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Next Generation Spectrum Regulation for Europe: Price-Guided Radio Policy

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Zusammenfassung

Dieses Projekt untersucht wie Marktsignale in Form von Preisinformationen im Bereich des Frequenzmanagements genutzt werden können, um nicht nur die Frequenzvergabe, sondern auch Festlegungen hinsichtlich der Nutzungsart, der Emissionscharakteristika und der Exklusivität optimal steuern zu können. Wir entwickeln ein mathematisches Modell um zu zeigen, wie eine mögliche Implementierung einer solchen preisgesteuerter Frequenzpolitik aussehen könnte. In den vergangenen zwei Jahrzehnten sind Marktmechanismen wie Auktionen von Institutionen, die mit dem Frequenzmanagement betraut sind, zur Frequenzvergabe eingesetzt worden um sicherzustellen, dass die Nutzungsrechte an bestimmten Frequenzbereichen denjenigen übertragen werden, die ihnen den höchsten Wert beimessen. Im Vergleich mit konventionellen Frequenzauktionen würde eine preisgeleitete Politik bei der Frequenzvergabe sicherstellen, dass nicht nur die Frequenznutzungsrechte an den Nutzer vergeben werden, der diesen den höchsten Wert entgegenbringt, sondern, das gleichzeitig eine möglichst effizientes Design dieser Rechte sichergestellt wird.

In dem mathematischen Modell, was in dieser Präsentation vorgestellt wird, können die Teilnehmer an einer hypothetischen Auktion ihre Forderungen nach Frequenz-Lizenzen frei äußern, die in verschiedenen Dimensionen variieren können wie bspw. der zulässigen Ausgangsleistung und Bandbreite. Diese Forderungen werden bestimmt durch das, was notwendig ist, eine bestimmte Datenrate auf einem festgelegten Level mit den Möglichkeiten drahtloser Kommunikation zu übertragen. Wir benutzen das Shannon Hartley Theorem, um die möglichen Zielkonflikte zwischen zulässiger Signalstärke und zugeteilten Kanal-Bandbreiten zu modellieren. Zur Überprüfung des mathematischen Modells haben wir eine vereinfachte MS Excel-basierte Version des Modells erstellt. Das Ergebnis des Modells war unter anderem ein Mix von Betreibern mit hoher und niedriger Leistung, bei unterschiedlichen Kanal-Bandbreiten und siegreichen Angeboten. Weiter überprüfen wir die Auswirkungen des deutschen und des EU-Rechts für eine solche marktgetriebene Frequenzverteilung. Marktgetriebene Frequenzverteilung ist in Europa realisierbar. Bei international harmonisierten Bandbreiten kann die marktgetriebene Frequenzverteilung jedoch nicht zur Zuteilung eingesetzt werden. Die ersten Schritte der Umsetzungen beinhalten das Festlegen von maximalen Leistungsgrenzen, Bandbreite, Dauer der Rechte und Bündelung. Andere mögliche frühe Implementierungen beinhalten boundary interference standards und möglicherweise verkehrsbasierte Protokolle.

Die marktgetriebene Frequenzverteilung ist ein viel versprechendes Verfahren, weil sie durch den Umstand, dass Bieter exakt die Frequenzrechte erhalten können, die sie brauchen, Spektrum effizient zuteilt. Außerdem entschärft die marktgetriebene Frequenzverteilung die Zuteilungsfehler, die administrativen Entscheidungen innewohnen (können).

Summary

This project examines how market signals in the form of pricing information can be introduced into spectrum management in order to optimally guide not only assignment, but also determinations concerning type of use, emissions characteristics and exclusivity. We construct a mathematical model to illuminate how one possible implementation of such price-guided policy might function to make these determinations. For the past nearly two decades, spectrum management authorities have used market mechanisms such as auctions to determine spectrum assignment in an effort to ensure that the right to utilize the spectrum is held by those who value it most. As compared to conventional spectrum auctions, price-guided mechanisms for determining allocation and policy would arrive at an assignment of spectrum rights to the highest value users as well as ensure that the contours of those rights were the most efficient possible.

In the mathematical model presented in this paper, participants in a hypothetical auction are free to express their demand for spectrum licences which are different on several dimensions such as permissible power output and bandwidth. These demands are dictated by what is necessary to satisfy a specified a pre-specified level data rate using wireless communications ability. We use the Shannon-Hartley Theorem to model the possible tradeoffs between permissible signal strength and allotted channel bandwidths. As a proof of concept of the mathematical model, we created a simplified MS Excel-based version of the model. The model's output was also a mix of high and low power users, at various channel bandwidths and winning bids. We also review the implications of German Law and EU for such price-guided policy. Price-guided spectrum policy is viable in Europe. However, price-guided policies cannot be used to determine allocations and assignments in internationally harmonised bands. The most actionable initial implementations include determinations of maximum power limits, bandwidth, duration of rights and channelisation. Other early potential implementations include boundary interference standards and possibly congestion-based protocols.

Price-guided policy holds substantial promise because it encourages allocative efficiency of spectrum due to the fact that bidders can acquire exactly the set of spectrum rights they need. Further, price-guided policy mitigates the allocation errors inherent in administrative determinations.

1 Introduction

This project examines how market signals in the form of pricing information can be introduced into spectrum management policy in order to optimally guide not only assignment, but also determinations concerning type of use, emissions and modulation characteristics, and exclusivity.

The primary social objective of spectrum policy is to maximize the benefit which society obtains from use of the limited radio spectrum. A major thrust in recent years has been to use market mechanisms to determine spectrum assignment in an effort to ensure that the right to utilize the spectrum is held by those who value it most.[1] This idea began to take shape in 1959, when the Federal Communications Commission called Ronald Coase to testify about his proposal for market assignment of radio spectrum rights.[2]

To date, spectrum management authorities have used auctions to assign spectrum licences to their highest value users, but not to guide other administrative determinations. We devise a mathematical model to show that next generation auctions can be used to help make these determinations.

This paper proceeds as follows. Section 2 provides some background spectrum policy and on the administrative determinations which could be improved by the application of price-guided policy. In Section 3, we offer a review of EU spectrum policy in general and German spectrum regulation in specific. We look at flexible approaches to spectrum regulation based on market-oriented solutions in Section 4. In Section 5, we describe the inherent error present in administrative determinations. In Section 6, we review the price-guided policies employed or considered by four different spectrum management authorities to make determinations concerning band planning and conditions of spectrum use. Our mathematical model which illustrates one possible implementation of price-guided spectrum policy is contained in Section 7. In Section 8, we report the results of a spreadsheet-based implementation of this mathematical model. In Section 9, we describe some of the implications for EU policy and German spectrum regulation of a price-guided approach. Finally, in Section 10, we offer our conclusions.

1 See Marcus, J. Scott/ Nett, Lorenz/ Scanlan, Mark/ Stumpf, Ulrich/ Cave, Martin/ Pogorel, Gerard (2005): Towards More Flexible Spectrum Regulation, a WIK study for the German BNetzA (Towards More Flexible Spectrum Regulation).

2 See Coase, Ronald H. (1959): The Federal Communications Commission, 2 J.L. & ECON. 1.

2 Background on spectrum regulation

This section provides: (1) background on the need for spectrum regulation; (2) how spectrum management authorities complete the process of spectrum regulation; (3) the decision mechanisms available to spectrum management authorities; and (4) four characteristics of spectrum use which spectrum management authorities must decide. These four use characteristics are not exhaustive of the decisions which spectrum management authorities must decide. However, we believe that decisions could be facilitated by the by price-guided policies like those envisioned in the main body of this report.

2.1 The Tragedy of the Commons

The need for spectrum regulation is due to a fundamental physical phenomenon. When electromagnetic waves are: (1) harmonic in frequency; (2) incident in time; and (3) alight on the same reception device, the ability of those waves to be used as information carriers is degraded. This deleterious effect is interference. Without some form of intervention, it is impossible to exclude or limit the use of a common resource such as spectrum. Without exclusion, users consume the spectrum without regard to fact that their usage causes the deleterious effect of interference for other would-be users. They, therefore, tend to overuse the spectrum, reducing the benefits obtained by all. This outcome where overuse reduces all users' benefit and the accompanying reduction in total social welfare is referred to as the Tragedy of the Commons.[3]

Spectrum management authorities have had to address the appropriate means of exclusion of rival uses for spectrum policy in order to solve the Tragedy of the Commons. They have employed a variety of tools to do so. Historically, spectrum management authorities have used administrative proceedings to select uses and users. Through this selection process, spectrum management authorities can coordinate behaviour to reduce the likelihood that spectrum will become over used.[4]

The determination of users is principally achieved through the creation and assignment of rights to emit radio frequency energy *and independently* the right to be free from the interfering radio energy of other users. As an implicit part of this inquiry, spectrum management authorities must set certain operational parameters for spectrum use. These parameters establish permissible emissions power, operating frequencies, and guard bands, *inter alia*.

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3 See Hardin, Garrett (1968): The Tragedy of the Commons, 162 pp. 1243, 1244.

4 See Marcus, J. Scott/ Burns, John/ Hansen, Paul/ Marcus, Michael/ Marks, Philippa/ Pujol, Frédéric/ Redman, Mark (2006): "Study on Legal, Economic, & Technical Aspects of 'Collective Use' of Spectrum in the European Community", a study on behalf of the European Commission (Collective Use' of Spectrum in the European Community).

Spectrum management authorities are making many of these decisions as to use and users purely as administrative determinations, in the absence of information about the monetary valuation of the possible alternatives.[5] Price-guided policy is a means of making policy determinations whereby administrative decisions are supplemented with pricing or market information, usually in the form of auctions.

2.2 Spectrum regulatory processes

Figure 1 shows the process of spectrum policy development, moving right as it matures.

Figure 1: Spectrum regulatory processes

Process	Allocation	Policy	Assignment	Oversight
Decisions/Actions	•Band Selection •Use decisions •Network architecture	•Modulation and emissions limits •Power limits •Interference •Tower siting •RF Safety	•Identification of Users •Awarding of rights through licenses	•Police Role
Mechanisms	Administrative Rulemaking	Administrative Rulemaking	Auctions Lotteries Comparative Hearings	Complaint Resolution Disciplinary/ Actions
Price-Guided	Auctions Spectrum Trading	Auctions	Auctions Spectrum Trading	Complaint Resolution Disciplinary/ Actions

wik CONSULT

Source: WIK-Consult

Spectrum policy begins with allocation. Here the spectrum management authority identifies, usually through an audit, bands available for use. At this stage, decisions concern-

5 The inherent issues in administrative determinations are discussed in Section 5.1.

ing use, such as whether the band will be used for mobile, nomadic (portable) or fixed, are made. This has a profound impact on the network architecture of the future service. In the policy phase, the spectrum management authority makes the rules which will govern operation in the band. These decisions include the establishment of rules defining modulation characteristics, bandwidths, channelisation of blocks within a band, power limits, permissible interference, tower siting rules, licence duration and RF safety. Allocation and policy determinations affect:

- The spectrum band which can be used;
- The geographical area where the spectrum band can be used; and
- The period of time when spectrum it can be used.

Heretofore, the allocation and policy stages were accomplished by administrative rulemakings. This paper proposes incorporating price-signal information into the policy and allocation processes as well.[6]

In the assignment phase, those who are granted usage rights are identified, and permissions are granted. These are normally individual rights and conveyed in the form of a licence. At present, price-guided policy in the form of auctions is used to determine assignment by numerous spectrum management authorities around the world. Administrative tools such as comparative hearings and lotteries have been widely used to assign such rights. Pioneer preferences – first in time, first in right – have also been used.[7] Usage rights are typically assigned as exclusive rights. However, general authorisations, which grant rights by licence to a limited number of individuals or to all comers, are also possible. Examples of licences in a shared regime include business licences, drivers' licences, or Ham Radio operator's licences.[8] The EU Authorisation Directive expresses a preference for general authorisations.[9]

The oversight stage represents the spectrum management authority's police role. These

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6 We are aware of one instance where a regulator has successfully used market forces to make band plan determinations. See Section 6.1 for a discussion of ComReg's 26 GHz auction.

7 All these mechanisms have been used to assign spectrum in Germany, except lotteries. To date, there have been three auctions: The ERMES auction in 1996, the auction of additional GSM-1800 frequencies (complementary spectrum) in 1999 and the UMTS auction in 2000. The GSM-900, original GSM-1800, and WLL licences were assigned by means of a beauty contest. See, Nett, Lorenz (2001): Marktorientierte Allokationsverfahren für Nummern, WIK Discussion Paper No. 213.

8 It is often wrongly assumed that shared and licensed approaches to spectrum management are collective and mutually exclusive. Snider, J. H. (2006): Spectrum policy wonderland: a critique of conventional property rights and commons theory in a world of low power wireless devices, Telecommunications Policy Research Conference, Arlington, VA. Given that these approaches are not mutually exclusive, there has to date been very little work done on finding an optimal balance between the two, non-mutually exclusive approaches. See, Carter Kenneth R. (2006): Policy Lessons from Personal Communications Services: Licensed vs. Unlicensed Spectrum Access, 15 CommLaw Conspectus 93 (Policy Lessons from Personal Communications Services). OFCOM has tried at least one approach to determining the societal need for licence-exempt spectrum. See, OFCOM (2005): Spectrum Framework Review.

9 See Section 3.1 for further details.

actions are accomplished by complaint resolutions, disciplinary actions and, at times, legal proceedings. It would present perverse public policy outcomes to introduce market forces into the oversight role. This would enable financial incentives to influence adjudications. In most jurisdictions, these incentives are called bribes and are punishable by law. Oversight rules are important to spectrum use. However, since they remain unaffected by price-guided policies we give them only scant attention here.

2.3 Use models and regulatory decision approaches

There are three basic approaches to usage rights in spectrum policy (use models).[10] These non-exclusive approaches to spectrum regulation are the exclusive use, shared use and commons models. In addition, there are three vehicles for deciding to whom to assign such rights (regulatory decision approaches). Assignment can be done by administrative determinations, by price-guided means, or by technical means (for our purposes lotteries can be considered a form of price-guided determination).

The exclusive use, shared use and commons use models describe the nature of the relationships among users and would-be users of the spectrum. Under the exclusive use model, usage rights are assigned to a licensee who obtains exclusive and usually transferable flexible use rights for specified spectrum within a defined geographic area. Proponents of this approach argue that exclusive rights, when coupled with tradability, will lead to economic efficiency. By comparison, a shared use model allows multiple users to enjoy rights to the same swath of spectrum, subject to some requirement that priority is on a co-primary basis. The commons model permits potentially unlimited numbers of unlicensed users to share frequencies, with usage rights that are governed by technical standards or etiquettes, but with no right to protection from interference. Advocates for shared and commons approach argue that it will promote technological advances for sharing, interference resilience and opportunistic use. While both shared use and commons models are general authorisations, the difference between shared and commons models is that shared users have some form of licences which conveys rights and priorities among the users. Commons users have no such rights, nor any form of interference protection.

Under any of these use models, rights can be assigned to individuals by administrative determinations, by price-guided means (such as auctions), by technical means, or even by lottery. Administrative assignments[11] are the traditional process of spectrum management under which allowable spectrum uses are determined based on regulatory judgments. This approach might be best suited to uses where market forces are not

10 See e.g., Towards More Flexible Spectrum Regulation.

11 The administrative assignment approach is analogous to the “command-and-control” approach described in a 2002 report by the U.S. FCC’s Spectrum Policy Task Force. Federal Communications Commission (November 2002): Spectrum Policy Task Force Report at 35–53 (Spectrum Policy Task Force Report).

present. However, it is generally viewed as inefficient because the spectrum is undervalued as compared to market approaches. It also presents the greatest chance of regulatory capture. Therefore, spectrum management authorities have used auctions to assign exclusive usage rights. This approach allays some of the concerns of the administrative assignment approach by ensuring that usage rights are assigned to those individuals who have the highest monetary value for those rights.[12] Technological assignment approaches do not result in long-term assignment of usage rights. Rather, technological assignments include opportunistic use. A technology such as Cognitive Radio could sense the spectral environment and make decisions regarding whether it is permissible to operate in certain bands. See, for example, the description of the Interference Temperature in Section 4.3. Technological assignments are both a decision approach and a coordination mechanism. See Section 2.4.

Finally, lotteries have been used on occasion to assign rights. Since they are in effect private auctions, whereby the lottery winners often resell their rights to higher value users. Auctions established by the spectrum management authority are usually preferable to lotteries. We eschew any detailed discussion of lotteries here.

Taken together, the three use models and the three decision approaches are a set of descriptors by which one can describe an entire suite of approaches to spectrum regulation. To illuminate this, we have created a matrix which compares decision making approach and use model. (See Table 1). Across the top are three approaches to allocating usage rights.[13] These are Administrative Assignment, Technological Approaches and Price-guided mechanisms. Down the left hand side, there are three models of exclusivity.

Table 1: Models and approaches to spectrum regulation

Decision Approach / Use Model	Administrative Determinations	Technological	Price-guided
Exclusive Use	Terrestrial Broadcast Television		PMLR (Spectrum Trading)
Shared Use	Ham Radio General Authorisations (Licence-by-Rule)	Technological Congestion Protocol	Economic Congestion Protocol
Commons	Licence-exempt Spectrum (Sufferance Basis)	Voluntary Etiquettes (Sufferance Basis)	Device Tax

12 For a detailed description of the issue, see Section 5.

Some examples mixing uses models and decision approaches include the following. One of the best known examples of administrative determination and exclusive use is terrestrial broadcast television. Normally, such bands are exclusive in that only user may use a given frequency in a particular geographic location. Licensing and use determinations for broadcast television are made by administrative regulatory proceedings. By contrast, auctions, such as the German UMTS Auction, have been used to award licences to mobile wireless operators.[14] Here, use is exclusive, but the assignment is based on price information.[15]

In recent years, the U.S. FCC has made efforts to encourage sharing of the spectrum through technological means. It did so in its 3650 MHz rules where it requires spectrum users to obtain non-exclusive, geographically-specific licences for radio links and employ technological "contention-based" coordination protocols.[16] The FCC has also considered means for introducing economic coordination protocols to enhance the value of licence-exempt spectrum.[17] Licence-exempt spectrum devices are a combination of an administrative assignment approach and a commons model. Licence-exempt users face rules on strict emissions limits based administrative determinations, but anyone may obtain and use these devices. A market-based approach to a commons model might likely impose a tax or fee on the sale of devices. In 2003, the Japanese Ministry of Information and Communications briefly considered imposing a "Radio Utilization Fee" on unlicensed devices to limit the possibility of over use. It quickly abandoned the idea. In the early 1990s, the U.S. FCC embraced an approach to imposing fees on unlicensed devices to facilitate relocation of incumbent users. The FCC's approach had the inadvertent effect of creating a licensed shared use regime and not a true commons regime.[18]

The means of assignment decision-making can affect all aspects in the spectrum policy process. (See Figure 1 on page 3). Specifically, these approaches impact: radio operation; use and architecture decisions; and licensing and assignment. As noted in Section 2.2 above, different decision-making approaches can be used in the spectrum policy process. For example, it is possible to have an administrative assignment approach to determine modulation and power concerns, while using price-guided mechanisms to assign rights. Indeed, this is how most spectrum auctions have functioned to date.

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13 Conceivably, other tables such as Table 1 could be devised, comparing use models and decision approaches to allocation and policy determinations. However, use determinations occur largely at the assignment phase of spectrum policy.

14 See Section 6.4.

15 We do not consider spectrum leasing or roaming to be shared use. Our definition of shared use is co-primary status of rights holders.

16 Federal Communications Commission (2007): Memorandum Opinion and Order, In the Matter of Wireless Operations in the 3650-3700 MHz Band Rules for Wireless Broadband Services in the 3650-3700 MHz Band Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band (ET Docket No. 04-151, WT Docket No. 05-96, ET Docket No. 02-380).

17 For a full description, see Section 6.3.1.

18 See Policy Lessons from Personal Communications Services.

2.4 Uncoordinated spectrum approaches and coordination mechanisms

In general, wireless systems can be categorized as being either coordinated or uncoordinated, depending on whether the system possesses a mechanism by which competing uses can be sequenced and ordered to reduce the possibility of conflict. The means by which coordination is achieved can be a technology, protocol, rule or even social norms. For example, certain radio systems employ code division multiplexing access (CDMA). This technology allows users to be assigned small swaths of spectrum within a certain tuning range, based on a coded sequence. It enables these users to effectively share the spectrum. By contrast, ham radio operators adhere to certain social norms and etiquettes which enable multiple users to peaceably coexist using the same spectrum. It is considered bad form for a ham radio operator to make lengthy or unnecessary transmissions. Ham operators do not “step” on the transmissions of others, and they allow emergency communications to get first priority. Ham radio is a coordinated system, but no specific technology or legal requirement is used to sequence competing transmissions. Rather, social etiquette is the coordination mechanism. Finally, an uncoordinated system such as Wi-Fi may also employ CDMA. Here, however, the technology allows a desired signal to be sorted out from the background noise or other users’ transmissions. However, the Wi-Fi system does not necessarily coordinate the transmissions of disparate users, but the system may contain protocols for “backing off” when it senses other users.

Table 2: Coordinated vs. uncoordinated spectrum access regimes

	Coordinated Spectrum Access	**Uncoordinated Spectrum Access**
Features	Centralized - base stations and terminals - time/spectral slots ~higher power	Distributed - radio devices only - no collision avoidance ~lower power
Advantages	Handles congestion well Low overhead cost at high utilization rates	Low overhead cost at low utilization rates No coordination across standards
Disadvantages	High overhead and opportunity costs at low utilization Requires coordination across standards Higher barriers to entry	High congestion costs No ability to exclude

Source: Kenneth R. Carter, WIK-Consult

Coordinated and uncoordinated regimes both posses comparative advantages, but neither holds an absolute advantage over the other. Both can, under the right circumstances, produce stable outcomes. Each approach has its own advantages and disadvantages, which may make it more or less suitable for achieving particular goals. (See Table 2.) Coordinated spectrum access systems tend to be centralized and hierarchical. In these systems, base stations control lower-level devices and allocate spectrum in time and frequency domains. By contrast, uncoordinated spectrum systems tend to be distributed and without the ability to avoid spectrum 'collisions'. These features make coordinated better suited for high power uses and better able to handle congestion well. However, at low utilization rates, coordinated systems present high overhead costs. Further, because coordination requires a grant of rights, normally exclusivity, coordinated regimes tend to present higher barriers to entry than uncoordinated.

The coordinated versus uncoordinated decision may also be affected by the nature of the communications which travel over that network. There are two categories of such transmissions isochronous operations and asynchronous operations.[19] Asynchronous data communications are generally short bursts of transmissions, and it is therefore hard to synchronize the devices to share the spectrum. By definition isochronous wireless systems can be synchronized since they have longer and more predictable transmissions. To achieve this, in isochronous systems a given wireless device's transmitter must be off while receiving. Coordination can be accomplished both in centralized, hierarchical systems coordinated by an access point or in the nodes in a peer-to-peer network.

For a price-guided sharing regime function, the wireless devices must include some mechanism for coordination. As a part of the coordination mechanism, the wireless system must incorporate bidding agents through which end-users can express their willingness to pay. In addition, such a mechanism needs to have the capability for communications between the users' applications and the network in order to report the necessary capacity and other items which the application requires. Advances in radio technologies now make it more than possible to incorporate these requirements into the operating protocols for the hardware and software of wireless devices. For our purposes it is of little consequence whether the coordination protocol is done in the band as the information is transmitted, or in a separate band. What is important is that the radio devices are capable of recognizing one another and coordinating their use.[20]

There is not a pure strategy reason to prefer coordinated regimes over uncoordinated, or vice versa. An ideal approach to spectrum management should contain features of both regimes.

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19 Historically, isochronous operations have been principally used for voice communications, while asynchronous operations have been principally used for data communications. The diffusion of VoIP technologies may to some degree obviate this, placing a greater importance on data communications.

20 Indeed, if multiple radio systems operate in the same band, in order to be coordinated, it is not necessary that the systems are interoperable to the extent that they are capable of sending messages back and forth among themselves. What is necessary is that the systems are capable of being coordinated to prevent their radio transmissions from interfering with one another.

2.5 Licence vs. licence-exempt determinations

The spectrum management authority must also make a determination regarding the licensing of a particular spectrum band. This is generally made independently of coordination determinations, but they do influence each other.[21] The inquiry is not a simple licensed- or licence-exempt-decision. Rather, it represents a continuum of determinations.

Licensing determinations are in essence a determination of level of exclusivity of use. Licensed use does not equate one-to-one with solitary use. Licences can be exclusive, but they can also be shared. Nonetheless, licences grant permission to use the spectrum for a specified period of time, at a specified frequency, and at a specified place. Licensed use prevents overuse by assigning the exclusive ability to make usage decisions to an individual or limited number of entities. Licences themselves can run the gambit from single, nationwide permissions to regional or site-specific permission to grants to individuals such as ham radio licences. These entities are responsible for coordinating use, and do so to a private optimum.

A spectrum management authority could also allocate spectrum to licensed-exempt use. Licence-exempt rules typically grant the right of use of low power spectrum on a sufferance basis with all other would-be users. Licensed-exempt use addresses the Tragedy of the Commons by strictly limiting the emissions characteristics in terms of frequencies, modulation, and power level. Radio devices must be certificated to show that they comply with the rules promulgated to ensure a low probability of harmful interference.[22] A similar regime is general authorisations, also called license-by-rule. Here radio devices are also certified for low power operation, but user licences are awarded to a class of persons. General authorisations can afford rights to be free from harmful interference, or not.

Licensing determinations are linked to the use and characteristics of the frequencies covered. For example, narrow spectrum beams used for point-to-point links possess a low risk of interference and can be licensed through registration in national database on a first-in-time is first-in-right basis. By contrast, high power, point-to-multipoint broadcast arrangements require a single licensee in a particular band. These licences can be awarded through lotteries, technical means, comparative processes or even auctions.

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21 Licensed regimes are generally coordinated and licence-exempt regimes are generally uncoordinated. In licence-exempt regimes, power and modulation policies can serve to take the place of coordination mechanisms, by reducing the likelihood of intercept. The authors are aware of a single example where a coordination mechanism was imposed on a licence-exempt regime. This is Unlicensed Personal Communications Services (U-PCS) in the United States. Due to this requirement and several other factors, U-PCS was never widely adopted commercially. See Policy Lessons from Personal Communications Services. While it is possible to have a coordinated, licence-exempt approach, this is highly unlikely.

22 Carter, Kenneth R./ Lahjouji, Ahmed/ McNeil, Neal (2003): Unlicensed and Unshackled: A Joint OSP-OET White Paper on Unlicensed Devices and Their Regulatory Issues, FCC OSP Working Paper Series.

2.6 Band plan determinations

The spectrum management authority must make band plans for various radio spectra. These determinations include setting rules for frequencies such as the size of spectrum blocks within a band, maximum power limits, placing and width of guard bands, and pairing decisions. Since all usable spectrum has been allocated and assigned, this process normally begins with an audit for under utilized spectrum resources. Once a potentially free spectrum band is identified, the spectrum management authority must decide certain parameters of the radio use with in this band. These parameters include the maximum permissible power, the width of spectrum blocks to be assigned and allocated, the spacing of those spectrum blocks, the width and spacing of guard bands, and the pairing or lack of pairing of assigned blocks.

Spectrum management authorities can prescribe maximum radio power in any number of ways. Limiting the amount of power density (usually isotropic) that can be emitted by a radio device is the most straight forward. Determinations of modulation characteristics can also be used by spectrum management authorities can control the amount of RF energy emitted which could result in harmful interference. This limitation can be described by the contours of a licence or by rules governing a general authorisation.

These determinations must be made *ex ante* and are closely tied to considerations such as network architecture, radio technology, and usage. For example, the pairing determination is closely related to multiplexing determinations. One arrangement, Frequency Division Multiple Access Frequency (FDMA), enables spectrum sharing by allocating separate carrier frequencies to different users within a single band of the radio spectrum. The separation of these carrier frequencies must be a harmonic multiple in order to take advantage of efficiencies in antenna design and radio tuning. Therefore, a system employing FDMA would require spectrum blocks to be paired rather than unpaired. The separation of those paired blocks would be determined by specific needs of the radio system design. By contrast, Orthogonal Frequency Division Multiplexing (OFDM) is a modulation scheme that divides a single digital signal across 1,000 or more signal carriers simultaneously (FDM). The signals are spaced at precise frequencies, which prevents the demodulators from seeing frequencies other than their own (hence, orthogonal) so that they do not interfere with each other. OFDM offers multiple access and signal processing, and allows wireless networks to use relatively small bandwidths highly efficiently. OFDM radio systems require contiguous (unpaired) spectrum blocks.

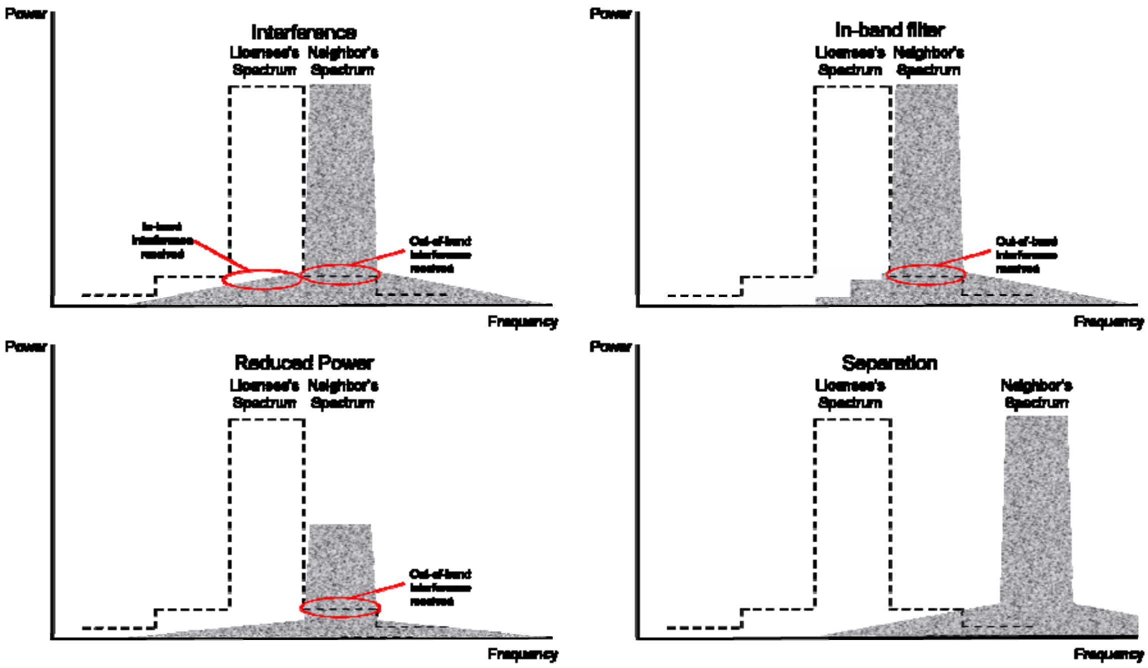
Within these parameters, spectrum users ought generally to be free to operate any way they see fit.

2.7 Setting receiver sensitivity standards

When we think of radio spectrum policy, all too often we fail to decompose radio operations into its two fundamental components: transmission and reception. Most spectrum policies regulate transmission thereby controlling unintended reception-interference. In next-generation spectrum policy, receivers and their sensitivity to the transmissions of others will be an important component.

No radio device can be perfectly engineered to reject all unwanted signals. Nor can every radio be tuned perfectly to operate on a specific frequency. Radios will emit and receive signals in the band adjacent to it in the spectrum range. Unwanted signals can be classified as coming from two sources: in-band and out-of-band. In-band signals, as the name suggests, are those radio signals which occur within the intended tuning range of the given radio. The source of in-band interference can come from noise in the spectral environment and other authorized users of the band. In-band signals can also come from the spurious emissions of authorized users in adjacent frequency bands and bands which are harmonic in frequency. Therefore, it may be necessary to form guard bands on either side of the centreline frequency. Further, radio receivers also accept some signals from outside of their intended tuning range.

Figure 2: In-band and out-of-band interference



Source: WIK-Consult

There are two basic solutions to this problem of in-band and out-of-band inference. First is to increase the receivers' robustness to reject unwanted signals. Second is to reduce the power of the interfering signals. Increasing receiver robustness involves the use of filtering and other techniques which increase cost and complexity of radio systems. However, in some cases the cost may be warranted. For example, the Wi-Fi suite of standards employs such techniques since it operates in bands which are typically afforded no interference protection. Here, the cost and complexity of obtaining interference protection in the form of a licence outweighs the cost of the filtering. There is also another benefit of this cost which accrues to other users who do not have to reduce the power of their emissions.

There are several means by which the power of interfering signals can be reduced. Most simple is to reduce the maximum permissible power in adjacent and harmonic frequencies. A second mechanism is to further separate the tuning ranges through the use of guard bands. A technological solution involves using filters to mask out-of-band users' emissions in the given band. This is very similar to reception filters. This has the effect of imposing cost on one radio user, while the benefits accrue to another.

There is a trade-off between the width of spectrum blocks and the technologies which give radio equipment the ability to reject undesired signals as noise. Given these constraints, the spectrum management authority must decide how to balance the width of spectrum blocks and impose costs and benefits in a fair, equitable and transparent manner. These determinations are subject to the errors inherent in other administrative determinations. In Germany, the BNetzA prefers Coasian outcomes for boundary interference disputes, leaving it to the licensees to negotiate for themselves. While generally more efficient, these outcomes can be subject to hold out problems and to bargaining power.

3 Spectrum Policy in Europe

3.1 Spectrum regulation in the EU

The EU framework addresses the management of radio spectrum. Spectrum management under this framework seeks primarily to mitigate harmful interference, and thus the Tragedy of the Commons. The goals of European spectrum policy include enabling a better level of use, decreased unit costs for radio devices, and greater flexibility of radio operations. These goals are laid out in the Framework Directive,[23] the Authorization Directive,[24] Decision of the European Parliament and of the Council on a regulatory framework for radio spectrum policy in the European Community (Radio Spectrum Decision)[25], the Radio and Telecommunications Terminal Equipment (R&TTE) Directive, and directives and decisions relating to specific services (including the GSM Directive and the UMTS Decision).

Since so much of spectrum regulation involves grants of permission, the Authorisation Directive is key to spectrum policy in the EU. The recitals of the Directive provide for objectivity, transparency, non-discrimination, and proportionality. These requirements are prevalent throughout the Directive. Further, recital 7 of the Directive provides that the least onerous authorisation system of spectrum management must be used. In addition, spectrum management authorities should not distort the market through authorisations, and should promote efficient use and efficient investment. Article 5 of the Authorisation Directive requires that where harmful interference is slight, spectrum management authorities must not assign individual rights to spectrum. Rather, general authorisations are preferred. Rights to use spectrum must be granted though open, transparent, and non-discriminatory procedures. The Radio Spectrum Decision recital 8 states that spectrum must be based on economic, political, cultural, health and social considerations in addition to purely technical parameters.

Competitive mechanisms such as auctions for assigning spectrum licensed for commercial uses have been widely employed by spectrum management authorities in Europe. Such spectrum auctions are expressly permitted under Article 7 of the Authorisation Directive. However, according to Article 13, any fees levied must be justified, transparent, non-discriminatory, and proportional.

Harmonisation and a single European Information Space are also important goals of EU spectrum policy. When it comes to issues of harmonisation, the national spectrum rules of Member States must not add criteria which would restrict, alter or delay the imple-

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23 Directive 2002/21/EC of the European Parliament and of the Council of 7 March 2002 on a common regulatory framework for electronic communications networks and services (OJ L 108, 24.4.2002).

24 Directive 2002/20/EC of the European Parliament and of the Council of 7 March 2002 on the authorisation of electronic communications networks and services (OJ L 108, 24.4.2002).

25 676/2002/EC.

mentation of the common assignment. According to Article 9, harmonisation should reflect the requirements of general policy principles identified at the Community level.[26] At a European level, spectrum use is coordinated by the European Conference of Postal and Telecommunications Administrations (CEPT). Within the CEPT, the European Communications Committee (ECC) is responsible for the actual task of coordinating spectrum usage across Europe. CEPT members reach agreements on the use of frequency bands in order to harmonise and coordinate pan-European spectrum usage. ECC has created a general European frequency plan for this purpose. To this end, a series of Detailed Spectrum Investigations (DSI) have been carried out, resulting in the creation of a European Table of Frequency Allocations and Utilisations. The latest version of the Table dates from January 2002; however, the European Frequency Information System is available on the public Internet.[27]

3.2 Spectrum regulation in Germany

The Authorisation Directive provides general principles for spectrum management, but the primary responsibility remains with the Member States. Thus, the Federal Republic of Germany pursues its own regulations regarding spectrum management. The *Telekommunkationsgesetz* (TKG – German Telecommunications Act), specifically sections 52 – 65, governs how spectrum regulation can be structured. Under the Act, the primary objective of German spectrum regulation is similar to that of the EU – to ensure efficient, undisrupted spectrum use. In section 2 (2) of the TKG, further objectives are detailed: “securing fair competition and promoting telecommunications markets with sustainable competition in services and networks and in associated facilities and services, in rural areas as well.” This analysis is not completed from a solely economic perspective. Rather, other considerations such as social, cultural or meritorious issues and defence policy are considered as necessitating spectrum allocations.

At the operational level under these regulations, spectrum usage is primarily determined by the following three items:

- National Table of Frequency Allocations
- Frequency Usage Plan
- Frequency assignment

The *National Table of Frequency Allocations* allocates bands of spectrum to radio services and other applications. These allocations are stipulated by the Federal

26 Radio Spectrum Decision Recital 11.

27 ERC (2002): The European table of frequency allocations and utilisations covering the frequency range 9 kHz to 275 GHz, Lisboa, January 2002, ERC Report 25. See also European Frequency Information System at: www.efis.dk.

Government, which enacts law to effectuate this. The main purpose of the National Table of Frequency Allocations is to implement international agreements concluded with the ITU (WRC), CEPT, and EU.

Pursuant to Section 54 of the TKG, the BNetzA (Federal Network Agency) is responsible for drawing up the *Frequency Usage Plan* on the basis of the frequency bands identified in the table of allocations. The plan includes a more detailed allocation of the frequency bands to particular frequency usages, as well as determines the additional parameters required to ensure efficient use and prevent harmful interference. It specifies the provisions setting the maximum permissible equivalent radiated power, channel separation, channel width, and channel subdivisions. Possible frequency usages under the Frequency Usage Plan include amateur radio, business radio, trunked radio, digital cellular mobile communications, aeronautical radionavigation, satellite-to-satellite links and maritime radio.

As a rule, each frequency usage requires prior *frequency assignment,* in accordance with the Frequency Usage Plan and as part of a transparent and objective process. A general assignment is the first choice for assigning frequencies. However, when the risk of harmful interference cannot be ruled out otherwise or when this is necessary in order to secure efficient use of frequencies, individual assignments will be made. Pursuant to Section 55(9) of the Telecommunications Act, award proceedings are only used to assign frequencies where spectrum is scarce. The frequency assignment specifies, in particular, the type and extent of the frequency usage, insofar as is necessary to secure efficient and interference-free use of frequencies. Secondary conditions may also be attached. Frequencies may be assigned either in perpetuity or for a limited period. Usage rights are also restricted to a particular geographical area. This may be the whole territory of the Federal Republic or one or more of its regions.

4 Advancing spectrum policy

For most of the Twentieth Century, spectrum policy tightly controlled all aspects of radio operation. It did so by imposing strict conditions on the rights of use. Since radio operations are a critical input into all areas of private economic and public activity, governments around the world have been engaged in a radical rethinking of spectrum policy. Prompted by the need to ensure the spectrum is allocated and used efficiently, national spectrum management authorities have been moving away from the stodgy, decades old regulatory regime towards approaches which afford greater flexibility. The more flexible regimes envisioned are based on technological and market-oriented solutions to achieve a more optimal level of allocation to particular services. This move towards technical and economic flexibility has also been fuelled by advances in radio signal processing afforded by ever increasing computing power.

4.1 Major trends in Europe

In recent years, the EU has made moves towards the development of a policy to promote more flexible use of spectrum and greater use of market approaches to spectrum management. The strategy is aimed at ensuring a common approach to managing spectrum resources at the EU level to allow innovators to place new technologies on the EU single market quickly, with technology- and service-neutral allocations.

In a 2005 Communication, the European Commission expressed concerns that spectrum policy is not keeping pace with the advance of radio technology.[28] If left unchecked and given the rising demand for radio spectrum use, it is possible that Europe could become a net importer of radio technology, rather than an innovator. The Communication urged lowering barriers to entry, improving flexibility of use, enabling licence-exempt use, and facilitating the use of market-based models (including spectrum trading). As part of the i2010 initiative, it urged the implementation of these practices by 2010. The Commission announced its intention to develop the following features in next generation spectrum policy:

- Tradability
- Technology neutrality
- Service neutrality
- Spectrum rights
- Transparency

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28 European Commission, Communication from the Commission to the Council, the European Parliament and the European Economic and Social Committee and the Committee of the Regions, A market-based approach to spectrum management in the European Union. 14 COM(2005) 400 final (September 2005).

The Communication further urged a step-wise approach, with test bands being used to prove out the value of a harmonised approach to ensuring tradability and flexibility. An essential element to this transition is the need for harmonised definition of rights. Technological and service neutrality are also important, but subject to the proviso that some constraints might need to be imposed in order to mitigate the likelihood of harmful interference.

In addition to the 2005 Communication, the European Commission included a review of radio spectrum management in its proposal of 13 November 2007 to amend the telecoms directives.[29] Subject to certain compromises not relating to spectrum policy the proposal was adopted on 5 November 2009. The Commission's proposal moves forward to codify many of the conclusions of the 2005 Communication into the existing directives. Indeed, one of the three main objectives of the proposal is moving towards more efficient management of the radio spectrum. The proposal reiterated the need to move to a more flexible approach which was expressed in the 2005 Communication. The Authorisation Directive would be changed to take on new policy for spectrum, creating harmonised rights and a smooth transition to spectrum trading. The proposal changes Article 9 of the Framework Directive, introducing the principles of technological and service neutrality for spectrum. This would be subject to needs for (1) mitigating harmful interference; (2) RF safety; (3) maximising sharing under a general authorisation; and (4) public interest needs such as public safety or social cohesion. In addition, Article 9 will be amended to require spectrum management authorities, starting on 1 January 2010, to examine existing use conditions for unnecessary restrictions. Article 9b would permit tradability of spectrum rights in certain bands, without prior approval. The Commission is empowered to adopt implementing measures for harmonising certain bands in which rights can be traded or leased.

Article 5 of the Authorisation Directive now permits spectrum management authorities to award individual rights of spectrum use when it is justified in order to: (1) avoid a serious risk of harmful interference; or (2) fulfil other objectives of general interest.

4.2 WAPECS initiative

Wireless Access Platforms for Electronic Communications Services (WAPECS) are platforms used for radio access to electronic communication networks and services, regardless of the bands in which they operate or the technology they use. WAPECS platforms can provide mobile, portable or fixed access to a range of electronic communications services. WAPECS applications may be either licensed or licence-

29 European Commission, Proposal for a Directive of the European Parliament and of the Council amending Directives 2002/21/EC on a common regulatory framework for electronic communications networks and services, 2002/19/EC on access to, and interconnection of, electronic communications networks and services, and 2002/20/EC on the authorisation of electronic communications networks and services. COM(2007) 697 final (13 November 2007).

exempt, which means that the term encompasses all second and third-generation mobile communications services, wireless data transmission services and WLAN/Wi-Fi as well as broadcasting and TV services. A survey of EU member states identified the following frequency bands as being suitable for WAPECS:

Table 3: Frequency bands identified for WAPECS

Broadcasting bands	174–230 MHz 470–862 MHz 1452–1479.5 MHz	
Fixed links/point to point (P2P)	5925–6425 MHz, 3600–4200 MHz, 1375–1400 MHz, 1492–1517 MHz, 1427–1452 MHz and 1350–1375 MHz	
Point to multipoint (P2MP)	(without MWS) 3400–3800 MHz, 24.5–26.5 GHz (with MWS) 24.5 GHz–26.5 GHz	
Mobile services	380–400 MHz 410–430 MHz 450–470 MHz 870–876 MHz 880–921 MHz 925–960 MHz	1710–1785 MHz 1805–1880 MHz 1900–1980 MHz 2010–2025 MHz 2110–2170 MHz
Licence-exempt bands	1880–1900 MHz (DECT) 2400–2483.5 MHz (RLANs) 5150-5350 MHz (RLANs) 5470-5725 MHz (RLANs)	

Source: RSPG

The definition WAPECS represents a deliberate attempt to move away from restrictive spectrum allocation. The object is to enable the frequency bands in question to be used by efficient, digital applications, while at the same time taking account of frequency restrictions designed to permit co-existence. One of the first questions to be resolved concerns the restrictions that the spectrum management authority must impose on the frequency bands in order to pursue the intended approach.

4.3 The Interference Temperature

In this section, we provide background on a novel technological approach to spectrum management which was postulated in the United States several years ago. The metric, dubbed the “Interference Temperature”, could have empowered technical flexibility, open access and efficiency. The U.S. has not yet moved to implement it.

First proposed by the U.S. FCC's Spectrum Policy Task Force in 2002, the interference temperature metric would have enabled the quantification of interference on a band-by-band basis, by establishing limits on the noise environment in which receivers would be required to operate. The interference temperature represents a maximum cap on the amount of RF energy that lower priority, underlay users could introduce into the band, to the extent it had not already been reached.[30] As such, it would provide spectrum certain to primary spectrum users in terms of quantifiable level of harmful interference which they could expect within their bands. At the same time this technological solution could encourage efficient use by provided means for enabling sharing by multiple secondary users.

While the interference temperature metric has yet to gain recognition in Europe, we think that setting an appropriate value for the metric is something which could be achieved through our price-guide policies proposed in the main body of this report.

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30 Spectrum Policy Task Force Report at 27-30.

5 Economics of policy determinations

5.1 Inherent error in administrative determinations

In public policy debates, the complex organs of society are oftentimes reduced to the hopelessly simplistic dichotomy: markets and bureaucratic institutions. It is widely observed that regulated markets, while imperfect, are more efficient at allocating society's scare resources than command economies are. Nonetheless, the preference for market institutions and administrative determinations, or *vice versa*, is driven by ideological concerns rather than the institution's efficiency at achieving a particular goal. A more apropos inquiry is what are the relative strengths and weakness of the institution in achieving desired outcomes.[31]

Regulators, especially those with sector-specific expertise, are able to make rational, well informed decisions. However, they lack the information gathering ability and profit incentives of larger, more diverse participants in a market. Therefore, regulators can err in arriving at a decision which is suboptimal. For example, in attempting to solve the Tragedy of the Commons problem, the regulator may err in creating rules which are overly restrictive and could possibly reduce societal welfare. This has been less poetically dubbed, 'the Tragedy of the Anti-Commons'.

Decisions regarding spectrum rules must be transparent and objective, considering all feasible options and using all available information on the costs and benefits of these options.[32] It might be possible to have transparent and objective determinations, but it is generally regarded that other systems might be preferable. Indeed, one observer considers the administrative process for determining licensing rules to be unsatisfactory.[33] This is because any spectrum management authority, with its limited resources, is likely to err in deriving optimal spectrum allocation and policy. These limited resources of the regulator lead to asymmetries of information and economic incentives which distort the process. A multitude of self-interested, private actors seem to fare much better. In addition, the information which the regulator receives through the consultation process is tainted at best.[34] This is not to suggest that participants in consultation are being wilfully

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31 European Commission, Proposal for a Directive of the European Parliament and of the Council amending Directives 2002/21/EC on a common regulatory framework for electronic communications networks and services, 2002/19/EC on access to, and interconnection of, electronic communications networks and services, and 2002/20/EC on the authorisation of electronic communications networks and services. COM(2007) 697 final (13 November 2007).

32 See Collective Use of Spectrum in the European Community at 13.

33 Cave, Martin (2006): "New spectrum-using technologies and the future of spectrum management: a European policy perspective," by, in Communications: The Next Decade, edited by Ed Richards, Robin Foster and Tom Kiedrowski, Ofcom at 224 (administrative approach to determining licence rules "arbitrary and unsatisfactory.").

34 Bykowsky, Mark/ Olson, Mark/ Sharkey, William (2008): A Market-Based Approach to Establishing Licensing Rules: Licensed versus Unlicensed Use of Spectrum, FCC OSP Working Paper Series at 1 (OSP Working Paper #43).

dishonest. Rather, since there are no penalties for over- or under-representations of the participants' true valuation of a certain set of rules, there is a perverse incentive to exaggerate as much as is possible without being fraudulent or viewed as simply not credible.

Further compounding the problem is the economic phenomena of regulatory capture. Regulatory capture is said to occur when a governmental agency acts, or appears to act in a way which favours narrow, private interests, rather than the public interest and enhancing societal welfare.[35] This can occur when commercial actors dominate in the industry which the regulator has authority over. These actors have a natural self-interest in the regulatory process and outcome. By contrast, private individuals have relatively little interest in the regulatory outcome, and might ignore the regulatory process altogether. This imbalance sets the stage for persuasive individuals to influence the regulatory staff or commission members to vote for an outcome which favours private rather than public interests.[36]

These effects thwart a set of spectrum rules which represents a true social optimum.

5.2 Price-guided determinations

It is widely accepted that free markets are better suited to efficiently allocating society's resources than are centrally planned economies. Price signal information can illuminate the societal costs of alternative allocations. Price signal information overcomes the exaggeration problem inherent in the administrative/consultation process as follows. The presence of prices for certain regulatory outcomes imposes penalties for over- and under-representations of true valuations. The penalty for a party which under-represents its true valuation of spectrum access would be not to have access to the spectrum. The penalty for over-representation would cut into the profits a winning bidder could make from the spectrum, by being committed to a bid which represents more than the value of access.

With regard to spectrum policy, price-guided mechanisms tend to promote economically efficient use in several ways. First, auctions, at least in theory, assign radio spectrum licences to those who value it most. Should a higher value user emerge, secondary markets allow those new, potentially more efficient users to acquire access to the spectrum, by motivating initial licensees to divest themselves of a resource for which they have paid substantial sums. Similarly, administrative incentive pricing policies mimic market forces to impose discipline on users, encouraging efficient use.

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35 Laffont, J. J./ Tirole, J. (1991): The politics of government decision making. A theory of regulatory capture. Quarterly Journal of Economics 106(4): 1089-112.

36 See e.g., Fast Net News, The 2+2=5 Crowd, available at: http://www.fastnetnews.com/policy/177-p/995-225crowd.

Markets can be preferable to pure administrative determinations, but when left to own devices, they can produce perverse results. To see an example of this one needs to look no further than global financial meltdown of 2008 - 2009. All economies suffer periods of boom and bust. Yet, economies function best when price signal information available to prioritize usage. Despite their ability to efficiently allocate resources, markets are highly inadequate to establish social norms and public policy. Perhaps this is due to the corrupting influence of the profit motive and perverse outcomes of individuals working in their own self-interest. All markets require some form of government intervention in order to make them function effectively.

Auctions have been a standard means for assigning rights of spectrum use in Europe for a long time. A recent trend is a broader scope for the use of auctions in spectrum policy. In the balance of this report, we demonstrate how market information in the form of price signals can be used to establish efficient parameters for spectrum regulations beyond just the assignment of rights of use. We believe that, while not supplanting the decisions of the regulator, price discovery mechanisms such as auctions are an effective tool for rationalising administrative determinations and could establish usage parameters which are more economically efficient.

6 Search for solutions

At least four spectrum management authorities have made steps towards introducing price-guided determinations in spectrum allocation and policy. One of these has been theoretical, the other three practical. ComReg conducted a two-part auction for spectrum in the 26 GHz which shaped both the allocation to specific applications and the assignment to specific users, completed in 2008. In 2006, Ofcom proposed a two-part auction which would not only identify the recipients of spectrum licences but also the pairing determinations associated with those licences. In February 2008, the U.S. Federal Communications Commission released a suite of three studies looking at price-guided commons and a market-based approach to forming licensing rules.[37] The German auction for UMTS licences in 2000 did not determine the band plan; however, plan was set by the RegTP based on the results from the auction. This section addresses several issues from the ComReg, Ofcom, FCC and RegTP work.

6.1 ComReg 26 GHz fixed service band auction

In 2005, ComReg (the spectrum management authority for the Republic of Ireland) set out to design an auction which could be used not only to determine the recipients of radio spectrum licences in the 26 GHz band, but also to solve technological and use characteristics regarding the band.[38] Specifically, ComReg sought comment on how to use market mechanism to determine whether spectral blocks would be allocated to either point-to-point or point-to-multipoint (or other multipoint) applications. The band consisted of two 504 MHz wide blocks. ComReg sought the selection of usage rights in a manner that would be objective, transparent, non-discriminatory and proportionate.[39] ComReg's objectives for the assignment included:

- Effective assignment, generating the greatest value for the Republic of Ireland;
- Efficient assignment, using market forces to determine the optimal split between point-to-point and point-to-multipoint allocation;
- Minimisation of the aggregation risks for bidders seeking multiple 2 x 28 lots of spectrum in order to have contiguous blocks;
- Reduction in the likelihood of unassigned spectrum;
- Mitigation of asymmetries between bidders;

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37 One of the authors of one of the U.S. FCC studies, Kenneth Carter, is the principle author of this report.

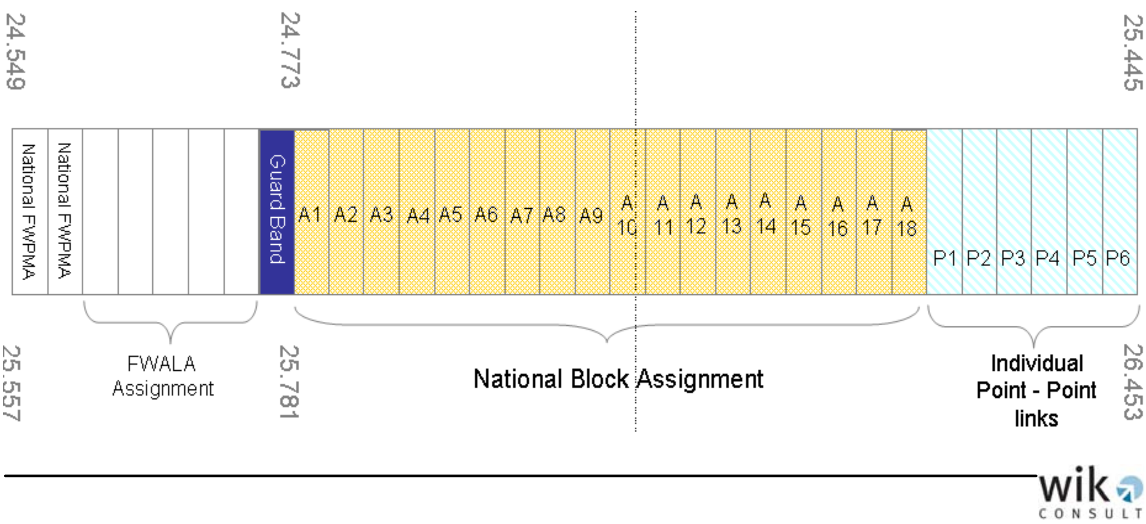
38 Commission for Communications Regulation (11 November 2005): Response to Consultation, 26 GHz Fixed Service Band – Spectrum, Document No: 05/84.

39 Commission for Communications Regulation (24 January 2008): Information Memorandum, The Award of National Block Point to Point and Point to Multipoint Assignments in the 26 GHz Band, Document No: 08/93R.

- Speed and simplicity of assignment; and
- Minimisation of the risk of strategic manipulation.

As can be seen in Figure 3, the 26 GHz band consists of two paired frequency ranges: 24.773 to 25.277 GHz and 25.781 to 26.285 GHz (the two blocks are overlaid on each other in the figure). The range is further comprised of 18 lots of 2 x 28 MHz. ComReg chose not to designate specific frequencies for particular technologies or applications. ComReg did follow a recommendation from CEPT to segregate point-to-point and point-to-multipoint uses in the band in order to minimise the need for guard bands to prevent interference between different access techniques and network topologies. The auction was intended to determine the appropriate arrangement blocks within the band. However, ComReg chose to allocate the upper part of the band to point-to-point and the lower part to point-to-multipoint. ComReg did not allocate guard bands based on the assumption that bidders could aggregate additional blocks themselves to serve as guard bands, up to a maximum of six blocks.

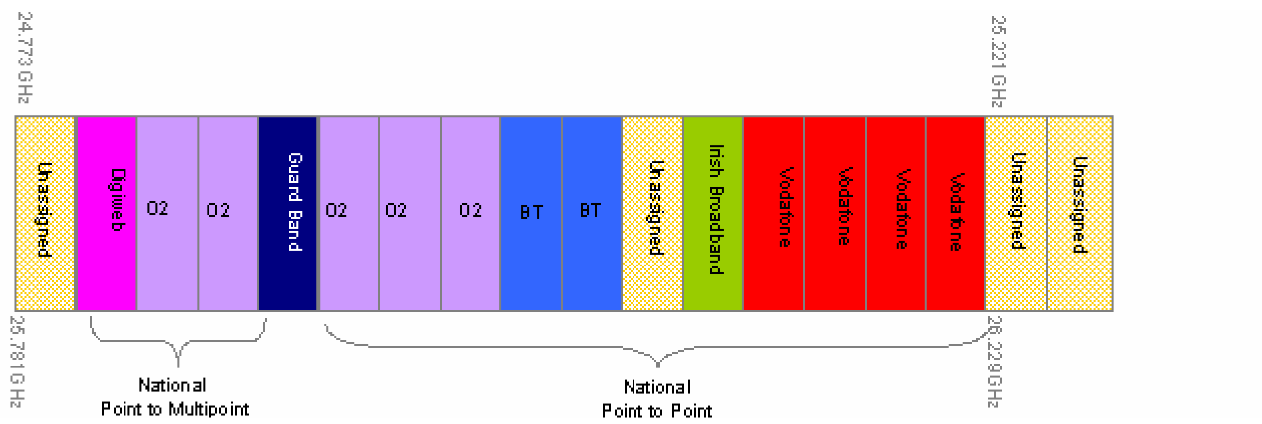
Figure 3: ComReg 26 GHz band plan



Source: ComReg

The auction rules which ComReg established comprised five separate stages: (1) Application Stage; (2) Qualification Stage; (3) Sealed Bid Stage; (4) Assignment Stage; and (5) Grant Stage. In the first two stages, ComReg accepted applications and determined the eligibility of participants. Deposits were also due with the applications. The Sealed Bid Stage was a single round auction where eligible participants could submit a bid for any possible combination of point-to-point and point-to-multipoint lots, up to the eligibility cap of six lots. This meant that each bidder could submit 27 bid options, paying a second price for the bid which, in combination with the other bids, would create the greatest value. The Sealed Bid Stage was planned to take place only if demand exceeded the available supply of spectrum (it did). In the Assignment Stage, winners from the Sealed Bid Stage were eligible, but not required, to submit one point to point and point to multipoint bid for contiguous frequencies. In the Grant Stage, ComReg determined how the available frequencies in the 26GHz band were distributed amongst the winning bidders, as well as the final price to be paid by each winning bidder.

Figure 4: ComReg 26 GHz band final allocation and assignment



Source: ComReg

ComReg announced the outcome of the 26 GHz auction on 6 June 2008. Thirteen national channels were licensed to 5 different bidders for national point-to-point or point-to-multipoint applications. As can be seen in Figure 4, final awards were as follows:

- BT Ireland was awarded 2 national point-to-point channels;
- Digiweb limited was awarded 1 national point-to-multipoint channel;
- Irish Broadband was awarded 1 national point-to-point channel;
- Telefonica O2 Ireland was awarded 3 national point-to-point channels and 2 national point-to-multipoint channels; and
- Vodafone Ireland was awarded 4 national point-to-point channels.

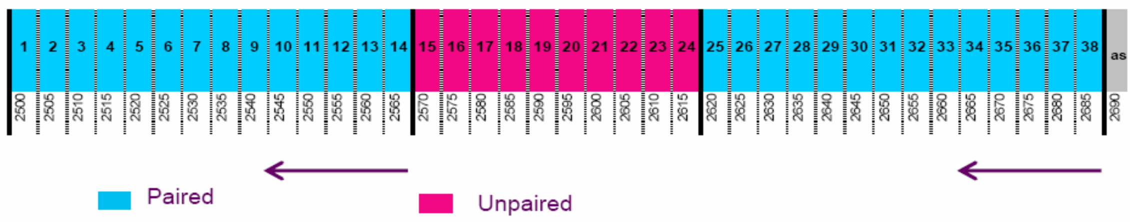
Each winner paid the reserve price of €70,000 per 2 x 28 MHz block. Telefonica O2 Ireland paid an additional €30,679 to acquire its preferred point-to-point frequency assignments and Vodafone Ireland paid an additional €158,435 for its preferred frequency assignments.[40]

6.2 OFCOM 2.6 GHz auction

In 2006, Ofcom proposed a two-part auction which would not only identify the recipients of spectrum licences, but also the pairing determinations associated with those licences. It seems that the auction was really intended to solve questions about the spectrum allocation, policy and assignment which would have the effect of favouring or disfavouring certain technologies.

The proposed auction would consist of two phases. In the initial phase, bidders would compete for assignment of 38 unspecified 5 MHz wide blocks in the range 250 MHz to 2690 MHz. Once the quantity of blocks are assigned, winners would participate in a second phase of the auction to determine which particular blocks are assigned and whether the block are contiguous or discontiguous, and paired or unpaired, and if paired, the spacing of those pairs.

Figure 5: OfCom 2.6 GHz band-plan



Source: OFCOM

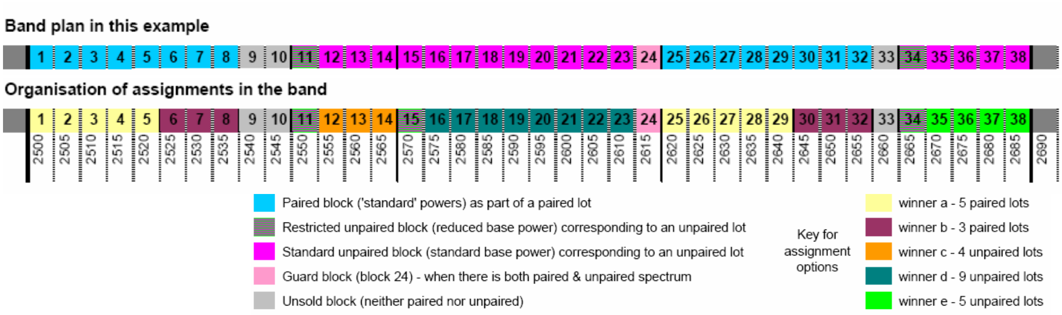
Figure 5 comes from the Ofcom consultation and shows the 2.6 GHz band-plan. Blocks 1 to 38 represent paired and unpaired spectrum as per the CEPT band plan. Blocks 1 to 14 could potentially be paired with blocks 25 to 38, respectively. However, depending on the outcome in the auction, they might either be assigned on a paired or an unpaired basis. Blocks 15 to 24 would only be available as unpaired.

The reason this auction would determine the technology used in the band is because paired blocks are necessary for use with for FDMA technologies which rely on paired blocks of frequencies separated by 120 MHz. One block provides the frequencies for the uplink and the other block for the downlink. Ofcom expected that the two main

40 http://www.comreg.ie/radio_spectrum/26ghz_spectrum_competition.691.html.

FDMA technologies to be used in the 2.6 GHz band would be Long Term Evolution (LTE), and a UMTS successor such as HSPA. TDMA technologies rely on unpaired blocks in order to receive and transmit at the same frequency, but in different timeslots, such as the mobile version of the WiMAX suite of standards.

Figure 6: OFCOM illustration of award outcome



Source: OFCOM

Figure 6, also from Ofcom, is an illustration of a hypothetical award outcome under this two phase auction. It represents the position of paired and unpaired blocks, including restricted unpaired blocks, for that single hypothetical outcome. Under restricted unpaired blocks, there is more unpaired spectrum than in the minimum in the CEPT band plan. Thus, there are 2 winners of paired spectrum and 3 winners of unpaired spectrum. The awards constitute 8 paired blocks and 18 unpaired blocks. Block 24 is a guard band, and 3 spectrum blocks go unsold.

To date, the auction has not been completed. It was help up by litigation with T-Mobile and O2. This litigation has subsequently been resolved. However, Ofcom decided to implement the proposal of the independent spectrum broker and make the 2.6 GHz band available coincident with its award of spectrum in the 800 MHz band, available from the transition to digital terrestrial television.

6.3 U.S. FCC research

In February 2008, the Office of Strategic Planning and Policy Analysis of the U.S. Federal Communications Commission released a suite of three working papers[41] employ-

41 The papers are: Bykowsky, Mark/ Carter, Kenneth/ Olson, Mark/ Sharkey, William (2008): Enhancing Spectrum's Value via Market-Informed Congestion Etiquettes, FCC OSP Working Paper Series (OSP Working Paper #41); Bykowsky, Mark/ Olson, Mark/ Sharkey, William (2008): Modeling the Efficiency of Spectrum Designated to License Use and Unlicensed Operations FCC OSP Working Paper Series

ing theoretical economics supplemented by experimental economic research to model economic behaviour under certain spectrum regimes. Experimental economics is an emerging discipline which seeks to study economic behaviour by creating an “economic environment” and asking live subjects to make decisions to simulate payoffs.

This work shows that a set of market-driven prices can be created by auction to determine not only spectrum assignment, but also band planning and usage rules. With the two exceptions noted in Sections 6.1 and 6.2, we know of no other instance where spectrum auctions have been used to determine assignment. Further, the FCC work strongly suggests that it is economically possible to embed certain algorithms in radio equipment in order to permit congestion-based pricing in real time. These two mechanisms could guide usage to an efficient, sustainable equilibrium.

6.3.1 U.S. FCC OSP Working Paper #41

OSP Working Paper #41 Enhancing Spectrum's Value via Market-Informed Congestion Etiquettes investigated economic efficiencies associated with introducing various different coordination mechanisms into the current uncoordinated system improvements of licence-exempt operation in the US. The work used a simplified model of wireless data network users to evaluate different wireless spectrum congestion etiquettes to promote the efficient use of wireless spectrum in the presence of licensed and unlicensed operations. The authors defined efficiency as the percentage of user’s communications demands which are satisfied, given the maximum demand which can be satisfied. According to the model, the average economic efficiency of the existing uncoordinated sufferance model employed in the current licence-exempt regime is between 42% and 57%. Using the economic coordination protocols suggested in the paper might increase that efficiency to as high as 70%.

In the research, eight subjects were asked to make the following decision in a multi-player, multi-period game. Each subject was required to elect between either a “freely available” spectrum service that is subject to congestion or a non-congestible “subscription” spectrum service in order to communicate their messages (i.e., megabytes of data). If they choose the freely available service, they might or might not have to pay depending on certain other factors, but there was some non-zero probability that their messages would be transmitted, depending on the behaviour of the seven other subjects. If the subject chose the subscription option, he was certain to have his messages transmitted, but would have to pay a pre-specified fee, which would reduce his payoff. The maximum ability of the two options to satisfy demand depended on having four

(OSP Working Paper #42); and OSP Working Paper #43. Working Paper #42 examined the performance properties of congestion etiquettes that utilize various types of user information to address the congestion problem. Since it is not immediately relevant to our model, we do not review it here.

subjects select the freely available service, two subjects select the subscription service, and two subjects be excluded altogether.

Before each round, each subject was informed of the following information:

- The level of his demand (i.e., megabytes of data he wants to transmit)
- The number of possible spectrum users
- The flat price of the subscription service
- The value per megabyte he places on sending a message
- His tolerance for congestion

The subject payoff would be the following. If the subject chose the subscription service, then his payoff would be the level of his demand times his valuation, less the subscription price. If the subject choose the freely available service, then his payoff would be his demand times his valuation, if and only if the congestion level in the freely available service was less than or equal to his congestion tolerance. Otherwise, his payoff would be zero.

The experiments went on to test efficiency under an uncoordinated protocol, willingness to pay protocols, and a random protocol for assigning use under the freely available spectrum service. The uncoordinated protocol allowed all subjects who chose the freely available option to have service even if it meant the congestion level was so high that none of these subjects received a pay-off. The willingness to pay and random protocols would exclude certain subjects selecting the freely available option, based on different means of prioritisation. The random protocol ranks all subjects based on this random priority assignment. The willingness to pay protocol allows the subjects to express the amount of money they are willing to pay, either as a lump sum or on a per unit basis. Of all the protocols willingness to pay protocol tends to generate the highest economic efficiency.

The authors concluded that the use of these protocols could enable a new type of spectrum allocation where spectrum is treated as a common resource in the absence of excessive spectrum demand, but is treated as an excludable good in the presence of excessive demand.

6.3.2 U.S. FCC Working OSP Paper #43

FCC OSP Working Paper #43 A Market-Based Approach to Establishing Licensing Rules: Licensed versus Unlicensed Use of Spectrum examined the ability of the U.S. FCC to replace the administrative process that otherwise would have been used for allocation and for definition of rules with an auction. The work postulated that a “clock auction" could efficiently determine the licence regime. In the model, spectrum designated for licence exempt use would be made freely available for uses which comply with appropriate technical standards, while spectrum allocated to licensed use would be generally awarded to private parties on an exclusive basis. The use of an auction mechanism would ensure an optimal allocation of spectrum between licensed and licence exempt use by mitigating the incentive for interested parties to misrepresent their spectrum needs during administrative proceedings.

To test the auction hypothesis, the authors conducted a series of 34 economic experiments. In each experiment, subjects participated in an experimental auction which determines the licensing rules for given blocks of spectrum. The licensing rules permitted: 1) spectrum which is freely available for all to use ('Unlicensed' in U.S. parlance), or 2) assigned to discrete individual users ('Licensed'). Experimental subjects were assigned one of two types of classifications: "L-Type" firms and "U-Type" firms. L-Type firms were assumed to resemble mobile network operators who build the necessary infrastructure and earn a return on that investment through revenue obtained from subscribers. L-Type firms must therefore obtain licensing rules which enable them to exclude non-payers, and which provide protection from harmful interference. By contrast, so-called U-Type firms prefer licensing rules that promote free, open access to spectrum. U-Type firms were intended to represent online service providers, equipment manufacturers, and hotspot operators. U-Type firms earn revenue indirectly as advertisers, through the sale of equipment, or by using wireless connectivity as a loss-leader to other retail sales, and not from subscription revenue. L-Type firms uniformly place a higher value on a block of spectrum than U-Type firms. However, since U-Type firms do not require exclusivity, it is possible that the aggregate demand of several U-Type firms could exceed the value placed on it by a single L-Type firm.

The experiment simulated a clock auction for 4 blocks of spectrum. In each auction, subjects expressed their preference and willingness to pay for either Unlicensed or Licensed determinations. U-Type bidders had their bids aggregated, and if the sum of their bids exceeded the lowest bid rejected, they were required to pay a pro-rata share of the market clearing price. The pro-rata share of market clearing price was used as a 'provisioning point' for the U-Type bidders to reduce the free riding problem by those bidders' tendency to under report their valuation to avoid paying a fee.

In the experiment, each subject knew:

- The level of his valuation for having a block allocated to preference
- The number of possible spectrum bidders
- The number of spectrum blocks available for auction
- That each bidder had a demand for two blocks of spectrum

Payoffs for each subject were calculated as follows. Each individual subject's payoff was their valuation less their bid, if and only if the bid exceeded the market clearing price. (For the U-Type bidders, the aggregate bid and pro-rata share were used. Otherwise, the subject's payoff was zero.

Using the data generated in these experiments, the authors could test whether a market approach could achieve the efficient assignment of licensed or unlicensed rules to four spectrum blocks. In the experiments, 28 of the 34 auctions resulted in one spectrum block being designated for unlicensed operations. In four of the 34 auctions (12%), two spectrum blocks were designated for unlicensed use.

6.4 BNetzA UMTS spectrum auction

The German regulator (then the RegTP) has also made efforts to address assignment and band planning through the use of auctions in 2000. The RegTP auctioned licences for third generation mobile telecommunications (UMTS) services in the 2 GHz band.[42] While the auction did not determine the band plan, the plan was set by the RegTP based on the results from the auction. Normally, the band plan is completed to prior to auction. The band to be auctioned consisted of 2 × 60 MHz paired spectrum blocks in the 1900-2025 MHz band. The RegTP further subdivided the band into 12 identical, individual blocks of 2 × 5 MHz each. In addition, the RegTP offered five blocks of 1 x 5 MHz unpaired spectrum. All the blocks were deemed to be "abstract". Bidders were not competing to acquire specific spectrum blocks as defined by a particular location within the band. Rather, the RegTP pledged to make the most efficient possible arrangement assignment of the spectrum blocks after the results of the auction were known so as to minimize the possibility of interference.[43]

Initially, 11 companies applied for UMTS licences, but 4 operators subsequently withdrew their applications. Seven bidders competed for 12 blocks of paired spectrum in the first auction.[44] The 12 blocks could be aggregated into either 4, 5 or 6 licences as bidders were restricted to bid on "at least two" and "at most three" blocks.[45] Thus, for the auction to conclude by awarding licences to 7 assignees was not a possibility.

42 For more information, see, e.g., Nett, Lorenz (2000): UMTS-Lizenzvergabe in Deutschland: Eine spektakuläre Auktion in der Wirtschaftsgeschichte, in WIK Newsletter, pp. 18-19 and Grimm, Veronika/ Riedel, Frank/ Wolfstetter, Elmar (2001): The Third Generation (UMTS) Spectrum Auction in Germany, CESifo Working Paper No. 584.

43 The auctioning rules are electronically available online. See, RegTP (2000): Entscheidung der Präsidentenkammer vom 18.02.2000 über die Regeln für die Durchführung des Versteigerungsverfahrens zur Vergabe von Lizenzen für UMTS/IMT- 2000; Mobilkommunikation der dritten Generation- Aktenzeichen: BK-1b-98/005-2.

44 The bidding companies were T-Mobil, Mannesmann Mobilfunk, E-Plus Hutchison, Viag Interkom, Debitel (backed by Swisscom), Group 3G (backed by Telefonica and Sonera) und Mobilkom (backed by France Telecom).

45 This rule may have had the inadvertent effect of distorting the outcome. By bidding for three blocks instead of two, incumbent operators could strategically thwart the entrance of competitors, concentrating the market two five players instead of six. Jehiel, Philippe/ Moldovanu, Benny (2001): The European UMTS/IMT-2000 License Auctions, University of Mannheim Working Paper. See also, Sokol, D. Daniel (2001): The European Mobile 3G UMTS Process: Lessons From the Spectrum Auctions and Beauty Contests, Virginia Journal of Law and Technology, Volume 6, Issue 17 at ¶¶50-52.

The RegTP divided the auction process into two discrete auctions which were simultaneous, open, and ascending. The first auction was intended to sell the paired spectrum and to allocate those licences. The second auction was limited to the winners of the first, and was intended to sell the unpaired spectrum blocks and any leftover paired spectrum from the first auction. An activity rule stipulated that bidding rights had to be exercised or they would be forfeited. In both auctions, only the highest bids were made public after each round. Thus, bidders could not directly observe their rivals' bids. The minimum bid was 100 million DM per block, and the minimum increment was 10%. However, the RegTP was free to change the increment, and actually reduced it towards the end of the auction.

The first auction began on 31 July 2000. After two weeks, prices for one block had reached around 5 billion DM, and Debitel withdrew from further rounds of the auction process. The auction continued with the remaining six bidders to bid for three blocks, until bidders reduced their demand to two blocks. T-Mobil and Mannesmann were the last companies to bid for three blocks. After 173 rounds of bidding, the first auction concluded on 17 August 2000. The second auction was finished within one day. A total of 561 million DM in proceeds from the auction was received for five blocks of 5 MHz unpaired spectrum. Unpaired blocks were allocated to E-Plus Hutchison, Group 3G, Mannesmann Mobilfunk, MobilCom Multimedia and T-Mobil.

The results of the auctions are shown in Table 4.

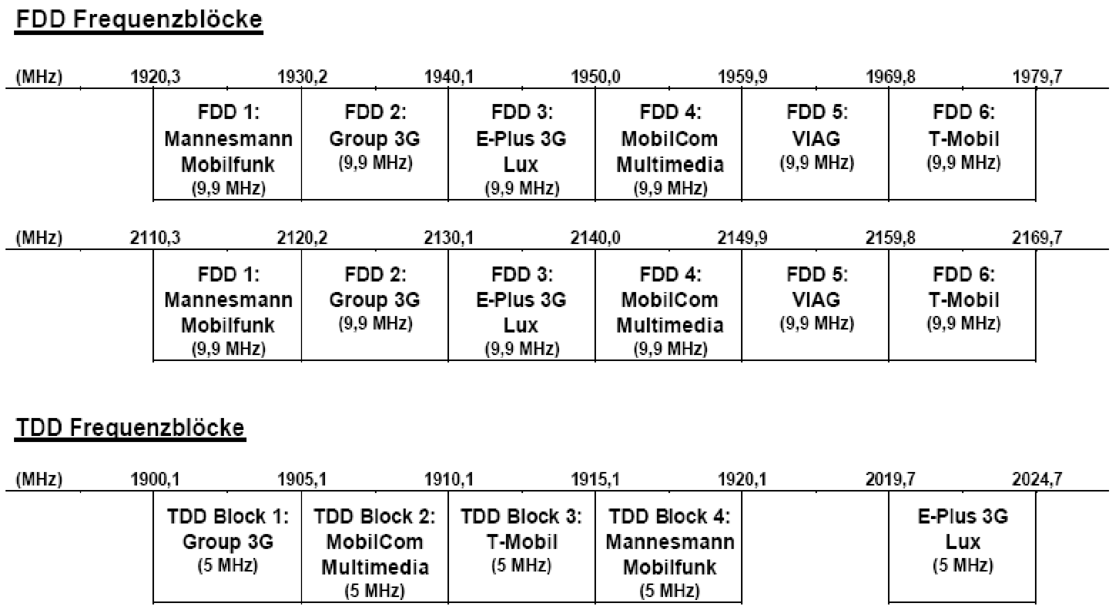
Table 4: German 3G auction results

Licensee	Auctioned spectrum	Price (in DM)
E-Plus Hutchison	2 x 5 MHz, 1 x 5 MHz	16,491,800,000
Group 3G	2 x 5 MHz, 1 x 5 MHz	16,568,700,000
Mannesmann Mobilfunk	2 x 5 MHz, 1 x 5 MHz	16,594,800,000
MobilCom Multimedia	2 x 5 MHz, 1 x 5 MHz	16,491,000,000
T-Mobil	2 x 5 MHz, 1 x 5 MHz	16,704,900,000
VIAG Interkom	2 x 5 MHz	16,517,000,000
Total Sum		**99,368,200,000**

Source: RegTP.

The RegTP then set about the process of allocating the awarded specific blocks. The final allocation of spectrum blocks is shown in Figure 7.

Figure 7: Band plan for German 3G auctions



wik CONSULT

Source: RegTP

When the auction completed, winners had paid so much for their licences that they found it necessary to share infrastructure such as towers, backbone, and switching in order to reduce capital expenditures.[46]

46 Taaffe, Ouida (Feb. 26, 2001): Europe’s UMTS Players in a Flirtatious Mood, TOTAL TELECOM.

7 Mathematical model of the problem

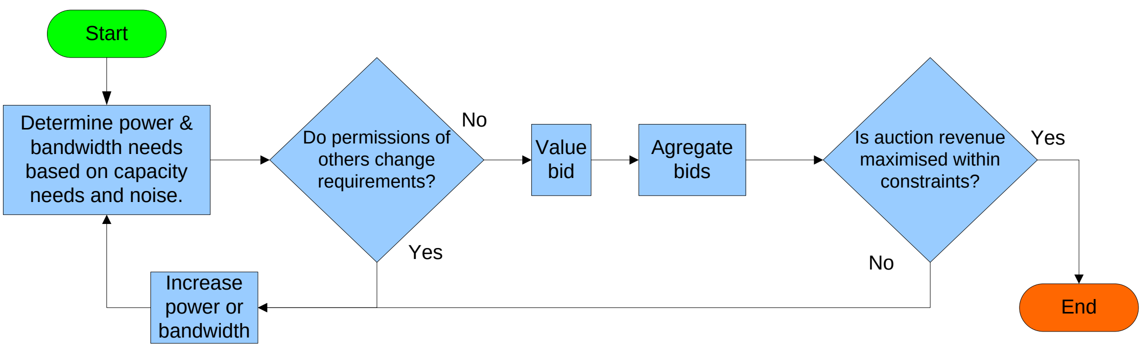
In this section, we present our mathematical model which illustrates the spectrum allocations and policy needed by participants in a hypothetical auction. We use the Shannon-Hartley Theorem as an indifference curve for the possible tradeoffs between permissible signal strength and allotted channel widths. Section 7.1 lays out the basic elements of the model. In Section 7.2, we describe the Shannon-Hartley Theorem. Finally in Section 7.3, we lay out our formulae and method of spectrum valuation.

7.1 Basic elements of the model

In order to better understand how price-guided mechanisms might be used to make spectrum policy determinations, we have created a mathematical model to examine whether an auction could be used to determine not only the recipients of spectrum licences, but also some of the characteristics of that licence.

The model is an iterative process and the logic is as follows. The model simultaneously determines the spectrum allocations, policy and assignments needed by participants in a hypothetical auction. These needs are dictated by what is necessary to satisfy a specified demand for wireless communications ability. The model then values those spectrum allocations, policy and assignments based on the bidders' per unit willingness to pay. Auction revenue in the model is the sum of all the bids for spectrum allocations, policy and assignments. The model is optimised by maximising auction revenue, subject to the constraints of available spectrum and maximum power output. (See Figure 8.)

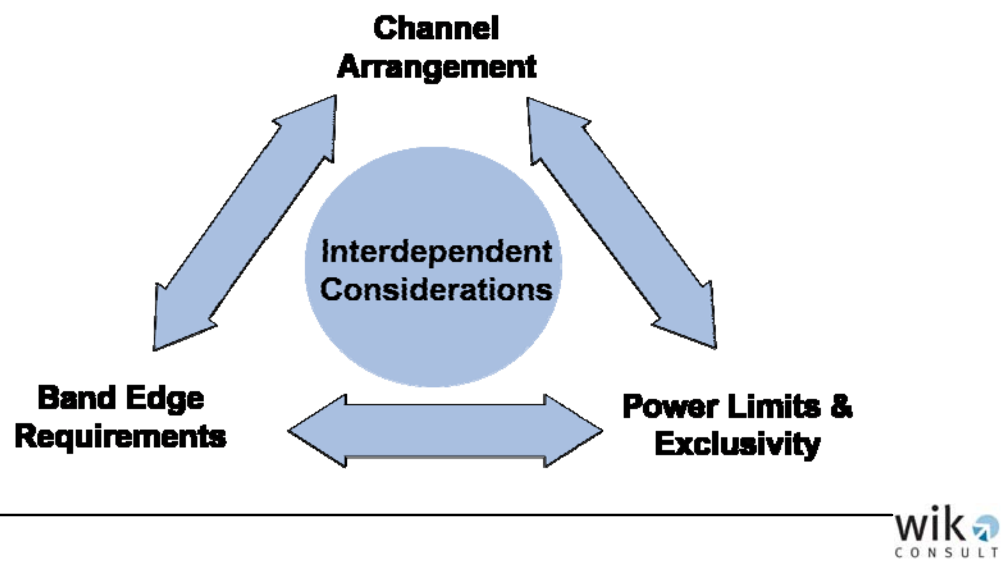
Figure 8: Flowchart of basic model



Source: WIK-Consult

In the model, potential spectrum users participate in a hypothetical auction in which they are free to express their demand for spectrum licences, not just for the licence but also for licences which are different on several dimensions of power, tuning range and spacing. As can be seen in Figure 9, these considerations are interdependent, affecting one another. For example, the power limits imposed on one user affect the band-edge masking requirements of adjacent users. If a high power use is permitted in one band, the adjacent band will need stricter masking at the edge. Similarly, if channel spacing or channel arrangement is reorganized, this may mitigate the impact of power limits on band-edge requirements.

Figure 9: Interdependency of band planning considerations



Source: WIK-Consult

In order to explore how the considerations affect one another, we model demand as a function of the ability to send data at a specified transfer rate (bit rate). We use the Shannon-Hartley Theorem (explained in Section 7.2 below) as an indifference curve for the possible tradeoffs between permissible signal strength[47] and allotted channel widths. At all points on the curve, bidders are indifferent between having more spectrum and less power, or vice-versa. Further, valuation is a function of noise in the spectral environment. Noise is a function of Gaussian background noise, use in adjacent bands (i.e., adjacent co-channel interference) and shared use of the band.[48]

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47 The power dimension, as it is contemplated in the model is receive power; however, we have assumed it to be a proxy for transmit power. Since the model does not simulate any geographic variables, transmit and receive powers are one and the same.

48 For simplification of the model, we have assumed away harmonic interference.

Thus, our model (mathematically developed below) shows a hypothetical efficient allocation of several different blocks of spectrum in a frequency range and their assignment. In this way, the auction could determine the organization of the band in question as well as the level of shared or commons use. They might be accomplished by specifying the maximum level of energy permitted in the band (i.e., the “interference temperature”) on an underlay or on a sharing basis. The auction could further determine band-edge requirements.

Figure 10: Possible outcomes using price-guide determinations

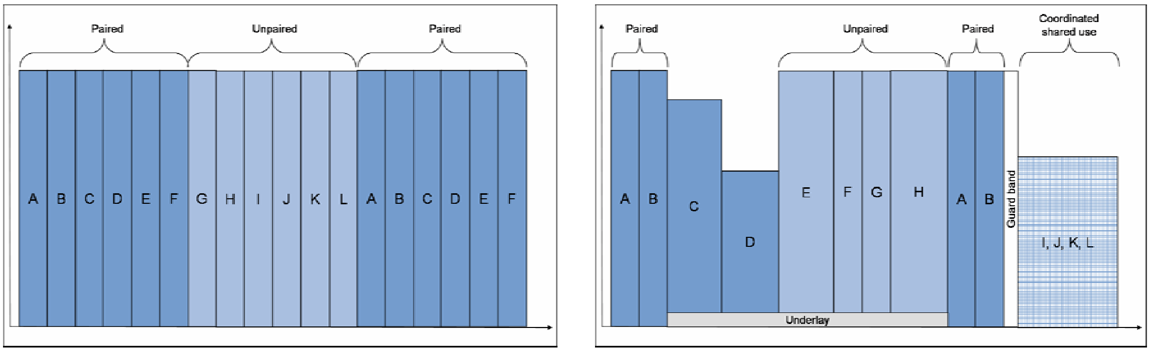


Figure 10 shows two simple examples where price-guided policy could be used to determine allocation, policy and assignment. The image at left shows how pair and assignment have been determined. Each spectrum user is assigned the same permissible power output (y-axis). This type of result was accomplished in the ComReg 26 GHz Auction and in the German UMTS auction. (It could potentially be accomplished in the OfCom 2.6 GHz Auction). The image on the right shows a somewhat more complicated result. Here, price-guide policy has created a mix of bandwidths permissible power outputs and pairings. In addition, certain assignments will come with the provision that low power licence-exempt use (underlay) is permitted in those bands. Finally, four assignees (I, J, K and L) have been grouped together in a block for shared use. Presumably the parameters of use for this block, such as the coordination protocol and a guard band to protect other assignees, have been determined through price-guided policy.

7.2 Shannon-Hartley Theorem as indifference curve

We use the Shannon-Hartley Theorem (named after Claude Shannon and Ralph Hartley) as the backbone for our mathematical model for two reasons. First, it describes the relationship between the amount, or tuning bandwidth, and the capacity of that channel to carry information, expressed in bits per second. Second, because the theorem relates both signal and noise to channel capacity, we can use it to model the effects that independent users have on one another's data rate, and hence on each user's valuation of the spectrum under those conditions.

The Shannon-Hartley theorem quantifies the maximum amount of information that can be transmitted error-free over a communication link.[49] This channel capacity is a function of: the power level of the signal; the bandwidth of the frequencies employed; and the presence of noise. The theorem states that channel capacity is a function of bandwidth multiplied by the logarithm of the signal-to-noise ratio. See Formula 1. The signal represents the output of a given radio operating in a given band, measured in watts. Noise is a function of two components: (1) ever-present, non-zero Gaussian noise, and (2) the in-band, adjacent, and harmonic emissions of third-party radios. The Shannon-Hartley theorem is expressed mathematically as:

Formula 1: Shannon-Hartley Theorem

$$C = W \log_2\left(1 + \frac{S}{N}\right)$$

with C = channel capacity in bits per second

W = bandwidth in hertz (cycles per second)

S = signal power watts

N = noise present in watts

For our model, the theorem holds that the capacity to transmit a data file of a given size in a given time across a wireless link can be increased only by either increasing the available bandwidth, or by reducing the signal-to-noise ratio (S/N). The speed of electromagnetic waves is fixed depending on the medium through which the waves travel.

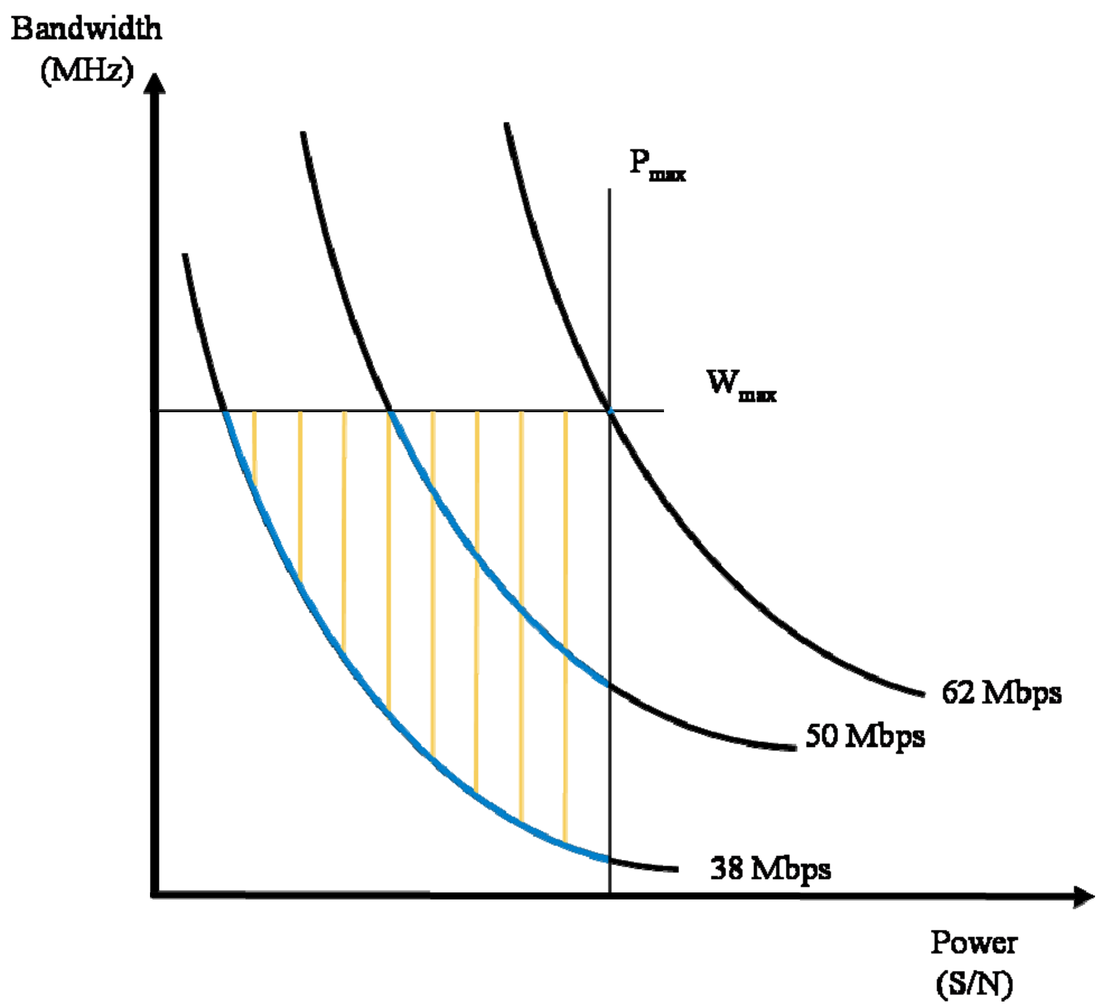
Figure 11 shows how the Shannon-Hartley Theorem functions as an economic indifference curve in our mathematical model. The figure shows the trade offs between power and bandwidth that produce the same channel capacity.

The y-axis in Figure 11 is bandwidth (tuning range) and the x-axis is power (signal-to-noise ratio). The three curves show the trade-offs between power and bandwidth for three spectrum users demanding capacity (data transfer rate) of 38 Mbps, 50 Mbps, and 62 Mbps, respectively. At each point along the curve the spectrum users are indifferent because they can obtain the same channel capacity. At points above their respective curves, the users are better off because they are receiving a higher data rate.

49 See Shannon, Claude E. (1949): The Mathematical Theory of Communication and Shannon, Claude E. (1949): Communication in the presence of noise, Proc. Institute of Radio Engineers vol. 37 (1): 10–21.

However, this comes with the cost of using more spectrum, more power, or both. At points below their curves, spectrum users are worse off.

Figure 11: Shannon-Hartley Theorem as indifference curve



Source: WIK-Consult

The line W_{max} represents the maximum allowable spectrum that could be acquired using price-guided policy.[50] The line P_{max} represents the maximum permissible power emissions, for reasons of RF safety. The shaded area shows the possible outcomes using price-guided policy. The blue (light grey in black and white) sections of the curves are possible outcomes for each user, given his/her demand for capacity.

50 For reasons of market power and competition policy, each individual spectrum user would be limited in the amount of spectrum he/she could acquire. See Section 9.3.

7.3 Modelling the value of exclusive, collective and licence-exempt use

Our model builds on the idea that valuation is directly and positively correlated with tuning range and permissible power levels. Valuations are negatively correlated with noise. The exogenous variables are unit spectrum valuation, noise tolerance, and desired throughput of the wireless link. The endogenous variables include maximum power, tuning width of the blocks, and noise. The constraints are the total bandwidth available for auction, and a cap on the maximum power for reasons of RF safety. The endogenous variables represent the policy determinations which could be determined by the price-guided policy envisioned in this paper.

The model first attempts to calculate the spectrum needs of the hypothetical bidders. There are *k* number of bidders (i.e., *i* = 1, 2, …, *k*). The spectrum needs of each bidder *i* are defined in terms of usable bandwidth (tuning range) and maximum allowable power. These needs are calculated according to Formula 1 as those necessary for a wireless link of certain data transfer rate, C.

Further, the emissions of other users' radios are part of the signal-to-noise ration, the costs other users' demands impose on those spectrum requirements, and vice-versa. The noise function is specified in Formula 2. For each bidder *i*, noise is calculated as the greater of Gaussian noise present in any communications link or the noise generated by spectrum users in adjacent spectrum blocks. For this 'noise floor', signals other than the ones intended to be received decrease the signal-to-noise ratio. In other terms, the presence of competing signals decreases the communications capacity of the link. This might mean that the bidder *i* would have use more power or greater bandwidth. The noise coming from adjacent blocks is based on the permissions allotted to users of those spectrum blocks or adjacent ones.

Formula 2: Noise of bidder *i*

$$n_1 = n_o + \frac{S_2}{W_2} \times \frac{1}{2}$$

$$n_i = \left(\frac{S_{i-1}}{W_{i-1}} + \frac{S_{i+1}}{W_{i+1}} \right) \times \frac{1}{2} \quad ; i = 2, \ldots, (k-1)$$

$$n_k = \frac{S_{k-1}}{W_{k-1}} \times \frac{1}{2} + n_o$$

with N_i = noise of bidder *i*

W_i = bandwidth of bidder *i*

S_i = power limit of bidder *i*

Once each bidder's spectrum needs are determined, the model calculates the value of the auction revenue from that bidder (his/her bid). Each bidder's valuation is the spectrum it required in terms of bandwidth and power times *P* – its unit valuation per megahertz per watt. This product constitutes each bidder's bid. This is described by Formula 3.

Formula 3: Auction revenue of bid of bidder *i*

$$U_i = P_i \times W_i \times S_i$$

with U_i = auction revenue of bidder *i*

P_i = unit valuation of bidder *i*

W_i = bandwidth of bidder *i*

S_i = power limit of bidder *i*

The auction revenue is the sum of the bids of each bidder *i*. The model would then be optimised to maximise auction revenue. This optimisation function is described in Formula 4 below.

Formula 4: Corresponding optimisation problem

max. $$U = \sum_{i=1}^{k} U_i = \sum_{i=1}^{k} p_i \cdot \left[W_i \cdot S_i\right]$$

s.t. $$\sum_{i=1}^{k} W_i \leq W_{\max}$$

$$S_i \leq S_{\max} \left(\forall i = 1,\ldots,k\right)$$

with U = total auction revenue

U_i = auction revenue of bidder *i*

P_i = unit valuation of bidder *i*

W_i = bandwidth of bidder *i*

S_i = power limit of bidder *i*

k = number of bidders

Model Assumptions:

Variables: P_i , W_i (decision of each bidder *i*)

Exogenous parameters: W_{max}, S_{max}, C_i, n_o

Model results: n_i, S_i, U_i, U

with C_i = data rate of bidder *i* (*i* = 1, …, *k*)

n_i = noise of bidder *i*

n_o = background noise

Formula 5: Transformation of the optimisation problem

$$\text{max.} \quad \sum_{i=1}^{k} P_i W_i n_i \left(2^{\frac{C_i}{W_i}} - 1 \right)$$

$$\text{s.t.} \quad \sum_{i=1}^{k} W_i \leq W_{\max}$$

$$\sum_{i=1}^{k} n_i \left(2^{\frac{C_i}{W_i}} - 1 \right) \leq S_{\max}$$

Valuation of a single spectrum block is determined by the uses in the adjacent blocks, which are in turn influenced by the use in the first block. The optimisation process ensures that spectrum allocations and policy are awarded to the highest value users.

Solving the optimisation of the model is incredibly complex. Any such an optimisation requires examining thousands of possible outcomes in search of the allocation, policy and assignment which maximises auction revenue. This does not suggest that such an auction is impossible. Indeed, the process is not harder in principle than the current administrative process. Each of the optimisations necessary to complete the model would still be present in an administrative proceeding, and the spectrum management authority would have to evaluate each of them without the benefit of mathematical guidance or price signals.

A proper optimisation might employ computer-based simulation with independent bidding agents. Alternatively, a solution could be achieved using experimental economics. As previously noted, experimental economics is an emerging discipline which seeks to study economic behaviour by creating an “economic environment” and asking live subjects to make decisions to simulate payoffs. Using experimental economics, future research might assign the valuations we have created for each of the bidders to “game players” and allow them to participate in simulated economic environment. This work would be very similar to that already completed by the U.S. FCC.[51]

The next chapter of this report describes our implementation of an MS Excel-based model that reflects the mathematical constructs presented in this chapter. It should be viewed as a proof of concept, based on a simplified version of the mathematical model. It is nonetheless sufficient to permit flexible policy and assignment determinations based on the interactions of numerous spectrum users.

51 See Section 6.3.

8 Proof of concept model

In order to demonstrate the value and practicality of our mathematical model, we created an MS Excel-based version of the model, with one simplifying assumption. We discuss our MS-Excel based model and its outputs in this section.

8.1 MS Excel model

Our MS Excel-based model links the usage and valuation of 10 hypothetical bidders for a particular 100 MHz-wide band to be auctioned. The valuations of each bidder are determined by the Shannon-Hartley theorem. Each of these hypothetical bidders is an independent agent, and they are heterogeneous on several dimensions. Unlike conventional auctions, the licences awarded in our hypothetical auction do not have spectrum blocks of a certain width and allowable power pre-specified in an administrative determination by the spectrum management authority. Rather, these factors are determined by the auction process itself.

Thus, the model must first calculate the necessary power and bandwidth for each hypothetical bidder. To do so, each hypothetical bidder is assigned a desired throughput (data transfer rate) in Mbps. For each bidder *i,* desired throughput is assigned as a random number, assuming a normal distribution, a mean of 50 Mbps, and a standard deviation of 12.5 Mbps. In order to achieve the desired throughput, bidders can use any combination of bandwidth and power which would yield that throughput under the Shannon-Hartley theorem, as described in Formula 1 on page 38 (subject to the auction's 100 MHz of spectrum and limit of a maximum power output of 100 watts for RF safety reasons). However, to further simulate the realistic needs of radio communications, bidders are only able to acquire bandwidth in 1.25 MHz increments. This constraint has the added benefit of making the model more linear and easier to solve.

Bidders are also subject to noise levels in their spectrum blocks with in the larger spectrum band. In this proof of concept, we made the expedient assumption that each bidder faces a constant background noise floor of 0.0019 Watts, which is intended to mimic Gaussian noise. This represents a simplification of the more general model presented in Chapter 7. Our system of equations in the full model describes the interrelationships and interactions of would-be spectrum users. The valuation of a single spectrum block is determined by the uses in the adjacent blocks, which are in turn influenced by the use in the first block. This cyclicality would have rendered model unsolvable with a basic tool such as MS Excel.

Finally, each bidder was further assigned its own unit valuation of spectrum *P*, as defined as Euro per megahertz per power output. We parameterised bidders' spectrum valuations for the model by using the results of the 2000 German 3G auctions which are described in Section 6.4. We calculated a spectral power density valuation based on the final bids divided by the tuning bandwidths, and assuming 100 Watt maximum power output of 6 licences awarded. We further calculated the standard deviation of valuations for the auction. We assigned individual unit valuations to the 10 bidders based on a random normal distribution using the mean and standard deviation derived from the German 3G auction. These values appear in Table 5 in Annex 1.

8.2 Results and analysis

We employed Solver in Excel to optimise the model. Solver is an optimisation tool which can be used to maximise or minimise certain values in a spreadsheet. It does so in an iterative process by changing the values of specified cells. The optimisation can be done subject to certain mathematical constraints. Solver will continue to recalculate values in the spreadsheet until an optimisation is reached.

The optimisation to maximise auction revenue was subject to the following three constrains: (1) the maximum power afforded to any one bidder was 100 Watts; (2) total bandwidth awarded to all bidders could be no more than 100 MHz; and (3) bandwidth was bid for in minimum increments of 1.25 MHz[52]. Since they are mathematically correlated through the Shannon-Hartley Theorem, we could have configured Solver to change either bandwidth or power levels in order to arrive at a valuation for each bidder. We selected bandwidth, and the spreadsheet program calculated the corresponding power required. The spreadsheet then calculated each bid based on the previously calculated bandwidth and power multiplied by the bidder's individual valuation. Solver repeated this process until an optimisation was achieved.

Our initial run of the model established a baseline result. In all, 51.25 of 100 MHz were assigned, resulting in total auction revenue of €7.81 billion. Each bidder received at least some assignment of spectrum (between 2.5 and 10 MHz each). There was also a mix of high and low power users. Certain bidders received maximum power permissions of less than 1 Watt, even as low as 46 milliwatts.[53] The highest maximum power level was slightly more than 85 Watts. The model also yielded a variety of valuations. The minimum bid was €2.13 million and the maximum bid was €2.49 billion. The average bid was €781,828,849. See Table 6 in Annex 1.

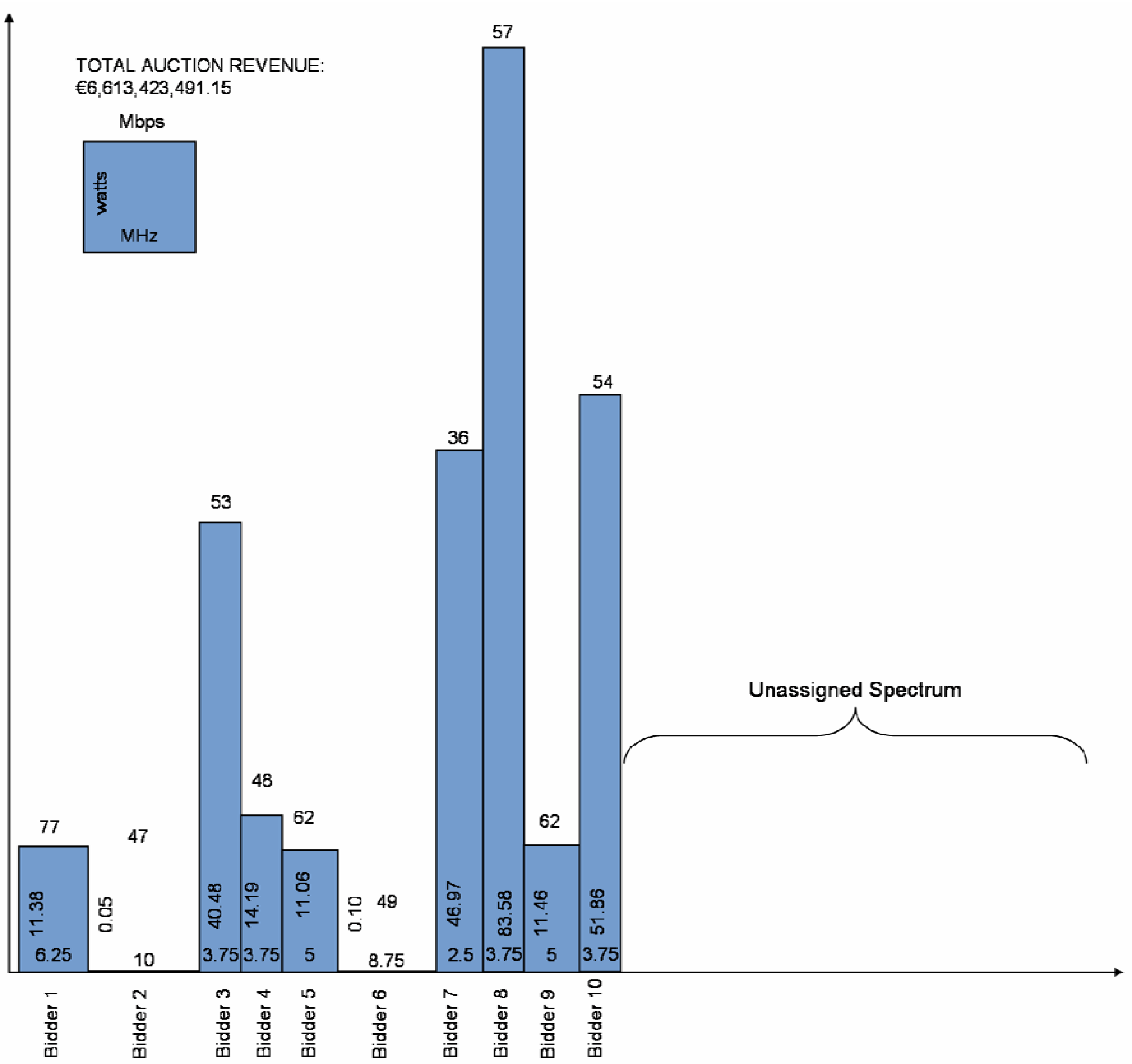
The second run of the model was meant to simulate a constraint imposed on the bidders' out-of-band emissions. Such a constraint would come in the form of a mask or filter, and would be required to keep the bidders from interfering with users in adjacent bands. This mask would have the necessary effect of reducing the efficiency of the ra-

52 The 1.25 MHz minimum requirement has the necessary effect of reducing the total bandwidth demanded, since bidders might purchase slightly more spectrum, if they could do so in smaller increments.

53 This is a power levels which is even below those permitted to licence-exempt uses.

dios employed.[54] To simulate the imposition of the mask, we re-ran the model, imposing a 1.5% "efficiency cost" on the theoretical performance of the radio to represent the effect of a mask or filter on out-of-band emissions. Each bidder therefore requires 1.5% more power or bandwidth to achieve the same level of channel capacity as before.

Figure 12: Model auctions results



Source: WIK-Consult

54 One can think of this as being very similar to the muffler employed on the exhaust system of the standard automobile. Without the added backpressure of the muffler the engine will develop more horsepower and consume less fuel for each mile driven. However, the absence of the muffler will make to automobile insufferably noisy to those any bystander.

The mask is in essence an additional cost on bidders' operations and therefore had the predictable effect of reducing demand for spectrum. The assignments to the bidders were similar, though one more unit of spectrum was required. In total, 52.5 MHz was assigned to all 10 bidders. However, total revenue was only €6.61 billion. Each bidder received between 2.5 and 10 MHz of spectrum. The lowest maximum power permission increased slightly to 49.5 milliwatts. The highest maximum power level was still slightly more than 83 Watts. The minimum bid rose to €2.24 million and the maximum bid fell to €2.24 billion. The average bid fell to €661,342,349. (See Figure 12 and Table 7 in Annex 1.)

We believe that not all of the spectrum available was assigned to bidders because the individual assignments more closely matched individual needs than would have been the case had the allocations been completed by administrative process. This left over spectrum represents an efficiency gain.[55] The left over spectrum might also be in part due to fact that capacity demanded is a constant. Clearly, additional capacity and hence spectrum has marginal utility. The left over spectrum could be, for example, held in reserve for future auctions, assigned to public sector users, or allocated to low-power licence-exempt use per existing rules.

While the model is conceived of as representing a single auction, it is not a far leap of logic to consider a second phase or a third. This is precisely how next-generation auctions such as the ComReg, OfCom and RegTP auctions work(ed). In the second optimisation, bidders with like needs could be arranged together. Bidders with conflicting needs might be separated in the frequency domain. For example, the second phase of the auction might aggregate low power bidders into a single block, and allocate slightly more bandwidth to allow for shared use. This would have the positive effect of making more spectrum available for other allocations, as mentioned above.

If we compare the results of the model to the German UMTS Auction, as a base case, we see several potential efficiency gains in using auctions to determine allocation and policy, as well as assignment. Total auction revenue in the model was only 13% of the €50.80 billion in the German UMTS, even though it was used to parameterise the model. (See Table 5 in Annex 1.) We believe that this is an efficiency gain. Maximising auction revenue is the objective function only because it determines when demand is satisfied, and no bidders are willing to bid more. The objective of spectrum auctions should not be to raise revenue for the government, but to allocate the spectrum resources efficiently.[56] Further, at the conclusion of the auction, additional spectrum resources are available for assignment to public sector or commons uses.

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55 Indeed, the ComReg auction described in Section 6.1 left 4 lots of 2 x 28 MHz spectrum unassigned after the auction.

56 See e.g., Noam, Eli (1998): Spectrum Auctions: Yesterdays Heresy, Today's Orthodoxy, Tomorrow's Anachronism." Journal of Law and Economics, pp. 765-790.

9 Discussion

We are not aware of any EU policy which would expressly prevent a Member State from holding an auction as outlined in the body of this report. Indeed, as we have chronicled, both the Republic of Ireland and the United Kingdom have completed or are considering auctions whereby the pairing of blocks is determined through the auction.

In this section, we discuss the interaction between international agreements and EU policies which need to be considered before implementing an approach along the lines of what we have presented. These interactions might serve to constrain the ability to implement certain features or permutations of price-guided spectrum policy. We begin with some ideas for the most actionable initial implementations of price-guided spectrum policy in Europe.

9.1 Most actionable initial implementations in Europe

We think that among the most actionable initial implementations of price-guided spectrum policy in Europe include: band planning, block bandwidth, duration of rights and maximum power output determinations. The ComReg and OfCom auctions accomplish the pairing of blocks through the auction. Other early or initial implementations could accomplish the determinations of: band-edge requirements; guard bands; exclusivity of use; and underlay characteristics such as the maximum interference temperature. We have also suggested that low power users, into unlicensed or licensed commons regime, in subsequent rounds such as the ComReg and OfCom auctions do. This would require a finely tuned distinction between shared and commons models as we have described above.

In essence, what many of the early potential implementations might do is to use price information to create rules for noise tolerance. Since noise is influenced by the presence of competing uses, the level of noise tolerance represents a spectrum user's preference for having either exclusive or shared use of the spectrum. In terms of technology, the noise tolerance is equivalent to the sensitivity to installing reception masks for adjacent co-channel interference and the presence of other low power users in the band (either as an underlay or co-primary users). Further complications of our model would include sensitivity to out-of-band filters by adjacent operators and a valuation of in-band coordination protocols for shared users.

In our model above, we have examined price-guide policy as a means for initial assignment of tradable rights. The tradability of these is possible so long as transferor does not convey more than the rights (along all dimensions such as bandwidth, power, exclusivity, duration of rights and other parameters) it has acquired. However, such price-guided policy could also be used to determine efficient allocation, policy and assignment of spectrum in conjunction with a two-sided combinatorial auction such as the one proposed by the U.S. FCC researchers Williams and Kwerel.[57] The Williams and Kwerel auction, sometimes referred to as the "Big Bang" auction, is intended to reallocate spectrum to flexible use by organising a large scale, two-sided auction in which existing licensees voluntarily offer already assigned spectrum licences to be auctioned together with presently unassigned spectrum. Because the auction would make complementary spectrum bands available in a single auction, it could reallocate and restructure those bands efficiently.

Similarly, the auction format of our MS Excel-based model is that of a first-price, simultaneous, multi-round, ascending auction. This auction format is rather straight forward. The selection of this format was influenced by the way in which the Solver tool functions as well as the format's simplicity. Given the complexities of auction design and strategic behaviour by auction participants, prior to an initial implementation of any price-guided policy, further research must be completed as to what the appropriate auction format is. Formats other than the one we selected might be possible, even desirable. Other auction formats worth considering include clock and single-round sealed bid auctions.

We offer two final caveats. First, in designing such auctions, careful attention must be paid to planning the order of bidding packages so as not to preclude a more efficient outcome. Second, our proposed auction mechanism is more complex than other spectrum auction. As a complex system, it is more susceptible to failure. Auction failure might include insufficient participation or multiple optimisations. A multiple optimisation might occur if, say, there are two possible and incompatible awards which both generation highest (and equal) amount of auction revenue. Before implementing an auction which determines allocation, policy and assignment, spectrum management authorities should in advance define what constitutes auction failure, and how it should be dealt with should it occur.

9.2 Implications of international and EU commitments

Price-guided policies cannot be used to determine allocations, policy and assignments in internationally harmonised bands. National spectrum allocations must be compatible with the ITU Table of Frequency Allocations[58] and with bands harmonised across EU Member States[59]. These requirements limit the ability of a Member State's spectrum management authority to devise its own spectrum regulations. By definition, the

57 Evan Kwerel and John Williams (2002): A Proposal for a Rapid Transition to Market Allocation of Spectrum, FCC Office of Plans and Policy Working Paper Series.

58 Frequency assignments that are at variance with the ITU Table of Frequency Allocations are only permissible "on the express condition that such a station, when using such a frequency assignment, shall not cause harmful interference to, and shall not claim protection from harmful interference caused by stations operating in accordance with the provisions of the Constitution, the Convention and these Regulations". See Article 4.4 of the ITU Radio Regulations.

59 The Framework Directive seeks to harmonise spectrum assignments across the EU in order to achieve a Single European Information Space. Framework Directive Article 9(2).

flexibility to determine the operational parameters by price-guided policy is at odds with these limitations. Given the ability of bidders to define the parameters of radio operation in particular bands based on the economic needs, it is possible that price-guided policy could create non-standard bands.[60] Granted, economies of scale from having the same radio systems manufactured and sold in numerous countries could affect the outcome of price-guided allocation and policy, making them similar to harmonised allocations. However, in the ITU and EU harmonised bands, such price-guided policies cannot be used to determine allocations, policy and assignments because those outcomes will be (or at least could be) incompatible with the agreed characteristics of the band.

These techniques for using prices to guide spectrum allocations, policy and assignments can be refined, and could be implemented in bands which are not expected to cause cross-border problems or to conflict with ITU or harmonised band descriptions

9.3 Market power and competition policy

There is very little difference between conventional spectrum regulation and price-guide approaches for allocations and policy when it comes to questions of market power and competition policy. Since bidders could acquire spectrum on a variety of dimensions, however, it requires some rethinking of way in which to calculate the caps restricting the maximum amount of spectrum a single licensee could posses.

Ideally, the increased flexibility afforded by price-guided policy might in the long run diminish rather than amplify potential problems of market power. There, however, remains the chance that certain licensees might engage in anti-competitive behaviour, in the form of an “excessive” acquisition of spectrum. This result did not happen in our model, but there is no reason to believe that it is possible that there is sufficient heterogeneity to have one bidder attempt to corner the market. In such an outcome, one licensee might acquire sufficient amount of spectrum so as to preclude other users. In a competitive market, companies seek to gain strategic advantages over their competitors. Spectrum owned exclusively by one company cannot be used by another. A strategic decision to hold spectrum can have a negative external effect on the competition. The solution to these problems is not very different.

The principle mechanism for preventing this anti-competitive behaviour is the imposition of spectrum caps. These caps can be imposed on the amount of spectrum a licensee can acquire at the auction, or on limits on spectrum trades and transfers subsequent to the auction. The German Telecommunications Act allows the BNetzA to impose spectrum caps, rules on trading and prior approval of trades or transfers of spectrum. These

60 Indeed, our MS Excel based model produced bands ranging in widths between 2.5 and 10 MHz, and maximum permissible power levels from 85 Watts down to less than 1 Watt.

tools ensure that competitors whether already in the market or seeking to enter, are able to gain access to the scarce resource of spectrum.

The spectrum caps imposed on licensees who obtain spectrum through the price-guided policy described in this report would not differ significantly from those imposed in conventional auctions. However, since the auction is used to determine spectrum rights in terms of bandwidth, power, exclusivity, duration of rights and other parameters, the spectrum management authority must now consider spectrum caps in terms of restrictions on the amount of spectrum density which can be permissibly acquired. Spectrum caps might have to become multi-dimensional and not just concerned with the bandwidth acquired.

Efforts to establish a competitive market structure do not stop at spectrum assignment. The *ex post* mechanisms of competition law and oversight by the competition authority are an important complement to the *ex ante* design of the auction. Both are necessary, neither is sufficient to ensuring a positive regulatory outcome. *Ex ante* regulation is necessary for safeguarding the market place. Even given low market access barriers, it is conceivable that one licensee might acquire all the parcels of spectrum, resulting in a monopoly. The spectrum management authority's definition of spectrum caps could help inform the competition authority's efforts to manage competition by means of *ex post* intervention.

10 Conclusion

In this paper, we have examined price-guided policy as a means for determine efficient spectrum allocation and policy, as well as their assignment.

The mathematical model presented here illuminates one of several possible implementations of an auction that could be used in place of the administrative determinations necessary for spectrum policy. As compared to conventional spectrum auctions, price-guided policy for determining allocations and policy would arrive at an assignment of spectrum rights to the highest value users as well as ensure that the contours of those rights are more efficient than those which could be achieved by using market mechanisms solely for assignment. As such, this price-signal information can be used to mitigate error in administrative determinations. It also helps to ensure technological and service neutrality.

This approach is both technically possible and viable in Europe. We are not aware of any EU policy which would expressly forbid or prevent a Member State from holding an auction as outlined in the body of this report. Indeed, as we have chronicled, both the Republic of Ireland and the United Kingdom have completed or proposed auctions whereby the pairing of blocks is determined through the auction. However, a price-guided approach to allocations and policy would not be possible in bands subject to international harmonisations. In bands which are not harmonised, the most actionable initial implementations include determinations of maximum power limits, bandwidth, duration of rights and channelisation. Other early potential implementations include boundary interference standards and possibly congestion-based protocols.

Price-guided policy encourages an efficient outcome for several reasons. First, price-guided policy would improve allocative efficiency of limited spectrum resources. Second, price-guided policy mitigates the allocative errors inherent in administrative determinations. Bidders can acquire exactly the set of spectrum rights they need, instead of a set determined by an administrative decision. These differentiated spectrum inputs could lead to differentiated networks and services in the market for wireless communications services. This in turn would lead to lower prices and networks which more closely match heterogeneous user demands. Further, in instances where the cost of coordinating interfering uses with other spectrum users is low, price-guided policy would allow users to acquire spectrum on a non-exclusive basis. This would enable certain users to share the cost of a spectrum licence, reducing the up-front cost of obtaining access to the band. Finally, the auction is not incompatible with spectrum trading further down the line. Price-guided determinations are a viable means for initial assignment of potentially tradable rights. This would not preclude the possibility of the auction being two-sided, whereby existing licensees could tender their licences as part of a massive band reorganization.

Price-guided policy such as the one we have described here holds substantial promise. We have provided a demonstration that advances the state of the art a little further.

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Annex 1. Model inputs and outputs

Table 5: Model parameters from the German 3G auction results

Licensee	Auctioned spectrum	Bandwidth	Power in Watts	Euro per DM	Price (in DM)	Price in Euro	Unit Price
E-Plus Hutchison	2 x 5 MHz 1 x 5 MHz	15	100	0.511291881	**16,491,800,000**	**€8,432,123,446**	**€5,621,416**
Group 3G	2 x 5 MHz 1 x 5 MHz	15	100	0.511291881	**16,568,700,000**	**€8,471,441,792**	**€5,647,628**
Mannesmann Mobilfunk	2 x 5 MHz 1 x 5 MHz	15	100	0.511291881	**16,594,800,000**	**€8,484,786,510**	**€5,656,524**
MobilCom Multimedia	2 x 5 MHz 1 x 5 MHz	15	100	0.511291881	**16,491,000,000**	**€8,431,714,413**	**€5,621,143**
T-Mobil	2 x 5 MHz 1 x 5 MHz	15	100	0.511291881	**16,704,900,000**	**€8,541,079,746**	**€5,694,053**
VIAG Interkom	2 x 5 MHz	10	100	0.511291881	**16,517,000,000**	**€8,445,008,002**	**€8,445,008**
Total Sum					**99,368,200,000**	**€50,806,153,909**	
Average							**€6,114,295**
Standard Deviation							**€1,142,128**

On 31 December 1998, the European Central Bank (ECB) fixed the irrevocable exchange rate, effective 1 January 1999, for DM to euro as DM 1.95583 = one euro.
http://en.wikipedia.org/wiki/Deutsche_Mark

Table 6: Model run: base case

	Bidder 1	Bidder 2	Bidder 3	Bidder 4	Bidder 5	Bidder 6	Bidder 7	Bidder 8	Bidder 9	Bidder 10
Bandwidth	5	10	3.75	3.75	5	8.75	2.5	3.75	5	3.75
Power Limit	85.07	0.05	34.86	12.42	9.72	0.09	40.36	71.20	10.06	44.49
Data Rate	77	47	53	48	62	49	36	57	62	54
Unit Valuation Fixed (in thousands)	€5,850	€4,525	€8,007	€6,766	€7,347	€6,795	€4,945	€7,322	€6,762	€4,854
Total Bid (in thousands)	€2,488,269	€2,126	€1,046,796	€315,011	€356,990	€5,434	€498,967	€1,954,740	€340,071	€809,885
Auction Revenue										**€7,818,288,487**

Table 7: Model run: out-of-band mask

	Bidder 1	Bidder 2	Bidder 3	Bidder 4	Bidder 5	Bidder 6	Bidder 7	Bidder 8	Bidder 9	Bidder 10
Bandwidth	6.25	10	3.75	3.75	5	8.75	2.5	3.75	5	3.75
Power Limit	11.38	0.05	40.48	14.19	11.07	0.10	46.97	83.58	11.46	51.86
Data Rate	77	47	53	48	62	49	36	57	62	54
Unit Valuation Fixed (in thousands)	€5,850	€4,525	€8,007	€6,766	€7,347	€6,795	€4,945	€7,321	€6,762	€4,854
Total Valuation (in thousands)	€416,103	€2,238	€1,215,607	€360,110	€406,582	€5,773	€580,726	€2,294,780	€387,514	€943,990
Auction Revenue										**€6,613,423,491.15**

Annex 2. Glossary of Terms

Note to the reader: This Glossary of Terms is intended to be useful to the uninitiated or novice reader, by providing definitions and explanations of commonly used terms. Not every entry appears in the main body of the text; however, these terms will be helpful to the understanding of the subject matter. This Glossary may also be helpful to those with more experience in the field by providing consistent acronyms and abbreviations.

A

Administrative assignment model: the traditional process of spectrum management under which allowable spectrum uses are limited based on regulatory judgments.

AM (Amplitude Modulation): a type of radio transmission which uses changes in the amplitude of the carrier wave to transmit information. Amplitude Modulation is used in either the standard radio broadcast band, shortwave broadcasting, and in some private radio services such as citizens band (CB) and aviation.

Analogue Signal: a method that uses continuous changes in the amplitude or frequency of a radio transmission to convey information.

B

Bandwidth: the term generally used to refer to the capacity of a channel to carry signals. More technically, bandwidth refers to the width of the range of frequencies that a signal occupies. The necessary bandwidth is the amount of spectrum required to transmit the signal without distortion or loss of information.

Bit (Binary Information Unit): The smallest unit of digital information. It is equivalent to a “yes” or a “no”.

Bits per Second (bps): A unit used to express the number of bits passing a designated point per second.

Broadband: a descriptive term for evolving digital technologies that provide consumers a signal switched facility offering integrated access to voice, high-speed data service, video-demand services, and interactive delivery services.

Bundesnetzagentur (BNetzA): the German Federal Network Agency, formerly the RegTP.

Byte: a set of bits that represent a single character. Eight bits comprise a Byte.

C

CODEC (coder decoder): An encoding or decoding device that enables the digitization and digital transmission of analogue information (such as voice).

Co-channel Interference or Crosstalk: a form of interference which occurs when a receiver on one communications channel inadvertently receives information being transmitted on a neighbouring communications channel.

Cognitive Radio (CR): also called “smart radios”, can sense the presence of other transmissions in the local area and automatically switch to unused channels. The cognitive functions are performed by applying a process where a sequence of ‘observe’, ‘orient’, ‘decide’ and ‘act’ is implemented.

Command-and-control model: see administrative assignments model.

Commons model: an approach to spectrum management which allows unlimited numbers of unlicensed users to share frequencies, with usage rights that are governed by technical standards or etiquettes but with no right to protection from interference.

Co-operative cognitive radio (CCR): one of two principal approaches to sharing spectrum using cognitive radio which works interactively with the licensed user.

D

Direct Sequence Spread Spectrum (DSS): the most widely used type of spread spectrum system. It is a digital modulation technique achieved by modulating a narrow band radio frequency carrier with a high speed spreading code sequence. The spreading code spreads the narrow band signal over a wider band of spectrum. Because the total power of the original signal is now spread over a much broader bandwidth, the power level at any given frequency is very low. This feature allows direct sequence spread spectrum systems to operate in the presence of narrow band systems without interfering. (See Spread Spectrum).

E

Exclusive use model: a spectrum licensing model in which a licensee has exclusive and transferable flexible use rights for specified spectrum within a defined geographic area. These rights are governed primarily by technical rules designed to protect spectrum users against interference.

F

FCC (Federal Communications Commission): the U.S. regulatory authority for telecommunications.

FDMA (Frequency Division Multiple Access): a radio system access technology that enables spectrum sharing by allocating different users separate carrier frequencies within a single band of the radio spectrum.

FM (Frequency Modulation): a signalling method that varies the instantaneous frequency of a carrier wave in accordance with the signal to be transmitted.

Frequency: the number of cycles occurring per second of an electrical or electromagnetic wave; a number representing a specific point in the electromagnetic spectrum.

Frequency Hopping Spread Spectrum: a form of signal spreading in which the frequency of the transmitted signal “hops” from channel to channel many times, commonly less than 10 milliseconds, in accordance with a pseudo-random list of channels. The receiver hops in strict conjunction with the transmitter, thereby collecting all data transmitted in order to avoid interference both to and from conventional users. (See Spread Spectrum).

G

Gbps (Gigabit per second): one billion (1,000,000,000) bits per second.

GHz (Gigahertz): the oscillation of a wave at 1,000,000,000 Hz or cycles per second.

GSM (Global System for Mobile communications, originally from Groupe Spécial Mobile): an ETSI standard which employs TDMA to provide cellular mobile networks operating in the 900 MHz or 1800 MHz bands. GSM often refers to a set of standards for second generation (2G) mobile communications.

H

HiperLAN: a European wireless data networking standard operating in two bands within the 5 GHz range on a licensed-exempt basis. However, the HiperLAN2 bands, is slightly different than the U.S. U-NII bands. While the two share the 5.15 – 5.25 GHz portion, the HiperLAN2 upper band is 5.470 – 5.725 GHz.

Hotspot: a wireless data network access point. Service providers are beginning to offer portable internet hotspot access for laptops and handheld computers in airports, hotels, cafes and other public places.

HSPDA (High Speed Packet Data Access): a standard for third generation wireless services for GSM-based networks, also sometimes called HSPA.

Hz (Hertz): a frequency measurement unit which is equivalent to one cycle per second.

I

Interference: a radio emission from another transmitter at approximately the same frequency, or having a harmonic frequency approximately the same as, another emission of interest to a given recipient, and which impedes reception of the desired signal by the intended recipient. Interference can only ever occur at a radio receiver.

IP (information packet or Internet Protocol): Internet Protocol, along with TCP, is a standard developed by the U.S. military, which allows computers to communicate with one another over long distance, digital networks. IP is responsible for moving packets of data between nodes. TCP/IP forms the basis of the Internet, and is built into every common modern operating system. For information packet, see packet switching.

ISP (Internet Service Provider): A firm which enables other organizations to connect to the global internet.

ITU (the International Telecommunications Union): a standards organization, founded as the International Telegraph Union in Paris on May 17, 1865, dedicated to international radio and telecommunications. It focuses on standardizing allocations of the radio spectrum and organizing interconnection arrangements between different countries to enable international telephone calls.

J

Jitter: Variability of delay.

K

Kbps (kilobit per second): One thousand (1,000) bits per second.

Kilohertz (KHz): the oscillation of a wave at 1,000 Hz or cycles per second.

L

LAN (Local Area Network): a local data network that is used to interconnect the computers and computer equipment.

Latency: Propagation delay.

Licence-exempt: See Unlicensed Wireless Devices.

LTE (Long Term Evolution): the name given to a project within the Third Generation Partnership Project to improve the UMTS mobile phone standard to cope with future requirements. Goals include improving efficiency, lowering costs, improving services, making use of new spectrum opportunities, and better integration with other open standards. The LTE project is not a standard, but it will result in the new evolved release 8 of the UMTS standard, including mostly or wholly extensions and modifications of the UMTS system.

M

Mbps (Megabit per second): one million (1,000,000) bits per second.

MHz (Megahertz): the oscillation of a wave at 1,000,000 Hz or cycles per second.

N

Narrowband: a term commonly referring to analogue facilities and to digital facilities operating at low data transfer rates which are capable of carrying only voice, facsimile images, slow-scan video images, and slow data rate transmissions.

Network Externality or Network Effect: Where network effects are present, the value of a network to its users is greater as the number of participants in the network increases.

O

OFDM (Orthogonal Frequency Division Multiplexing): a modulation scheme that divides a single digital signal across 1,000 or more signal carriers simultaneously (FDM). The signals spaced at precise frequencies which prevents the demodulators from seeing frequencies other than their own (hence, orthogonal) so they do not interfere with each other OFDM offers multiple access and signal processing and allows wireless networks to pack high efficiencies into relatively small bandwidths.

P

Passive cognitive radio (PCR): one of two principal approaches to sharing spectrum using cognitive radio, whereby the radio can make decisions on frequency use autonomously and without any interaction with the licensed user.

PLMN (Public Land Mobile Network): a wireless communications network intended for use for mobile telephone communications or data and Internet access.

Price-guided policy: a means of policy determinations whereby administrative decisions are supplemented with pricing or market information, usually in the form of auctions.

Propagation delay: the time that it takes for light or electricity to reach its destination in a network. This is a function of the distance that the signal must travel, and the speed of light in the medium employed (typically wire or fibre).

Q

QoS (Quality of Service): in an IP-based environment, QoS often denotes measures of delay, variability of delay, and the probability of packet loss. It could also denote other measures of service quality.

R

RegTP: See Bundesnetzagentur.

RF (Radio Frequency): See Spectrum.

S

SDR (Software Defined Radio): a radio using programmable software for digital signal processing that allows the radio's fundamental characteristics such as modulation types, operating frequencies, and access schemes to be easily changed.

SMP (Significant Market Power): A firm is “deemed to have significant market power if, either individually or jointly with others, it enjoys a position equivalent to dominance, that is to say a position of economic strength affording it the power to behave to an appreciable extent independently of competitors, customers and ultimately consumers.” Framework Directive, Article 14(2).

SMR (Specialized Mobile Radio Services): a private, two-way radio system providing land mobile communications service to eligible persons on a commercial basis for such uses as dispatch communications or multi-site construction jobs.

Spectrum: the range of electromagnetic radio frequencies, ranging from 9 kHz to 3,000 GHz, used in the transmission of sound, data, and video images.

Spectrum Allocation and Spectrum Management: the coordination and assignment of available spectrum use to maximize efficiency and to prevent interference.

Spectrum Auction: a public sale of spectrum access in which the price is increased by bids until the highest bidder becomes the purchaser.

Spectrum Licence: a grant of radio spectrum usage rights from a spectrum management to an individual or group of individuals which conveys the permission to operate on certain frequencies, up to maximum permissible power output, in a geographic area and for a specified period of time. Spectrum licences normally convey the guarantee to be free from a level of interference considered to be harmful.

Spread Spectrum: a wireless communication system using special modulation techniques that spread the energy of the signal being transmitted over a very wide bandwidth. This increases the number of users that can share a particular band of frequencies, rather than assigning a discrete frequency to each user. Devices currently marketed in the United States primarily use one of two forms of spread spectrum signal: direct sequence spread spectrum and frequency hopping spread spectrum.

Spurious Emission: any radio emission or part of it which appears outside of the authorized bandwidth.

T

Teledensity: the number of communications access (or other metrics) in a given population or geographic area.

Tragedy of the Commons: the economic phenomenon that without some form of exclusion, user of a common resource consume the resource without regard to negative impact on other would-be users. The result is overuse, reducing all users’ benefit and total social welfare.

Transmission Control Protocol (TCP): a data communications protocol used to assure reliable delivery of data in an IP network.

U

UHF (Ultra High Frequency): the part of the radio spectrum from 300 to 3000 megahertz.

Ultra-Wideband Devices (UWB): a technology which relies on extremely short pulses that generate signals with very wide bandwidths, sometimes up to several gigahertz. UWB signals go undetected by most conventional receivers, minimizing their threat as harmful interferers. UWB technologies are currently being used in a variety of applications such as ground penetrating radar and are likely to be used in a variety of emerging applications such as through-wall imaging and high-speed data transmission.

UMTS (Universal Mobile Telecommunications System): one of the third-generation (3G) cell phone technologies, which is also being developed into a 4G technology. Currently, the most common form of UMTS uses W-CDMA as the underlying air interface. It is standardized by the 3GPP, and is the European answer to the ITU IMT-2000 requirements for 3G cellular radio system.

Unlicensed Wireless Devices (also, Licence-exempt): radios that are permitted to emit RF energy, but require no specific device or user authorization, either through registration or grant of a licence.

V

VHF (Very High Frequency): the part of the radio spectrum from 30 to 300 megahertz.

VoIP (Voice over IP): a set of data communications protocols and technologies to enable voice to be sent over individual IP-based networks or over the Internet.

W-Z

WAN (Wide Area Network): a data network used to interconnect remote sites or widely-dispersed computer equipment.

Wireless Access Platforms for Electronic Communications Services (WAPECS): platforms used for radio access to electronic communication networks and services, regardless of the bands in which they operate or the technology they use.

Wi-Fi (Wireless Fidelity): the suite of IEEE 802.11 standards adopted starting in 1999, for short-range wireless digital connectivity. It is by far the most widely adopted WLAN standard and performance and speed these standards can provide rivals that of 10BaseT wired Ethernet networks. It now includes, *inter alia*, the 802.11a, 802.11b, 802.11e, 802.11g and 802.11n standards.

WiMax (Worldwide Interoperability for Microwave Access): the IEEE 802.16 standard intended to wireless data communications over long distances in both point-to-point links to full mobile cellular type access. The name WiMAX was created by the WiMAX

Forum, which was formed in June 2001 to promote conformance and interoperability of the standard. The forum describes WiMAX as "a standards-based technology enabling the delivery of last mile wireless broadband access as an alternative to cable and DSL."

W-LANs (Wireless Local Area Networks): LANs which use wireless data connections to provide short-range, high-speed wireless digital communications.

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