ECONOMIC EFFICIENCY OF SPECTRUM ALLOCATION

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Abstract – *Spectrum demand is rapidly expanding, driven by the developments of incumbent radio systems, as well as with the requirements of new technologies and market players to get spectrum access. In this regard, one of the fundamental functions of the state spectrum regulator is to create an enabling administrative and legal environment to ensure efficient spectrum use and to mitigate scarcity of this valuable natural resource. This paper analyses the economic value of spectrum use and suggests an extension of the spectrum's traditional technical boundaries, in order to take into consideration energy, environmental, sanitary and bio-geotechnical limits. The study reviews the phenomena of increasing transaction costs and negative externalities of spectrum access requiring economic criteria and assessment to achieve optimum resource allocation with a spectrum's demand growth. Results develop an input-output matrix as an allocation instrument to achieve spectrum efficiency and optimum equilibrium based on analysis of the economic effects from different band utilization scenarios, supplemented by currently used technical criteria. Practical application of proposed economic methods should improve the existing spectrum management system.*

Keywords – Input-output matrix, spectrum efficiency, spectrum externalities, spectrum management

1. INTRODUCTION

Satisfying the ever-growing material, physical and social needs of humanity under conditions of limited resources, places the implementation of an overall strategy for sustainable development at the heart of contemporary economic, political, environmental, social, and technical research. Invention of data transmission by means of electromagnetic waves gave humanity a new invisible resource: radiofrequency spectrum. Every single radio system uses artificially-produced or naturally-emitted electromagnetic waves as a carrier of data. Radiofrequency spectrum is defined as the electromagnetic frequency continuum ranging from 3 kHz to 3 000 GHz. Originating from maritime applications in the past, nowadays spectrum plays an essential role in all areas of human activity. For the time being, spectrum is primarily utilized based on an exhaustive approach, relying predominantly on technical limits defined by Shannon theorem and absence of mutual harmful interference between the growing number of space and terrestrial radio systems.

The growing problem of spectrum scarcity requires spectrum efficiency evaluation and introduction of modern methods for its improvement. Nobel laureate Prof. R. Coase emphasized that spectrum allocation should be determined by market forces rather than by administrative decisions, leading to zero transaction costs and coping with any externalities [1]. Later on his idea was developed in more detail, advocating for the implementation of alternative spectrum management instruments including spectrum privatization, secondary trading and auctioning [2]. Several fundamental studies designated the introduction of a spectrum fee, deregulation of management systems, and delegation of some administrative functions to the private sector as the basic economic methods to improve spectrum management systems [3]. In 1996, International Telecommunication Union (ITU) initiated studies aimed to develop a guidance for Member States in applying economic methods to improve their spectrum management systems [4]. In 2001, 37 world famous American economists, including four Nobel laureates, addressed the US Federal Communications Commission with the need to implement radical changes in the principles governing spectrum usage that would be required to ensure the harmonious development of telecommunications [5]. Their proposals included modifying users' rights to allow spectrum trading and, accordingly, implementing auctions and market mechanisms for the resource allocation.

However, the problem of spectrum efficiency is still vital. Conflicts of interests between different spectrum users, newcomers and incumbents, public

* The ideas expressed in this paper are those of its author and they do not necessarily represent those of the International Telecommunication Union, the Radiocommunication Bureau or any known institution.

and private operators, national and regional telecommunication groups provoke a lot of controversial technical discussions leading to non-optimal allocation decisions. The latter are producing negative externalities, innovation delays, late comer price, increases in transaction costs and non-harmonized spectrum exploitation. The key reason for the inefficient decision-making mentioned above is the choice of solely depending on technical criteria in spectrum management such as electromagnetic compatibility with incumbent applications. In some cases, the principle of "protection of existing radio services" could be seen as somewhat obsolete and the introduction of new technologies would benefit from the reallocation of spectrum from incumbent operators to newcomers. The traditional approach requires further improvement in international and national spectrum management systems by applying economic criteria and valuations to accommodate booming spectrum demand.

This paper defines the place and role of the spectrum in the digital economy, specifies major spectrum users and considers the economic value of spectrum use. The author embraces multivariable direct and indirect boundaries, related to energy, environmental, sanitary and biogeotechnical restrictions. The study covers the phenomena of increasing transaction costs and negative externalities of spectrum access. This work proposes input-output Leontief matrix as an allocation instrument to achieve spectrum efficiency and optimum output based on an analysis of the economic effect from different band utilization scenarios. The arguments of the present article deal with the problem of spectrum efficiency, but comments received seem equally applicable for post-pandemic economic development in order to choose an optimal scenario of natural resources use on a global and national level.

2. ECONOMIC VALUE OF SPECTRUM USE

Table 1 shows that in recent decades spectrum is directly or indirectly used practically in all industry sectors, standing as one of the key factors promoting economic, social and cultural development, increasing consumer and producer surplus, enhancing public welfare, protecting safety-of-life and improving living standards.

Some facts illustrating the economic value of spectrum use for the modern economy and society are as follows:

- the contribution of the mobile industry to global GDP in 2018 achieved nearly USD 4 trillion [6];
- the economic benefits of accurate weather forecasts obtained from satellite Earth monitoring systems that can mitigate the economic consequences of natural disasters in EU countries is estimated at 61 billion Euros annually [7];
- reallocation of 500 MHz spectrum band from TV companies and federal agencies to mobile operators created 250 000 new jobs in the United States of America [8];
- as a part of the US federal plan to combat the coronavirus, 600 MHz of the spectrum has been reallocated from satellite to mobile operators for 60 days, "supporting social life, to keep economy going and to connect remotely to health care professionals during this crisis" [9].

Earth observation and meteorological systems contribute towards achieving all the United Nations Strategic Development Goals (SDGs), without a single exception. In addition, data obtained by using relevant radio systems are essential for monitoring the results of SDG initiatives. Around 30 of the 232 indicators developed for monitoring progress towards the SDGs can be verified only based on data obtained from Earth observation satellites.

Additional important areas where spectrum use has a significant impact are radio astronomy and space research, which are crucial to studies of classical physics and Universe evolution. Research in these areas, based on data obtained with the aid of the relevant radio systems, have an enormous impact on the development of other sectors of the economy which, at first glance, would appear to have no relation to those spectrum-based systems. For example, the success of algorithms for processing large data volumes in radio astronomy and cosmic research have been a foundation of the digital economy.

Spectrum use has considerable social importance from the point of view of a State's obligations to protect the basic rights of its citizens in democratic society. It is not coincidental that basic provisions concerning spectrum management in France are set by legislation on freedom of speech and information. Radiocommunication is critical in all phases of disaster management. Aspects of radiocommunication associated with disasters

Table 1 – Main spectrum users

Users	Radio systems used	Applications	End use output	Intersectoral use output
Defence	Mobile and satellite communication systems, microwave links, radiolocation, radars, navigation	Operational control, management	Safeguarding national security, border control, antiterrorist operation	Development of radio-electronic industries and science
Security and law-enforcement agencies	Mobile and satellite communication systems, microwave links, radars	Operational control of subordinate units	Maintenance of internal security and law enforcement, government communications	Radio-electronic industries and science
Communications and informatization	Mobile and satellite communication systems, microwave links, sensor systems	Provision of access to data transmission systems and public communication networks	Public communication and informatization services, maintenance of economic security	Radio-electronic industries and trade, satellite industry, social development, disaster relief
Broadcasting	Satellite and radio-relay communication systems, broadcasting networks	Broadcasting of TV and radio programmes	Freedom of thought, expressions and public information	Commerce, advertising, security, disaster relief
Earth exploration and monitoring	Remote Earth sensing satellites	Collection of data on the state of the Earth's natural characteristics	Cartography, geoinformation, data on the state of the climate and natural resources	Construction, natural resources management, disaster relief
Radionavigation	Satellite and land-based navigation systems	Transmission of time signals and frequency standard emissions	Precise determination of the location, shift and speed of objects	All branches of industry
Meteorology	Remote earth sensing and data collection satellites, radars, meteorology probes and sensors	Collection, transmission and distribution of meteorological data	Weather forecasting, prediction of natural disasters, monitoring of climate change and SDGs indicators	Defence, emergency agencies, transport, agriculture and forestry, green energy
Transport	Mobile and satellite communication and navigation systems, sensors, radars	Remote monitoring and control of transport, broadband access	Improving safety of passenger and cargo transport, optimization of traffic, unmanned transport	World trade, hotel and tourism sector, postal services
Radio astronomy	Ground and space radio astronomy stations	Collection of data on the Universe	Development of fundamental science	All branches of industry
Space research	International Space Station, piloted and robotic space missions	Studies on the near-Earth space environment and space objects	Development of fundamental science, search for natural resources, protection from potential hazards from space	All branches of industry
Production industry	Office and corporate networks, control, automation system	Improving production efficiency and safety	Optimizing use of resources	All branches of industry

include disaster prediction, detection, alerting, and relief. In certain cases, when the wired infrastructure is significantly or completely destroyed by a disaster, only radio systems can be employed for disaster relief operation in a timely manner.

With technology evolution, spectrum appears to play an even more critical role and is becoming an essential element of the numerous governmental *e*-programs, such as *e*-medicine, *e*-government, *e*-education etc. A future digital economy implies a transition from current intuitive manual forms of management to an algorithm-based one that relies on the development and use of coherent models for political, economic, technological and behavioural analysis, as well as decision-making and artificial intelligence. It will depend critically on a powerful complex of different types of radio systems to gather, deliver and disseminate a variety of data, boosting spectrum demand. Information collected by different sensors and receivers on-board satellites, aircraft, and ships, fitted to buoys, livestock, and so on, once disseminated, will help humanity to fight against bureaucracy and mismanagement by means of better understanding of the relevant technocratic, natural and socio-economic processes and their interactions and impact.

In terms of importance, the spectrum ranks alongside national energy resources or reserves of raw minerals. The efficient use of the spectrum in the modern world has a major impact on economic development and is a critical factor of sustainable development.

3. LIMITATION OF SPECTRUM USE

The spectrum as a natural resource can be classified as follows [10]:

- a category of energy resources, subcategory artificially activated energy sources, along with atomic and thermonuclear energy;
- a renewable resource;
- spectrum sharing by multiple radio systems is possible using a combination of factors relating to time/phase, space, frequency dimensions and performance characteristics.

Complex technological processes of spectrum exploitation define interdependent vectors of interfaced limitation:

- Physical limits. The choice of spectrum for most radio technologies is complicated by the varying quality of the resource in terms of radiowave attenuation and propagation characteristic. As an example, only a few specific bands are suitable for monitoring particular natural features, depending on the unique resonance frequencies, and they must be protected from all man-made radiation in order to ensure measurement quality. Physical limits have a major strong impact on economic indicators of spectrum use projects. Sometimes a radio application can utilize a less occupied, higher frequency range alternative, but it will require more investment/operational costs to provide the same quality of service, challenging project efficiency;
- Technological limits. With industry evolution, the upper boundary of the usable spectrum is constantly raised. Currently the spectrum between 3 kHz and 100 GHz is actively used, while the range from 100 to 275 GHz has a certain potential for use, although at present it is not heavily occupied. Existing wireless technology cannot meet the demands of future ultra-wideband networks, since data rates beyond 10 Gbps are not achievable by current millimeter wave systems, which are typically operating below 60 GHz. The frequency band of 275~3 000 GHz is especially of interest for future wireless systems with 100 Gbps data rates. Although radio equipment for this range is still in a very early stage of development, some studies show its potential applications [11]. Any future use of the range will be extremely constrained by the propagation characteristics, and in particular by high levels of rain attenuation and transmission path loss. Such quality of spectrum will make ultra-high frequencies unsuitable for the majority of conventional applications;
- Technical limits. Spectrum use is limited by the extent to which it can be shared by different radio systems, given the potential for harmful interference which can have a major impact on the quality of service. In other words, technical conditions for a given system to use spectrum is determined by electromagnetic compatibility conditions imposed by other radio systems, operating in the same band and in the same location. From the economic theory, unintentional interference could be regarded as a negative externality. Waves emitted by a radio system constitute a wanted signal for the receiver within that system and enable it to operate, but may cause harmful interference to other radio systems, degrading their operating quality or preventing operation altogether. Mutual interference is a main reason for international and national spectrum management systems, to ensure the possibility of a globally coordinated use of the resource. The potential of a radio system in terms of the creation of and sensitivity to interference is determined by the performance of the radio equipment used, which is dependent on the operational quality and ultimately the cost of the radio systems;
- Administrative limits. International and national use of the spectrum is based on block allocation of the resource among different users/radio services in technical terms. Any radio system may use a frequency band that is administratively defined in an international

and/or national allocation table to the radio service in which the radio system in question refers. At the international level, questions pertaining to the international frequency allocation table are decided at the ITU World Radiocommunication Conference (WRC);

– Health-related limits. The harmful effects of artificially generated electromagnetic fields on human health is a matter of growing concern and is being actively studied by a number of medical institutions under the umbrella of the World Health Organization. Further uncontrolled increases in the intensity of use of the spectrum may prove harmful to human health [12]. At present, two types of limits have been established, namely, basic restrictions and reference levels. Basic restrictions are standards relating to the effect on human beings of time-varying electrical, magnetic and electromagnetic fields. These are based directly on their proven exposures on human health, although measuring them is difficult (for example, induced current density in the human body). Reference levels are derived from the basic restrictions and are expressed in easily measurable units. They set maximum permissible emission power for specific types of radio system. It is considered that, when applying reference levels, the overall effect on the body should not exceed the established basic restrictions. Increasing the density of radio systems especially in urban areas could call into question the viability of the current approach, as it would be necessary to improve current WHO and ICNIRP regulation taking into account the aggregated field strength in order to protect public health;

– Environmental limits. The large-scale use of different radio systems creates the problem of electronic waste (e-waste), in other words, the necessity to recycle large quantities of obsolescent or defective radiocommunication hardware. ITU reported that the total global volume of e-waste had reached around 53.6 million tonnes in 2019 with a forecast that this figure may be tripled by 2021. Of this total amount, 44.5 million tonnes of e-waste were discarded in landfills, burned, or illegally traded, causing so called "export of the environmental crisis" and leading to air and water pollution, soil contamination, and biodiversity loss. Environmental limits for spectrum use should consider space debris also. Under current practice and regulations, a geostationary satellite that has come to the end of its operational life is to be transferred to a higher altitude orbit, but it stays in space. There are plans to launch huge constellations into non-geostationary orbits in order to provide direct broadband access with global coverage requiring thousands of satellites. Near-Earth space is already polluted by artificial junk as a result of satellite collisions and explosions, including around 20 000 fragments larger than 10 cm in size and around 500 000 between 1 and 10 cm in size [13]. The problem of space debris is expected to be left for future generations.

Delivery of all planned satellites and space missions into space will dramatically increase demand for rocket launches. Up to now rocket launches occur irregularly and annually do not exceed 100 globally so that concerns about the damage done to the ozone layer by rocket emissions have not elicited regulation. ITU study predicts, more than 1 000 returning launches only for suborbital vehicles in 2025, raising a question on appropriate mitigation measures at the international level against potential negative impacts on Earth's atmosphere, carbon emissions increase, ozone depletion etc [14].

Booming of radio equipment production causes the growth in CO_2 emissions. By 2023, total carbon emissions resulting from the growth in production of mobile equipment alone could reach 235 megatons CO_2 per year [15].

– Power limits. The use of higher bands and increasing demands for transmission speed, as well as a growth in the number of radio systems of different types result in a considerable increase in power consumption, which exacerbates the global energy shortage. ITU estimates that the information and communication technology (ICT) sector's share of global electricity consumption in 2015 was 3.9 per cent. A typical 5G base station consumes up to twice or more the power of a 4G base station. To address this challenge, some countries plan further development of coal power plants to support an intensive introduction of new generation radio networks in spite of international carbon emission limitations;

– Bio-geotechnical limits. According to the "1 per cent" law, an artificial change of 1 per cent in the energy of a natural system as a rule causes it to depart from a Chatelier's equilibrium [16]. In other words, our biota cannot compensate the volume of artificially generated energy that exceed 1 per cent of its natural level. Experience of using other natural resources suggests that violating that rule may lead to catastrophic change in the natural environment, such as global warming. A part of solar energy transforms into a natural electromagnetic field of the Earth forming a 1 per cent limit. An aggregate assessment of man-made emissions is required when the strategy of spectrum use is defined to avoid transgressing this threshold.

4. INPUT-OUTPUT ANALYSIS FOR SPECTRUM MANAGEMENT

A definition of limits is just the first step of any economic analysis of efficient resource management. Regulators should establish an accurate economic model, enabling them to find an optimum scenario of development under conditions of resource scarcity and negative externalities. Nobel laureate W. Leontief pointed out that "the essence of input-output analysis in study of the resources problem consists in constructing several alternative scenarios with different combinations of input-output vectors describing the technological structure of the different methods of production and usage". The input-output matrix enables a resolution to the problem of a shortage of resources, taking into account externalities, through planning and redistribution. From the analysis of the technological process, of interdependencies between industry sectors and of the economic impacts of spectrum usage, the inter-sector input-output matrix for spectrum can be used as the economic model for assessing spectrum efficiency. The proposed matrix for spectrum use is presented in Table 2.

Explanation of the values used in Table 2:

n — number of users (i.e. industry sectors) or radio services using the spectrum (see Table 1 for example);

k — spectrum allocation scenario;

s_{nk} — aggregate spectrum allocation for the n-th user (radio service) in the k-th scenario. Here it must be understood that account needs to be taken not only of the bandwidth directly accessible for the user, but also of other technical conditions and restrictions on its utilization stemming from shared use. In some cases, analysis of this component is simplified thanks to the decisions on global or regional spectrum harmonization for a specific standard;

S_k — aggregate spectrum allocations in the k-th scenario. Analysis of this value is complicated by the possibility of shared use of the spectrum, i.e. $S_k \neq \Sigma s_{nk}$;

Table 2 – Input-output matrix for spectrum use

		Main spectrum users				**Aggregate bandwidth for *k*-th scenario**	**Economic impact**		**Overall impact for *k*-th scenario**	**Overall cost for *k*-th scenario**
		1	**2**	**...**	***n***		**Output for end user for *k*-th scenario**	**Inter-industry output for *k*-th scenario**		
Spectrum allocation scenarios	1	s_{11}	s_{12}	...	s_{n1}	S_1	y_{int1}	y_{ext1}	Y_1	W_1
	2	s_{21}	s_{22}	...	s_{n2}	S_2	y_{int2}	y_{ext2}	Y_2	W_2
	...	...	...	...	...	...	...	...	...	...
	k	s_{n1}	s_2	...	s_{nk}	S_k	y_{intk}	y_{extk}	Y_k	W_k
Revenue		p_1	p_2	...	p_n					
Capital costs		cap_1	cap_2	...	cap_n					
Operating costs		op_1	op_2	...	op_n					
Transaction costs		tc_1	tc_2		tc_n					
Externalities costs		ec_1	ec_2		ec_n					
Spectrum user costs		w_1	w_2	...	w_n					

y_{intk} — economic impact of spectrum use in the k-th scenario, as the sum of the impacts of the production of the n-th spectrum user for the end user;

y_{extk} — economic impact of spectrum use in the k-th scenario, as the sum of the impacts of the production of the n-th spectrum user for inter-sector use of output $Y_k = y_{intk} + y_{extk}$ — Overall contribution of use of the resource to the country's GDP for the k-th allocation scenario. Given the complexity of the inter-sector relationships and technological processes involved in the use of a resource, of direct and indirect assessments of a resource's economic impact and of the different manifestations thereof (e.g. the creation of new jobs), this is a multifaceted task that calls for the accumulating and processing of Big Data. The simplest approach of direct evaluation is spectrum auction. One of the latest example is underway C-band auctioning in the US already bidding USD 80 billions [17];

p_n — revenue of the n-th user. State operators use spectrum in order to fulfil political, economic and social purposes, so normally $p_n = 0$. Where commercial operators are concerned, taking this component into account is very important for establishing a favorable investment climate in the relevant segment of the market;

cap_n — capital costs of the n-th spectrum user in the k-th scenario. The costs of a radio system depend on the available bandwidth and the technical conditions of the spectrum use, e.g. propagation [4]. The wider and less occupied the required band, the lower the capital costs for network development, both in terms of coverage of the service area and cost of the equipment itself. Therefore, when analysing the input-output matrix, it is necessary to examine the relationship $cap_n = f(s_{nk})$. In the analysis of a spectrum reallocation scenario, this item has to take into account the associated expenses and of compensation of losers in accordance with potential Pareto criteria;

op_n — operating costs of the n-th spectrum user in the k-th scenario. These are also a function of bandwidth since, first, according to Shannon, bandwidth shortfalls for a given quality of service can be offset by increasing transmission power, and, secondly, in congested parts of the spectrum achieving interference-free operation of radio networks calls for highly qualified technical staff and the implementation of special technical measures requiring specialized hardware and software. On the basis of these considerations, it is necessary to examine the relationship $op_n = f(s_{nk})$. This item may also take into account an annual spectrum fee if such a fee is levied on users in the band in question;

tc_n — transaction costs for the n-th spectrum user in the k-th scenario. These can include the license and spectrum/auction fees, as well as reallocation costs;

ec_n — externality costs of the n-th spectrum user in the k-th scenario, defined by spectrum limitations. Inclusion of this contributor in economic analyses allows the principle on internalization to be met and to define real social cost of resource use resulting in a Pareto-optimal plan.

The overall costs for the n-th spectrum user in the k-th scenario may be expressed as follows:

$$w_n = p_n + cap_n(s_{nk}) + op_n(s_{nk}) + tc_n(s_{nk}) + ec_n(s_{nk}) \quad (1)$$

The basis of the input-output method lies in assessing the ratio of impact to costs, such that efficiency in use of the spectrum for the n-th user may be expressed as:

$$e_n = y_n / w_n \quad (2)$$

In cases where it proves impossible in practice to place an objective monetary value on the impact generated by use of the specific spectrum use, the cost ratio a_k may be used as an economic criterion to study allocation scenarios:

$$a_k = s_{nk} / w_n \quad (3)$$

The proposed approach offers an economic mechanism to objectively assess the overall impact of a decision in regard to the use of a band at any stage of the management cycle, and to compare alternative options with a view to selecting the optimum one in terms of the regulator priorities. A full scale introduction of the proposed method in order to improve efficiency of the spectrum allocation system requires development of big data system to support the processing of all required information. However, even simplified economic criteria (3) could provide essential results to be taken into account. For example, WRC-19 allocated two possible bands for 5G introduction – 3.4-3.8 GHz and 4.8-4.99 GHz. A study of propagation model [18] and required base station density [19] in two bands shows that cost ratio a_k for the second frequency band will be almost twice as much, making low band utilisation more efficient under all other equal conditions (penetration rate, spectrum availability, economies of scale, border coordination, etc.).

5. CONCLUSIONS

Transition to a sustainable model of development through the digital economy is the guiding force driving the current stage of human technological progress. This is of immense importance, not so much for generating economic profit, as for identifying ways of ensuring humanity's continued survival. Humanity on board "Noah's Ark" consumes resources in an uncontrolled way through constantly increasing consumption that "bores holes in the hull", and thus unthinkingly destroys its critical life-support systems. We should hope that artificial intelligence will help us to understand that our current irrational devouring of resources has no future, and that even our immediate descendants would encounter catastrophic problems bequeathed to them by their grandparents.

Successful worldwide implementation of a digital economy initiatives must be based on the optimization of all available resources use with respect of available resources boundaries. One of these essential resources is the spectrum, playing a role as an integral element of the digital economy ecosystem. In terms of economic value, the spectrum could be ranked alongside national reserves of energy and raw materials. Multisided limits of spectrum use require international and national actions to avoid them to be transgressed. The digital economy urgently requires a digital spectrum management system to accommodate new radio technologies and to facilitate economic growth.

The input-output model can be considered as the proper mechanism for appropriate assessment and optimization of the use of resources at the macroeconomic level, providing a complex evaluation of the consequences of all possible scenarios and to assist decision makers in selection of those which best serve their strategic goals. Our "Noah's Ark" needs not only the wind of A. Smith and R. Coase market forces to fill its sails, but a steering wheel of W. Leontief and L. Kantorovich is required also, heating and bearing to true at all times in order to avoid reefs and shoals and to overcome storms. As the current situation shows, the market economy in some cases cannot resolve problems of negative externality and protect public interest. Resource management policy should consider social costs and internalization of negative externalities to ensure optimal social welfare, including environmental quality and protection of future generation interests.

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