MEASURING SPECTRUM EFFICIENCY – THE ART OF SPECTRUM UTILISATION METRICS

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INTRODUCTION

Increasing demand for spectrum in recent years has led to a greater emphasis on the efficiency with which spectrum is used. This is reflected in European telecommunications licensing legislation, which makes specific provision for optimising the use of scarce spectrum resources when setting up national licensing regimes. But what factors determine whether spectrum is being used efficiently, and what steps can be taken by users and regulators to achieve optimal use? Is it possible to "measure" spectrum efficiency in any meaningful way?

Optimal use of a scarce resource like radio spectrum requires more than a purely technical consideration of efficiency. From a user's perspective, the effectiveness with which the spectrum use meets the requirement may be far more important than simply squeezing the maximum amount of data into the available bandwidth. This is particularly so where health and safety is involved, or where reliable radiocommunication is an essential requirement of the user's business.

Economic factors are of course also crucial in evaluating the overall efficiency of spectrum utilisation. The potential economic value of radio spectrum has been highlighted by recent auctions, which resulted in multi-billion pound payments for the right to use spectrum for 3G mobile services.

This paper considers some of the parameters that might be taken into account when considering how optimally spectrum is being used. It does not attempt to define a single, all-embracing measure of efficient spectrum utilisation, since the requirements of applications such as mobile phones, television broadcasting and air traffic control are all fundamentally different.

Optimal use of spectrum requires the needs of users of the spectrum to be met in the most efficient and effective manner possible, taking account of the economic, functional and technical constraints that apply to different services. Assessing how well this is achieved in practice requires a large degree of qualitative judgement as well as quantitative measurement – hence measuring efficiency is an art as much as a science.

WHAT IS SPECTRUM EFFICIENCY?

Spectrum efficiency can be viewed in several ways, however we consider there to be three principal dimensions, namely technical, economic and functional, as illustrated in the following diagram:

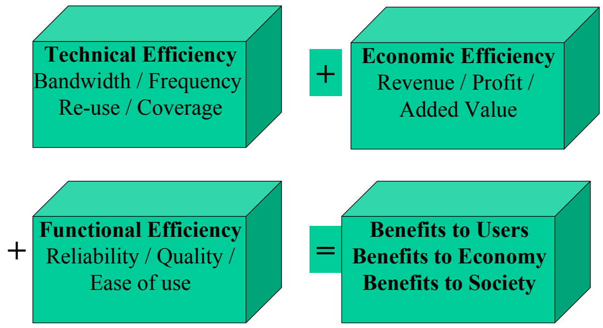

Fig 1: a 3-dimensional view of spectrum efficiency

Technical efficiency essentially means conveying the maximum volume of data or voice traffic with a given amount of spectrum resource, which typically includes geographic area or volume as well as pure bandwidth. Hence parameters like erlangs/MHz/km^2 or MBit/s/MHz/km^2 may be used to compare the relative efficiency of mobile phone networks.

Economic efficiency can be expressed in terms of the maximum revenue, profit or added value that can be generated from a finite amount of spectrum resource. This measure has become increasingly important with the advent of market based licensing and spectrum pricing.

Finally, **functional** efficiency may be regarded as the extent to which the use of radio spectrum meets a user's specific needs, so enabling a particular task to be carried out more efficiently or effectively than would otherwise be the case. For example, a taxi firm or fleet operator's business may depend heavily on the ability to communicate instantly and reliably at minimal cost whilst on the move, which may not be compatible with a public network's objective to maximise overall traffic throughput on its network. Reliability and speed of connection are even more paramount for public safety applications such as the emergency services or air traffic control.

Typically all three of these aspects need to be considered when assessing how optimally spectrum is being used. For example, when comparing the efficiency of mobile radio services, cellular networks may score highly in terms of technical efficiency relative to private mobile radio, but the latter may well win out on functional efficiency.

TECHNICAL EFFICIENCY

The approach to measuring technical spectrum efficiency depends on the nature of the service, e.g. whether it is a one to one service like telephony or a one-to-many service like broadcasting. Another key difference exists between point to point services (e.g. microwave fixed links) or point-to-area.

However, there tend to be three principal technical factors determining spectrum efficiency, namely bandwidth efficiency, frequency re-use, and time. Bandwidth efficiency is simply the amount of information that can be conveyed within a given amount of radio spectrum and may, for example, be expressed in bits per Hz. Re-use is rather more complex, and is a measure of how easily the same radio spectrum can be used simultaneously at multiple locations.

Typically there is a trade off between these two factors, since technologies that provide very high bandwidth efficiency tend to have inferior re-use characteristics. Time is also a factor in determining overall efficiency, in that most applications do not use spectrum on a continuous basis and users typically share resources on a time basis. A number of techniques have evolved to take advantage of this, including trunking, TDMA systems and, more recently packet based data transmission and voice activity detection.

In telecommunications networks, these three factors can be combined to provide an overall measure of technical spectrum efficiency, typically expressed as erlangs / MHz / km^2 (voice) or MBits/MHz/ km^2 (data).

By way of example, the following table illustrates how the technical efficiency of typical cellular networks, expressed in terms of erlangs/MHz/km^2 has evolved over the three cellular generations.

	TACS	**GSM**	**UMTS**
Speech channels / MHz	40	40	32
Cell repeat factor	7	4	1
Average cell area (sq km)	3.14	0.79	0.79
Speech chan/MHz/sq km	***1.82***	***12.66***	***40.51***

Fig 2: Technical Efficiency of Cellular Networks

On the basis of this comparison, it can be seen that the overall *technical* efficiency of a 3rd generation UMTS network is over three times that of GSM and over twenty times that of the early analogue networks.

For broadcast systems, a different approach is required. In simple terms, efficiency can be defined in terms of addressing the maximum potential audience with the minimum amount of spectrum. Bandwidth efficiency is the key determinant, particularly for national networks where the latest digital technology enables the same frequency to be used to serve the entire country. However, for local or regional services different frequencies must be used and the benefits of single frequency networks are diminished. Satellite delivery can be seen as highly efficient for the delivery of national services where the same material is supplied throughout the satellite footprint, but it is likely to be far less efficient for delivery of localised services.

Efficiency may in the future be further enhanced by developing multi-mode delivery platforms. For example, a joint working group addressing possible synergies between 3G mobile and digital TV standards compared the delivery of a 100 second video clip to a million mobile subscribers, using UMTS and DVB technologies. Assuming a 100 kbit/s data rate and a latency of 1000 seconds, the report suggests that delivery of the clip via a conventional 3G network would require the entire network capacity for up to fifteen minutes. The same video clip could be delivered, in the same time, via a broadcast network using around 0.1% of its capacity, thereby offering a far more economical solution. [1]

ECONOMIC EFFICIENCY

The gains in technical efficiency of cellular networks highlighted above translate to some extent into economic gains, since more traffic over the network means more revenue. However, the gains are not realised without cost, e.g. a denser or more complex network infrastructure. Also, the demand for mobile voice communication can be largely met by existing GSM networks, so a simple expansion of voice capacity is unlikely in itself to justify a multi-billion pound investment in a new generation network.

Where 3G really scores is in its ability to deliver high speed, multimedia services that were simply beyond the reach of previous technologies. The availability of faster speeds and flexible packet based transmission enables a wide range of value added services to be developed, such as multimedia messaging and entertainment services, enhancing the potential revenue that can be generated from the spectrum.

Economic efficiency can be encouraged by applying market-based mechanisms such as auctions or secondary trading to radio spectrum. However, assigning a monetary value in advance to radio spectrum is not without risk, as some of the bidders in early 3G mobile auctions have found to their cost. The following graph shows the estimated price per capita paid by bidders in European 3G auctions:

1 The Convergence of Broadcast & Telecomms Platforms, report no.1 by ad hoc Group DVB-UMTS, March 2001.

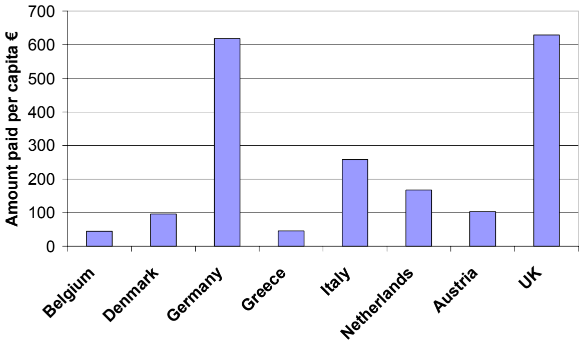

Fig 3: Amounts paid in European 3G auctions

FUNCTIONAL EFFICIENCY

For some users, simple functionality and reliability are the most important aspects of a radiocommunication service. Such needs may not be fully met by a cellular service geared towards maximum call capacity. So private mobile radio (PMR) systems continue to play a vital role for those who need instant connectivity, tailored coverage and modest, fixed operational costs. Public access mobile radio can provide similar benefits for those who do not wish to run their own systems.

Whilst PMR cannot match the technical efficiency levels of high density cellular services, the functionality of the service, particularly the relatively short call duration, the ability to make group calls and almost instantaneous call set-up scores highly in efficiency terms. These characteristics mean that up to 100 users can share a single PMR voice channel compared to around 40 for GSM.

Functional efficiency is difficult to quantify, as it often involves subjective criteria like ease of use in difficult or dangerous situations. However, the benefits of functional efficiency to users tend to be reflected in the value placed on mobile services by the users.

This can be expressed quantitatively by conducting "stated preference" research where users are asked to state what they would be prepared to pay for various service attributes. Subtracting this value from the amount users actually pay for their service yields the "consumer surplus", a measure of the benefit derived from the service functionality relative to the price paid for it.

Recent RA studies into mobile users' willingness to pay for various services have indicated that the average consumer surplus per PMR user is £95 per annum (3), compared to £47 for business cellular users (4), reflecting the value placed on PMR's unique functionality by many users.

Service	CS per user
GSM personal	£16
GSM business	£47
PMR	£95

Fig 4: Consumer surplus for GSM and PMR

CONCLUSIONS

This paper has provided an overview of three key dimensions that are considered to influence the optimal use of radio spectrum, and examples are given of how these might be "measured" in practice. The key efficiency dimensions are technical, economic and functional. All of these should be considered when assessing the extent to which optimal use of spectrum is being achieved.

In general, maximising economic efficiency would seem to be the priority in the case of larger, national services such as cellular or TV broadcasting. Conversely, for more specialist applications such as private mobile radio or air traffic control, functional efficiency or "suitability for purpose" should be the overriding concern. In both cases, there is a need to optimise the technical efficiency in so far as this can be achieved without negating the functional benefits or rendering the service economically non-viable. There is no single, all-embracing algorithm that can compare the efficiency of one spectrum-using application with another. Hence the measurement and comparison of spectrum utilisation efficiency may rightly be considered to be as much an art as a scientific process.

REFERENCES

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4. Consumer Surplus for cellular and pager users, 2001, Hague Consulting Group and Accent Marketing and Research on behalf of the Radiocommunications Agency.