Resource Sharing in Wireless Networks: The SAPHYRE Approach

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Abstract: Physical resource sharing between wireless operators and service providers is necessary in order to support efficient, competitive, and innovative wireless communication markets. By sharing resources, such as spectrum or infrastructure, which are usually exclusively allocated interference is created on the physical layer. Therefore, the economic gains, regulatory overhead, and engineering efforts need to be addressed by a consolidated cross-layer approach. This paper describes briefly the approach taken by the EU FP7 project SAPHYRE.

Keywords: Spectrum sharing, infrastructure sharing, spectrum regulation, business models, interference networks.

1. Introduction

In current wireless communication systems, the radio spectrum and the infrastructure are typically used such that interference is avoided by exclusive allocation of frequency bands and employment of base stations. SAPHYRE[1] will demonstrate how equal-priority resource sharing in wireless networks improves spectral efficiency, enhances coverage, increases user satisfaction, leads to increased revenue for operators, and decreases capital and operating expenditures.

The vision of the Wireless World Research Forum (WWRF) formulated in 2008[1] forecasts that 7 trillion wireless devices will serve 7 billion people by 2017. The mobile users expect reliable high-data rate services with strict delay constraints and ubiquitous and transparent access 24 hours a day, 7 days per week.

The International Mobile Telecommunications (IMT) 2000 global standard for cellular communications was developed and established by the International Telecommunication Union (ITU) in 1999. Currently, a new standard, IMT-Advanced, is being developed that will enable enhanced communication services for end-users. It supports both low and high mobility applications and a wide range of data rates. The envisaged deployment is between 2012 and 2015. The key features of IMT-Advanced include enhanced peak data rates (100 Mbit/s for high and 1 Gbit/s for low mobility)[2], capability of interworking with other radio access systems, and high-quality mobile packet-based services.

The technical requirements for the air interface in IMT-Advanced include modern contention-based multiple access techniques, multi-antenna systems including space-division multiple-access (SDMA), adaptive modulation and coding schemes, and modern channel coding schemes, especially turbo and low-density parity-check (LDPC) codes[3]. Novel adaptive transmission techniques such as software-defined-radio (SDR), cognitive radio (CR), and co-operative communications are also explicitly included.

These developments and requirements lead to an indispensable paradigm change from exclusive resource allocation to *cost-, spectrum-, and energy-efficient voluntary physical resource sharing* and can be realised by innovative use of radio spectrum and network infrastructure under economic and regulatory constraints.

1.1 Physical resource sharing

The idea of physical resource sharing can be described using Figure 1. There is a general set of common resources, divided into two classes, namely spectrum and infrastructure. The set of players consists of operators and users. To keep things simple, there are no other stakeholders like service providers, content providers, manufacturers, spectrum brokers, central network controllers, or vendors included. Each player has a set of private information, e.g., operators have their business models and their revenue strategies, users have their private interests and their partly private state information including traffic, mobility, and channel parameters. These goals and parameters are usually not revealed to others.

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[1]The SAPHYRE (Sharing Physical Resources – Mechanisms and Implementations for Wireless Networks) project starts January 2010 and is a STREP funded by the European Union within framework program seven (FP7-ICT-248001). `http://saphyre.eu`

[2]Data rates sources from ITU Recommendation ITU-R M.1645.

[3]ITU: 'IMT advanced drafts', `http://www.ieee802.org/21/doctree/IMT-Advanced/`.
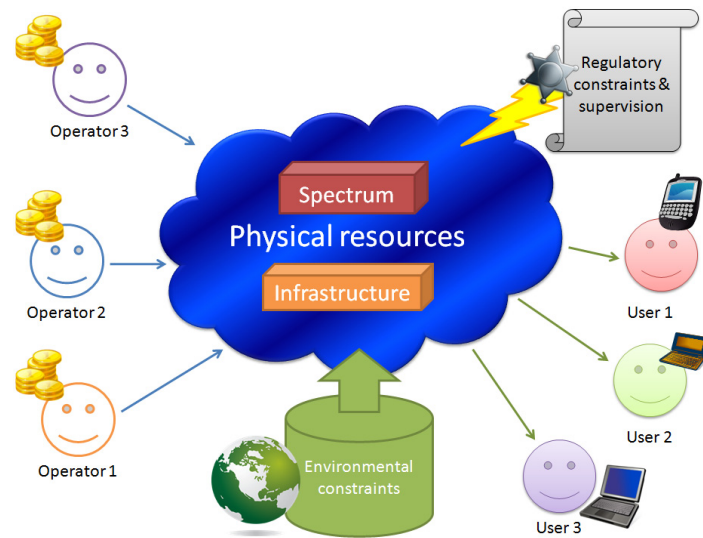
Figure 1: Conceptual overview of spectrum and infrastructure sharing.

Constraints are divided into two areas, namely regulatory and environmental constraints. They can partly overlap as in the case of spectrum masks and power constraints which are both regulatory and environmental. The main difference between these two areas is that regulatory constraints contain fairness and social welfare or legal issues whereas environmental constraints contain fundamental limitations imposed by physics.

The resource sharing problems are interdisciplinary and require regulatory and political bodies, business and market experts. Furthermore, communication and network engineers provide technical input7. The ongoing discussion about spectrum commons is led mainly from a regulatory and market point of view. However, advances in communication systems (e.g., multi-antenna systems, multi-carrier systems, adaptive receivers, software-defined-radio, interference cancellation) are recognised already to have a very strong impact since they enable the efficient and concurrent use of spectrum [2]. The technical requirements of IMT-Advanced as outlined above include next-generation mobile radio technologies that can enable efficient sharing of resources.

1.2   Some recent results in resource sharing

From a communications engineering point of view, different types of orthogonality in frequency, time, space or coding domain were used for resource allocation depending on the type of interference: For users in one cell operated by one operator (intracell interference) TDMA combined with FDMA (used in GSM systems) or CDMA (combined with TDMA/FDMA in 3G systems) is applied to separate their signals at the receivers. For different sectors or cells, the intercell interference is controlled by applying different frequency reuse factors [3]. Fractional and adaptive frequency reuse is discussed in LTE and WiMAX [4]. Recently, techniques for separating transmissions from different operators (inter-operator interference) without orthogonal resource allocation are developed: First flexible resource sharing approaches are developed and results indicate that the overall efficiency of the system can be improved by sharing different resources in the network between different operators [5, 6].

Sharing of spectrum or infrastructure ends up in creating *interference on the physical*

layer. Therefore, physical and MAC layer optimisation for resource sharing has become an active research area. The competition between service providers or operators is often modelled using game theory [7]. There is a fairly rich literature on applications of game theory to spectrum conflicts in wireless systems, even though this topic is relatively new. Preliminary studies of the spectrum sharing problem from a game theoretic point of view have appeared in search of fair, effective, and self-enforcing protocols [8]. The spectrum sharing problem in the context of cognitive radio has been formulated as a static and dynamic (repeated) Cournot[4] game [9]. Both co-operative and non-co-operative schemes for power control optimisation in interference networks have been proposed [10]. Co-operation has been used to agree on fair allocation of the spectrum [11]. Interference channels with phase coherent multi-antenna transmission have been recently studied from a game-theoretic viewpoint [12, 13].

2. State of the art and problem characterizations

In this Section, we present an overview of the state of the art and characterize the problems associated with physical resource sharing.

2.1 Fundamental limits

A fundamental objective of resource sharing is to find a stable operating point based on certain fairness and efficiency criteria [14]. Many well-known concepts, like proportional fairness [15] and bargaining theory [16], were derived in a context other than wireless communication. The used utility models do not typically explicitly model resource/infrastructure sharing and adaptive interference filtering at the physical layer. However, adaptivity plays an important role in fully exploiting the potential system performance, so it should be incorporated in the utility model. Adaptive designs for wireless networks depend on interference, channel fluctuations, and resource constraints. This causes complicated dependencies between the physical layer, medium access control, and the network. Up to date, there is no established framework for modelling such interdependencies, only partial results exist [17]. An important aspect, especially for resource sharing scenarios, is to model the interference. The conventional approach is based on a static 'link gain' matrix that models the power cross-talk between users [18]. A more general model is the axiomatic framework of interference functions [19, 20]. This non-linear model already provides the degrees of freedom necessary for jointly optimising adaptive receivers and transmission powers. This was demonstrated in the context of power control. However, for the more intricate problem of resource and infrastructure sharing, extensions are needed to include dependencies on discrete-valued resources, MIMO processing, and antenna infrastructure.

2.2 Signal processing for resource sharing

Signal processing and coding schemes (including channel estimation, channel coding, decoding, synchronisation) have traditionally been designed only from the perspective of the particular individual radio link. The presence of other radio links (belonging to other users in the network) has been represented by two extreme cases. When no information about the interfering signal is available, a simple Gaussian random signal

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[4]Cournot competition is an economic model used to describe an industry structure in which companies compete on the amount of output they will produce, which they decide on independently of each other and at the same time.

approximation is used. On the other hand, assuming full knowledge of the interference signal structure, various interference cancellation and multi-user detection techniques have been developed. These techniques take into account the coexistence only in a static manner, considering either full or zero co-operation.

Partial steps forward have recently been achieved in the areas of multi-user MIMO systems [21], traditional cognitive radio systems [22], network coding [23], as well as various physical layer co-operative and distributed processing algorithms (virtual MIMO, distributed and co-operative coding, etc.) [24]. These techniques have limited capabilities to solve the problem. Therefore, new challenges, some of them listed below, need to be approached:

- Infrastructure sharing between competing operators leads to new constraints for channel estimation, blind and semi-blind signal processing [25, 26] interference suppression, as well as interference cancellation algorithms.

- Real-time spectrum analysis is not only required for new adaptive spectrum sharing models, i.e. to estimate the noise floor and to identify and to characterise the spectrum holes. It is also beneficial for channel estimation (equalisation), channel matrix identification (in MIMO systems), multi-carrier communications (real-time analysis and synthesis), beamforming (spatial domain), and radio scene analysis.

- Efficient co-ordination mechanisms for resource sharing scenarios require the development of compact and efficient channel representation schemes with limited feedback [27].

- The coding, decoding, and signal processing will have to be aware of the network structure, available physical resources (power, spectrum), and interference. This information will be unreliable and incomplete. The problem will be solved by various forms of the physical network coding and corresponding network-aware soft-information message passing receiver processing.

2.3 Spectrum policy and regulation

The development of technologies that enable a more flexible access to the radio spectrum supported by a suitable regulatory framework is regarded as a solution to a further increase in the efficiency of spectrum use. This will cater for the increasing demands for mobile communication services. To enable these developments, need for changes in the regulatory framework has been acknowledged [28]. The approach of granting long-term licenses for the exclusive use of spectrum, that was very effective in the prevention of interference and therefore employed for a long time, is nowadays abandoned. The main reason behind this is that, although the frequency spectrum is fully allocated to various services, the actual utilisation is low for important bands. Flexibility in spectrum allocations and increased efficiency in spectrum use are strived for in current spectrum management. The different options that are identified and will further be explored are: infrastructure sharing, new adaptive spectrum sharing models, efficient co-ordination, and high spectral efficiency. The common background is that there is a *voluntary sharing* of spectrum between the different users (wireless communication network operators in this case), based on the principle that they will all gain from the collective approach.

Sharing the infrastructure as such can also lead to obvious benefits and is in fact already done to some degree [29]. It is common for operators to share site locations and masts. Some vendors offer a service to host the equipment of multiple vendors, and it is in some cases even technically possible to share antennas and pieces of active hardware. There are also examples of sharing complete network operations. However, with a high degree of shared resources using today's technology, the stimulation for competition is reduced.

When determining success criteria or targets for cost and energy reduction, it is useful to distinguish capacity driven network deployment from coverage driven network deployment. Further, we should realise that the main cost driver in *deployment* of a radio access network is the number of base stations. Moreover, the total network operation is an expensive venture. The largest energy consumption in radio access networks also takes place in the base station, so that cost reduction and energy reduction go hand-in-hand. The capacity driven scenario is characterised by a high traffic density, a dense network, and usage of all available spectrum. In this scenario, the conventional manner to further increase capacity is to add sites. With spectrum sharing, the total capacity gain is at least in the order of the gain in spectral efficiency, but can be even higher thanks to higher user diversity and trunking efficiency. The cost and energy reduction in this scenario is of a similar magnitude, since more traffic can be served with the same equipment before additional sites are needed.

The coverage driven scenario is characterised by the need for providing coverage. Capacity is typically fulfilled in the simplest configuration, e.g., using one carrier of a standard bandwidth. In this case, increased spectral efficiency or spectrum sharing only gives a gain on the long term, since higher bandwidth services can be offered and the time for adding more capacity will be postponed further into the future. However, infrastructure sharing provides immediate and large gains of cost (operational and capital) as well as energy.

2.4   Business models

The first generation of mobile networks, built on different analogue standards (e.g., Nordic Mobile Telephone) and often only supporting a voice service, were in most countries deployed by the same incumbent telecom operator which already operated a fixed analogue network. A vertical business model was common practice, where the same operator was responsible for all parts of the value chain. Often being owned by the state, access to radio spectrum was always granted.

With the second generation (in Europe GSM), regulators recognized the importance of a competitive market on the one hand in order to ensure low prices and a common standard on the other hand to achieve economy of scale and compatibility across national boarders. In practically all European countries, multiple licences were granted for access to spectrum for the exploitation of wireless networks to offer mobile communication services to end users. With GSM, also text messaging (SMS) was introduced, which has become an important revenue source. With the second generation of networks it also became possible to become a Mobile Virtual Network Operator (MVNO).

Only with the third generation of mobile networks (in Europe dominated by UMTS) data services have become equally or even more important than voice services and openend up new business models. Mobile operators still tend to remain vertically organised and supply network capacity to MVNOs, and most revenues still come from

voice services and text messaging, but data traffic is currently experiencing a very fast uptake. In most markets a relatively low cost flat-rate that can compete with fixed line prices for broadband data access, has been the trigger for the fast uptake. In order to avoid a role as a mere bit carrier, operators tend to bundle third party services with terminals (e.g., Google or Facebook directly from the network providers portal).

The goal of SAPHYRE is to enable not only a more efficient use of resources, but *new business models*. SAPHYRE will facilitate competition on more levels in mobile networks than it is possible today. With a higher degree of competition on both spectrum and infrastructure, less regulation is needed, benefiting end users and society in general. For example, parties can specialise in providing services (like today's MVNOs), operating networks, or managing spectrum [30, 31, 32]. Next to developing suitable business models, the project will also investigate how competition policies need to be adjusted and which minimum set of rules needs to be applied, taking into consideration that competitors by nature aim foremost at maximising their own gain.

3.   The SAPHYRE approach

The approach envisaged spans wireless communication systems, information theory, game theory, networking, business and regulatory models and the interdisciplinary connections between these fields.

Over the past decade, European industry has established a clear global industrial and technology leadership in the field of mobile communications. Mobile communications is one of the few technology sectors in which Europe has a clear global leadership position. This success in global markets was developed from the results of EU-funded collaborative research on second and third generation mobile technologies, which formed the basis of successful global standards.

SAPHYRE will reinforce European research and industrial leadership and competitive position in spectrum and infrastructure sharing by enabling operators to adapt to the new business opportunities, enabling regulatory bodies to agree on easily maintainable sharing mechanisms, and enabling vendors to develop the new base stations and mobiles using the required radio technologies. The approach of SAPHYRE underlines the systematic collaboration of all sector actors within a consistent framework and a shared vision.

Economics plays a key role in SAPHYREs collaboration. The importance of mobile communications to society is large, citizens and business, can not be underestimated. The European economy has benefited from the take-up of GSM over the past decade and the evolution towards broadband services over mobile networks will continue to drive economic growth in the coming decades. This is possible only if the right mechanisms are applied which guarantee competition and efficiency.

References

[1]   N. Jefferies, "WWRF setting the research agenda for the wireless world," in *Int. Conf. On Beyond 3G Mobile Communications*, 2008.

[2]   J. Brito, "The spectrum commons in theory and practice," *Stanford Technology Law Review*, vol. 1, 2007.

[3]   T. S. Rappaport, *Wireless Communications*. Prentice Hall, 1996.

[4]   K. H. Teo, Z. Tao, and J. Zhang, "The mobile broadband WiMAX standard [standards in a nutshell]," *IEEE Signal Processing Magazine*, vol. 24, pp. 144–148, Sept. 2007.

[5]   M. Bennis and J. Lilleberg, "Inter-operator resource sharing for 3G systems and beyond," in *Proc. IEEE ISSSTA*, 2006.

[6] V. Heinonen, P. Pirinen, and J. Iinatti, "Capacity gains through inter-operator resource sharing in a cellular network," in *Proc. IEEE WPMC*, 2008.

[7] "Game theory in signal processing and communications, dedicated issue of IEEE signal processing magazine, vol. 26, no.5, sept. 2009."

[8] R. H. Etkin, D. N. C. Tse, and H. Wang, "Gaussian interference channel capacity to within one bit: the general case," *Proc. IEEE ISIT*, 2007.

[9] D. Niyato and E. Hossain, "A game-theoretic approach to competitive spectrum sharing in cognitive radio networks," in *Proc. IEEE WCNC*, 2007.

[10] E. Altman, T. Boulogne, R. El-Azouzi, T. Jimenez, and L. Wynter, "A survey of networking games in telecommunications," *Comput. Oper. Res.*, vol. 33, pp. 286–311, 2006.

[11] J. E. Suris, L. A. DaSilva, Z. Han, and A. B. MacKenzie, "Cooperative game theory for distributed spectrum sharing," *Proc. IEEE ICC*, 2007.

[12] E. G. Larsson and E. A. Jorswieck, "Competition versus collaboration on the miso interference channel," *IEEE Journal on Selected Areas in Communications*, vol. 26, pp. 1059–1069, 2008.

[13] E. A. Jorswieck, E. G. Larsson, and D. Danev, "Complete characterization of the Pareto boundary for the MISO interference channel," *IEEE Trans. on Signal Processing*, vol. 56, pp. 5292–5296, Oct. 2008.

[14] J.-Y. L. Boudec, "Rate adaptation, congestion control and fairness: A tutorial," *Technical report, Tutorial, Ecole Polytechnique Federale de Lausanne (EPFL)*, 2003.

[15] F. Kelly, A. Maulloo, and D. Tan, "Rate control for communication networks: Shadow prices, proportional fairness and stability," *Journal of Operations Research Society*, vol. 49, p. 237252, March 1998.

[16] H. J. M. Peters, *Axiomatic Bargaining Game Theory*. Kluwer Academic Publishers, 1992.

[17] A. Perez-Neira and M. Realp, *Cross-Layer Resource Allocation in Wireless Communications. Techniques and models from PHY and MAC layer Interaction*. Elsevier Science and Technology. Academic Press, 2009.

[18] S. Koskie and Z. Gajic, "SIR-based power control algorithms for wireless CDMA networks: An overview," *In International Conference on Dynamics of Continuous, Discrete and Impulsive Systems, Guelph, Ontario*, 2003.

[19] R. D. Yates, "A framework for uplink power control in cellular radio systems," *IEEE J. Select. Areas Commun.*, vol. 13, pp. 1341–1348, 1995.

[20] M. Schubert and H. Boche, "QoS-based resource allocation and transceiver optimization," *Foundations and Trends in Communications and Information Theory*, vol. 2, p. 383529, 2005.

[21] Q. H. Spencer, A. L. Swindlehurst, and M. Haardt, "Zero-forcing methods for the downlink spatial multiplexing in multi-user MIMO channels," *IEEE Trans. on Signal Processing*, vol. 52, pp. 461–471, 2004.

[22] "Cognitive radio technology, dedicated issue of IEEE signal processing magazine, vol. 25, no. 6, November 2008."

[23] R. Ahlswede, N. Cai, S.-Y. Li, and R. W. Yeung, "Network information flow," *IEEE Trans. on Information Theory*, vol. 46, pp. 1204–1216, 2000.

[24] "Challenges in multi-terminal communications, dedicated issue of IEEE signal processing magazine, vol. 24, no. 5, September 2007."

[25] A. M. Kuzminskiy and Y. I. Abramovich:, "Nonstationary multiple-antenna interference cancellation for unsynchronized OFDM systems," in *in Proc. IEEE International Conference on Acoustic Speech and Signal Processing, Las Vegas, April*, 2008.

[26] A. M. Kuzminskiy and Y. I. Abramovich, "Nonstationary multiple-antenna interference cancellation for unsynchronized OFDM systems with distributed training," *EURASIP Signal Processing*, vol. 89, pp. 753–764, May 2009.

[27] D. J. Love, R. W. Heath, V. K. N. Lau, D. Gesbert, B. D. Rao, and M. Andrews, "An overview of limited feedback in wireless communication systems," *IEEE Journal on Selected Areas in Communications*, vol. 26, pp. 1341–1365, Oct. 2008.

[28] "Sport views: 'final report' (www.sportviews.org), May 2007."

[29] R. S. P. Group, "Opinion on wireless access policy for electronic communications services (WAPECS): A more flexible spectrum management approach," 2005.

[30] O. Rietkerk, G. Uitema, and J. Markendal, "Business models enabled by ambient networks to provide access for anyone to any network and any service," *Ambient Network publication, the Helsinki Mobility Roundtable*, 2006.

[31] P. Ballon, "Business scenarios, challenges and role models for next generation wireless systems and services: the WWI perspective," *Wireless World Initiative Cross Issue Business Models White Paper*, 2006.

[32] D. Raychaudhuri, "Future wireless network architecture and business models," in *Presentation at 4WARD BIRD Workshop*, 2008.