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Spectrum Micro-trading Analysis

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Abstract:

This deliverable reports the main achievements from the study on spectrum micro-trading in the QoSMOS project. The main goal and contribution of this research is on defining metrics for spectrum micro-trading. Several areas within spectrum micro-trading are studied in order to define these metrics which on their own are key contributions; the survey of state of the art and related work in the literature and by regulators, the definition of an ecosystem, the characterisation of necessary information to enable spectrum micro-trading, the specification of a flexible and practical model referred to as the "spectrum micro-trading pixelation" model and finally the implementation of a simulator based on multi-agent reinforcement learning used to study a spectrum micro-trading market.

Keyword list:

Cognitive Radio, Spectrum Trading, Spectrum Micro-trading, Spectrum Market, Trading Metrics, Ecosystem

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Abbreviations

ACE	Agent-based Computational Economics
ACI	Adjacent Channel Interference
AP	Access Point
BER	Bit Error Rate
BM	Band Manager
CAPEX	Capital Expenditure
CCI	Co-Channel Interference
CDMA	Code Division Multiple Access
CEPT	European Conference of Postal and Telecommunications Administrations
CF	Cash Flow
CM-RM	Cognitive Manager – Resource Manager
CM-SM	Cognitive Manager – Spectrum Manager
COGEU	COGnitive radio systems for efficient sharing of TV white spaces in European context (EU FP7 project)
DCF	Discounted Cash Flow
DSA	Dynamic Spectrum Access
DoS	Denial of Service
EBITDA	Earnings Before Interests, Taxes, Depreciation, and Amortization
ECC	Electronic Communications Committee
FCC	Federal Communications Commission
GRGR	Global Regulator Repository
IMT	International Mobile Telecommunication
ISD	Inter Site Distance
LTE	Long Term Evolution
M2M	Machine to Machine
MIMO	Multiple Input – Multiple Output
NOBM	No Band Manager

NPV	Net Present Value
Ofcom	Office of Communications
OPEX	Operational Expenditure
PLPD	Piecewise Linear Price-Demand
QoE	Quality of Experience
QoS	Quality of Service
ROI	Return On Investments
SENDORA	SEnsor Network for Dynamic and cOgnitive Radio Access (EU FP7 project)
SINR	Signal to Interference and Noise Ratio
SIR	Signal to Interference Ratio
SISO	Single Input Single Output
SPRR	Spectrum Provider Repository
TCE	Transaction Cost Economics
TVWS	TV White Space
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network

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1 Executive Summary

This deliverable reports the main achievements from the study on spectrum micro-trading in the QoSMOS project. The main goal and contribution of this research is on defining metrics for spectrum micro-trading. Several subjects are investigated in the process of defining the metrics which also are considered as key contributions. The first step in this process is to survey state-of-the-art and related work on spectrum trading in the literature and by regulators. Next, the ecosystem required to introduce spectrum micro-trading is described defining roles and actors. Furthermore, the information and parameters necessary to support spectrum micro-trading is characterised before a flexible and practical model to support spectrum micro-trading is proposed. Finally, a simulator based on multi-agent reinforcement learning is implemented and used to analyse a spectrum micro-trading market and to test some of the metrics defined.

Spectrum micro-trading can be defined as the possibility to buy and sell spectrum resources on a smaller scale than has currently been used in one or more of the spatial, temporal and frequency dimensions. This would enable wireless service providers to acquire spectrum for small or wide geographical areas, for short or long time periods and for narrow or wide bandwidths. Hence, spectrum utilization and the opportunity to acquire spectrum resources might increase when optimizing metrics and specifying policies properly.

The ecosystem defined for the spectrum micro-trading market consists of the following main actors;

- *Spectrum traders* sell, buy, lease or rent spectrum in the market. Actors taking on this role are spectrum license owners, secondary cognitive radio operators and spectrum speculators.
- *Spectrum brokers* arrange transactions between the traders.
- *Spectrum database operators* maintain information about the spectrum to be traded, and trade this information.
- *Wireless sensor networks* can be used to monitor and gather information about spectrum to be traded.
- The *spectrum regulator* should be interested in high utilization of spectrum and has the main task to set out the rules, policies and processes that must be adhered to in a spectrum market.

A final set of actors in the ecosystem are the vendors which are important to implement hardware and software systems for the above actors. Note that other actors such as an actor taking care of payment between traders could be included, but these are left out in the scope of this report.

The main parameter identified that enables trading between different actors is the information about available spectrum resources, which can be defined by its spatial, temporal and frequency dimensions. Other parameters such as maximum transmit power and regulatory constraints on spectrum resource usage are also identified.

A model referred to as the “spectrum micro-trading pixelation” model is then proposed, whose main aim is to implement spectrum micro-trading in all dimensions; the micro-spatial, micro-temporal and micro-frequency scale. Each dimension is defined as pixels whose micro-granularity can be specified to fixed parameters for optimized performance by using the metrics defined. Furthermore, a qualitative analysis of auction design for spectrum micro-trading is given as a first step that should be subject for further study. The auction design is characterised by the following:

- bidder granted multiple spectrum bands,
- asynchronous bids in the temporal dimension with a maximum limit on time granted,
- bidder granted all or nothing in the spatial dimension,
- substitutable/non-substitutable:
    - substitutable in the frequency dimension with option to require consecutive bands,
    - non-substitutable in the temporal dimension, and
    - non-substitutable in the spatial dimension,

- sealed bids,
- first price.

A focused study of metrics for the evaluation of spectrum-micro trading systems and markets results in the definition of 10 key metrics;

1. *Liquidity*: is the market viable?
2. *Trading volume*: is the market sustainable?
3. *Spectrum price*: is there excess in supply or demand?
4. *Profitability*: is the actor's participation in the market profitable?
5. *Blocking ratio*: is the market viable?
6. *Spectrum exploitation efficiency*: how well does the market and allocation algorithm exploit spectrum resources?
7. *Spectrum allocation delay*: does the allocation algorithm or auction cause market overhead?
8. *Interference*: does the market and allocation algorithm satisfy interference constraints?
9. *User experience*: how do actors participating in the spectrum market perceive QoS and QoE?
10. *Social welfare*: does the spectrum market increase the well-being of the entire society?

These metrics might be specific to one or more of the actors defined in the ecosystem; for example, social welfare could be specific to the regulator. A measure is defined for each of the quantifiable metrics.

Finally, the "spectrum micro-trading pixelation" model is used as basis to implement a simulator for spectrum micro-trading using multi-agent reinforcement learning and Q-learning heuristic. For our market study to test the metrics, we consider the "cellular extension in white spaces" use case [D1.2] in which the service providers acquires additional spectrum through the spectrum micro-trading market. The service providers act as spectrum traders. A realistic scenario for service providers demanding additional spectrum over a 24-hour period is studied. We focus on the average reward when evaluating performance in our simulator. We show that the service providers participating in the market are learning not to bid excessively high as demand increases. It is also found that when smaller bandwidth units are used in the "spectrum micro-trading pixelation" model, the average reward increases since it allows the spectrum users to bid for the actual required spectrum rather than having to bid for too much. Smaller bandwidth units will also enhance the spectrum exploitation efficiency. We also study the introduction of an additional service provider that does not hold existing spectrum, and show that the average reward (economic utility) still only gradually falls as the peak demand increases. This indicates the potential for new entrants in the spectrum micro-trading market.

2 Introduction

Spectrum trading, also referred to as secondary trading of spectrum, allows the holders of certain spectrum licences to transfer or lease all or part of their rights and obligations under their licence to another party. Several countries have implemented spectrum trading, but the trading process is often time consuming, hence hampering the usage. Lack of incentive to trade, though, is probably the greatest impediment. The UK regulator Ofcom is at the forefront on the spectrum trading arena, allowing trading in terms of both sale and leasing of spectrum rights [Ofcom11]. Ofcom has also taken steps towards streamlining the trading process and allowing trades without requiring notifications in advance of the actual trades. We consider these steps to be in the direction of spectrum micro-trading which has the potential to improve spectrum utilization and promote innovation.

Spectrum micro-trading can be defined as the possibility to buy and sell spectrum resources on a smaller scale than has currently been used in one or more of the spatial, temporal and frequency dimensions. This would enable wireless services to acquire spectrum for small or wide geographical areas, for short or long time periods and for narrow or wide bandwidths. Hence, spectrum utilization and the opportunity to acquire spectrum resources might increase when optimizing metrics and specifying market policies properly.

Note that spectrum micro-trading is a larger category than spectrum real-time trading which requires a trade to be committed in real-time when the spectrum is going to be used. Real-time trading will therefore require tight time constraints. Spectrum micro-trading could be real-time, but could also be non-real-time where a trade is committed some time in advance of the actual spectrum use. Non-real-time trading will enable the use of more complex trading models which require longer time to execute.

To describe the micro-scale at which the spectrum micro-trading market can operate, we refer to the definition of spectrum micro-trading above and discuss the micro-scales for all three dimensions. For the micro-spatial scale, the market should support spectrum transfers of small areas such as down to $10m^2$ for short-range systems such as M2M and 60GHz. For the micro-frequency scale, the market should support transfers of narrow frequency blocks such as down to 100 kHz for narrow-band systems such as wireless microphones. For the micro-temporal scale, the model is required to support short time intervals between spectrum transfers such as down to one second for systems such as wireless metering. It should be noted that the spectrum micro-trading market should also support systems requiring larger scales of each dimension such as mobile broadband.

Most trades today are direct trades between organizations with the regulator as an intermediate giving the final consent to commit the trades. However, in order to facilitate spectrum trades on a shorter time scale an organizational unit such as a band manager could be introduced to mediate between traders. Furthermore, organizational units could be introduced to monitor for compliance with committed trades and to ensure that the spectrum is not misused. Overall, an ecosystem with the necessary actors is required in order to realize the implementation and sustainability of a spectrum micro-trading market. In this report we describe the ecosystem required for spectrum micro-trading and discuss the responsibilities and critical challenges for each of the actors in the ecosystem.

Spectrum micro-trading is a relatively new area which raises many questions related to the requirements of such a system: how can we establish a viable market for spectrum micro-trading?; how can we measure the performance of such a market?; how will it impact the quality of the channels in wireless systems?; and will social welfare be improved or negatively impacted? By studying state-of-the-art on spectrum trading in the literature, we notice that many different metrics are used to study the performance of the assumptions and models used. The main task of this work is to define the main metrics for spectrum micro-trading that can be used to measure the performance of a spectrum micro-trading market.

Many models for spectrum trading have been studied, using different simulation tools and methods. These include discrete-event system simulations [Peha04], multi-agent reinforcement learning [Abji10][Abji11], agent-based computational economics [Tonm06][Caicedo09][Caicedo11], and game theory [Niyato08][Niyato09]. Many of these tools and models are found to be suitable for the modelling of a spectrum micro-trading market; however, we find limitations in that none of the models currently support implementation of spectrum micro-trading in all dimensions (spatial, temporal, frequency, price). Therefore, we propose a model with high flexibility referred to as the "Spectrum Micro-trading Pixelation" model, of which the main aim is to implement spectrum micro-trading in all dimensions, especially on the micro-spatial, micro-temporal and micro-frequency scale. Furthermore, we discuss the major challenges that are introduced with spectrum micro-trading and the proposed model; e.g., what is the optimal time step between trades in the market; what is the minimum area that can be traded; and should the spectrum bandwidth be minimal or should entire channels be traded?

To analyse the spectrum micro-trading model and market, we implement a spectrum micro-trading simulator with bid-proportional auctions. End-users use a multi-agent reinforcement learning mechanism [Abji10][Abji11] to refine their future bidding behaviour using a heuristic formula from Q-learning theory [Watkins89] based on reward from previous auctions. We consider the "cellular extension in white spaces" use case [D1.2] in which the service providers acquires additional spectrum through the spectrum micro-trading market. The service providers act as spectrum traders. The use-case is a single cell with several service-providers and multiple end-users. A realistic scenario is considered with varying traffic load during a 24-hour period where spectrum demand will exceed supply in the market during busy hours. Performance evaluations presented are focused on the spectrum micro-trading dimensions in time and frequency.

There are four main contributions in this deliverable: first, the definition of an ecosystem, second, the proposal of a flexible and practical model for spectrum micro-trading, third, the key contribution on the definition of the most important metrics for spectrum micro-trading, and fourth, the implementation of a simulator used to model a spectrum micro-trading market and test some of the metrics.

Throughout this report, primary users will refer to spectrum license holders and secondary users to users utilizing unused capacity in the primary license holders' spectrum. A spectrum transfer denotes the sale or lease of a spectrum resource from primary to secondary. A primary user that sells or leases spectrum is referred to as a seller or leaser respectively, and a secondary user that buys or rents spectrum is referred to as a buyer or lessee respectively. The common term for a seller and leaser is transferor, and the common term for a buyer or lessee is transferee.

The rest of this report is organized as follows: background and state-of-the-art in spectrum micro trading is given in Section 3. The ecosystem is described and discussed in Section 4. The parameters and a model enabling spectrum micro-trading are presented in Section 5. The metrics are given in Section 6. The simulator implementation and market study are given in Section 7. The deliverable is concluded and further work is given in Section 8.

3 Background and State-of-the-art on Spectrum Trading

This section presents state-of-the-art in spectrum trading in the literature, in the regulatory and relevant EU projects. In the literature, we focus on the models, metrics and the main results. In the regulatory, we focus on the current policies, rules and processes used in spectrum trading.

3.1 State of the Art on Spectrum Trading in the Literature

Valletti [Valletti01] argues that the current centralized model of spectrum management is highly inefficient and should be replaced with decentralized solutions. Furthermore, he proposes that in the new system, the default rule should endow operators with the highest flexibility, leaving the regulator to monitor the proper working of competition rather than deciding who does what. Especially he discusses the benefits of a market for spectrum, potential market failures and how a spectrum market could work.

Leese et al. [Leese02] look at the economic effects of spectrum trading using a model with few dominant service providers (oligopoly) which are able to trade spectrum licenses. The trade is modelled as a two person bargaining problem. They have shown that trade can enhance the productive efficiency of the service provision, likely through spectrum pricing optimization and more efficient spectrum use. They also show that this may have negative impact on the service consumer prices resulting in negative welfare implications.

Peha et al. [Peha04] quantitatively assess real time secondary markets for the special case of a cellular license-holder. They demonstrate that many secondary users can access spectrum with little impact on the primary cellular customers, and that cellular carriers may profit even if the price for secondary access is quite low. The results also indicate that the break-even price of secondary access (i.e. the per-minute rate that the carrier needs to charge each secondary call in order to generate the same revenue as in the case where there is no sharing) would be roughly proportional to bandwidth, and to distance from secondary transmitter to its receiver. In [Peha09], Peha discusses policies that can enable or facilitate use of many spectrum-sharing arrangements. The arrangements are categorized as being based on coexistence or cooperation and as sharing among equals or primary-secondary sharing.

Xavier & Ypsilanti [Xavier06] focus on the policy issues relating to the development of well-functioning secondary markets for spectrum. The main finding states that while there is a persuasive case for spectrum trading, countries have been slow to introduce it because of a number of concerns in regards to spectrum trading and liberalization (year 2006). The main concerns are low spectrum trading activity, inefficient use of spectrum, high transaction costs of spectrum trading, risk of increased interference, impact on anti-competitive conduct, impact on investment and innovation, impact on international co-ordination, windfall gains, disruptive effect on consumers, and reduced ability to achieve public interest objectives.

Tonmukayakul & Weiss [Tonm05],[Tonm06] and [Tonm08] use Transaction Cost Economics (TCE) as a framework to examine the relationship between transaction characteristics and suitable organizational forms to carry out the transactions. TCE identifies markets and firms (hierarchy) as two polar forms in which a transaction between buyer and supplier can take place. Furthermore, an Agent-based Computational Economics (ACE) model is used as a tool to model the development of transactions in secondary spectrum use. In [Tonm06], it is shown that if the transaction costs of secondary use are relatively high, allocating additional spectrum for unlicensed use may be more desirable. Furthermore, it is shown that the additional unlicensed spectrum is highly beneficial to spectrum users with small coverage area in a high density setting, whereas the secondary spectrum use is a preferred method for spectrum users with large coverage area and rigid application requirements. In [Tonm08], it is shown that the secondary use is a viable alternative for spectrum users who find the exclusive licenses too expensive or the unlicensed band too crowded. They also note the important fact that auction-based secondary use only emerges when there is sufficient number of secondary traders in the market.

Caicedo & Weiss [Caicedo07] analyse several proposed kinds of trading interactions that may arise in a spectrum trading market and propose taxonomy of architectures that could be used to implement them. Furthermore, they discuss benefits and limitations of using a single or restricted set of wireless standards in the implementation of a spectrum trading infrastructure as a step towards wireless bandwidth trading. The paper highlights the importance of a regulatory framework for spectrum trading to be realized, with the requirements that it protects transmission rights, deters spectrum hoarding, promotes information transparency (for trades) and liberalizes spectrum use.

Caicedo & Weiss focus on determining the conditions for viability of spectrum trading markets by considering scenarios with different market structures, number of trading participants and amount of tradable spectrum by using ACE to analyse each market scenario and the behaviours of its participants [Caicedo09][Caicedo11]. The spectrum users bidding for spectrum can obtain resources to serve traffic by either acquiring spectrum in the form of spectrum units in the trading market or investing in a unit of transmission of an alternate technology. The choice between the two options is based on the economic benefit a spectrum user might receive from making a selection as it tries to minimize its costs for providing wireless service. They determine the viability of spectrum trading markets with respect to liquidity and sustainability characteristics using metrics such as midpoint price for spectrum bandwidth units, relative bid/ask spread, percentage of offered spectrum and number of completed market runs. They indicate that spectrum markets can be viable in a service if sufficient numbers of market participants exist and the amount of tradable spectrum is balanced to the demand. Interestingly, they conclude that given that a minimum of five to six active spectrum users (wireless service providers) are necessary in a particular service area, it seems unlikely that spectrum markets will be viable in mobile markets unless the barriers for market entry for new service providers are lowered. Also, they conclude that it will be important to develop useful (and observable) proxies that enable regulators to estimate how well markets are balanced. In this report we address this latter point by having wireless sensor networks as actors able to monitor the spectrum use and regulators able to establish policies that allow it to retrieve information from spectrum database operators and spectrum brokers.

In Caicedo's PhD thesis [Caicedo09], he concludes that market environments (that meet the conditions of the viability region identified in his thesis) can be achieved where the number of market participants will be large enough (≥6 for scenarios without a Band Manager (NOBM) and ≥10 for Band Manager (BM) scenarios where the BM matches asks and bids from spectrum traders) and where the amount of spectrum available for trading will not generate oversupply situations. BM based markets are more sensitive to spectrum undersupply and oversupply conditions than NOBM markets but if spectrum is available at an amount enough to serve the average traffic demands of the secondary units, then NOBM scenarios can work with a number of users as low as 5. In this report, we will base our definition of the viability metric on the work presented by Caicedo.

Weiss and Liu [Weiss11] present the concept of interference rights as instruments analogous to covered financial options that may be written by license holders. They conclude that interference rights offer some advantages to exclusive usage rights from three perspectives; First, primary users can partially sell their spectrum depending on the trade-off between losing customers and earning leasing fees. Second, regulators have less involvement in the trading process, which reduces the transaction cost. Third, it improves the spectrum utilization since primary and secondary subscribers can co-locate and use smaller guard bands.

An auction based approach for service provider spectrum trading was studied by Abji & Leon-Garcia in [Abji10] and [Abji11] using a bid-proportional auction and multi-agent reinforcement solutions. In [Abji10], they show that when there is a single provider, revenue can be maximized by artificially limiting supply and creating contention. However, when there are multiple providers from which the customers can dynamically choose, there is no longer an incentive to restrict supply between service providers. They demonstrate that the allocation of spectrum is efficient and fair [Abji11]. Furthermore, customers and service providers of varying size are shown to benefit from the approach while system spectrum efficiency is also significantly improved. In this report, we will implement a simulation model based on the work presented in [Abji10].

Xu et al. present a dynamic double auction mechanism, which makes it possible for users to bilaterally trade their channel holdings, where cognitive users are sellers and buyers such that trading happens between cognitive users themselves instead of the model where primary users transfer spectrum to secondary users [Xu10a][Xu10b]. In [Xu10b] they present an algorithm to solve the trading decision making problem based on a portfolio optimization framework widely used in finance. Each channel is viewed as a unique stock with dynamic characteristics that each user keeps track of, and at each trading period an optimization problem is solved to maximize the utility of the channel portfolio with budget and quality-of-service constraints. In this report, we propose a model that both supports the model where cognitive users trade between themselves and the model where primary users transfer spectrum to secondary users.

Huang et al. propose two auction mechanisms for allocating received power amongst users in a spread spectrum system [Huang06]. One auction charges for a received SINR while the other charges for a received power. The mechanism maintains that the interference temperature [FCC02], [FCC03b], [Kolodzy06] at a particular measurement point is kept below a particular threshold. In this work the measurement point and receivers are collocated. In [Huang08] the auction mechanisms proposed in [Huang06] are extended for resource allocation in systems with relays. This includes systems with both multiple-hops and multiple relays.

Gandhi et al. [Gandhi07] propose a spectrum auction framework for low-complexity, fast resource allocations. The framework uses simple piecewise linear price-demand (PLPD) bids where a user can show their demand for spectrum at different unit prices. Various pricing models are compared to show the tradeoffs between revenue and fairness. Conflict graphs are used to identify neighbouring users who could cause interference.

Chapin & Lehr [Chapin07a] provide an overview of potential market success for DSA. This includes the identification of potential value chains. Options for cooperative and non-cooperative DSA are outlined. [Chapin07b] proposes that certain radio hardware systems be provided with (and only be licensed to operate with) a licence deeply embedded in the hardware, and this licence automatically stops the operation of the radio after a predefined period. The motivation is to allow operation in circumstances in which the regulator is not certain that interference will not be caused. Thus a learning period is allowed, after which the licence might be extended if no adverse effects were observed.

Sengupta et al. [Sengupta07] look at a system where service providers already have their own static spectrum allocations. They lease extra spectrum to meet user demands. The end users then select service providers on short timescales, thus creating a two-tier trading system; there is a spectrum broker to sell spectrum to service providers and a service broker to sell service provider capacity to users. Sengupta et al. [Sengupta08] list three important issues behind auction design for dynamic spectrum access in attracting bidders, preventing collusion to prevent bidders from controlling the auction and finally maximizing auctioneer’s revenue. Furthermore, they investigate auction mechanisms for DSA and provide a classification of auctions which we will follow in this deliverable for analysis on auction design for spectrum micro-trading.

Niyato et al. [Niyato08] first surveys spectrum trading in general, then proposes an approach appropriate for situations in which there is no central spectrum broker, but rather a distributed set of traders. In such conditions, there will be imperfect information about offered prices. So the authors propose a learning algorithm, which is really just an exponentially-weighted moving average of past prices. In [Niyato09] they also look at an approach where there is no central spectrum broker (i.e., involving multiple sellers and multiple buyers of spectrum). Buyers can adjust buying behaviour by monitoring variations in the price and quality of available spectrum opportunities. Sellers adapt their pricing of spectrum opportunities to maximise their utility functions.

Bae et al. [Bae08] provide a discussion of the potential for spectrum markets, mainly considering cellular deployments. A two-tier spectrum market structure is discussed, where local spectrum auctions can take place, which could lower barriers to entry for the wireless services market and improve competition.

Spectrum leasing is based on a cooperative network and opportunistic routing by Stanojev et al. in [Stanojev10]. Essentially, secondary users bid for the time slots that the primary user would have used for a retransmission. The secondary users can act as a relay to retransmit a primary user's failed transmission and can use the rest of the timeslot for itself. An auction mechanism is proposed that only requires local interactions to show that there is potential for this scheme to be used for secondary trading.

Zargar et al. presented a study on security issues in both market-based and MAC-based Dynamic Spectrum Access (DSA) networks in [Zargar09]. For market based DSA networks they identify various attacks such as Denial of Service (DoS) attacks, system penetration, repudiation, spoofing, authorization violation, malware infection, data modification and suggest various approaches to address these. They conclude that convincing spectrum owners to implement secure DSA on market-based DSA is more likely since the service providers are being compensated. In doing so, service providers would allow for competition in business between the various providers as they are offering a more attractive (secure) product for a given price. They further state that the market based DSA option is a more "business friendly" approach than the simple MAC-based DSA in which, though the services are free, they are not regulated or guaranteed to be secure. In this report, we will not focus on security in the spectrum micro-trading market, but we note that it is an important topic.

Jin et al. studied a contract based spectrum trading market with insurance in which spectrum trades are done between primary users (PUs) and secondary users (SUs) [Jin12]. They modelled a hybrid market consisting of a spectrum market and an insurance market in which the players have incomplete knowledge of each other's characteristics. The primary and secondary users have double identities in which they act as spectrum sellers and buyers as well as insurance sellers and buyers. The insurance is thought of as an incentive towards the secondary users to buy spectrum from the primary users. Jin et al. considered a cognitive radio network with one primary operator (PO), multiple PUs and multiple SUs. In the model, the PO can be a base station or an access point. The SUs are dedicated Tx-Rx pairs. When the SUs have packets to send they need to purchase a channel from a PU. The insurance market part is that the PU can offer and sell an insurance contract to the SU against transmission failure due to low SINR. The SUs are classified according to high and low risk for interference (accident probability). SUs can decide whether they will buy insurance together with the spectrum or not. Insurance is offered in two types designed for high or low risk. SUs have private knowledge of their own risk and have an incentive to misrepresent their risk types and sign contacts for low risk insurance. If transmissions fail, the SU can file a claim towards the PU. It is then up to the PU to perform a risk verification, which also has a cost attached to it. Thus, the PU has to evaluate the cost related to accepting the claim or performing risk verification, and possibly determine whether the SU is cheating. Most of their work consists of showing the different players strategies and in the end they also conclude that the use of insurance as an incentive for trading increases spectrum utilization and the utilities for both PUs and SUs. The insurance part of this market model could improve the secondary users' QoS performance.

3.1.1 Related work in the EU FP7 Project COGEU

We consider the EU FP7 project COGEU, COGnitive radio systems for efficient sharing of TV white spaces in European context, as related work. In [COGEU11b], two modes of spectrum trading are investigated; the merchant mode and the auction mode. Merchant mode is used when demand is less than the offer and auctions mode is used when demand is higher than the offer. The merchant mode uses administrative incentive pricing (AIP) to determine price, whereas the auction mode uses auction approaches with the recommendation sealed-bid, first-price and time-simultaneous/combinatorial. Their proposed time granularity of auctioning is 1 hour in urban areas with 24 hour allocation period cleared every day, and 1 week in rural areas with 4 weeks allocation period cleared every month. They also propose a set of metrics to evaluate the market; sum of players' demands, sold spectrum, auction efficiency, valuation of sold 1 MHz and LTE user satisfaction rate. Simulation studies in [COGEU11b] are also reported in the two publications [Mwangoka11] and [Parzy11].

A multiple-dimension auctioning mechanism through a broker to facilitate an efficient secondary spectrum market is proposed by Mwangoka et al. [Mwangoka11]. Auction is used for trading where a multiple-winner determination problem is used and cast into a multidimensional multiple-choice knapsack problem. Two heuristics for spectrum allocation are used to solve the multiple-winner determination problem, an area-by-area algorithm and a maximum-utility-first algorithm. They find that the former is better for the operator because it has the potential of lowering running costs by avoiding roaming costs, and that the latter is better for fixed services and that it has the potential of enabling start-ups to acquire spectrum bands and compete in their locality.

Parzy et al. [Parzy11] considers a spectrum sharing approach in TVWS using a combinatorial auction of non-identical objects when considering the bandwidth and power requirements of the secondary mobile operators. They define a spectrum allocation problem as an optimization problem to maximize the spectrum broker's profit, and show by simulations that their solution is efficient in the case of spectrum broker's profit maximization and spectrum usage efficiency.

3.2 Background on Spectrum Trading by Regulators

Spectrum trading has been addressed and allowed by many regulators. A detailed overview is given by the EU FP7 project COGEU in [COGEU11a]. In the following we give some details about state of the art on spectrum trading by Ofcom, FCC and ECC/CEPT.

3.2.1 Ofcom

Many regulatory issues related to spectrum trading at higher time scales have been addressed by the UK regulator Ofcom (Office of Communications) [Ofcom04a], [Ofcom04b], [Ofcom04c], [Ofcom08]. This involves topics such as what type of transfers are possible (total or partial licence), the steps and information required in a transfer process, authorization of a transfer and the legal background. The authors of this deliverable consider that many of the issues discussed will be applicable for a spectrum micro-trading market, but that the trading process is often complex and should be automated in order to execute on a micro time-, geographical- or frequency scale. However, it is important to maintain the security and trust while automating this. Therefore it is important with well-defined interfaces and contracts between the actors that participate in a spectrum market.

Consent from Ofcom is required before a trade can be put into effect. Ofcom ensures that the spectrum holder licence obligations have been fulfilled, that fees for the licence have been paid and that security or international obligations are not compromised by the trade.

Two different types of transfers are allowed by Ofcom [Ofcom04b]; (i) outright transfer in which all rights and obligations of a license transfer from one party to another, and (ii) concurrent transfer in which the transferred rights and obligations become rights and obligations of the transferee (could be buyer or leaser) while continuing, concurrently, to be rights and obligations of the person making the transfer. Such a transfer enables licensees to share rights to use spectrum. Furthermore, Ofcom allows both a total transfer in which the whole licence is transferred and a partial transfer in which only some rights and obligations of the licence in certain cases. To summarize, Ofcom regulates the different ways to identify the different spectrum transactions as illustrated in Table 3-1.

Table 3-1: Combination of spectrum transfer types regulated by Ofcom

	Total transfer	Partial transfer
Outright transfer	All rights of the license are transferred to the transferee.	All rights for a part of the license are transferred to the transferee.
Concurrent transfer	Some rights of the license are transferred to the transferee.	Some rights for a part of the license are transferred to the transferee.

To give an example we consider the most complex combination; concurrent transfer and partial transfer. Suppose that a primary user holds a nationwide license of 10 MHz in the 2.6 GHz with duration 20 years that it wants to sell on the spectrum micro-trading market. An example would be that a secondary trader rents 5 MHz for a subset of the area such as a city in the nation for one month. In this case, the transfer is concurrent in that the secondary trader rents the spectrum resource, and the transfer is partial in all spatial, temporal and frequency dimensions.

Spectrum trading in the UK has been limited to certain bands, but a notice of proposals to extended spectrum trading to mobile and cellular bands (900 MHz, 1.8GHz and 2.1 GHz) was published in [Ofcom11].

Recently, Ofcom introduced spectrum leasing which mainly differs from the spectrum transfer in that the responsibility for compliance with the licence regulations remains with the spectrum lessee (the one leasing the spectrum). Furthermore, Ofcom has taken steps towards simplifying the spectrum trading by simplifying the leasing process and allowing limited sub-leasing [Ofcom11]. We see this as a step in the direction of micro-trading for leasing of spectrum.

3.2.2 FCC

The US regulator FCC (Electronic Communications Committee) introduced spectrum trading in [FCC03a] and simplified the scheme further in [FCC04a]. It distinguishes between the transfers of:

- de jure rights (assignment of the licence to another party) and
- de facto control (the transferee retains the licence and legal responsibilities, but transfers management control of the spectrum).

The process to trade spectrum is quite straightforward where an application to transfer spectrum between two parties is submitted to FCC and published online. Other parties then have 30 days to request FCC to reconsider the transaction and FCC themselves has 40 days to reconsider the transaction before it is executed. We note that this process could work in a spectrum micro-trading market, but it is notable that the time constraints would limit the flexibility and speed of spectrum transfer. It should also be noted that real-time spectrum trading not would be supported with this process.

FCC proposed a new concept named the "private commons" to assist with spectrum trading in [FCC04b], which basically can be explained by the primary-secondary regime where a secondary user; e.g., a cognitive radio, adjusts its spectrum usage to take advantage of under-used spectrum. This is only allowed device-to-device communications and not end-to-end infrastructure based communications.

3.2.3 Europe

The Electronic Communications Committee (ECC) within the European Conference of Postal and Telecommunications Administrations (CEPT) has collected information on current practices of spectrum trading in [ECC11], It describes how countries approach trading possibilities, whether trades can be for an entire frequency allotment, the geographical area of the spectrum rights that can be traded and the duration of the trade.

It distinguishes between “general authorizations” and “individual rights of use” (usage rights). The first is basically the type of regulation used for licence exempt bands like the 2.4 GHz ISM band. Frequency bands under general authorization are not tradable.

Individual right of use is what commonly is referred to as licensed bands, like e.g. the IMT bands. Legal frameworks for spectrum rights are regulated at the national level and there are no CEPT recommendations addressing these. However, within EU there is a harmonised regulatory framework for rights of use, which are transferable, in the context of Electronic Communications Networks & Services (ECN&S). The framework also distinguishes between trading and leasing with a focus on trading.

In Europe, 18 of the 22 CEPT countries allow trading of usage rights. It has been allowed since 1997 (in Denmark) and most of the other countries opened for this between 2002 and 2006. Specific procedures for spectrum transactions are similar to the ones proposed by FCC, which may include:

- Notification of the intention to trade
- Publication of notified information
- Approval of transaction
- Publication of final transaction

There are specificities in different countries, but basically these four steps are followed. The ECC report [ECC11] contains an overview of the differences.

The ECC gave a general discussion on spectrum trading with some emphasis on how it may affect competition, however there exists little empirical evidence on this issue.

An analysis of trading activity has not been done, due to the limited data, but it is possible to see that there are two scenarios for secondary trading:

- Secondary trading in bands where the number of licenses is high. In this case competition issues do not seem to arise as long as spectrum is used by many different users.
- Secondary trading in bands where the number of licenses is small, such as the mobile network bands. In such cases competition issues may be critical.

In principle, spectrum trading is expected to enhance competition by making it easier and faster for market entrants to gain access to spectrum. However, the risk is that spectrum is concentrated in the hands of a small number of market players (spectrum hoarding). Two countries report to have observed this, the others not. Competition issues can be handled either before or after a transaction. The first implies notification of authorities in advance of the intention to trade, which in fact is a requirement of the EU framework. The second requires conditions attached to licenses that enable revocation of a license on grounds of competition.

Two basic parameters could be used to analyse the secondary market: the number of transactions and the value of the spectrum rights of use.

Leasing of usage rights is allowed in 9 of the 22 CEPT countries. The EU framework does not provide any details of the procedure for spectrum leasing, and ECC has not done any analysis of this.

3.3 Background on Incentive Auctions in TV White Spaces

Legislation is currently being produced in the US to allow for incentive auctions in the TV band [FCC12a][FCC12b]. This would mean that TV broadcasters can give up some or all (in which case they would no longer be broadcasters) of their spectrum allocation. This will be voluntary so a TV broadcaster would likely only release some of its unused allocation. Realignment (also known as repacking) of the TV broadcasters would then follow so that the spectrum that is made available for auction can be more efficiently utilised. The FCC would then auction off this unused spectrum in the

TV band; the proceeds of which would go towards TV broadcasters (This is the “incentive”, plus extra compensation might be due to compensation for realignment process), to contribute towards the US deficit reduction, and also to fund an emergency services network. The FCC hope that these auctions can also provide more good quality spectrum for mobile broadband, which will help to cope with the expected increase in demand for data services over the coming years.

There are currently two forms of legislation competing with each other to create a national public safety broadband network. This legislation would decide the details of such an incentive auction [Wash11]. A key difference is that one form of legislation requires that all auctioned spectrum is sold for licensed use. This would mean that no spectrum is reserved specifically for unlicensed use.

So what are the concerns for TV white space devices? First of all, if TV broadcasters release some of their unused spectrum for auction, then the amount of white space in the remaining broadcasters’ spectrum after realignment will be reduced. If, however, some of the freed up spectrum is reserved for unlicensed use, this would mean that there is now a guarantee that there will always be white space available, whereas previously it had to assume that the primary users didn’t start to use their spectrum more effectively. If, however, none of the freed up spectrum is reserved for unlicensed use, then the amount of white space available would be significantly reduced. The FCC wants to have some TV spectrum for unlicensed use and this is currently receiving support with some senators [WIA12]. If the amount of white space was significantly reduced then providers of services intended for white space use would have to consider buying some of the spectrum in the spectrum auctions.

How does this affect TV white space in Europe? First of all, we have to see how the legislation resolves in Europe. A model has been recommended in EU project COGEU where some TV spectrum can be assigned to unlicensed use while other TV spectrum can be traded using secondary auctions [COGEU11a]. Although a recommended timescale for these auctions is not specified, the model is designed to allow for real-time trading. One current issue with incentive auctions or a broadcaster being involved in secondary trading of its TV spectrum is that public service broadcasters do not function to make a profit and may not be allowed to trade their spectrum allocations for a profit unless it is returned to the government.

3.4 Addressing the Main Objectives of QoSMOS

This report aims to address the main objective in the QoSMOS project; efficient use of spectrum. This is done by analysing spectrum micro-trading that should be able to utilize and trade spectrum on the micro-scale in the spatial, temporal and frequency dimensions. Hence, spectrum micro-trading has the potential to utilize and trade spectrum for short periods, in small geographical areas and for narrow bandwidth increments in the frequency dimension.

A second objective in the QoSMOS project is to address QoS in spectrum sharing and cognitive radio networks. With a spectrum micro-trading market, this is addressed by having contracts between the primary and secondary users (the transferor and transferee). Furthermore, a complete ecosystem involving actors such as the regulator, the spectrum database operators, wireless sensor networks and spectrum broker aims to improve the reliability and to ensure compliance of QoS. Hence, the spectrum micro-trading market can provide QoS for both the primary and secondary users.

4 Ecosystems for Spectrum Micro-trading

4.1 Ecosystem Overview

Spectrum trading is a market-based mechanism where, ideally, buyers and sellers determine the assignments of spectrum and its uses. That is, it can address both the allocation and assignment aspects of spectrum use [Caicedo09].

The ecosystem will be very similar to the general ecosystems for telecommunication markets and cognitive radio networks, studied by Grøndalen et al. [Grondalen11]. But an entity such as a spectrum broker that arranges transactions between spectrum sellers and buyers might be necessary in order to mediate between sellers and buyers (actors) in most market structures. A typical topology of actors is in shown in Figure 4-1.

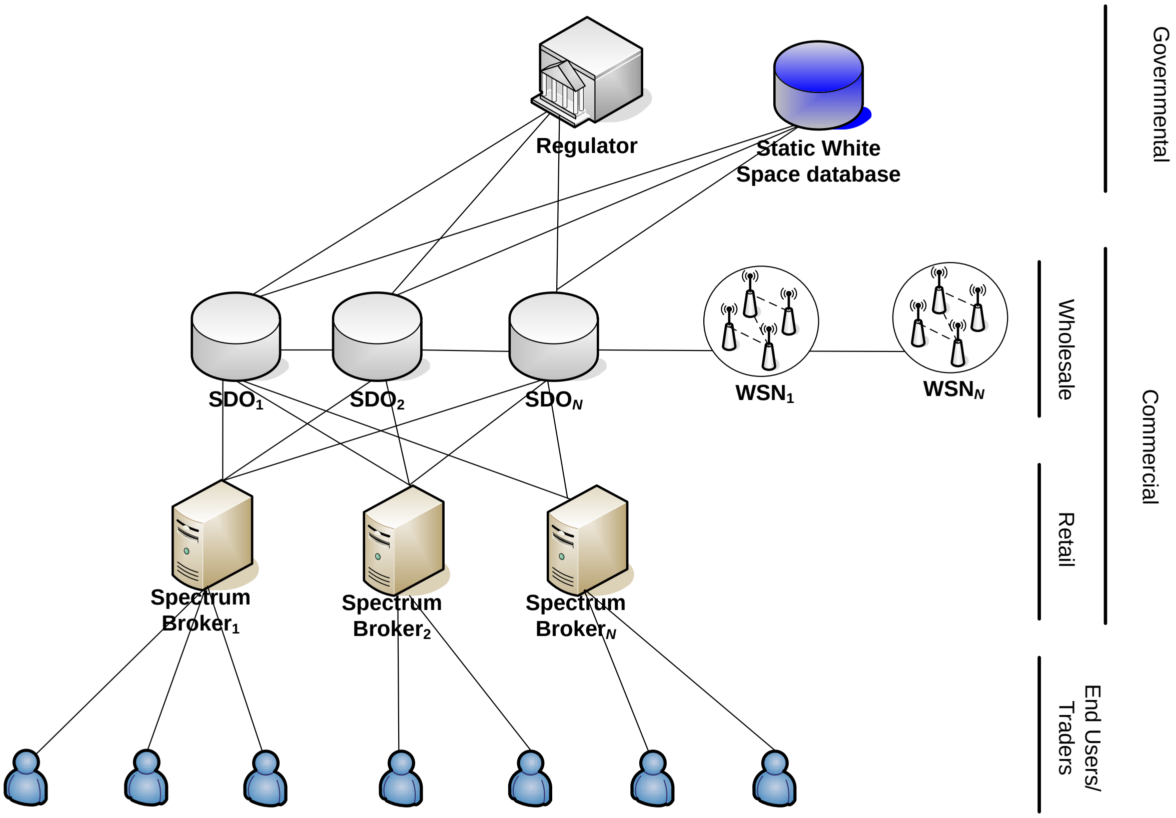


Figure 4-1: Typical actors in an ecosystem for spectrum trading

When defining the ecosystem, we first focus on the actors involved in a spectrum market. Furthermore we will analyse each of these actors to see what type of actors are typically involved. Our ecosystem definition relates to state-of-the-art where many of these actors have been identified and used. We consider the ecosystem described in this deliverable to involve the most important actors in order to implement and provide sustainability in a spectrum micro-trading market. The actors in the spectrum micro-trading market are described as follows:

- **Spectrum trader/end user**: an actor who buys, sells, leases or rents spectrum.

- **Spectrum broker**: a commercial actor that mediates at a retail level between a buyer and a seller of spectrum, or between a leaser and lessee of spectrum.
- **Spectrum database operator:** a commercial actor at a wholesale level who maintains an overview of spectrum usage in a given area; e.g., the frequency and bandwidth used in a given area for a specific period. This corresponds to the component SPRR (Spectrum Provider Repository) in the QoSMOS system architecture, for which see [D6.5], Section 4.
- **Spectrum regulator**: a governmental actor which regulates and defines policies for the spectrum market. It might also take the role to control the spectrum market. This corresponds to the component GRGR (Global Regulator Repository) in the QoSMOS system architecture, for which see [D6.5], Section 4.
- **Wireless sensor network (WSN)**: a commercial actor which owns a network of wireless sensors that monitors spectrum and provides a real-time overview of the spectrum status such as occupancy, technology used and interference.

Multiple spectrum brokers, databases and WSNs can be possible in a spectrum market. When implementing the spectrum trading market, a hierarchical structure of physical spectrum brokers and spectrum databases can be required when considering the query and transaction load. It should be noted that not all the actors need to be present. For example, there might not necessarily have to be a WSN if the spectrum information is obtained in another way. A final set of actor in the ecosystem are the vendors which are important to implement hardware and software functionality for devices and systems for the above-mentioned actors. We note that other roles such as a role taking care of payment between roles could be included, but these are left out in the scope of this report. Another potential benefit from introducing the spectrum micro-trading system and ecosystem is the potential to bundle access and infrastructure for trading, but this will not be addressed further in this report.

4.2 Elaboration on the Actors in the Ecosystem

4.2.1 Spectrum Trader

The spectrum trader can further be divided into the following roles:

- **A seller** sells spectrum (e.g. the spectrum owner)
- **A buyer** buys spectrum (e.g. cognitive radio operator).
- **A leaser** rents out spectrum (e.g. the spectrum owner)
- **A lessee** rents spectrum (e.g. cognitive radio operator)

The difference between a seller and leaser is that the former sells the spectrum on a permanent basis whereas the leaser leases the spectrum for a temporary period. Furthermore, each spectrum trader can both be a seller and buyer or a leaser and lessee. It will therefore also be possible for a spectrum trader to speculate in the spectrum market.

The spectrum trading actors that can be expected to participate in the spectrum market are:

- **Spectrum licence holder:** this actor holds the right for spectrum usage that it wants to sell or lease on the spectrum market. Typical spectrum licence holders are TV broadcasters, wireless and mobile operators, the military, radar communications operators, public safety operators (health care, fire brigade, police), and aviation operators.
- **Secondary or cognitive radio operator**: this actor will participate in the spectrum market as a spectrum buyer or lessee in order to buy or rent spectrum. This will typically be a new operator without existing wireless spectrum licences that need spectrum to offer a wireless service. However, a spectrum licence owner (as in the point above) that needs more spectrum in order to serve increasing spectrum demand could also act as a secondary or cognitive radio operator.

- **Secondary or cognitive radio device**: this actor will have the same role as the secondary or cognitive operator, but will differ in that it is the radio device or end user that participates in the spectrum market as a buyer or lessee instead of the operator. This could be machine to machine (M2M) communications such as wireless metering that rents spectrum for a very short period in order to transmit metering information.
- **Spectrum speculator**: this actor will participate in the spectrum market with the intention to make profit by buying spectrum at low prices and selling at higher prices. A spectrum market-maker as used in price driven markets will act as a spectrum speculator.

4.2.2 Spectrum Broker

A spectrum broker in the spectrum trading market is analogous to a broker in the stock exchange market. The spectrum broker can then be defined as a party which arranges transactions between a buyer and a seller or leaser and lessee, and gets a commission when a deal is executed. A spectrum broker might have several additional properties such as providing market information about prices, spectrum details and market conditions.

A spectrum broker would behave different depending on the spectrum marketplace used, but the concept of a spectrum broker could be used in auction-driven, price-driven and order- driven markets.

Little practical experience on spectrum brokerage exists, but in theory several different actors could operate a spectrum broker. A first option is that an independent third party operates the spectrum broker. The third party could either be a non-profit organization established by the regulator or it could be a commercial company aiming at profiting from running the spectrum broker. In both cases, the spectrum broker operator could be independent of the interests of the spectrum sellers or buyers. Another option is that the regulator operates the spectrum broker itself. As a third option, in the case where a primary operator owns many licences that it wants to lease, the primary operator could operate the spectrum broker itself.

The number of spectrum brokers in a spectrum market is not limited to one. Several models are possible. In the simplest model, one spectrum broker organization is responsible for operating the spectrum market and the whole frequency band. In this model, several spectrum brokers operating in a hierarchical structure serving different geographical areas could also be required. In a second model, multiple spectrum brokers could be present where each is responsible for trading a subset of the total spectrum. As an example of this model, each spectrum licence owner could operate its own spectrum broker. In a third model, different spectrum broker organizations could operate different regions or different spectrum bands.

In cases where spectrum bands are unlicensed, the only fee from the traders could be to obtain information about spectrum. In this case, the spectrum broker could operate as a relay towards the spectrum databases. An agreement should be made between the spectrum broker and database in this case.

Note that real-time spectrum trading is different from spectrum micro-trading. If real-time spectrum trading should be supported the spectrum broker will have to operate on very short time scales. In this case, spectrum broker functionality would have to be implemented in devices close to the wireless communication network such as in the base stations. The spectrum broker functionality might also have to be distributed in the base stations as opposed to only using the centralized spectrum broker illustrated in Figure 4-1.

However, if real-time spectrum micro-trading should be supported the spectrum broker will have to operate on very small time scales. In this case, spectrum broker functionality would have to be implemented in devices close to the wireless communication network such as the base stations. In QoSMOS, the spectrum broker functionality could then be implemented in the CM-RM module developed in WP5. The spectrum broker in QoSMOS could be considered as an option to be implemented as part of the CM-SM developed in WP6.

4.2.3 Spectrum Database Operators (SDOs)

A spectrum database contains information about the radio spectrum to be traded. This could be information about who owns the licence of the spectrum, who uses the spectrum, spectrum occupancy, spectrum availability, noise and interference in a spectrum band etc. This information could be retrieved from sensor networks, geo-location database, wireless communication operators or it could be downloaded from databases held by the regulator.

A spectrum database operator is a commercial actor operating at the wholesale level. It has access to the higher regulatory level and competes with other SDOs by attempting to add local value-added services such as specific sensing and PSME information not available in the static global database [D6.5].

The number of spectrum database operators is not limited to one. As an example in the US, 10 spectrum database owners [FCC11a][FCC11b] have applied to operate a database system for the same secondary spectrum resources (TV White Spaces [FCC10]) in the same areas, which is considered to be important for increased innovation. Communication between the spectrum databases is then required since the databases maintain the same spectrum bands.

In a micro-trading market with small increments to be traded in the spatial, temporal and frequency dimensions, it might be challenges related to the speed of these databases for spectrum micro-trading. These databases would also have to be updated on frequent time scales. In this case a hierarchical structure of databases could be required.

4.2.4 Wireless Sensor Network

A wireless sensor network (WSN) will monitor the radio spectrum to be traded for a given area. The WSN can provide much of the same information as a database. However, it can provide more detailed information about the real-time spectrum status such as noise, interference and detailed location information of radio emitters. This information can also be reported (sold) to a spectrum database.

This concept was studied in detail in the EU FP7 project SENDORA [Sendora]. The WSN can be embedded in the cognitive radio terminals, or it can be a separate standalone WSN. It can also be a hybrid approach. The density of the standalone WSN must be sufficiently high to ensure an acceptable probability for detecting primary users. The required density was estimated by [Grondalen11] for the case of a LTE network as the primary system. Solutions for dense sensor networks in WSN aided cognitive radio systems have been proposed and evaluated both economically [Grondalen11] and technically [Gronsund11].

There can be multiple WSN owners present in a spectrum market. First of all, the multiple WSN owners could sense different spectrum bands. Second, multiple WSN owners are important for innovation and for cooperation to drive down costs for information about spectrum status. Multiple WSNs could also cooperate to enhance the performance and reliability of spectrum detection.

As a potential solution to the problem of monitoring compliance of committed spectrum trades and that the spectrum trading regime is not misused, the WSN could act as spectrum police. Sensors could be stationary or mobile operating as the spectrum police. Handhelds with embedded sensors could also go undercover to detect mal usage of spectrum and to monitor compliance of committed spectrum trades.

4.2.5 Spectrum Regulator

The spectrum regulator should be interested in having a high utilization of the spectral resources and that people get high quality services, whilst also ensuring that this is the most efficient use (e.g. better to clear out an old technology to allow a newer perhaps more dynamic technology to be deployed). Efficiency might be defined to include dimensions other than technical signal presence. Since a spectrum market will simplify access to spectrum, enable more dynamic use of spectrum and hence lead to higher spectrum utilization, the regulator will be interested in this. However, with incautious regulation of a spectrum market there might be a risk that the spectrum market will lead to unfair spectrum allocations, increased interference and unhealthy competition. The main task of a spectrum regulator in a spectrum market will be to set out the rules, policies and processes that must be adhered to in a spectrum market. The UK regulator Ofcom and US regulator FCC have implemented spectrum trading as reported in Section 3.2, but especially the trading process must be simplified in order to execute spectrum trades on a micro timescale. It was noted in Section 3 that process involving publication of trades is the most time consuming process. Micro-trading will therefore aim to replace that process by a technical solution providing the same degree of openness (socio-economic and political reasons). We have already seen that Ofcom is taking steps towards a simpler trading process for spectrum leasing [Ofcom11].

An important area for the regulator in a spectrum trading market is to control the impact of trading on competition. This is one of the reasons why long periods are required to execute a spectrum trade such that competition checks can be carried out before committing a trade. Alternatively, ex-post regulation could be used for competition checks and then act if unhealthy competition is found.

In order to oversee the spectrum micro-trading market, the regulator could enforce policies that require the spectrum data base operator and the spectrum broker to log trading activity. As mentioned above, it could also use the WSN to monitor the spectrum trading market, and legal use by the trading actors.

4.2.6 Vendor

Both hardware and software vendors will be important in the ecosystem. For example, terminal, base station and core network vendors are important in order to implement the required cognitive functionality and the trading functions and interfaces in wireless networks. The vendor will also be important for implementing the spectrum broker, spectrum database and WSN.

5 Parameters and Model Enabling Spectrum Micro-trading

This section first identifies the parameters and sufficient level of information needed in the spectrum broker and spectrum databases or exchanged between actors in the spectrum-micro trading market. Second, a model referred to as the "Spectrum micro-trading pixelation" model is defined. Finally, a discussion on auction design for spectrum micro-trading is given.

5.1 Parameters enabling spectrum micro-trading between different actors

The main parameter enabling trading between different actors is the information about available spectrum resources. The available spectrum resource can further be defined by three dimensions; the spatial, temporal and frequency dimensions. The necessary information for a spectrum resource can then be described by

- Spatial dimension
  - Geographical area (coordinates in latitude and longitude)
  - Height extent (meters)
- Temporal dimension
  - Time interval (seconds)
- Frequency dimension
  - Frequency band (Hz)
  - Frequency bandwidth (Hz)

For spectrum micro-trading to be available, the granularity of each of these spatial, temporal and frequency dimensions should also be obtainable by a query to the spectrum database operators.

It should be noted that other dimensions could be considered for trading such as code division multiple access (CDMA), but this will not be considered in the spectrum micro-trading model definition.

For each spectrum resource unit in the spectrum broker, there will be a set of regulatory constraints specified by the regulator. This information should also be available from the database operator and in the spectrum broker enabling spectrum micro-trading. In addition to the above parameters for spectrum resources, such information will typically also include some of the following if specified:

- allowed effective radiated power (ERP) levels,
- height above terrain (HAAT),
- terrain data (e.g. dense woodland, hilly, flat)
- directional antenna radiation pattern,
- spectrum masks,
- limitations on technology allowed to be used (modulation types, duplex mode),
- restrictions on organisations allowed using the spectrum resource.

5.2 A Practical Approach: The "Spectrum Micro-trading Pixelation" Model

5.2.1 Requirements for the "Spectrum Micro-trading Pixelation" model

The main requirement for a micro-trading model is that a required number of parameters and units should be defined such that the trading market can match asks and bids in trades and make them measureable and comparable across a market place. We have especially identified the following parameters and units that could be fixed; price, frequency, bandwidth, location, coverage, maximum transmit power, time and certain technology specific parameters important for trading market functions (e.g. modulation, codes).

The second requirement is that the spectrum micro-trading model should support micro trading in three dimensions; the spatial, the temporal and the frequency dimensions.

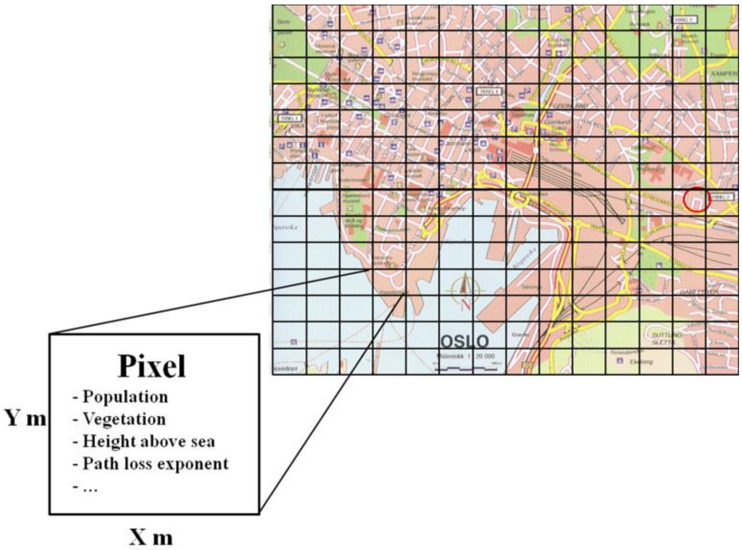
To support micro-trading in the spatial dimension, the model is required to support spectrum transfers of small areas such as down to $10m^2$. Such sizes could for instance be useful for applications such as M2M and personal area communications. However, the areas to be traded should be dynamic such that traders that requiring medium sized (e.g. hotspots and femtocells) and larger sized areas (e.g. cellular networks) could participate in the (same) market.

For the micro frequency scale, the model is required to support transfers of narrow frequency blocks such as down to 100 kHz. This could for instance be useful for applications such as wireless microphones and metering. It should be noted that the frequency blocks should be dynamic such that wider frequency blocks also should be supported for applications such as hotspots and broadband networks.

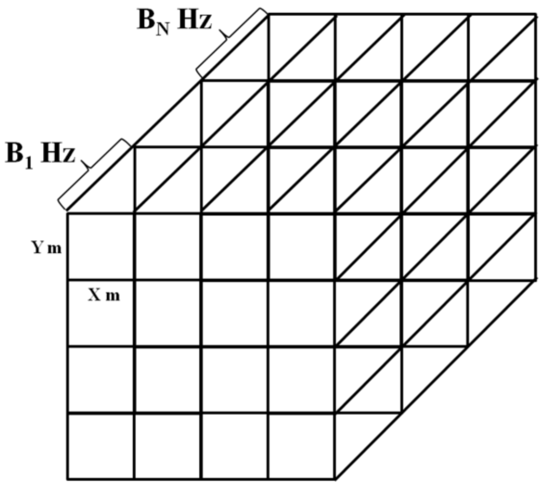
For the micro-temporal scale, the model is required to support short time intervals between spectrum transfers such as down to one second. This would for instance enable applications such as wireless metering to rent spectrum for a very short time period. Longer time leases should also be supported for applications such as cellular networks. Note that the time-scales for micro-auctions and spectrum leasing or purchase need not be the same. Auctions might be held every minute, but it is not assumed that bidders necessarily want to purchase the entire next minute. It should be possible to bid for a certain fraction of the next time period.

5.2.2 The "Spectrum Micro-trading Pixelation" model

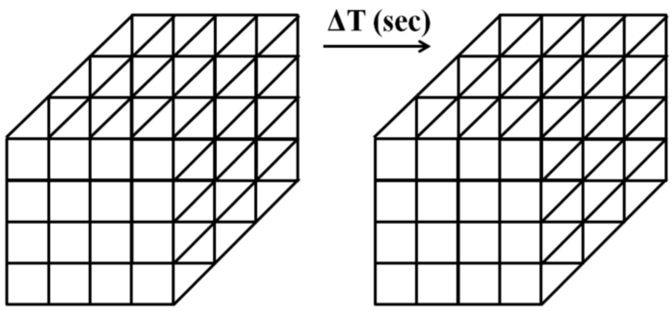
To meet the above requirements, we introduce a model for spectrum micro-trading referred to as the "Spectrum Micro-trading Pixelation" model illustrated in Figure 5-1. In this model, we fix the parameters and units for the spatial, temporal and frequency dimensions in addition to the price unit. Each dimension is described in the following.



(a) The spatial dimension defined by Pixels with sixe *X*mY*m**



(b) The frequency dimension in Hz



(c) The time dimension in seconds

Figure 5-1: Illustration of the “spectrum micro-trading pixelation” model

The Spatial Dimension

The spatial or geographical area is fixed into pixels of two geographical dimensions $X*Y$ meters (e.g. 100*100 meters), where X and Y are longitudinal and latitudinal dimensions respectively. This concept is illustrated in Figure 5-1(a) and will be referred to as *pixelation*. Most European countries have local coordinate systems (for example, National Grid in Britain) with units in metres, and transformation formulae are available to convert these to and from global longitudes and latitudes. We envisage that it will be most convenient to work in the local system most of the time.

Furthermore, we note that a third axis, the Z axis, could be introduced to describe the height, which might be useful in densely populated urban areas with tall buildings. In this case, the pixels would transform into boxes.

With such a model of the spatial dimension, short-range devices and services such as wireless microphones and device to device communications could bid for a low number of pixels. At the same time, long-range communications such as rural broadband could bid for several consecutive pixels.

A set of information elements important for the trading process can be associated with each pixel. We have identified the following information elements; population, vegetation (e.g. trees, building heights), propagation effects (e.g. average pathloss exponent), height above sea, type of customers (e.g. business, school), and weather (e.g. rainy, snowy). Many of these information elements could for instance be used to determine the price of a pixel. The information could be accessible to the spectrum broker itself, the traders and the regulator.

The major challenge is to determine the optimal pixel size to maintain a dynamic system with high flexibility and at the same time optimize the metrics defined in Section 5. It should be noted that there are issues related to poor receiver performance when allocating the allowed transmit range, but this will not be addressed further in this report (this is addressed for the QoSMOS spectrum manager in WP6 [D6.3]).

A second challenge with this model is the location accuracy of wireless devices. A location uncertainty probability could be used such that a spectrum trader could be forced to buy or lease one or more pixels adjacent to the actual wanted pixel.

The Frequency Dimension

The frequency dimension is divided into spectrum bandwidths of fixed spectrum blocks of B Hz as illustrated in Figure 5-1(b). To support micro-trading of narrow bandwidths, the bandwidth will typically be quite low (e.g. B=100 kHz). This will enable devices such as wireless microphones that require a narrow bandwidth to participate in the market. Simultaneously, other devices and services such as wireless broadband requiring wider bandwidths could participate in the market by bidding for consecutive bandwidth blocks.

One major challenge is to define the optimal value of the bandwidth B. Low values of B would enable a plethora of devices to participate in the market without having to acquire wide bandwidths. However, low values of B would not necessarily optimize the metrics defined in Section 6. For instance, low values of B could lead to fragmentation of the spectrum band; hence the spectrum utilization might be lower without sufficient technology that is able to utilize defragmented spectrum bands. Initially, to obtain market viability, it might therefore be that the best solution is to set B to the bandwidth as used by existing systems today. Low values of B could also lead to increased number of bids and increased auction overhead and complexity, which potentially could increase transaction costs.

The Temporal Dimension

The time dimension is fixed into time blocks of ΔT seconds as illustrated in Figure 5-1(c). Since we deal with spectrum micro-trading, the tradable ΔT should also be quite small (e.g., ΔT =1 second) in order to support a range of different wireless service usage patterns. For instance, wireless metering might require 1 second each month to transmit the measured result, which with ΔT =1 would be one block.

A challenge will be to define the time block ΔT. Above, we reasoned for small values to maintain high flexibility. To bid for longer periods the trader could bid for as many consecutive time blocks as desired.

Low values for the time block ΔT could lead to high defragmentation in the time domain, which would not necessarily increase spectrum utilization due to blockage of services requiring long consecutive time periods such as broadband networks not able to utilize spectrum defragmented in time. Therefore, it will be important to define policies that ensure maximization of the metrics defined.

The Pricing Dimension

The price will be a monetary unit such as Euro and USD, and a single monetary unit P to be used for trading can be defined such as 1 Euro or USD. We note that for device-level trading to be supported it might also be necessary to consider micro-payment methods.

The Tradable Unit

The minimum tradable unit then becomes:

$$\text{Pixel} * B * \Delta T \tag{1}$$

where Pixel is a single pixel defined by its X and Y values (e.g. 100*100 meters), B is the bandwidth defined in Hz (e.g. 100 kHz) and ΔT is the tradable time unit defined in seconds (e.g. 1 second).

Furthermore, a trading bid or ask in a spectrum market (e.g. auction or exchange) can be described by:

$$a_x a_y \text{Pixel} * bB * cT \tag{2}$$

where a determines the number of consecutive pixels a_x the number of pixels on the x-axis and a_y the number of pixels on the y-axis), b the number of spectrum blocks and c the number of time blocks to be traded.

These variables can also be used to regulate the market by setting minimum and maximum values of a, b and c. For instance, if $a_{\min} = 20$ and $a_{\max} = 200$ the smallest area to be traded with X=100m and Y=100m is 0.2km^2 and the largest 2km^2.

5.3 Auction Design for Spectrum micro-trading

The auction design in a spectrum micro-trading market is important. Sengupta et al. lists three important issues behind auction design for dynamic spectrum access in [Sengupta08] attracting bidders, preventing collusion to prevent bidders from controlling the auction and finally maximizing auctioneer's revenue. Furthermore, [Sengupta08] investigates auction mechanisms for DSA and provides a classification of auctions as illustrated in Figure 5-2 which we will follow in our analysis of auction design for spectrum micro-trading below. We note that [Sengupta08] and most other works in the literature have limited focus on the spatial domain, but most focus on the frequency and temporal dimension. In the following we provide a qualitative analysis of auction design for spectrum micro-trading.

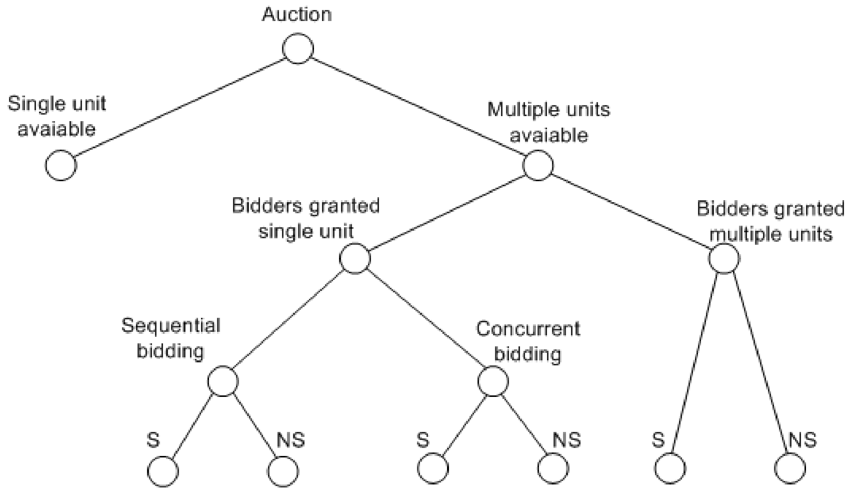


Figure 5-2: Auction classification (S substitutable, NS non-substitutable) [Sengupta07]

Auction design can first of all be distinguished based on whether it is a single-unit auction or multi-unit auction, i.e. whether a single unit or multiple units are auctioned. Multi-unit auctions are suitable in a spectrum micro-trading market since multiple spectrum resources are auctioned, in all frequency, spatial and temporal dimensions.

Next, the multi-unit auction can be distinguished based on whether bidders are granted a single unit or multiple units out of the total auctioned units. In a micro-trading market where spectrum resources are defined on the micro level, a trader would in most cases be interested in buying and concatenate multiple spectrum resources at the same time. Hence, the multiple units granted auction seems most feasible. However, the auction policy could be that a trader would have to bid for one item by one, then using the single unit granted auction.

For the single grant auction, the bid mechanism might be either sequential or concurrent. In the sequential mechanism, spectrum resources are auctioned one after another in one auction period and winning bidders are not allowed to bid for additional spectrum resources in that auction period. In the concurrent mechanism, each bidder submits all their bids concurrently in each auction period. It was found in [Sengupta08] that revenue generated by the spectrum broker (auctioneer) is higher with sequential than concurrent auction of spectrum bands when the objective is to maximize the spectrum brokers revenue.

For the multi grant auction, [Sengupta08] differs between synchronous and asynchronous bids in the temporal dimension. With synchronous bids the time unit allowed to bid for is 1, and with asynchronous bids the time units allowed to bid for can differ. In wireless communications especially, there might often be a need to reserve a certain time period in order to offer the required service. Hence, asynchronous bids would be desired by the bidders (wireless service providers). However, a maximum limit on the number of time intervals allowed to bid for could be set in a spectrum micro-trading market. [Sengupta08] shows that the spectrum brokers' revenue and the average spectrum utilization are highest with synchronous bids. The latter would probably also depend on the scenario and wireless service provider's use case and demand.

The spatial dimension has not yet been addressed, and might therefore be considered simple in that the bidder requires all or nothing of the geographical area requested. Another potential could be to use a mechanism for sequential bids where the bidder would have the opportunity to request a subset of the total area if available in case it loses the total area, which could increase spectrum utilization.

However, this would increase complexity in the auction model considerably. Hence, it could be recommended to use all or nothing as a first approach. In the case of sequential auctions, the outcome of one auction determines the price of spectrum for the next. A perfectly legal grant at one point in time may block a large amount of spectrum for the following auction. That way this could discriminate mobile users in favour of fixed users.

Another design issue is whether the auction units (spectrum resources) are substitutable or non-substitutable. If substitutable, the trader will not care which spectrum resource that is granted. If non-substitutable, the bidder differentiates the spectrum resources and bids for specific resources. This will also be different for the trading dimensions in spectrum micro-trading:

- The frequency dimension might be both substitutable and non-substitutable. Since the spectrum micro-trading model auctions spectrum bandwidths of fixed size, the bidder might not care which specific frequency is granted as long as the physical characterization and bandwidth of the spectrum resource are similar. However, the bidder might require spectrum resources with consecutive spectrum bands which will be of higher importance in the multi grant auction.
- The spatial dimension will mostly be non-substitutable since the bidder usually knows the location where it wants to offer its wireless service.
- The temporal dimension will in most cases be non-substitutable since the bidders usually know when to use the wireless service. However, this will depend on the service since some services might accept delays (e.g. file download) and others not (e.g. voice).

To prevent collusion, the sealed bid auction policy is suitable such that no traders observe the bids by the other traders during the auction period [Sengupta07][COGEU11a].

Finally, the auction can be designed to let the winning bid be the first price or second price. In first price, the winning bidder pays its winning bid. In second price, the winning bidder pays the second highest bid. First price is mostly used in traditional spectrum auctions. However, from the revenue equivalence theorem in auction theory it is stated that given certain conditions, any auction mechanism that results in the same outcomes also has the same revenue [Vickrey61].

To give a recommendation on auction algorithms to be used in spectrum micro-trading would require extensive analysis and is out of the scope of this deliverable. However, when considering the qualitative analysis presented above a first proposal could be to use the following auction design:

- bidder granted multiple spectrum bands,
- asynchronous bids in the temporal dimension with a maximum limit on time granted,
- bidder granted all or nothing in the spatial dimension,
- substitutable/non-substitutable:
  - substitutable in the frequency dimension with option to require consecutive bands,
  - non-substitutable in the temporal dimension, and
  - non-substitutable in the spatial dimension,
- sealed bids,
- first price.

We would like to note that this is not implemented nor tested in our simulations in Section 7. Therefore we also note that this not is a recommendation, but a first approach for recommendation to be considered for further evaluation.

As an example use of this auction design in QoSMOS we consider the “cellular extension in white spaces” use case. The example micro-trading market is characterised by X=Y=100 metres, B=1 MHz and T=3600 seconds. The auction design has parameter value *maximum time granted*=10 days. The operator sends sealed bids for coverage area with radius 500 metres, a bandwidth of 5 MHz and a time period of 1 month. The operator would then bid for 79 pixels, 5B and 720T. If the operator is not able to get all 79 pixels, it would get nothing. The operator bids for 1month which cannot be granted in one auction period due to the *maximum time granted* policy, hence the operator must bid in three consecutive auction rounds. The operator would get all or nothing in each of these time periods. The operator did not specify the requirement for consecutive spectrum bands, hence 5 bands not necessarily consecutive can be allocated to the operator. The operator would have to pay the price submitted in the bid (first price).

In this example, the operator trades with one spectrum broker at a time only. We noted in Section 4 that there could be multiple spectrum brokers present in the ecosystem, hence the operator could trade with different spectrum brokers for different time periods and different spectrum bands. Prices could then also differ for similar spectrum resources with different spectrum brokers. The operator would have to define an internal strategy to select which spectrum broker(s) to trade with.

6 Spectrum Micro-trading Metrics

In this section we define the main metrics for spectrum micro-trading. The goal is a recommendation of a vector of metrics that can be used to evaluate a spectrum micro-trading market.

A spectrum trading metric could be any type of measurement to measure some quantifiable component of the performance of a spectrum micro-trading market. The metrics used will depend upon the market structure, e.g. it could be a primary-secondary regime or a regime where market participants are only primary or only secondary users. In this section we focus on determining the metrics for the spectrum micro-trading market for the primary-secondary regime where primary license holders trade spectrum to users becoming secondary license holders. Furthermore, we focus on leasing of spectrum licenses.

Spectrum metrics can also be specific to some of the roles and actors defined in the ecosystem, e.g. a measure of social welfare could be specific to the spectrum regulator.

The process of defining the metrics for spectrum micro-trading followed three stages;

1. Definition of initial metrics based on a literature survey
2. Refinement of metrics and definition of additional metrics
3. Definition of a recommended vector of metrics

The results from each of these stages will be described resulting in metric definitions and a recommended vector of metrics for spectrum micro-trading.

6.1 Initial Metrics based on Literature Survey

As a first step in defining the most important metrics for spectrum-micro trading, we surveyed the literature of articles on spectrum trading and identified the metrics used. It was found that many authors used similar metrics. As a first step to identify the most important metrics, we used the results from the survey to define a set of metric categories for the evaluation of the spectrum micro-trading market:

- Market Viability – can micro-trading be a profitable business?
- Channel Quality – will channel throughput, latency and so on be improved by micro-trading?
- Spectrum Utilization – will micro-trading make better use of available spectrum?
- Social welfare - will the general well-being of society be improved by using micro-trading?

These high level metrics were further detailed into a set of sub-metrics found in the literature. We will not detail each of them here, but the actual metrics to be used will be defined in the next subsection.

Since the concept of a spectrum micro-trading market is relatively immature, it is first of all important to verify that we manage to establish a viable market. If we fail to establish a viable market, the conclusion might be that there is no real need for spectrum micro-trading. The conditions over which spectrum trading markets are viable were determined in [Caicedo10], where viability is determined by the liquidity and sustainability of the market. Five metrics were identified in the literature for market viability; liquidity, sustainability, spectrum price, profitability and blocking ratio.

The quality of each channel is important to measure both before the trades take place and during spectrum usage. The channel quality will be important for both spectrum leasers and lessees. Especially four metrics were identified in the literature for channel quality; throughput, interference, allowed transmit power and propagation effects.

One of the main aims of the spectrum micro-trading market is to increase spectrum utilization. As a high level metric, this can be stated as the fraction or percentage of utilized spectrum out of the total spectrum portfolio held by participants in the spectrum market at any time. Different metrics were found in the literature; the total spectrum blocks being used, the number of spectrum blocks being offered for sale and the spectrum allocation effectiveness.

In order to support implementation of spectrum micro-trading, market viability, increased spectrum utilization and good channel quality might not be enough. The regulator would also need to determine if the spectrum micro trading market improves the social welfare. For example, some governments are trying to provide broadband to rural areas to reduce the digital divide between rural and urban communities [Fitch11]. Second it would be important to see who benefits from the micro-trading market. A social welfare function could be used which ranks conceivable social states, e.g. complete descriptions of the society, from lowest to highest. Two ways in which to measure social welfare was considered in [Abji11], the *utilitarian* approach that considers the average node reward (utility to be defined more precisely in Section 7.3) in the system, and the *elitist* approach that takes the highest node reward as the social welfare, where the reward function captures both the expenditure as well as the buffer size.

6.2 QoSMOS Definitions of Metrics for Spectrum Micro-trading

Having identified high-level metrics and a set of sub-metrics for each, it was found that some of the sub-metrics specified for each had direct dependencies on each other. This is undesirable in a vector of metrics to be recommended. For instance, for the channel quality metric, the two sub-metrics throughput and interference have dependencies.

Furthermore, it was not evident that the above-discussed metrics would cover a complete study of spectrum micro-trading market performance.

The next stage in the process of defining metrics was to refine the metrics in the existing literature and define new metrics to capture the total performance of a spectrum micro-trading market. The result of this process is the metrics defined in the following. For each metric, a description and a measure will be given.

For all metrics with quantities averaged over a time period, the averages are exponentially-weighted moving averages; in this case the only free parameter is the time-constant of the exponential.

The different metrics used by studying the spectrum micro-trading market defined by QoSMOS are listed in Table 6-1. It is possible to divide the use of them in three types. One metric can have more than one use.

- Metrics directly needed or useful by actors in the trading process
- Metrics used by actors for internal assessment of the participation in the market
- Metrics which can be used to evaluate the trading market from an external point of view

We have evaluated how the different metrics can be used and included this in the table; however this is not a comprehensive analysis. The metrics are also sorted against the categories defined in section 6.1.

Table 6-1: QoSMOS defined spectrum micro-trading metrics

	Metric	Description	Use
Market viability	Liquidity	An asset's ability to be sold without causing a significant movement in the price and with minimum loss of value.	Market evaluation
	Trading Volume	The number of completed trades.	Market evaluation
	Spectrum Price	Low values of spectrum price would indicate that there is an excess in supply of spectrum, whereas high values would indicate that there is low supply or high demand.	Trading process, Market evaluation
	Profitability	In telecommunication it is common to measure the NPV (Net Present Value) of a project when evaluating the profitability.	Actor internal assessment
	Blocking ratio	The number of spectrum buyers or leasers that fail to acquire spectrum through the spectrum market.	Market evaluation
Spectrum utilization	Spectrum exploitation efficiency	A measure of how well the allocation algorithm exploits available spectral resources, regardless of the time taken to perform the allocation.	Market evaluation
	Spectrum allocation delay	The time required to allocate spectrum. This will be a measure of market overhead.	Market evaluation
Channel quality	Interference temperature	Interference is the level of electromagnetic disturbance from other RF sources and noise.	Trading process, Actor internal assessment
	User experience	A subjective measure of the quality of using the spectrum micro-trading market by the user.	Actor internal assessment
Social welfare	Social welfare	An important metric for the regulator when introducing spectrum micro-trading. Social welfare is a broad term meaning the well-being of the entire society.	Market evaluation

The metrics are defined in more detail in the following subsections.

6.2.1 Liquidity

Description: Market liquidity is defined as an asset's ability to be sold without causing a significant movement in the price and with minimum loss of value. High liquidity in a market is a good indicator that the market is viable.

Relevant for Actors: Spectrum Broker and Regulator.

Measure: To measure liquidity we build on the measure defined in [Caicedo10] as the bid-ask spread relative to the mid-price of a spectrum block in the market, which can be defined by the following equation:

$$\text{Liquidity} = \frac{\text{Ask}_{\text{min}} - \text{Bid}_{\text{max}}}{\text{Price}_{\text{mid}}}, \tag{3}$$

where Ask_{min} is the best sell price in the market found by the minimum ask value and Bid_{max} is the best buy price in the market found by the maximum bid value. The denominator in the equation is the mid-point price of a spectrum block which is found by combining the average values of the Bid_{max} and Ask_{min} measured over a certain time interval *n*; $\text{Price}_{\text{mid}} = \frac{\sum_{t=0}^{n}(\text{Ask}_{\text{min}}(t) + \text{Bid}_{\text{max}}(t))}{2n}$.

High and low values of Liquidity would indicate high and low marked liquidity. If the value is high, there would be high resistance in the market to go from a selling position to a buying position. If the value is low, the resistance to trade is low since it would be easy for a trader to establish a trade with only a small change in price.

6.2.2 Trading Volume

Description: The trading volume is defined as the number of completed trades. The trading volume is related to market sustainability which relates to the running behaviour of the market. If the trading volume and hence trading activity is low, the market might not be sustainable.

Relevant for Actors: Spectrum Broker and Regulator.

Measure: The trading volume is found by taking the number of trades (Trades) for a trading period relative to the average number of trades in the market ($\text{Trades}_{\text{avg}}$) which will be calculated over a longer time period spanning multiple trading periods. The equation is given as follows:

$$\text{Trading Volume} = \frac{\text{Trades}}{\text{Trades}_{\text{avg}}}. \tag{4}$$

6.2.3 Spectrum Price

Description: Low values of spectrum price would indicate that there is an excess supply of spectrum, whereas high values would indicate that there is low supply or high demand.

Relevant for Actors: Spectrum Broker and Trader.

Measure: The spectrum price in for a spectrum resource in a trading period is measured relative to the average spectrum price over a certain time period spanning multiple trading periods:

$$\text{Spectrum price} = \frac{\text{Price}}{\text{Price}_{\text{avg}}}. \tag{5}$$

6.2.4 Profitability

Description: The main motivation for most commercial actors in the ecosystem is to increase profit by participating in the market. The best measure of profitability for one actor would be ROI (Return on Investment) for participating in the market, including both revenues and costs. A second measure is EBITDA (earnings before interests, taxes, depreciation, and amortization) which would be useful when comparing with other alternatives of acquiring spectrum and spectrum sharing. In telecommunication it is common to measure the NPV (Net Present Value) of a project when evaluating the profitability, which is the sum of a series of cash flows (revenues subtracted by costs), when discounted to the present value.

Relevant for Actors: Spectrum Broker, Trader, Database Operator and WSN operator.

Measure: A measure of profitability when participating in the spectrum market can be found by calculating the NPV over a certain time period *T* (typically 5 years in telecommunication projects):

$$\text{Profitability} = \text{NPV}(T). \tag{6}$$

In this equation, NPV is found by first calculating the cash flow (CF) over the period *T* as:

$$\text{CF}(T) = \sum_{t=0}^{T} (\text{revenues}(t) - \text{costs}(t)),$$

where revenues constitute additional revenues when participating in the market and costs constitute capital expenditures (CAPEX) and operational expenditures (OPEX) when participating in the market. The time step *t* is typically yearly. Furthermore, to discount to the present value, the discounted cash flow (DCF) with discount rate *r* for each time *t* is found by:

$$\text{DCF}(t) = \frac{\text{CF}(t)}{(1+r)^t}$$

Finally, the NPV can be calculated by summing the discounted cash flow for each year by the following equation:

$$\text{NPV}(T) = \sum_{t=0}^{T} \text{DCF}(t).$$

6.2.5 Blocking Ratio

Description: Blocking ratio can be characterized by the number of spectrum buyers or leasers that fail to acquire spectrum through the spectrum market. If this number is high, it might be that the demand is higher than the supply in the market, which indicates low market viability.

Relevant for Actors: Spectrum Broker and Trader.

Measure: The blocking ratio can be defined as the number of bidders that are blocked ($\text{Bidders}_{\text{blocked}}$) relative to the number of total bidders in the market ($\text{Bidders}_{\text{total}}$):

$$\text{Blocking ratio} = \frac{\text{Bidders}_{\text{blocked}}}{\text{Bidders}_{\text{total}}}. \tag{7}$$

6.2.6 Spectrum Exploitation Efficiency

Description: This metric is defined as a measure of how well the allocation algorithm exploits available spectral resources, regardless of the time taken to perform the allocation.

Relevant for Actors: Spectrum Broker and Trader.

Measure: Let *d* be demand (measured for example in MHz), let *s* be total available spectrum, and let *a* be actual spectrum assigned (which must be less than *s*). Then the spectrum exploitation efficiency can be defined as:

$$\text{Spectrum Exploitation Efficiency} = \frac{a}{\min(s,d)}, \tag{8}$$

thus unity means all demand is satisfied, if it is possible to satisfy it.

6.2.7 Spectrum Allocation Delay

Description: Spectrum allocation delay is defined as the time required to allocate spectrum. Since the spectrum will remain idle for the time period required to allocate the spectrum, the allocation effectiveness directly affects spectrum utilization. This will be a measure of market overhead. This metric will be of highest importance in real-time spectrum auctions, but not that important if auctions are run in advance of the actual spectrum usage.

The actual spectrum allocation delay will depend on the auction mode. Ascending bids auctions would require more iterations than single sealed bid auctions. The metric will also depend on sequential auction versus concurrent auction, for example auction different bands in sequential order versus auction all bands at the same time. The time used to compute the auction algorithm in the spectrum broker would also influence the spectrum allocation delay. This metric will therefore be useful when evaluating different auction modes to be used in the market.

Relevant for Actors: Spectrum Broker and Trader.

Measure: Let t_s be the time of sending the bid to the spectrum broker and let t_r be the time of receiving notification of allocated spectrum from the spectrum broker. The spectrum allocation delay can then be defined as:

$$\text{Spectrum Allocation Delay} = t_s - t_r. \qquad (9)$$

6.2.8 Interference Temperature

Description: Interference is the level of electromagnetic disturbance from other RF sources and noise. This can be co-channel interference from neighbouring areas and adjacent channel interference. A high interference level is a measure of degraded channel quality.

Relevant for Actors: Trader, Spectrum Database Operator and Regulator.

Measure: Interference should be measured or estimated as the power present at the antenna output connected to the receiver front-end. The interference power spectral density is a bandwidth independent measure:

$$I_0 = \sum_{n=1}^{N} I_{0,n}, \qquad (10)$$

The sum is taken over all interference contributions $I_{0,n}$.

The FCC has proposed using the *interference temperature* [FCC02][FCC03b] as a way to have unlicensed transmitters share licensed bands without causing harmful interference. FCC abandoned the original idea in 2007 [FCC07], however using interference temperature as a metric should not be limited to regulatory analysis. As mentioned in section 3.1 Huang et al. [Huang06] has studied the use of the interference temperature in auction design.

Any mobile RF transmission system should benefits from defining interference metrics in order to use the RF spectrum optimally. The alternative is using worst-case geometry for interference analysis (i.e., the closest proximity) resulting in stricter limits on transmission power [Kolodzy06].

FCC's definition of an interference temperature model (ITM) might be useful in defining a metric for channel quality [Clancy07]. In the ITM, radio nodes treat licensed users, other unlicensed radio networks, other unlicensed nodes within the same network, interference, and noise all as interference. These are all affecting its signal-to-interference ratio (SIR). Higher interference means lower capacity is achievable for a given signal bandwidth. In a cognitive radio system radio nodes may search for gaps in frequency and time where the measured interference is low enough to achieve communication at a target capacity, subject to overall interference constraints defined by the interference temperature model. This is a coexistence model opposed to the more common avoidance models [Clancy07].

Interference temperature is analogous to the noise temperature, a measure frequently used to quantify the thermal noise received by satellite dish antennas and noise figure in receivers. We then define interference temperature as a measure of the RF power generated by undesired emitters plus noise sources that are present in a receiver system (I+N) per unit of bandwidth:

$$T_I = \frac{I_0 + N_0}{k}, \tag{11}$$

Where k is the Boltzmann constant: $k = 1.38 \cdot 10^{-23}$ J/K.

Based on the constraint assuming AWGN type of interference Clancy shows that the interference temperature can be used to estimate available capacity [Clancy07].

6.2.9 User Experience

Description: User experience is a subjective measure of the quality of using the spectrum micro-trading market by the user. It can be based on the QoS or QoE perceived by the user. This metric will therefore not be a technical measurement, but should be defined as a score from the user's perspective.

This measure is certainly dependent on other metrics defined, but the metric is a subjective measure which differs from the other metrics which are quantitative measures.

Relevant for Actors: Spectrum Broker and Trader.

Measure: The user experience is defined by averaging the scores from actors in the spectrum market. The score from each participant is a value between 1 and 5, with 5 being best. Then, the following equation defines the user experience score on a scale from 1 to 5 for n actors:

$$\text{User Experience} = \frac{\sum_{i=0}^{n} \text{score}(i)}{n}. \tag{12}$$

6.2.10 Social Welfare

Description: Social welfare is an important metric for the regulator when introducing spectrum micro-trading. Social welfare is a broad term meaning the well-being of the entire society. Ideally, a metric for social welfare should cover all aspects of social welfare, but that might be challenging to measure.

The social welfare could be calculated by using a health index. This would involve a set of measures after the spectrum micro-trading market is installed and put into operation. Furthermore, the measures could both be subjective and quantitative.

Social welfare in auction theory is often calculated as the total value brought to all participants in the auction, though this will not cover the total welfare of the society. This is a simpler measure than the health index.

Relevant Actors: Regulator and Trader.

Measure: From an auction theory perspective, social welfare can be calculated as the total value brought to all the direct participants in the market (auction), which are the traders and the spectrum broker, by the following equation:

$$\text{Social Welfare} = \sum_{i=0}^{n} V(i), \tag{13}$$

where $V(\text{i})$ is the spectrum valuation by each of the n bidders in the spectrum micro-trading market. This can be deduced from the following equation: $\text{Social Welfare} = \sum_{i=0}^{n}(V(i) - p(i)) + \sum_{i=0}^{n} p(i)$, where the first term is the sum of values for all n bidders with valuations $V(i)$ and prices paid $p(i)$, and the second term is the value for the sellers (i.e. the sum of prices $p(i)$ payd by the n bidders.

6.3 Metric Vectors

Its components can be any subset of the preceding scalar metric functions. Our overall metric will be a scalar product of this vector with a vector of constant weight (or cost) coefficients. Components of the metric vector found to be heavily dependent on others can be given low (even zero) weight. There is clearly much arbitrariness here, and different actors may choose different weight vectors. The final choice will come down to the actor's own utility function; that is, the function which the actor's company policy is trying to maximize.

If the scalar metric vector *M* is defined as:

$$M = [m_1, m_2, m_3, \dots, m_n], \tag{14}$$

and the weight (or cost) vector *W* is:

$$W = [w_1, w_2, w_3, \dots, w_n]. \tag{15}$$

Then a final single scalar metric is the scalar product between *M* and *W*:

$$\text{Overall metric} = M \cdot W. \tag{16}$$

W will normally also be chosen in order to impose a normalization, for example, so that the maximum possible value of the overall metric is unity. In our case, *n* can be as high as 10, since we have defined 10 scalar trading metrics. Separate weights vectors *W* are determined by each actor in the market.

7 Spectrum Micro-trading Simulations

In this section we present work on the implementation of a simulator to study a spectrum micro-trading market and to test some of the metrics defined in Section 6. We implement and extend a simulator inspired by the work presented in [Abji10]. The spectrum micro-trading model is implemented in a simulator with bid-proportional auctions. End-users are using a multi-agent reinforcement learning mechanism to refine their future bidding behaviour using a heuristic formula from Q-learning theory based on reward from previous auctions. We consider one of the key use cases defined in QoSMOS [D1.2] to increase capacity in the wireless networks; the “cellular extension in white spaces” use case in which the service provider will acquire additional spectrum through the spectrum micro-trading market. The service providers act as spectrum traders. A realistic scenario is considered with varying traffic load during a 24-hour period where spectrum demand will exceed supply in the market during busy hours. Performance evaluations presented are focused on the spectrum micro-trading dimensions in time and frequency in a single cell with multiple operators.

7.1 The Q-learning Heuristic

The Q-learning heuristic was introduced by Watkins [Watkins89]. It is a simple form of machine learning intended to make an agent perform state transitions which improve its long-term reward. The ingredients are an agent, a finite set of discrete states, and for each state, a set of actions, which are transitions to other states. Additionally the agent maintains a so-called Q-matrix, intended to represent its knowledge of the “quality” of each transition. Quality is measured by a specified reward function (which could also be thought of as agent utility); upon reaching a state, the agent can evaluate its reward for that state, and the reward is used to update the Q-matrix. The update formula is the heart of the method, and the major innovation of Watkins; it is

$$Q_{sa} \leftarrow \beta Q_{sa} + \alpha(\text{reward in new state} + \gamma M), \qquad (17)$$

where the indices s and a refer to states and actions, α, β and γ are constants which weight the contribution from the old Q value and the new, and M is the maximum reward over all transitions from the current state.

The final ingredient is a rule for choosing transitions: the rule states that a transition from a state is chosen with probability proportional to the corresponding Q-matrix element.

In the classical example of Q-learning, the agent is walking on a graph (or trying to solve a maze game) and attempting to reach a target node which has highest reward; it is found that after a few trial walks to build up the Q-matrix, the agent then reaches the target with high probability in a small number of steps.

The internal details of the Q-learning heuristic are irrelevant for understanding its application to spectrum auctions in this report. It is sufficient to know that a method exists for adapting bids to the current situation, based on information gathered in previous rounds of the auction. We emphasize that Q-learning is, strictly speaking, only intended for a single agent operating in an unchanging environment, not a set of competing agents. Nevertheless, we find in practice that it does perform well in the multi-agent scenario.

7.2 Metrics used for Evaluation

The reward function defined in Eq. (18) is not mapped directly to the metrics in Section 6. High states as mentioned can be measured by the “spectrum exploitation efficiency” metric, while the penalty introduced is related to liquidity, trading volume and spectrum price.

7.3 Simulator Implementation and Evaluation

In order to demonstrate the feasibility of these approaches, we implemented a complete system simulation in C++. In this initial study, we restricted simulations to one cell (base-station). In this cell, several service providers use co-located infrastructure for base stations. One auction is run at regular intervals (which we could imagine to be one hour).

We will consider one of the key use cases defined in the QoSMOS project [D1.2] to increase capacity in the wireless networks; the “cellular extension in white spaces” use case in which the service provider will acquire additional spectrum through the spectrum micro-trading market. A typical market with a number of service providers providing wireless mobile broadband such as LTE is considered. Each of the operators already has an amount of licensed spectrum, e.g. 20 MHz. Furthermore, all the networks are assumed to be in the urban area and that the networks are capacity limited due to increased data usage by the mobile users. Each service provider has mobile users (customers) who never switch to other service providers. The mobile users will be uniformly distributed throughout the area. User demand fluctuates on a time-scale much longer than the auction period; we studied the case in which the demand has a strong 24-hour periodicity, as typically observed in retail networks. During the period the demand is varying cyclically with two high peaks illustrating the typical busy hour behaviour in the morning and evening.

The auction is run periodically and synchronously. The auction sells multiple units of spectrum blocks. The bidders can each be granted multiple units of spectrum blocks and these spectrum blocks are substitutable. Sealed bids are used. Allocation of spectrum by the broker is proportional to the bid price. The allocation is quantised, using the floor function, to an integer number of spectrum blocks. Each spectrum block has bandwidth *B*. The service provider reward is measured through one or more of the performance metrics. The overall performance of the auction is then based on the long-term average of the reward function. The spectrum being auctioned by the broker could be owned by the regulator or could be previously auctioned spectrum using secondary trading (this includes spectrum speculators) or a combination of the two. To apply the Q-learning heuristic to this system model, we assume that states of the agents (service providers) are defined as discretizations of the amount of spectrum currently owned (both permanently owned as well as spectrum currently owned from the most recent micro-auction) in comparison to the current demand. Currently we assume the agents can accurately predict their demand for each auction period (In practice this would be an estimate which carries an element of risk for over-prediction as well as under-prediction). Note that the resolution defined in the auction could be as small as desired for micro-auctions since the resolution is mainly limited by the resolution of possible bids in the bid-proportional auction. Actions (transitions) are of three types: decrease the bid by one price unit, keep the bid constant, or increase the bid by one price unit. The fundamental reason for using Q-learning is to ensure that service providers do not pay more than is necessary to acquire the spectrum they need to service their customers. This is required to be done whilst maintained some sense of fairness in the overall spectrum allocation.

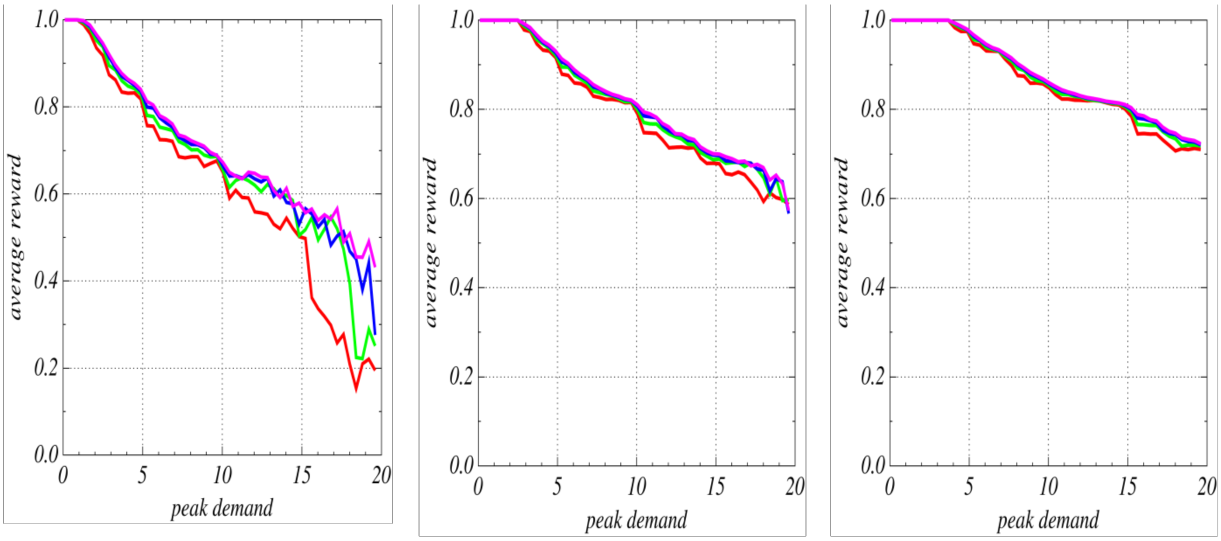
For the reward function we follow Abji and Leon-Garcia [Abji10] in using a function structured like this:

$$\epsilon_1 \log(1 + \text{state}) - \epsilon_2 \frac{\text{bid}}{\text{maximum bid}}, \tag{18}$$

Here ϵ_1 and ϵ_2 are constants (typically $\epsilon_2 = 0.1$, and ϵ_1 is chosen to make the maximum reward=1). This reward function gives credit for high states (high spectrum allocation), but penalizes high bids.

In the scenario summarized in Figure 7-1, we used 6 service providers. The x-axis is the amplitude (peak value) of the periodic spectrum demand. There were 24 auctions per day, one per hour. The auction contains three 8MHz channels (24MHz in total). We averaged the value of the reward function over all service providers. In this cellular-extension use case we assume the SPs also own spectrum. In Figure 7-1a, Figure 7-1b and Figure 7-1c each SP owns 8MHz, 16MHz and 24MHz of spectrum respectively. The red, green, blue and magenta lines show the performance for *B*=8MHz, 4MHz, 2MHz and 1MHz respectively.

When the peak demand is low, the average reward stays at its maximum value of 1 as additional spectrum is not required and the SPs have learned that there is no need to bid for spectrum. As the peak demand increases the SPs average reward begins to fall; this decline is more gradual when the SPs have more owned spectrum. This shows that the competing SPs are learning not to bid excessively when they attempt to meet increased demands.



(a) Each SP has 8MHz of permanent spectrum

(b) Each SP has 16MHz of permanent spectrum

(c) Each SP has 24MHz of permanent spectrum

Figure 7-1: Spectrum micro-trading performance *B*=8MHz (red), 4MHz (green), 2MHz(blue) and 1MHz (magenta).

By comparing the curves in any of the three subfigures we can also see the benefit of micro-trading in the frequency domain. For the scenario shown it can be seen that the average reward is higher for smaller values of *B*. This is because the finer granularity allows each SP to only bid for the amount of spectrum they need, rather than having to bid for too much. Coarser granularity therefore increases demand between SPs while also meaning more auctioned spectrum will be unused. Also, if an SP fails to meet its demand, this is usually to a lesser extent when the granularity is finer. As demand gradually changes an SP can also make small changes to its bidding behaviour in an attempt to be allocated slightly more/less spectrum, rather than having to make an aggressive change in behaviour when they suddenly need one extra/fewer large block of spectrum.

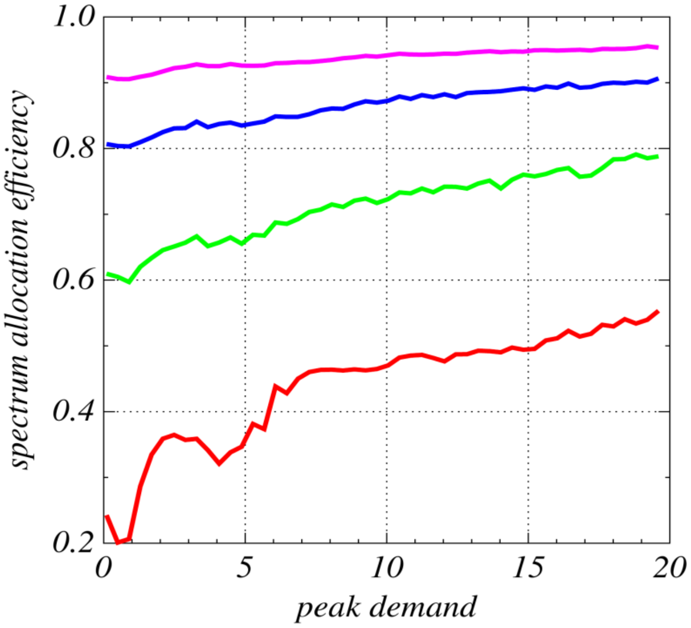


Figure 7-2: Spectrum Allocation Efficiency. Each SP has 8MHz of permanent spectrum. *B*=8MHz (red), 4MHz (green), 2MHz (blue) and 1MHz (magenta)

Finer quantisation/granularity of the frequency dimension can improve the spectrum allocation efficiency of the quantised bid-proportional auction. This can be seen in Figure 7-2. These show results for a system where each SP owns 8MHz of spectrum in addition to the extra spectrum it bids for. The red, green, blue and magenta curves represent *B*=8MHz, 4MHz, 2MHz and 1MHz respectively. The floor function is used to make sure that the bid proportional allocation for each bidder is rounded down to an integer number of spectrum blocks (each block has size *B*). The larger *B* is the more this floor function causes spectrum to not be assigned in the auction process. In Figure 7-2 this is clear to see. For example when *B*=8MHz the spectrum allocation efficiency is always below 0.6 yet when *B*=1MHz the spectrum allocation efficiency never falls below 0.9.

Furthermore larger *B* can mean that bidders leave some of their allocated spectrum unused (e.g. If a bidder requires 2MHz but *B*=8MHz then that bidder has to buy at least 8MHz of spectrum to meet its demand, wasting at least 6MHz of the spectrum that they bought). Alternatives could be chosen for the auction design so that the quantized bid-proportional allocation doesn't use the floor function, but this would add complication. Using the current auction design the unallocated spectrum could be used to give guard bands between each SP's allocation, which can improve the performance achieved in the spectrum that is actually allocated.

Figure 7-3 extends on the previous scenario by introducing a seventh SP. This new SP, however, does not own any fixed spectrum and can only meet its demand using spectrum gained from micro-trading. The other six SPs all own 8MHz of spectrum and, again, the red, green, blue and magenta lines show the performance for *B*=8MHz, 4MHz, 2MHz and 1MHz respectively. The results do show that for lower values of peak demand the average reward is now slightly lower. This makes sense as one of the SPs now has to bid for spectrum even when the demand is low. As the peak demand increases the average reward is similar to the system without the seventh SP. This result is encouraging as it shows that there is the potential for a new entrant to enter the market without the need to buy a fixed spectrum allocation in addition to the micro-auctioned spectrum. These results can be compared to the curves in Figure 7-1a.

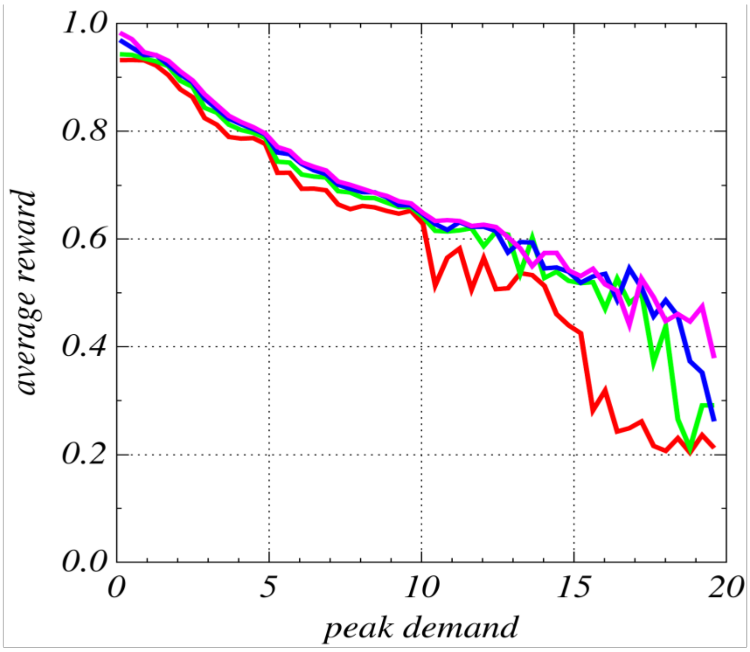


Figure 7-3: Spectrum micro-trading performance. Introduction of an SP that only uses spectrum micro-trading. The other 6 SPs each own 8MHz of spectrum. *B*=8MHz (red), 4MHz (green), 2MHz (blue) and 1MHz (magenta)

8 Conclusions and Further Work

Spectrum micro-trading was defined as the possibility to buy and sell spectrum resources on a smaller scale than has currently been used in one or more of the spatial, temporal and frequency dimensions. This would enable wireless services to acquire spectrum for small or wide geographical areas, for short or long time periods and for narrow or wide bandwidths. Hence, spectrum utilization and the opportunity to acquire spectrum resources might increase when optimizing metrics and specifying market policies properly.

An ecosystem is required for a spectrum micro-trading market to be implemented and be sustainable. Especially, we identified a centralized spectrum broker as an actor with the main task to arrange transactions between spectrum traders. This spectrum broker will run and control the required market mechanisms such as an auction facilitating trading between the spectrum traders that can sell, buy, lease or rent spectrum in the market. The spectrum trader actor can be spectrum license holders, secondary cognitive radio operators and spectrum speculators. Furthermore, we defined a spectrum database operator as a commercial actor at a wholesale level who maintains an overview of spectrum usage in a specific region. Another innovative commercial actor defined in the ecosystem is the wireless sensor network which owns a network of wireless sensors that monitors spectrum and provides a real-time overview of the spectrum status such as occupancy, technology used and interference useful for the other actors in the ecosystem. Finally, the regulator was defined as a governmental actor which regulates and defines policies for the spectrum market.

We defined a model referred to as the "spectrum micro-trading pixelation" model, whose main aim is to implement spectrum micro-trading in all dimensions, especially on the micro-spatial, micro-temporal and micro-frequency scale. Each dimension in the model is defined as pixels whose micro-granularity can be specified to fixed parameters for optimized performance by using the metrics defined. The model is considered to be practical and possible to implement with the defined ecosystem in a real market and to be implemented in simulators for performance evaluation.

One of the main focuses in this report was on defining key metrics for the evaluation of spectrum micro-trading. We first studied state-of-the-art and identified a set of metrics which we mapped into four metric categories; market viability, channel quality, spectrum utilization and social welfare. Furthermore, we defined ten key metrics for spectrum micro-trading for use when evaluating the market, the trading process and for internal actor assessment. The ten metrics were described and defined with equations. Furthermore, for each metric we identified the potential actors in the ecosystem that have interest in using that metric for performance evaluation. A metric vector was described that can be used by each actor when defining different and normalized weights for each metric. Further work is needed to define the weights.

The "spectrum micro-trading pixelation" model was used as basis to implement a simulator for spectrum micro-trading using multi-agent reinforcement learning and Q-learning heuristic. For our market study to test the metrics, we considered the "cellular extension in white spaces" use case [D1.2] in which the service providers will acquire additional spectrum through the spectrum micro-trading market. The service providers act as spectrum traders. A realistic scenario for service providers demanding additional spectrum over a 24-hour period was studied. We focused on the average reward when evaluating performance in our simulator. We showed that the service providers participating in the market are learning not to bid excessively high as demand increases. It was also found that when smaller bandwidth units were used in the "spectrum micro-trading pixelation" model, the average reward increases since it allows the spectrum users to bid for the actual required spectrum rather than having to bid for too much. Smaller bandwidth units will also enhance the spectrum exploitation efficiency. We also studied the introduction of an additional service provider that not holds existing spectrum, and showed that the average reward still only gradually falls as the peak demand increases. This indicates the potential for new entrants in the spectrum micro-trading market.

8.1 Further Work

In this section we specify the topics for spectrum micro-trading that we find most important and interesting to work further on. We note that we will not be able to consider all these items for further work within the QoSMOS project.

The main focus of this work was on defining metrics. Furthermore, we did also implement a simulator model that can be used to test and evaluate the metrics defined. Many important metrics were tested, but the main further work is to test all the metrics defined in this report.

A simulator implementation of the "spectrum micro-trading pixelation" model in more detail including all dimensions specified able to test and evaluate the metrics defined is important in order to evaluate the introduction of a spectrum micro-trading market. This is also important to optimize the metrics defined and the pixel sizes in the model defined. The simulator model in this deliverable is implemented in C++ with good performance and the opportunity to be extended. A first future work item on this simulator model is to implement the spatial dimension in more detail. Further work is also to implement novel auction algorithms, different scenarios, spectrum valuation functions, more of the metrics defined, and to evaluate the option for auction design described in this report. The main purpose of this will be to provide a foundation to enable a spectrum micro-trading market.

A second option for further work is to integrate a simulator model for spectrum micro-trading with the business case analysis in Task 1.4 in QoSMOS. To do the same scenario as specified in Task 1.4 to be implemented in the spectrum micro-trading simulator including number of base stations or femtocells, number of users, deployment models, coverage assumptions etc. One way to integrate is to use the spectrum micro-trading simulator to find the spectrum price when participating in a spectrum market and use this as input to the business case analysis. A second way is to use spectrum valuation based on NPV calculations from business case analysis as input to spectrum pricing in the spectrum micro-trading simulator. Third, a dynamic real-time integration between the spectrum micro-trading simulator model and the business case model can be implemented.

Furthermore, there are several subjects that should be investigated further. A qualitative study of auction design was given, which could be studied through simulations. The "spectrum micro-trading pixelation" model and state-of-the-art TVWS databases implementations use similar models in the spatial domain, which could be subject for integration and further study. Market policies for spectrum micro-trading will be of high importance for the success of spectrum micro-trading which should be investigated further. Sensor networks were proposed as an actor in the ecosystem to support the other actors, and the use of sensor networks in this context should be studied further.

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