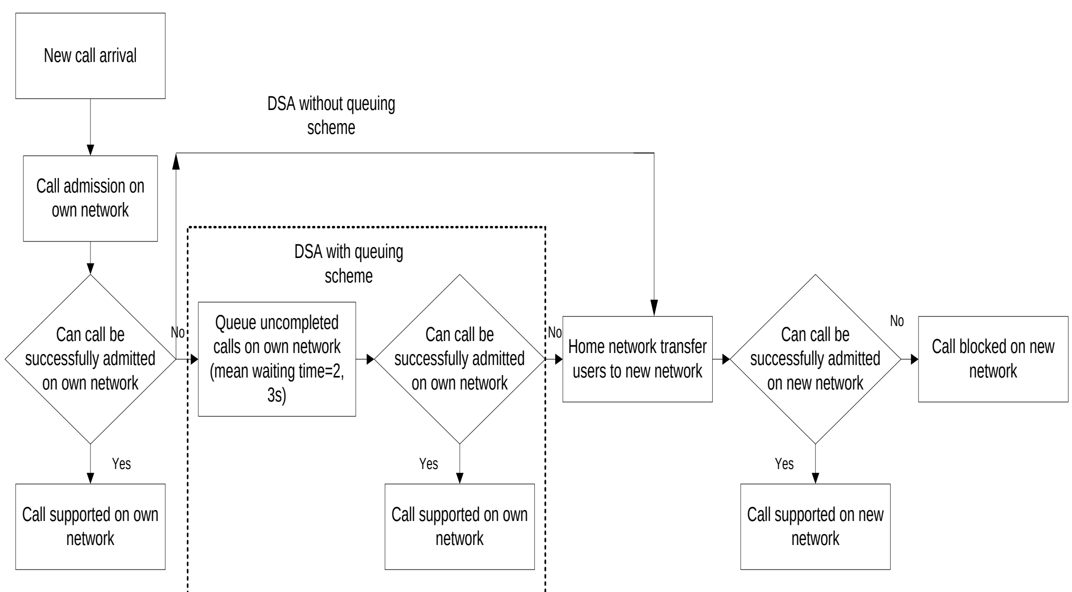

FIGURE 6: Flowchart of the FSA and DSA spectrum admission procedure

3. Call Setup Analysis

The process of establishing a call involves a number of procedures before the resource is assigned to the user equipment (UE). In this section the call setup involved in FSA and DSA is analyzed. Three cases have been identified.

3.1 FSA or Non-shared mode

This refers to the mode when no spectrum sharing occurs. Hence, users are only admitted in their home networks. In the FSA mode, the call setup phase includes the Radio Resource Connection (RRC) establishment, security handshake, radio bearer setup, alerting, connect acknowledge, etc. The recommended one way end to end delay for conversational voice service according to [33] is less than 150ms and the limit should be no more than 400ms. All call requests are assumed to be originated from the UE [31].

Neglecting practical constraints such as the actual radio channel condition, the estimate shown in [31] assumes the best case scenario. However, it has been shown in [25] that the typical delay budget is usually between 6-8 seconds under practical conditions. In [31], the UE is assumed to be in the idle mode initially. The reason for the different UE states (idle and connected) as defined in [25] is for terminal power efficiency and network resource maximization. The main components introducing delays in the FSA call setup is the RRC connection establishment and the radio bearer setup.

3.2 DSA Mode with shared RNC

In the shared Radio Network Controller (RNC) mode, the operators share the same RNC. An agent in the RNC proactively monitors the base station loading of the two operators. In this case, the delay budget will be similar to that described for FSA in [31]. Since the information is contained in the network, capacity can be served directly to the users without additional delays.

3.3 DSA Mode without shared RNC

In the non-shared RNC mode, additional delay is incurred in granting resources on the foreign network. It is an assumption that the Common Pilot Channel (CPICH) of both operators can be decoded by the terminal. The paper [34] has presented the call flow procedure for FSA and DSA. We further analyze the impact of queuing and call setup latency on the spectrum sharing gain in this work.

In addition to the modes mentioned above based on the infrastructure, the connection requests can be queued on the home network. This measure aims to reduce the connection signaling overhead associated with inter-network transfers. For the FSA mode, two main methods are identified. These are; the FSA with queuing, and FSA without queuing modes. In FSA with queuing the calls are queued but not transferred to the foreign network. In the FSA without queuing, calls are either blocked or dropped and no queuing is implemented.

Similarly for the DSA schemes, two modes are identified. These are; the DSA with queuing and the DSA without queuing modes. In the DSA with queuing, the calls are queued for 2-3 seconds respectively as shown in Fig. 7. After this period, the calls are transferred to the foreign network. In the DSA without queuing scheme, the connection requests that cannot be completed on the home network are transferred to the new operator without further queuing on the home network. The main focus of this work is on the DSA schemes and hence simulation results presented in section VI focus on the latter scenarios.

4 Simulation Results

A simulation tool described in [32] has been developed to evaluate the performance of the DSA algorithms. The main simulation parameters used in this work is shown in Table I. The call arrivals are modeled using the Poisson distribution, while the call holding times are exponentially distributed with a mean of 120 seconds.

Parameters	Values
Service type	Speech traffic
Data rate	12.2 Kbps
Call Duration	Mean = 120 seconds (Exponential)
E_b/N_o	7 dB
Adjacent Channel Interference	2 %
Soft handover Gain	3 dB
Cell radius	1 Km
Voice Activity Factor	0.67
UMTS carrier bandwidth	5 MHz
Chip rate	3.84 MCps
Simulation borders	Wraparound mobility of MS at simulation borders
Propagation Model	Path loss model with 4^{th} order power exponent
User distribution	Uniform and Non-Uniform (3 Hotspots)
Frequency re-use factor	1
Handover	Based on geometric cell boundaries
Total Number of cells	12 (with interference modeling)
Carrier distribution	Primary (3 carriers), secondary (3 carrier)
Cell layout	Hexagonal with omni-directional antenna Deployment
Connection queuing times	1 second, 2 seconds

Table I: Simulation Parameters

To evaluate the spectrum efficiency gain, the FSA scenario when no spectrum sharing takes place is compared with the DSA scenario with and without queuing. The gain is measured in terms of the capacity improvement at 98 % Satisfaction Ratio (*SR*). The *SR* is defined in (4). This value is considered sufficient to give the desired level of Quality of Service *(QoS)* in an operator's network.

$$SR = 1 - (P_B - (10 \times P_D)) \qquad (4)$$

P_B is the call blocking probability and P_D is the call dropping probability. The dropped calls are given a higher weighting since there are less tolerable than blocked calls. The spectrum efficiency gain (Δη) is defined in (5) as

$$\Delta\eta = \frac{\text{Load}_{\text{DSA},98\%} - \text{Load}_{\text{FSA},98\%}}{\text{Load}_{\text{FSA},98\%}} \qquad (5)$$

$Load_{DSA,98\%}$ is the Users/Cell/Hour for DSA at 98% Satisfaction ratio, $Load_{FSA,98\%}$ is the Users/Cell/Hour for FSA at 98% Satisfaction ratio.

4.1 Dynamic spectrum sharing system level protocol performance and analysis

The simulation results are presented in this section. Fig. 7 and Fig. 8 show the FSA and DSA performance curves for network 1 and 2 respectively for the uniform traffic case. According to the figure, the satisfaction ratio decreases as the traffic offered (Mobile Subscribers/Cell/Hour) increases. Similarly, the results show that the DSA without queuing provides a least spectrum efficiency gain compared to the other two techniques. This is due to the fact that in the DSA scheme without queuing, no further measures are taken to account the call if the operator is unable to accommodate the call it is either blocked or dropped.

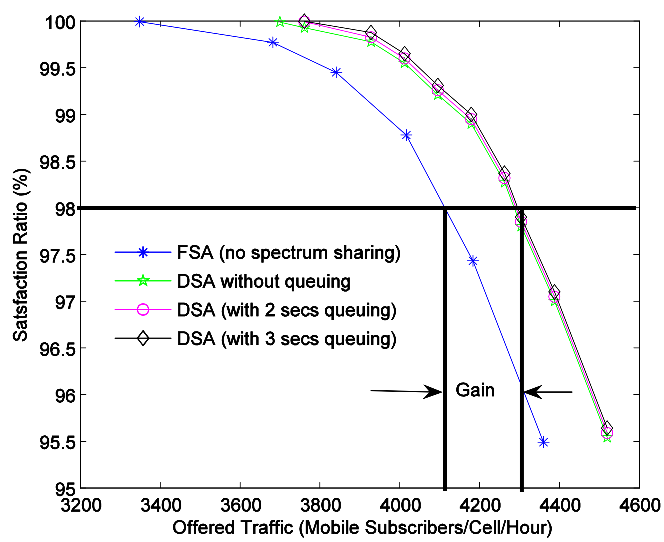

FIGURE 7: Performance comparison between FSA and DSA with and without queuing for network operator 1 (Uniform traffic).

Similarly, the results show that queuing improves the gain at low and medium load (offered traffic). It also shows that queuing is not effective at high load. This is because the probability of both operators being able to accommodate more users on their network during heavy traffic period is very low. Furthermore, the performance of DSA with 3 seconds queuing is slightly better than DSA with 2 seconds because further delays on home network results increases the probability of a service connection at low to medium load. In all the cases investigated, the call setup delay is transparent to the end user. The gain for the three schemes is 4.6 %, 4.3 % and 4.2 % respectively at 98 % satisfaction ratio on network 1. Similarly, the spectrum efficiency gain on network 2 is 4.1 %, 4.0 %, 3.9 %. These figures are obtained by substituting the values on the horizontal axis of Fig. 7 and Fig. 8 into (9).

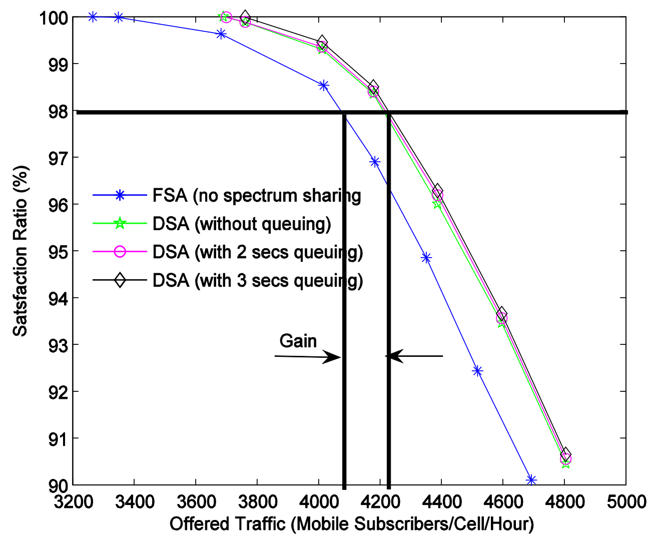

FIGURE 8: Performance comparison between FSA and DSA with and without queuing for network operator 2 (Uniform traffic)

Fig. 9 and Fig. 10 show the performance for FSA and DSA with and without queuing for the three schemes investigated in the non-uniform traffic case. Three (3) hotspots which represent areas of temporarily high traffic have been included in the simulation area. The trend in performance for the three schemes is similar to that discussed previously. However, the main difference is that the carriers in the non-uniform traffic case approaches saturation faster due to higher call volumes. It is important to note that the spectrum efficiency gain for all the three schemes is similar at 98% satisfaction ratio regardless of queuing. This fact is more visible at high load due to congestion. It is also observed that the performance of the DSA algorithm approaches that of FSA at high load due to the inclusion of the hotspot.

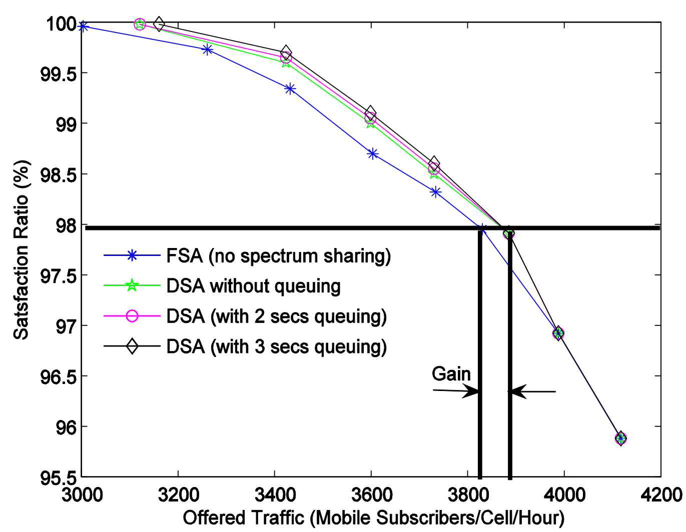

FIGURE 9: Performance comparison between FSA and DSA with and without queuing for network operator 1 (Non-Uniform traffic)

Based on the graphs plotted above for both scenarios, the spectrum efficiency gain for the non-uniform traffic scenario for the three DSA schemes for network 1 and 2 is 2.2 % and 2.0 % indicating a reduction in gain compared to first scenario. There is also no significant benefit due to queuing at 98 % SR.

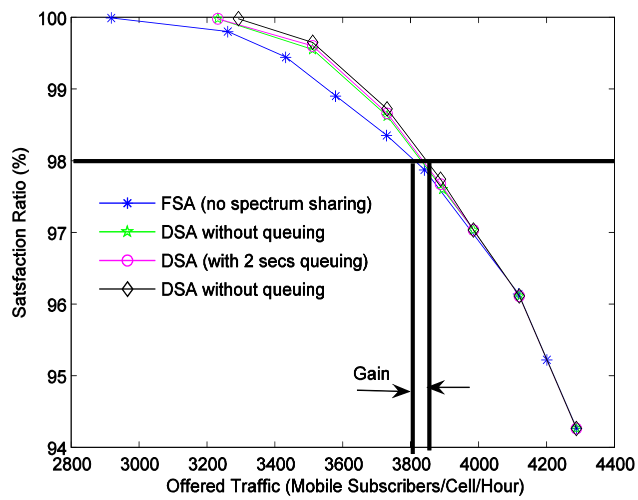

Figure 10: Performance comparison between FSA and DSA with and without queuing for network operator 2 (Non- Uniform traffic).

4.2 Call setup messages and latency

The detailed description of the call setup sequence is presented in [34]. Here we provide the simulation results in terms of total call setup messages for the two operators at a particular satisfaction ratio. According to Fig. 11 and Fig. 12, the total setup message for the non-uniform traffic (Fig. 12) case is generally higher than Uniform case (Fig. 11). A high number of subscribers results in a higher number of signaling messages. Similarly, it is shown that DSA results in a higher number of signaling messages compared to FSA for all the 3 schemes considered.

It is observed that DSA without queuing has the higher signaling messages since users are directly migrated to the foreign network without any attempt to support them on their home network. The other two schemes minimize the inter-network signaling by trying to support the calls on their home network. DSA with 2 seconds queuing performs better than DSA with 3 seconds queuing since it accommodates less subscribers compared to the latter.

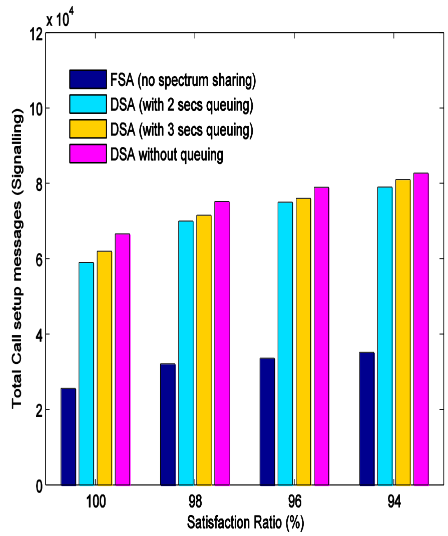

Fig. 11a. Total call setup messages versus SR for the DSA schemes (uniform traffic) network 1.

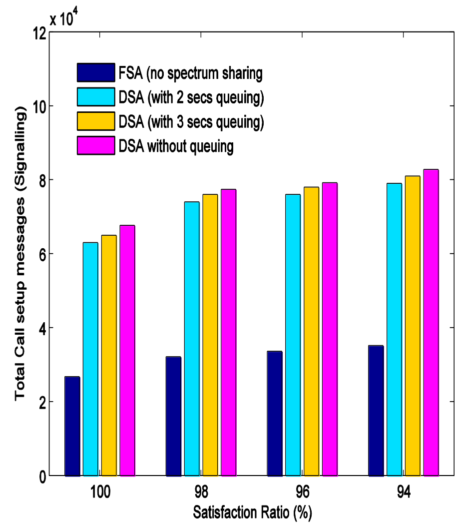

Fig. 11b. Total call setup messages versus SR for the DSA schemes (uniform traffic) network 2.

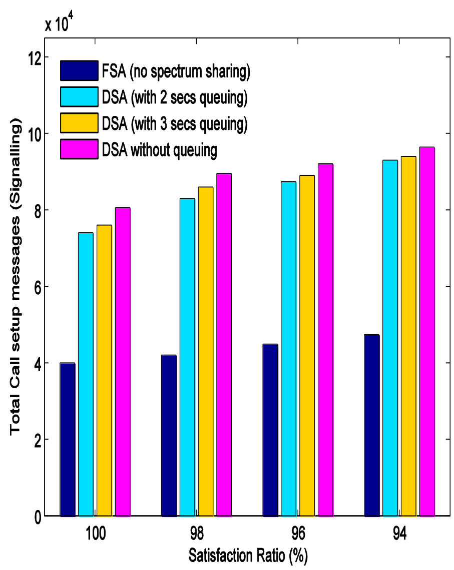

Fig. 12a. Total call setup messages versus SR for the DSA schemes (non-uniform traffic) network 1.

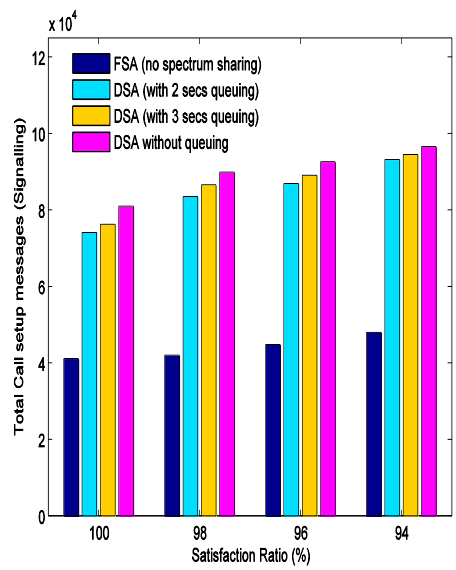

Fig. 12b. Total call setup messages versus SR for the DSA schemes (non-uniform traffic) network 2.

To adequately serve users, it is necessary to avoid long call setup delays [25]. Connection request delays should be transparent and imperceptible to the end user. The mean queuing times of 2-3 seconds chosen in the work is considered adequate to reflect these issues. The main implications are that operators will need to carefully weigh the trade-offs between not accommodating a subscriber and hence loss of revenue, to queuing of subscriber for short periods after which they can be served as soon as capacity becomes available. It is also important to note that additional latency is introduced due to spectrum sharing, so that the maximum tolerable delay need to be matched with the service requirements.

5 Conclusions and Future Work

This paper has presented a spectrum access framework for dynamic spectrum sharing between operators using the UMTS network as a case study. Three schemes to address UMTS spectrum sharing have been presented. The simulation results show that significant spectrum efficiency gain can be obtained in the low and medium traffic regions for the uniform and non-uniform cases. For the scenarios considered spectrum sharing gain above 4.0 % and 2.0 % was obtained for the uniform and non-uniform traffic at 98 % satisfaction ratio. The DSS gains are primarily due to the statistical multiplexing of call arrivals. The decrease in the gain in the latter scenario was due to the significantly higher call volumes associated with hotspots. The results also show that queuing does not significant improve the spectrum sharing gain under heavy traffic conditions.

The paper has also investigated the trade-off associated with spectrum sharing taking into account the call setup signaling and delay. It is important to note that DSA with queuing schemes provide a more practical approach to increase the gain while minimizing the inter-network signaling overhead. Furthermore, it was shown that the non-uniform traffic scenario presents challenges in terms of signaling for network operators in all the DSS cases. Future work will address operator networks with heterogeneous services and packet level simulations to determine if further gains are possible due to statistical multiplexing of packet transmission.

ACKNOWLEDGEMENT

This work has been supported, in part, by the European ICT Project QoSMOS.

REFERENCES

1. D. Willkomm, S. Machiraju, J. Bolot, A. Wolisz. "*Primary Users in Cellular Networks: A Large-scale Measurement study"*. In Proceedings of the 3rd IEEE Symposium on Dynamic Spectrum Access Networks. Chicago, IL, USA, 2008.
2. Shared spectrum company website, Available online: http://www.sharedspectrum.com/measurements/recent.html, [Accessed online December 2008
3. FCC 04-167, "Promoting efficient use of spectrum through elimination of barriers to the development of secondary markets," Jan. 2004.
4. Q. Zhao, B. M. Sadler. "*A Survey of Dynamic Spectrum Access*". IEEE Signal Processing Magazine, 24(3), pp. 79-89, 2007.
5. I. F. Akyildiz, W. Y. Lee, M. C. Vuran, S. Mohanty. *"A survey on spectrum management in cognitive radio networks (Cognitive radio and communication networks)".* IEEE Communications Magazine, 46: 40-48, 2008.
6. P. Leaves. *"Dynamic Spectrum Allocation between Cellular and Broadcast systems",* PhD Thesis, Dept. of Electronic Eng., University of Surrey, Guildford, United Kingdom, January 2004.
7. M. Buddhikot, K. Ryan. *"Spectrum Management in Coordinated Dynamic Spectrum Access Based Cellular Networks".* In Proceedings of the IEEE Symposium on Dynamic Spectrum Access Networks (DySPAN 05), Baltimore, MD, USA.
8. S. Haykin. *"Cognitive radio: brain-empowered wireless communications".* IEEE Journal of Selected Areas in Communication, 23, pp. 201-220, 2005.
9. G. Salami, O. Durowoju, A. Attar, O. Holland, H. Aghvami, R. Tafazolli. *"A Comparison between the centralized and distributed approaches for spectrum management".* Accepted in IEEE Communications Surveys and Tutorial, Second quarter 2011.
10. A. Attar, S. A. Ghorashi, M. Sooriyabandara, A. H. Aghvami. "Challenges of Real-Time Secondary Usage of Spectrum". *Journal of Computer Networks (Elsevier)*, Special Issue on Cognitive Wireless Networks, 52(4), pp. 816-830, 2008.
11. A. Attar, A. H. Aghvami. "*A Framework for Unified Spectrum Management (USM) in Heterogeneous Wireless Networks"*. IEEE Communications Magazine, 45, pp.44-51, 2007.

12. L. Berlemann, S. Mangold, G.R. Hiertz, B. Walke. *"Policy Defined Spectrum Sharing and medium Access for Cognitive Radios".* Journal of Communication (Academy Publisher), 1, pp. 1-12, 2006.
13. DARPA XG Program Website, Available online: http://www.darpa.mil/ATO/programs/XG/index.htm , [Accessed online: 5th March 2009].
14. I. Katzela, M. Naghshineh. Channel assignment schemes for cellular mobile telecommunication systems: a comprehensive survey. *IEE Personal Communications*, 3, pp. 10-31, 1996.
15. IST DRiVE Project Website, Available online: http://www.ist-drive.org/index2.html , [Accessed online: 18th May 2007].
16. IST Over-DRiVE Project Website, Available online: http://www.comnets.rwth-aachen.de/~o_drive/ [Accessed online: 16th May 2007.
17. D. Thilakawardana, K. Moessner, R. Tafazolli. *"Darwinian approach for dynamic spectrum allocation in next generation systems"*, IET Journal of Communication, 2, pp. 827-836, 2008.
18. IST FP6 E2R2 Project Website, Available online: http://e2r2.motlabs.com/ [Accessed online: 15th February 2009].
19. IST FP7 End to End Efficiency Project Website, Available online: https://ict-e3.eu/project/, [Accessed online: 30th January 2009].
20. IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks, Available online: http://www.ieee-dyspan.org/2008/, [Accessed online: 30th March 2009].
21. Third International Conference on Cognitive radio Oriented Wireless Networks and Communication, Available: http://www.crowncom.org/2008/, [Accessed online: 31st March 2009.
22. G. Salami, R. Tafazolli. *"On the Performance evaluation of spectrum sharing algorithms between two UMTS operators".* In Proceeding of IEEE International Conference on Telecommunications (ICT), Marrakech, Morocco, 2009.
23. J. M. Peha. Approaches to spectrum sharing. *IEEE Communication Magazine*, 43, pp. 10-12, 2005.
24. J. Guo, F. Liu, Z. Zhu. *"Estimate the Call Duration Parameters in GSM System Based on K-L Divergence Method".* In Proceeding of the International Conference on Wireless Communications, Networking and Mobile Computing, *WiCom*, pp. 2988-2991, 2007.
25. H. Holma, A. Toskala. "*WCDMA for UMTS-HSPA Evolution and LTE"*, Fourth Edition, John Wiley & Sons, 2007.
26. S,-P. Chung, M.T. Li. *"Performance Evaluation of Hierarchical Cellular CDMA networks With Soft Handoff Queuing",* IEEE Trans. Vehicular Technology, 54(2), pp. 652-672, 2005.
27. W. H. Tranter, K. S. Shanmugan, T. S. Rappaport, K. L. Kosbar. *"Principles of Communication Systems Simulation with Wireless Applications"*, Pearson Education, 2004.
28. J. S. Lee, L. E. Miller. *"CDMA Systems Engineering Handbook*". Artech House Publishers, pp. 1013-1017(1998).
29. A. M. Viterbi, A. J. Viterbi. Erlang Capacity of a Power controlled CDMA System. *IEEE Journal on Selected Areas in Communications*, 11, pp. 892-900, 1993.
30. K. I. Kim. "CDMA Cellular Engineering Issues". *IEEE Transaction on Vehicular Technology*, 42(3), pp. 345-350, 1993.
31. Third Generation Partnership Project, Technical Specification Group RAN; TR 25.815 v7.0.0, Signaling enhancements for Circuit-Switched (CS) and Packet-Switched (PS) Connections (Release 7), Sept. 2006.
32. G. Salami, A. Quddus, D. Thilakawardana, R. Tafazolli. *"Non-pool based spectrum sharing for two UMTS operators in the UMTS extension Band"*, *In Proceedings of 19th IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, pp. 1-5, 2008.
33. Third Generation Partnership Project, Technical Specification 25.853. Delay Budget within the Access Stratum, 2003.
34. G. Salami, S. Thilakawardana, R. Tafazolli. *"Dynamic Spectrum sharing between two UMTS operators in the UMTS Extension Band".* In Proceedings of the IEEE International Conference on Communication Workshops, Dresden, Germany, 2009.