



FAU Studien aus der Elektrotechnik 17

Georg Fischer / Thomas Ackermann

Spectrum demand of professional wireless production tools (PMSE)

Study report

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Zusammenfassung

In dieser Studie werden Trends bei der Nutzung des UHF-Spektrums und der Bedarf der Nutzer des UHF-Spektrums analysiert. Dank der Verfügbarkeit einer großen Datenbank, die Spektrum-Scans einer Vielzahl von Ereignissen über einen großen Zeitraum enthält, können Trends in der Verfügbarkeit von PMSE-Spektrum und PMSE-Bedarf abgeleitet werden. Die Schlussfolgerungen beruhen somit auf realen Daten aus der Praxis.

Es wird eine statistische Modellierung des verfügbaren und genutzten Spektrums mit PMSE durchgeführt. Dies ermöglicht wahrscheinkeitsbasierte Schlussfolgerungen, wann es in Zukunft nicht mehr möglich sein wird, PMSE in dem ursprünglich geplanten Umfang zu nutzen. Eine Verknappung der PMSE-Frequenzen im UHF-Bereich ist absehbar. Wann diese Knappheit immanent wird, wird wissenschaftlich fundiert auf Basis stochastischer Betrachtungen abgeleitet.

Wie bei früheren Studien wird die Rolle des technologischen Fortschritts bei PMSE, Mobilfunk und Rundfunk im Hinblick auf die Effizienz der Frequenznutzung diskutiert.

Neben den technologischen Trends gibt es auch gesellschaftliche Trends, wie z.B. ein erhöhtes Bewusstsein für Inklusion, barrierefreien Zugang zu Veranstaltungen und Fernteilnahme, die weitere Triebkräfte für eine größere PMSE-Nutzung sind.

Abschließend werden in dieser Studie Schlussfolgerungen und Empfehlungen für die Politik, die Regulierung, die Normung, die Mobilfunkbetreiber und schließlich die Anbieter von PMSE- und Mobilfunkgeräten abgeleitet.

Abstract

This study analyses trends in UHF spectrum use and demands by users of UHF spectrum. Thanks to availability of a large database that contains spectrum scans of a multitude of events over a large timespan, trends in availability of PMSE spectrum and PMSE use can be derived. Thereby conclusions are based on real world data from the field.

A statistical modelling of available and used spectrum with PMSE is conducted. This allows for probabilistic conclusions when in future it will no longer be possible to use PMSE to an extent as initially planned. A shortage of PMSE frequencies at UHF is up on the horizon. When this scarcity becomes immanent is scientifically derived on the basis of stochastic considerations.

As with earlier studies the role of technological advancements with PMSE, cellular and broadcast are discussed with respect to efficiency of spectrum use.

Aside of technological trends there are also trends in society, like an increased awareness about inclusion, barrier-free access to events and remote participation, which are further drivers to larger PMSE use.

Finally, this study will derive conclusions and derive recommendation towards Politicians, Regulation, Standardization, Mobile Network Operators and lastly PMSE and cellular equipment suppliers.

About FAU Friedrich-Alexander-Universität Erlangen-Nürnberg

75 years of university history form the foundation for our success today

Established on 4th November 1743 by Margrave Friedrich von Brandenburg-Bayreuth and expanded from 1769 by Margrave Alexander von Brandenburg-Ansbach and Brandenburg-Bayreuth, Friedrich-Alexander-Universität was transferred to the state of Bavaria in 1810. It has been housed in the former margraviate residence in Erlangen since 1818.

In the summer semester of 1890, the number of students enrolled at the University reached 1,000 for the first time. The Nürnberger Hochschule für Wirtschafts- und Sozialwissenschaften, a college of business, economics and social sciences, was integrated into FAU in 1961, as was the Pädagogische Hochschule Nürnberg, a teacher training college, in 1972. Today, approximately 40,000 students study at FAU campuses in Erlangen, Nuremberg and Fürth.

At an international level, FAU stands out as an innovative university founded on diversity with an outward-looking, international perspective.

The most important key figures at a glance

- 38,299 students, 19,424 of which are female and 6,158 are from abroad
- 267 degree programs of which are Bachelor's, are Master's and are Staatsexamen (state examination) degree programs
- 6,241 graduates
- 837 doctoral degrees
- 50 habilitations (postdoctoral teaching qualification)
- 623 professors
- 243.19 million euros third-party funding
- Ranked number 1 in Germany and number 14 worldwide in the Reuters Innovation Ranking
- The Highly Cited Researchers List 2019 lists the world's most influential researchers from 21 scientific disciplines. FAU is ranked among the top 200 universities in the world [1, 4].

FAU in Telecommunications and microwave

FAU is very strong in the fields of Telecommunications, Electronics and Microwaves. Its researchers work in the fields of digital communication, information theory, wireless communications, coding, MIMO / Massive-MIMO, Transceiver electronics, Chip integration.

FAU actively contributes to standards through its Membership in ETSI and 3GPP.

Furthermore, FAU also actively contributes to regulation via ECC CEPT, esp. SE21, SE7

FAU actively contributes to advancements in tools for Compatibility studies through researches on efficient algorithms e.g. for treating nonlinear effects in transceivers, see e.g. efficient frequency domain algorithm for calculating outage due to RX intermodulation brought into STG (SEAMCAT Technical Group CEPT STG)

FAU with its institute for Electronics Engineering is the birthplace of the MP3 compression, which later was commercialized by Fraunhofer IIS.

About the authors

Prof. Dr.-Ing. Georg Fischer

Georg Fischer was born in Lower Rhine region, Germany, in 1965. He received the Diploma degree in electrical engineering with focus on communications, microwave, antennas and electrodynamics from RWTH Aachen University, Aachen, Germany, in 1992, and the Dr.-Ing. degree *summa cum laude* in electrical engineering from the University of Paderborn, Paderborn, Germany, in 1997. From 1993 to 1996, he was a Research Assistant with the University of Paderborn, where he was involved in research on adaptive antenna array systems for mobile satellite communications and On Board Units for toll payment. He also headed the microwave and antenna lab there. From 1996 to 2008, he performed research with Bell Laboratories, Lucent (later Alcatel-Lucent, now NOKIA), where he focused on the RF and digital architecture of mobile communication base stations for global system for mobile communications (GSM), universal mobile telecommunications system, and features for network coverage and capacity enhancements.

In 2000, he became a Bell Labs Distinguished Member of Technical Staff, and in 2001, he became a Bell Labs Consulting Member of Technical Staff. In 2007, he was nominated for Bell Labs Fellow promotion.

He also acted as the Chairman of SMG2 WPB EDGE group of the European Telecommunications Standards Institute (ETSI) during the physical-layer standardization of the 2.5G GSM-EDGE system. From 2001 to 2007, he was a part-time Lecturer with the FAU University of Erlangen–Nuremberg, Germany. During that time, he lectured on base station technology.

Since 2008, he has been a full Professor for Electronics Engineering with the Friedrich-Alexander-Universität Erlangen–Nuremberg (FAU). He is named inventor with over 50 patents concerning microwave and communications technology. His research interests cover transceiver design, analog/digital partitioning of electronic systems, Software Defined Radios (SDR), Cognitive Radio Technology (CR), Dynamic Spectrum Access, A/D and D/A converters, enhanced amplifier architectures, duplex filters, metamaterial structures, GaN transistor technology, circuit design and RF microelectromechanical systems with a specific emphasis on frequency agile, tunable, and reconfigurable RF

systems for frequency agile radio applications. He is also a Senior Member of the IEEE Microwave Theory and Techniques, Antennas and Propagation and Vehicular Technology Society. Further, he is also a member of VDE-ITG and the European Microwave Association (EUMA).

Georg Fischer also served as chairman of ETSI Specialist Task Force STF386 focusing on Cognitive PMSE. He also actively contributed to the C-PMSE project funded by German Ministry of Economics and Trading (BMWI) that led into a Demonstrator on Cognitive PMSE Technologies at Messe Berlin. He also took part in further PMSE related projects like PMSE-xG funded by German Ministry on Traffic and Digital Infrastructure (BMVI) and LIPS (live Interactive PMSE services) funded by German Ministry of Trading and Energy (BMWI).

The author Georg Fischer also served as co-author of the STRATIX Study “Digitisation of wireless microphones - The effects on spectrum use” [5], which was initiated by the Dutch regulator. This study especially looked at the implications of transitioning from analog narrowband to digital narrowband transmission schemes for PMSE.

Georg Fischer is an active contributor to ECC CEPT. He contributes to SE21, SE7, FM51. Currently his interest there is on receiver and transmitter nonlinear intermodulation effects and their impact on efficient spectrum use.

Further details on author can be found here [2].

M.Sc. Thomas Ackermann

Thomas Ackermann studied Master in Mathematics at FAU University with special focus on theoretical stochastics. He obtained Master of Science degree in Mathematics in April 2015.

From 2016 to 2022 he was a research assistant at Institute for Electronics Engineering. He lead the group on Radio Communication Systems and Power Amplifiers. This group deals with cellular IoT, embedded wireless systems and SDR/CR solutions for Ue, Node-B and network modelling.

His research fields include linearization of microwave power amplifiers, broadband active load modulation, non-linear system identification and mathematical modelling.

Further details on author can be found here [3].

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List of Abbreviations

3GPP	Third Generation Partnership Project
AGC	Automatic Gain Control
AMC	Adaptive Modulation and Coding
APWPT	Association of Professional Wireless Production Technologies
BER	Bit Error Rate
BLER	Block Error Rate
CA	Carrier Aggregation
CAGR	Cumulative Annular Growth Rate
CBR	Constant Bit Rate Codec
CCI	Cultural and Creative Industry
CDMA	Code Division Multiple Access
CEPT	European Conference of Postal and Telecommunications
CR	Cognitive Radio
CSI	Channel State Information
CTO	Chief Technology Officer
DAB	Digital Audio Broadcast
DVB-T	Digital Video Broadcast Terrestrial
DTT	Digital Terrestrial TV
ECC	Electronic Communications Committee
ETSI	European Telecommunications Standards Institute
EUMA	European Microwave Association
FAU	Friedrich-Alexander-Universität Erlangen-Nürnberg
FD	Fully Digital architecture for MIMO
feMBMS	Further evolved MBMS
FER	Frame Error Rate
FH	Frequency Hopping
FR ₁	Frequency Range 1, 410...7125 MHz

List of Abbreviations

FR ₂	Frequency Range 2, 24.250...52.600 MHz
GSM	Global System for mobile Communication
HADB	Hybrid Analog Digital Beamforming architecture for MIMO
HARQ	Hybrid Automatic Repeat Request schemes
IEM	In Ear Monitor
IPR	Intellectual Property Rights
IPTV	IP based TV
LLC	Low Latency Communication
LTE	Long Term Evolution 4G
LTE	Lehrstuhl Technische Elektronik, Institute for Electronics Engineering
MBMS	Multimedia Broadcast Multicast Service
MEC	Mobile Edge Cloud
MIMO	Multiple Input Multiple Output
MNO	Mobile Network Operator
OFDM	Orthogonal Frequency Division Multiplexing
PMSE	Program Making and Special Events
PWMS	Professional Wireless Microphone Systems
QoS	Quality of Service (measurable, e.g. BER, BLER, FER, latency)
QoE	Quality of Experience (perceptual)
RAN	Radio Access Network
RF	Radio Frequency
RRM	Radio Resource Management
SDL	Supplementary Downlink
SDMA	Space Division Multiple Access
SDR	Software Defined Radio
SINR	Signal to Noise plus Interference Ratio

SNR	Signal to Noise Ratio
STF	Specialist Task Force
UHF	Ultra High Frequency (470...960 MHz)
URLLC	Ultra Reliable Low Latency Communication
VBR	Variable Bit Rate Codec
VHF	Very High Frequency (30...300 MHz)
VRAN	Virtual RAN
WMAS	Wireless Multichannel Audio Systems
WOA	Wacken Open Air

List of Symbols

C	Capacity in bit/s
BW	Bandwidth in Hz
k	Boltzmann constant, $1.38 \cdot 10^{-23}$ J/K
ld	logarithm dualis
ln	logarithm naturalis
N_{TX}	Number of transmit antennas with MIMO
N_{RX}	Number of receive antennas with MIMO
S/N	Signal to Noise ratio
SNR_{dB}	Signal to Noise ratio in dB
T	Absolute Temperature in Kelvin
W	Work, energy

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1 Introduction to PMSE

The term PMSE (Program Making and Special Events) is used to reflect various kind of wireless multimedia transmission equipment for audio, video and effect control. PMSE equipment is used as a wireless production tool, whether for artistic performance, news gathering, conference centres, music halls, film production, tour guides, festivals, churches, conference centres, lecture halls and more. PMSE serve as an essential tool for omitting cables and allowing for flexible movement of subjects.

PMSE e.g. reflects wireless microphones, wireless instrument transmitters, wireless in ear monitors, wireless cameras, intercom or wireless effect control boxes.

Further information on the definition of PMSE can be found in the system reference document [9].

2 Special requirements of PMSE

2.1 Low latency

PMSE demands for low latency transmission. This e.g. is the case if sound of an artist is picked via microphone and fed back to the artist via IEM (In Ear Monitor). Drummers regard more than 5 ms of roundtrip latency as distracting. PMSE is quite unique in the sense that in contrast to other wireless communication systems the information source and information sink are collocated as with above drummer example.

Doing Music together demands low latency on the order of less than 5 ms roundtrip. This is the big challenge artists are facing if they want to play music or sing together over the internet in these Corona times. Over the internet, one-way delays of 20 ms equal 40 ms round trip are pretty typical. Given that 1 ms roughly reflects acoustic propagation along 33 cm, 40 ms reflects an acoustic distance of about 17 m, which makes it difficult to stay in beat and pitch.

From this perspective, PMSE shows up with similar requirements as automation industry and autonomous driving. They all demand for ultra low latency communication (LLC).

Classically, digital transmission has mainly profited from interleaving as a means for spreading information along time axis, thus exploring temporal diversity. In light of low latency demands, this performance benefit of digital transmission is not present with low latency communication. Even on the opposite, low latency requirements call for higher operational SNR and lower interference, which also calls for additional spectrum need in order to reduce interference in the systems.

The latency of a digital communication link equals at least twice the interleaving length. As temporal diversity cannot be explored as a means for making digital transmission more robust than analogue, other diversity schemes like frequency diversity through wideband air interfaces and antenna/space/polarisation diversity schemes like MIMO need to be explored.

It was also a key finding with the STRATIX study [5] that the benefits by transitioning from analogue to digital narrowband PMSE are somehow limited and that no dramatic savings in spectrum need by PMSE can be obtained. This was somehow perceived as a disillusion as it was expected

that digitization would lead into less spectrum need. It became evident that one must clearly distinguish between narrowband and wideband digitization, as only the wideband systems have the opportunity to explore frequency and interference diversity for robustness increase. The requirement for low latency immediately implies that temporal diversity cannot be explored.

During the course of the BMWI project LIPS [6] technologies for conducting music together on distance and synchronisation schemes were researched. A concert between Hannover and Munich was practically demonstrated. However the concert on distance was only feasible by renting a dedicated glass fibre line (dark fibre) between the two locations. Otherwise, latency would have been too high.

5G wireless claims to deliver the low latencies by special tailored physical layer channels as demanded by PMSE, automation industry and automotive. However, practical studies still identified large latency contributors from radio resource management and core network. Only special adaptations of 5G equipment together with edge computing (MEC Mobile Edge Cloud) have shown to practically meet the low latency requirements by PMSE [32, 33]. This was also demonstrated by NOKIA and Sennheiser during Mobile World Congress in Barcelona. Mainstream, the low latency is not available in cellular.

In the publically funded project PMSE-xG [7] funded by German Ministry for Traffic and Digital Infrastructure, the capabilities of 4G, 5G cellular technologies were studied with respect to latency for audio, video and effect control PMSE. It was concluded that as video PMSE latency requirements are less demanding, these video PMSE services are more feasible in cellular technology. However, serving Audio PMSE demands still is not possible in cellular, even not immediately with 5G cellular of 3GPP. However, there are other 5G standards like DECT 2020/DECT evolution that can meet these latency demands. They also have strong backing from the automation industry and other verticals. More details can be found here [34].

2.2 Reliability

PMSE has high demands on reliability. Dropouts cannot be tolerated in professional use. With large scale events there would be monetary damage claims for a dropped radio link. An artist would leave stage. In

news gathering a story must be recorded immediately as historic events cannot be repeated.

Surprisingly, digital links may suffer from longer dropouts than analogue ones, as digital links have to resynchronize, which is not the case on analogue ones. Analogue links can recover from dropouts quicker.

Managing the risk of dropouts leads to a precautionary approach, where fading margins of 15...20 dB are placed into radio link budgets. This is also the reason why more transmit power is used than is needed on average. This also limits the opportunity for managing interference by transmit power reduction. A retransmission of lost data packets is not possible due to stringent latency requirements. Managing interference is one key element in cellular networks to raise capacity, see e.g. uplink and downlink power control schemes. In non-latency critical applications retransmission of lost packets is feasible, thus interference management by power control is feasible. But this is no option for PMSE.

2.3 High quality demands

In communications, spectrum savings mostly have been obtained from source coding, also named compression. However, large-scale compression comes along with quality reduction. PMSE links are at the beginning of many distribution options. They have to match the highest quality level demanded, e.g. a Studio or CD quality. They cannot be designed for low quality internet downloads. Quality can only be scaled down, never up.

In digital PMSE compression factors of 2:1 max 4:1 (for dense spectra) are in place, assuming a QoE (Quality of Experience) goal around CD quality. However, compression is not new with digital. In analogue PMSE there are compander (compression and expansion) systems which also offer equivalently around 2:1 compression. As now analogue and digital PMSE use about the same compression factors, it is no surprise that there was no massive spectrum saving by the transition from narrowband analogue PMSE to narrowband digital PMSE when having to meet the same quality objectives QoE. This was discussed in detail within the STRATIX study [5].

As with Internet download lower quality is accepted, larger compression factors can be realized. One can take a simple example. A classical CD has about 500 Mbyte. Consider 10 tracks, then each track is about 50

MByte. Now in the internet, files of size 5...2.5 Mbyte are downloaded, which reflects compression factors of 10:1 up to 20:1.

2.4 Battery operated Equipment

PMSE typically reflects portable and body worn equipment. Just consider handheld wireless microphones, bodypack instrument and microphone transmitters or bodypack receivers for IEM (In Ear Monitors). Especially with artistic performance, PMSE equipment has to be hidden within the costumes of artists. This means there are severe form factor and weight constraints that have to be met.

As battery size is restricted, complexity and allowable current drawn by transmitters and receivers is also limited. This may be managed by dedicated integrated chip solutions. However, this is only cost attractive in large quantities and stable regulatory frameworks. Given today's fast changes in spectrum regulations and esp. spectrum assignments and coexistence scenarios for PMSE the development costs for dedicated transceiver and receiver chips of advanced transmission schemes are difficult to justify.

Depending on each coexistence case, also different modifications to transmission schemes are needed. In PMSE also advanced receivers conducting interference cancellation schemes (Interference Cancellation Receivers) were studied, however the properties of interfering systems must be known in advance to match the cancellation or concealment scheme, but this is neither stable from regulatory perspective, to justify huge investments for PMSE development.

Also, it has to be considered that PMSE equipment typically has a rather long period of use. A theatre for instance wants to use PMSE equipment for 10...30 years, which is far longer than the usage period of a smartphone of about 2...3 years.

2.5 Antennas with Body Worn Equipment

As PMSE equipment is mostly carried body worn, the electromagnetic properties of the human body have to be considered as the antenna of the body worn equipment interacts with the human body.

As human tissue has dielectric properties, thus the transition from air to tissue constitutes a discontinuity in permittivity. The relative permittivity of air is 1, whereas the relative permittivity of the human

tissue up to the GHz range is about 80. Thus, a massive discontinuity in permittivity from 1 to 80 is in place when electromagnetic waves transition from air to body.

Such a discontinuity in permittivity approximates a PMC (perfect magnetic conductor) with reflection factor equal +1, equal 0° phase. This implies that the body acts like a mirror, similar to the metal reflector of a satellite dish antenna, whereby a satellite dish's reflector approximates a PEC (Perfect Electric Conductor) with reflection factor equal -1, equal 180° phase. The effect is similar but with different reflection phase. The body as well as the dish both act as reflectors leading to directed radiation.

This directivity is prominent when the aperture size of antenna is larger than the wavelength, which is the case for satellite dish antennas, where e.g. 12 GHz for home TV reflects about 3 cm wavelength in relation to dish sizes of e.g. 60 cm.

In PMSE the situation is the opposite. Especially in the frequency range 470...694 MHz, the wavelength is about 63...43 cm, thus larger than the body diameter. Strong directivity isn't in place. At higher frequencies, strong directivity by PMSE shows up. The effect was studied intensively in VDE DKE [8] based on an exhaustive measurement campaign by Swiss regulator BAKOM.

When going higher in frequency the wavelength will get smaller than body diameter leading to directivity of antenna. This implies severe problems on stage and at set. If an artist moves, its overall antenna directivity constituted by the PMSE equipment's antenna interacting together with the body may point to wrong direction leading to strong fading and thus dropouts of radio link.

From this perspective access to the very low frequency range of 470...694 MHz is of essential necessity for body worn PMSE equipment.

In conclusion, this means a loss of access to the range 470...694 MHz cannot simply be compensated by assigning the same frequency span at a higher frequency band.

One may argue that there are further frequencies even lower than 470 MHz, like VHF (very High Frequency), which are also assigned to PMSE. Yes, there are assignments in VHF range, but these frequency ranges typically suffers from a lot of EMC noise as experience tells. Sources of EMC noise are computers, large screens, light walls. Digital

bus of PCs often operate at 166 MHz and data is of random nature, which leads into wideband interference noise floors, that turn frequencies lower than 470 MHz problematic.

2.6 Transmitter intermodulation

It is not very seldom, that one artist carries multiple PMSE transmitters or artists carrying each a PMSE transmitter stand close on stage. This means the distance between multiple PMSE transmitters can be rather small, which amplifies the risk of transmitter intermodulation. This happens if the transmit signal of one PMSE transmitter enters backwards into the transmitter of a neighboured PMSE transmitter. The consequence is that intermodulation products are generated that lead into additional spectrum occupancy. Due to the high operational SNR needed to provide the demanded QoS resp. QoE and the fairly low transmit power by PMSE transmitters, PMSE links are very vulnerable to interference. This implies that in careful frequency plans for multiple PMSE links, not only intermodulation products of 3rd order are considered, but also of 5th and even 7th order. The consideration of potential intermodulation products is taken care of during generation of frequency coordination tables.

The additional spectrum need to manage transmitter intermodulation is depicted in the System ref document [9] (cf. Figure A.2: Required spectrum vs. numbers of channel in Intermodulation free operation).

This close spacing of multiple transmitters with its associated risk of transmitter intermodulation and implication of additional spectrum need is also a speciality of PMSE.

As studied in the STRATIX Study [5], circulators would reduce the risk of transmitter intermodulation, but they come at a cost, complexity and battery hit. Circulators come with RF losses, which means an RF power amplifier of higher output power is needed drawing more current and running the battery empty earlier or equivalently demanding a battery of larger form factor.

Furthermore, circulators are also narrowband, which means if a wireless microphone has large tuning range a bank of circulators to be switched is needed. This problem of needing a bank of circulators is pronounced the more fragmented the PMSE spectrum assignments get.

Other systems like cellular and DTT also allow for limited emissions on first and second neighbour channel due to nonlinearities present in their power amplifiers. The limits are given as adjacent channel protection ratio ($ACPR_1$, $ACPR_2$).

In conclusion, it can be said, that regardless which wireless system is being looked at, there is additional spectrum need induced by non-linear effects.

2.7 Flexibility, harmonisation and frequency agility

If artists go on tour, they typically have a contract with an equipment provider and it is highly desirable that identical equipment can be used at different places. Harmonisation therefore is highly welcome. Furthermore, in order to address scenarios, where one cannot profit from harmonisation, it is desired that PMSE equipment is frequency agile. A very fragmented spectrum assignment to PMSE with small pieces of spectrum here and there is problematic. It requires very flexible tuning ranges. However, what is even more challenging is that as one wants to relax on transmitter intermodulation problem through RF circulators/isolators, they tend to be very narrowband (10% relative Bandwidth for low loss), which means that spectrum fragmentation implies a bank of circulators/isolators, which constitutes a high cost burden and extra form factor.

Therefore, large chunks of spectrum are much more attractive than many small pieces of spectrum here and there.

3 General growth laws, trends and bounds

This chapter is intended to discuss general trends in microelectronics and communications that have led to the current spectrum situation in UHF for PMSE, broadcast and cellular.

3.1 Moore's law in microelectronics

In 1965 Gordan Moore, who was with Texas Instruments semiconductor supplier, made the statement "*complexity of an integrated circuit is doubling every 2 years*" [10]. What he meant was that the number of transistors in a given chip area doubles every 2 years. As the price of a chip is mainly determined by its chip area, this means that thanks to doubling the density of transistors, a desired functionality can be realized in half of the chip area, thus at half of the cost. In consequence, this has led to the dramatic price erosion that is seen with electronics dominated products like smartphones and TV sets.

However, this price erosion of -50% in two years or -30% per year does not apply to analogue electronics or high quality transducers like microphone capsules, loudspeakers and headphones. Nevertheless, it has led to the fact that our smartphones are more and more powerful computers and multimedia terminals.

Although the end of Moore's law is discussed heavily in literature, current data proves, it is still in place, see e.g. [11].

Gordan Moore identified a 2D trend. With "density" he meant chips per area (2D). The next law is to come which states transistors per volume (3D). Such a 3D integration can already be observed with chiplet integration in heterogeneous SiP (System in Package) integration. Thus one can assume that the price erosion with microelectronics will persist.

3.2 Edholm's law of bandwidth

In 2004, a famous article showed up in IEEE spectrum [12], which was written based on analyses by Phil Edholm, CTO of Nortel networks. He constituted that "*Telecommunication data rates are as predictable than Moore's law*". The momentum in electronics similarly shows up in the physical layer interfaces, whether wired, wireless nomadic (wifi), or wireless mobile (cellular). The data rates possible to run over each type

of link double every two years. This was also proven by APWPT in 2011, see below Figure 3.1.

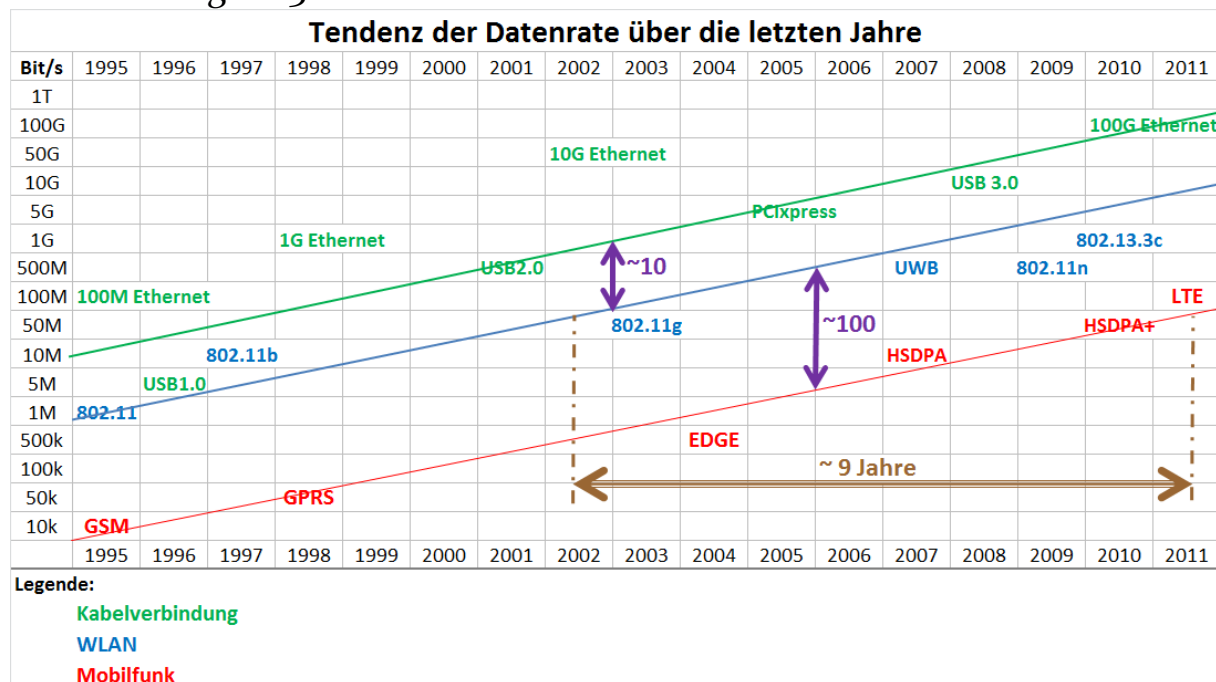


Figure 3.1: Evolution of data rates over wired, nomadic wireless and mobile wireless inter-face

This proves that the advancements in microelectronics are the key driver for innovations in data rates and communication services.

Moore’s law and Edholm’s law are both exponential growth laws having the same momentum of doubling in two years.

However, it has to be clearly stated, that higher data rates defined on a wireless interface due to fundamental Shannon law naturally go along with larger spectrum demand. But spectrum is a naturally limited resource, which cannot be magnified, especially if the propagation wise attractive spectrum below 7 GHz (FR₁) is being looked at. This spectrum is fixed size.

3.3 Cisco law

In 2011 Cisco presented a study about evolution of data traffic [13]. In 2016, they provided an update to their study [14]. They come to the conclusion that in the western world there is a wireless traffic growth around 54% (CAGR). This value is higher than Moore’s law or Edholm’s law, which reflects a CAGR of +41% (square root of two). In certain markets also a growth of doubling year over year was observed.

CISCO analysed that data traffic more and more gets dominated by video, e.g. video downloads, but also video chats and video conferences.

One may now ask why the momentum on data traffic is higher than the momentum on Moore's law and on Edholm's law? The reason is clear. In video, Moore's law applies both horizontally and vertically on a display, which drives the number of pixels with file formats and displays to double more or less year over year. If traffic would solely be dominated by video, than data amount would double year over year.

It has to be clearly stated that CISCO not only looked at mobile wireless, but also included nomadic wireless like WiFi.

3.4 Fundamental properties of spectrum

As stated above, spectrum pieces at low frequency like the low UHF spectrum of 470...694 MHz cannot simply be substituted by spectrum pieces at higher frequencies due to different propagation properties and antenna of body worn equipment interacting with body. Only in Low UHF wavelength is larger than human body diameter.

The properties of spectrum at low and high frequencies can be compared as depicted in Table 3.1.

Table 3.1: Comparison between low and high frequencies

Low Frequency (UHF)	High Frequency (e.g. mm wave)
☺ Low Doppler	☹ Very High Doppler
☺ High Mobility	☹ Only static or nomadic use
☺ Excellent propagation	☹ High attenuation with propagation
☺ Good penetration into Building	☹ Worse penetration into building
☺ Gets around the corners, good coverage	☹ mainly LOS (line of sight)
☹ Limited spectrum	☺ Large spectrum available
☹ Limited instantaneous bandwidth	☺ High instantaneous bandwidth
☹ moderate data rates through MIMO	☺ Highest data rates by very large instantaneous bandwidth
☹ High capacity through network densification	☹ High capacity through Massive MIMO
⇒ Most valuable for network coverage and high mobility use	⇒ Most valuable for network capacity, static and nomadic use

As spectrum is a scarce resource, spectrum assignments should be done on the basis whether there is a coverage or capacity challenge to be met. PMSE users are facing both, coverage and capacity challenges.

Using low frequencies just to address capacity shortages in cellular is not reasonable. These frequencies are most valuable in terms of their propagation properties. On the opposite, using very high frequencies to achieve largest distances and address coverage problems neither works.

As said, spectrum is a naturally limited resource. It cannot be magnified. The UHF spectrum below 1 GHz offers very attractive radio propagation characteristics but at the same time it is of finite size.

3.5 Shannon bound

The Shannon bound is a fundamental bound on how much capacity in bit/s can be gained from a given Spectrum in MHz. The classical Shannon bound is given as:

$$C = BW \cdot \log_2(1 + S/N) ,$$

whereby C means capacity in bit/s, BW Bandwidth/spectrum amount in Hz and S/N Signal to Noise Ratio being the delog of SNR_{dB} .

Often C as a data rate metric is also called bandwidth, which is technically wrong. The capacity of a wireless or wired link in bit/s should not be called bandwidth. Therefore statements like “*we need a broadband strategy*” are wrong. Instead one should say “*we need a capacity strategy*”.

In the context of MIMO antenna array systems, above formula needs to be expanded:

$$C = \text{Min}\{N_{\text{TX}}; N_{\text{RX}}\} \cdot BW \cdot \log_2(1 + S/N) ,$$

whereby N_{TX} reflects the number of antenna elements on the TX side and N_{RX} reflects the number of antenna elements on the RX side. In consequence, this means that there is a further degree of freedom by choosing more antennas to increase capacity. More bandwidth, say more spectrum isn't the only way to enhance capacity, this can also be achieved through MIMO, multi- and intelligent antenna techniques. Thus if one runs out of capacity there is an alternative way to more spectrum by MIMO techniques.

The transition from 3G to 4G cellular according to Ericsson papers provided a spectral efficiency gain of about 2.4. This creates the expectation that with further generations spectral efficiency can be increased further thanks to advancements in physical layer transmission schemes. Taking a careful look, one recognizes that the factor 2.4 is mainly the consequence of demanding at least 2x2 MIMO as a minimum set with 4G. This means the net gain by the transition from 3G to 4G is $2.4/2=1.2$. The gain from 2x2 MIMO (factor 2) is therefore much higher than the gain from advancements at the physical layer, say transition from CDMA in 3G to OFDM in 4G, which was only factor 1.2. In 3G already Turbo Codes were introduced which are 0.2 dB close to the Shannon bound. However, Turbo Codes only can get close to Shannon bound with long interleaving, say large block sizes, which is contrary to low latency communication.

As we have already reached the Shannon bound at least for non-latency critical communication, we cannot expect dramatic improvements in future from new transmission schemes. That is also the reason why 5G is still based on OFDM modulation and just introduced only some moderate modifications to the physical layer.

Since 3G we have arrived at the Shannon bound and improvements have been made mainly by MIMO multi antenna technology. In consequence, this means that in future MIMO techniques must evolve even further to higher order beyond 2x2 today, towards e.g. 8x8 MIMO as capacity scales with number of antenna elements. Migrating from 2x2 to 8x8 MIMO delivers a 4-fold capacity boost. MIMO technology is commodity. It already is in widespread use with WLAN. But by today MIMO is mainly operated in low order regime.

Today, PMSE is using receiver diversity, which constitutes a 1x2 MIMO system. There would somehow be potential that PMSE migrates to 2x2 schemes. Larger number of antennas at portable PMSE devices however is problematic due to form factor and battery constraints.

As stated above PMSE has stringent latency requirements. It must be said that above Shannon formula assumes infinite block length. Thus the Shannon bound ignores latency constraints. This implies that more bandwidth, say more spectrum or cleaner spectrum (higher SINR - Signal to Noise plus Interference ratio) is needed for the same capacity in the case of stringent latency requirements. This is often overlooked

that stringent latency requirements imply additional spectrum need beyond Shannon prediction.

NOKIA and Sennheiser showed a demo at MWC (Mobile World Congress, Barcelona) for PMSE over 5G, however it was found that the stringent latency requirements of PMSE cannot be met by standard 5G equipment. Special tailored equipment was needed. Persistent scheduling reserving radio resources is a way to avoid latency hit by dynamic radio resource management. If dynamic RRM (Radio Resource Management) is enables, additional latency hits from scheduler come into play.

3.6 Landauer bound

Aside the Shannon bound there is another fundamental bound given by the Landauer bound. It constitutes a relation between information and energy. Landauer formulated that alteration of one bit needs:

$$W = k \cdot T \cdot \ln(2) \approx 4 \cdot 10^{-18} \text{ mJ / bit}$$

The interpretation is that handling of information is tight to an energy need. Practical values of today are several orders larger, on the order of 0.1 mJ/bit than this bound, so there is large room for improvement.

3.7 Radio Scaling law

Regarding size of radio frontend modules there exists another law given in [15]: “in a decade, the number of bands and the number of modes have been tripled at one third of the space”.

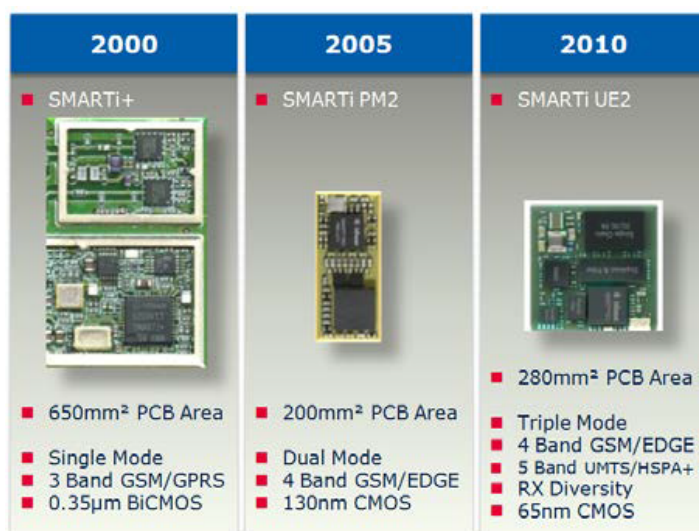


Figure 3.2: Radio Scaling Law, taken from [15]

This means there is shrinkage of analogue frontends, but the shrinkage momentum on analogue frontends is much less than Moore's law for digital circuits.

3.8 Conclusion on growth laws

The advancements in microelectronics are central for all other growth laws. Microelectronic advancements are the driver behind Edholm's law and Cisco law.

In two years, the data rate across a wireless or wireline interface doubles. However, this does not mean that spectrum demand shrinks. The evolution of data rates and monthly data volume follow an exponential growth. If considering just the simple Shannon bound this would imply also an exponential spectrum need. This is of course impossible to be served. Looking at the Shannon bound for MIMO, one can see that higher order MIMO schemes are a realistic option to catch up.

Betting on advancements in spectral efficiency without taking into account MIMO is a hopeless desire as we have arrived at the Shannon bound already since 3G. However, MIMO schemes also come along with additional signalling need, which carefully has to be balanced.

4 General Audio PMSE growth trends

4.1 Audio quality and Immersion

Generally, in audio business people are looking for increased immersion. This can be observed with advancements in surround sound with more and more channels. Starting at Mono, sound migrated to Stereo, Quadro, Surround 5.1, Surround 10.1 and Surround 19.1.

The demand for high audio quality is rising. There are now streaming services like TIDAL [16] that offer studio quality over the internet, that goes beyond classical CDs. In addition, the Berlin philharmonic orchestra is offering the “digital concert hall” [17] at studio quality.

A CD offers 16 bit at 44,1 kSa/s, whereas Studio quality reflects 24 bit at 192 kSa/s. The following Table 4.1 reflects the increase in data rate:

Table 4.1: Audio data rates

Scheme	Resolution in bit	Sample rate in kSa/s	Type Mono/ Stereo	Datarate in Mbit/s
PMSE Standard			Mono	0,17
PMSE high quality			Mono	0,35
CD Mono	16	44,1	Mono	0,7
CD quality	16	44,1	Stereo	1,4
Studio quality I	24	96	Stereo	4,6
Studio quality II	32	192	Stereo	12,2

There are trials going on regarding 5.1 Audio over DAB and via Satellite and cable. In cinema installations one can find advanced installations like Dolby ATMOS. There are even gaming consoles that include hardware accelerators to provide immersive sound. One can conclude that more immersion is a general trend in audio.

However providing more audio channels on distribution implies that also more audio channels are needed on production. As production more and more is using wireless techniques thanks to lower production cost, this implies that more audio PMSE links are also needed during production constituting a growing demand in Audio PMSE.

4.2 Inclusion of impaired persons

In the context of the BMWI funded Project LIPS (Live Interactive PMSE systems) within the funding scope “Smart Service Welten” [6], streaming architectures were developed that allow for better inclusion of impaired persons. A use case for instance was that hearing impaired persons sitting in the audience can receive the individual audio streams of all artists live on stage and mix sound by themselves so that they can give priority to an individual artist. Such a use case also faces tight latency requirements, as the sound mixed for the impaired should not be delayed compared to direct sound for the general audience. It was studied whether local cellular based technologies could offer the required latency. It was discovered that 5G is not yet fully there to offer the latency required. This is in line with the findings by the other project PMSE-xG [7].

4.3 Evolution from analogue to digital PMSE

During the course of the STRATIX study [5] the benefits by transition from analogue to digital PMSE were studied. It was the expectation that digitization of PMSE would bring dramatic savings in spectrum need by PMSE. There was large frustration that in practice no savings could be drawn. However, it was found that digital allowed for easier scaling of quality. The reasons are manifold. In the study narrowband analogue PMSE was compared with narrowband digital PMSE both in 200 kHz channels. Digital transmission in that study still stuck to narrowband transmission. Thus, the robustness obtained from frequency and interference diversity being present in wideband systems does not show up. Furthermore, digital transmission mostly obtains its spectrum savings from compression but analogue and digital transmission use about the same compression ratio of 2:1. In analogue transmission compander systems together with analogue preemphasis and deemphasis are used, whereas in digital systems digital source coding is used. It is thus no surprise that in the comparison study of analogue and digital narrowband PMSE these are parity.

The study also revealed that in narrowband digital transmission some companies offer a “robust mode” to manage scenarios with large number of active PMSE links. “Robust mode” reflects a compression of about 4:1, which allowed for tighter frequency reuse thus higher link density (number of PMSE links per MHz), but then one gets into the trade-of

between audio quality QoE (Quality of Experience) versus number of PMSE links.

The contracting party Agentshap Telecom, the Dutch regulator, also asked why analogue PMSE links are still in use. It was found out in the intensive interviews conducted that analogue PMSE links were widely used with In Ear Monitors (IEM), because they offer lower latency than digital links. Having lower latency and thus staying in rhythm and pitch was more important for the artists than a slightly better audio quality offered by digital systems.

Beyond these findings a further issue was identified. Analogue PMSE offers a soft degradation in case the radio link quality decreases. In contrast to this digital systems face a “digital cliff”. Audio Quality stays high even if the radio link quality starts to degrade. But at a certain radio quality, the audio link immediately breaks totally. A resynchronization has to be triggered that causes a longer dropout.

In summary it had to be concluded that digitization not per se offers spectrum savings, especially if one sticks to narrowband systems.

4.4 Evolution from Narrowband to Wideband PMSE

Standardisation and regulation have paved the way for wideband PMSE systems. These are called WMAS Systems (Wireless Multichannel Audio Systems) [18]. These may offer RF bandwidths of typical 6, 8 and even up to 20 MHz, thus matching TV channel and cellular spectrum grids. They are called wideband because the system’s radio bandwidth is wider than the coherence bandwidth of the radio channel, i.e. the radio propagation environment. The coherence bandwidth is on the order of a few MHz with most PMSE scenarios. Now, in order to obtain frequency diversity, the system’s radio bandwidth must be much larger than the coherence bandwidth. From this perspective WMAS Systems with 2 or 3 MHz would provide only limited benefits. Exploring frequency diversity is a means for drawing diversity and increasing robustness without drawing robustness from temporal diversity, which is implemented by interleaving and channel coding in classical digital systems, but which comes along with large latency.

It is obvious that digital narrowband system with RF bandwidth of 200 kHz can never draw benefits from frequency diversity and will be exposed to large scale fading, facing dips as deep as -20...30 dB.

WMAS allows for easier setup of large scale events as no classical PMSE frequency coordination considering Intermodulation products has to be conducted. WMAS does the transition from narrowband to wideband radio transmission thereby taking profit from frequency and interference diversity.

In the cellular domain the same processes have taken place. 2G Systems like GSM also were narrowband with 200 kHz channels. But since 3G W-CDMA (Wideband Code Division Multiple Access) and 4G OFDM (Orthogonal Frequency Division Multiplexing) these systems were wideband. 2G GSM virtually synthesized a large bandwidth by doing frequency hopping, which enabled this narrowband system to profit from frequency and interference diversity. PMSE through WMAS will draw similar benefits as the other wideband systems.

But the advent of WMAS also makes clear that the classical spectrum licensing for PMSE does no longer work. PMSE spectrum assignments so far are pretty fragmented, with small chunks of spectrum here and there, see e.g. duplex gaps. In order for PMSE to draw full benefits from the frequency and interference diversity as facilitated by WMAS, large spectrum chunks are needed e.g. 6...20 MHz. The technical reason behind is that frequency diversity must span a bandwidth that is much larger than the coherence bandwidth of the channel, which is about a few MHz in lower UHF range.

The coherence bandwidth heavily depends on surrounding scenario and scale of mobility. Practical channel measurements were presented to ETSI ERM TG17 [35, 36].

Another consequence of the advent of WMAS is that in order to draw high spectral efficiency WMAS must be the only active user in the spectrum.

Both aspects together indicate that the assignment of a large exclusive PMSE spectrum is the only way for PMSE to raise its spectral efficiency.

As said, WMAS systems take profit from frequency and interference diversity as an inherent feature. Again, as said above, in order to profit from frequency diversity the spectral width of a WMAS system must be larger than the coherence bandwidth of the channel. Now it is a nasty

thing, that the coherence bandwidth gets larger the slower the communication nodes move. In GSM frequency hopping it was demanded that for slow moving cars at least jumps of 1.5 MHz must be conducted in order to decorrelate channels before and after frequency jump. This was also the reason why in GSM the frequency assignments to different MNOs were interleaved. It was just for the sake to facilitate large enough frequency jumps. Otherwise frequency hopping would not provide the expected frequency diversity gains.

Now in low UHF (470...694 MHz) the frequency is half compared to GSM900, which means for slow moving cars twice the coherence BW has to be assumed which is on the order of 3 MHz. In order to provide sufficient frequency diversity gains for even slower moving terminals like pedestrians – e.g. an artist standing or dancing on stage - WMAS systems running bandwidth of 8, 10 or 20 MHz on the order of TV channel or LTE signals are to be supported by regulation.

PMSE is very widely used with pedestrians, consider wireless mic, instrument transmitter, IEM receiver and talkback. The PMSE infrastructure of course is location fixed.

In cellular 4G/5G OFDM systems, which use bandwidths of 10 or 20 MHz or multiples of 100 MHz the radio resource scheduler schedules transmission across the radio resource blocks, which means across the subcarriers. Thereby, the radio resource scheduler maximizes the benefits from frequency diversity. Thanks to permanent channel state information (CSI), the radio resource scheduler acts in an opportunistic way. It instantly knows which frequencies are currently in upfade or downfade. So it does opportunistic scheduling to maximize benefit from frequency diversity.

For PMSE to profit in a similar way from frequency diversity, PMSE needs access to wide spectrum chunks, not just small fragments of spectrum here and there.

4.5 Audio Codecs

In information theory, the theorem of separating source and channel coding holds. Today's advancements in digital communications are mostly been made by improvements at source coding (compression) as with channel coding we have already arrived at the Shannon bound. Already in 3G W-CDMA Turbo codes are used with channel coding which are 0.2 dB close to the Shannon bound. This means there is

nothing left to catch with channel coding and communications has arrived at a wall that cannot be pushed out. Advancements are made by channel codecs that are optimized for short block length, like LDPC codes. This work is aimed at getting closer to Shannon bound under low latency constraints.

In Digital Dividend I, one analogue TV channel was replaced by four digital ones. This was only possible by compression of video data. Watching a football match is much worse on DVB-T compared to previous analogue. So an increased number of video streams came at a quality hit, thus a degraded QoE. The quality hit in video is barely accepted by the public and indeed where possible a transition to DVB-T2 is conducted to raise video quality.

In DVB-T/T2 there is a multiplex of multiple video streams, which facilitates statistical multiplex. In source coding the produced data rate at the output of a coder is related to the detail richness of the source. A coder with high average compression therefore always is a variable bit rate one (VBR). This is similar whether video or audio sources.

In a statistical multiplex it happens very seldom that all coders in the same moment produce their peak data rate. The produced data rate follows a statistical distribution. This is yet another reason, why communication systems should bundle several streams. In DVB-T/S/C this is standard. WMAS will also give the PMSE community the chance to profit from statistical multiplex. It also provides flexibility to assign different quality levels to different users, which is not possible when each PMSE link has its own PHY of fixed configuration.

In today's digital PMSE links of a single audio stream in 200 kHz radio bandwidth, always constant bitrate (CBR) codecs are used. As PMSE is used for production, a high quality (high QoE) is demanded. Therefore, high compression ratios are not used. Today's compression ratios are low to moderate on the ballpark of 2:1 or 4:1. Typical 2:1 is used. 4:1 is only used in cases of challenging radio interference conditions, where the higher source compression enables drawing more robustness from channel coding. A trade-of between audio quality and radio link robustness is in place.

High quality audio streaming services on the internet like e.g. TIDAL also use Codecs of only 2:1 compression, e.g. FLAC codec. It wouldn't make sense to use higher compression on production than on distribution. Furthermore as compression schemes are used on

production and distribution, there is a serious risk of artefacts from concatenating compression techniques. That is yet another reason why on PMSE as a production means compression rates are fairly low.

As said that high average compression ratios are typically coming along with VBR codecs there is yet another risk. VBR codecs tend to modify phase of audio signals, which already in Stereo and furthermore in surround techniques lead to perceptual irritations that audio sources move although physically the source is static.

It is also obvious from information theory that higher compression is only feasible with longer observation, which means that higher compression would come at longer latency, which neither is acceptable when considering the strict latency constraints of PMSE.

At the beginning of the STRATIX study there was big expectation that the transition from analog to digital PMSE (both narrowband in 200 kHz channel) would bring significant gains. This did not hold as analogue PMSE already used some sort of compression technique. In analogue PMSE there is the Componder System and the Pre-/Deemphasis which accounts for about 2:1 compression in analog way. If this is compared with a digital compression of 2:1, there is nothing to catch from digitization. And indeed this was the frustration at the end of the STRATIX study.

The contracting body of STRATIX study also asked why still so much analogue IEM were in place. As the spectrum benefits of a transition from analog to digital were such marginal, higher priority was given to the latency issue. Analog IEM do not suffer from latency as digital systems and for an artist it is more important to stay in rhythm and pitch, rather than to have digital audio.

In this context, it must also be said that already analogue video used some sort of compression. In PAL video system the bandwidth of colour signal (chrominance signal) was chosen less at 1.5 MHz in contrast to the luminance/intensity signal having a bandwidth of 5 MHz. We thus have to conclude that some sort of source coding was already in place with analogue transmission schemes whether video or audio and source coding is not totally new with digital. This backs the statement that the benefits in digital transmission are mainly drawn from compression thus source coding and not from digital radio transmission itself.

There is even a burden by digital technology, which comes from the overhead induced by channel sounding and pilot symbols, drawing channel state information (CSI) and signalling. Thus digital transmission becomes beneficial only if high compression is used, where the benefits from high compression outweigh the drawbacks from additional overhead. In conclusion, it means that based on typical codecs with low compression no dramatic gains in efficiency of spectrum use can be expected from digitization.

4.6 Detail Richness of Audio source and VBR/CBR Codecs

With audio codecs detail richness of an information source is linked to produced data rate. That is why quietness would lead to low produced data rate and a snare drum of a drum set due to its complexity would produce high data rate. From that perspective, it is intuitive that a codec that has to preserve audio quality (high QoE) must be a VBR one in order to achieve on average a higher compression ratio.

For a radio transmission system this implies that the radio resource consumption would have to be dynamically managed to follow the variable bitrate which means further signalling is implied. This constitutes yet another overhead with digital transmission. It is also clear that a radio technology, which defines one radio link per audio link as was done so far with narrowband digital PMSE cannot take profit from VBR. Therefore narrowband digital PMSE typically uses CBR codecs of low compression.

Only WMA systems are capable of handling multiple audio links together and taking profit of multiple VBR codecs in a pool, facilitating gains by statistical multiplex.

From this perspective, it is evident that a long term spectrum strategy must allow for sufficiently wide spectrum chunks that allow for deployment of WMA systems.

VBR codecs also challenge the radio resource management and scheduler. As it cannot be predicted what the produced data rate by the VBR codec will be in the next moments, the scheduler cannot reserve radio resources upfront. It will be of reactive nature. But signalling changes in radio resource assignments act as a further source of latency, which barely can be tolerated. This means that a system that has to deal

with VBR and at the same time must ensure low latency, must be specifically optimized, which is feasible only with WMAS systems.

4.7 Artistic excellence

An artist is exercising a lot, consider e.g. an instrument player before he/she is going to act on stage or for recoding. Compression is based on exploring psychoacoustic effects, e.g. that weak tones closely spaced alongside strong ones are typically not heard by a human. This is for instance the fundamental idea underlying the mp3 codec. However, there are skilled and less skilled ears. With codec selection at the moment of production, it is typically not known who will be addressed later on distribution. Once quality is degraded on production, it cannot be recovered for distribution.

Figure 4.1 is showing the information theory model.

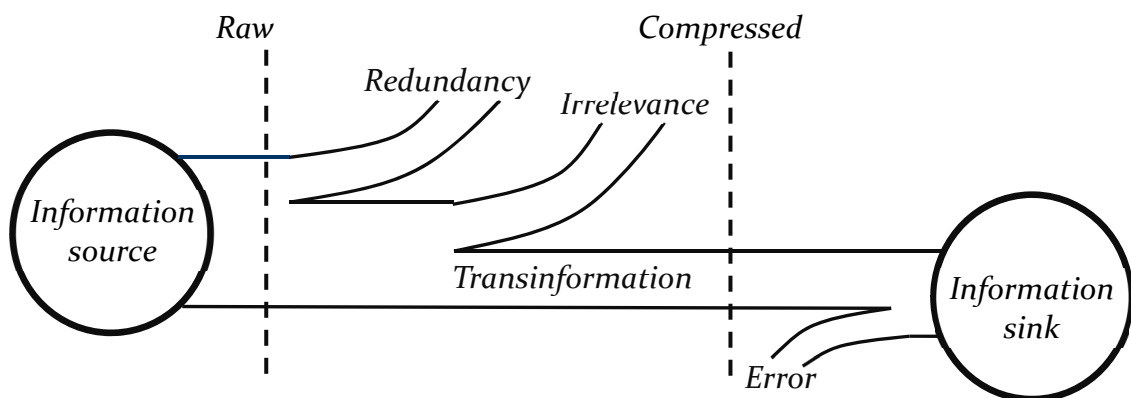


Figure 4.1: Information theory model for transmission

Compression is based on identifying and stripping of redundancy and irrelevance in raw data. Redundancy can be stripped of without loss of QoE, however irrelevance is debatable. What is irrelevant information is dependent on the receiver (listener) at information sink. How can the transmitter at information source decide what is irrelevant information without knowing the receiver at the moment of source coding (compressing)?

Some parties therefore prefer plain audio without any compression at all or limitation to small compression factors like 2:1 and at max 4:1.

If high compression is used, artistic excellence and performance is shaded. The result is low QoE (Quality of Experience).

4.8 Dynamic codec management

In a production, PMSE equipment like wireless microphones and IEMs are integrated into costumes. The PMSE equipment – as it is anyhow present – typically therefore is also used for talkback and there is no extra wireless equipment simply for talkback. Talkback is used before and after being on stage. For talkback, much less quality is needed than for performance.

This brings up the idea to swap codecs dynamically or alter parameters of codec during an event. This is not possible on classical narrowband digital PMSE equipment as with them there is one radio link with fixed parameters per audio link. However, with WMAS equipment this is typically feasible. With them, the radio resource consumption is a function of QoS and QoE currently configured and needed.

4.9 Artistic trends

Talking to event organizers and theatre stage directors they tell that they would like to do more with wireless production tools. However, spectrum limits force them to adapt their performances to the number of wireless links possible. This means that already by today cultural richness, performance and creativity in CCI (Cultural and Creative Industry) is hindered by spectrum shortage for PMSE. Artistic creativity cannot be brought across to audience due to shortage of spectrum for PMSE.

In consequence, this means that spectrum scans of PMSE usage do not reveal the true need by PMSE community. The need is higher than what the scans show. This is important to note when analysing spectrum scans.

4.10 Need for large contiguous spectrum chunks

2G GSM started with 200 kHz RF channel bandwidth, which is similar to narrowband PMSE. Then frequency hopping was introduced in GSM, artificially turning the narrowband GSM system into a virtual wideband system. A GSM speech frame is spread across 8 radio bursts. Each radio burst then can take a different carrier frequency, which makes a radio frame being transmitted across 8 frequencies. This implies large frequency and interference diversity within a GSM frame. Narrowband PMSE whether analog or digital, although suffering from the same

problem of being narrowband never could explore relief by frequency hopping and thus frequency and interference diversity. Only with the Advent of WMAS, PMSE is given the opportunity to profit from frequency and interference diversity. This avoids dropouts due to deep fades.

In contrast to cellular, PMSE reflects use cases with lower mobility. Artists on stage likely are not to move similar to pedestrians or cars with cellular. If mobility is less, the risk of dropouts due to deep fades gets pronounced raising the need for frequency diversity.

With frequency hopping in GSM, each frequency jump must be sufficiently large, larger than channel coherence bandwidth to explore frequency diversity. Assuming a minimum frequency jump of 1,5 MHz and 8 hopping frequencies, a frequency span of 7 times 1.5 MHz equal 10.5 MHz should be covered. Now, comparing other systems in UHF, one can see that DTT uses about 6 or 8 MHz and LTE uses 10 or 20 MHz.

PMSE must be given a similar opportunity of contiguous 10 MHz chunks to draw full benefit of frequency diversity similar to the other systems in UHF.

4.11 Conclusion on Audio PMSE growth

Let's summarize our findings on audio PMSE needs and trends and their relation to digital transmission and codecs.

Like the cellular industry addressing the ever raising need for larger and larger data volumes with the wireless internet, also PMSE has need for growth due to wish for higher QoE (Quality of Experience), immersion and artistic advances. In the past, spectrum savings were mainly drawn from ever evolving radio transmission. However, since the advent of turbo codes for channel coding in the 90ies, e.g. in 3G, which are close to Shannon bound, there is nothing to catch on improving radio transmission schemes and channel coding. What is explored since the Shannon bound was reached, are improvements on source codecs to facilitate higher average compression – at least on average. Higher source coding reduces data rate to be transmitted and thus implies less spectrum need.

Going this route with audio PMSE is not possible due to stringent quality and latency requirements in PMSE. Higher average compression rates are only possible at longer observation, which is contrary to strict

latency requirements in PMSE, which do not apply to other wireless systems in UHF, especially not the non-realtime ones. Also higher average compression ratios preserving quality lead into VBR (variable bit rate) codecs, which do not match current narrowband digital PMSE systems, which assume constant bitrate. VBR codecs and dynamic codec parametrisation and codec swap are only feasible with future broadband WMAS PMSE systems.

In consequence this means that spectrum regulation must allow for deployment of broadband WMAS PMSE systems profiting from sufficiently large spectrum chunks. Narrowband systems need the low UHF range to avoid strong antenna directivity and thus large fading with body worn equipment. In future, a mix of narrowband and broadband (WMAS) PMSE systems should be supported in UHF.

5 Economic and societal view on spectrum

There is a known saying “*spectrum fuels the cellular industry*”. However, this applies also to other businesses like DTT and PMSE. All would like to expand, offering larger amount of, enhanced and more immersive audio/video services. On the opposite, spectrum at UHF is a finite resource that cannot be magnified. The classical way has been to go digital and compress media content (source coding) as compression allows to operate more links in a given spectrum but at the burden of degraded QoE.

A simultaneous unbounded growth based on a simple scheme of ever more spectrum for every UHF system (DTT, Cellular, PMSE) is not possible. Moore’s Law, Edholm’s law and Cisco Law as discussed in Chapter 3 reveal a near exponential growth in data traffic. The simple classical way to grant more spectrum to serve more traffic does no longer work. Sustainable approaches are needed. These exist, like MIMO multi antenna technology, network densification and SDMA (Spatial Division Multiple Access). More spectrum is not the only answer to an increased traffic and indeed this is the core principle of the cellular approach to implement cells with frequency reuse patterns as derived by Bell Labs in 1947 [19].

A fair scheme between the needs for UHF spectrum by DTT, cellular and PMSE has to be identified. Each party has its specific needs and there are further options for capacity growth aside more spectrum. There are also options for coexistence, sharing and coordination by clever frequency management schemes that explore differences in locational and temporal spectrum need.

Sometimes economic arguments are played that cellular is the most important and needs to be served with priority as cellular constitutes the base for trading, business and therefore economic growth and wellbeing of society, overcoming the digital divide with rural areas.

The report by German Federal Ministry on Economic Affairs and Energy (BMWi) on the Cultural and Creative Industry (CCI) in Germany [20, Page 6, Fig. 2.2] revealed that the CCI has an economic strength about the same order than the financial sector at third rank directly after Machinery and Automotive sector. It engages around 1.8 million employees in Germany.

Also the relevance of digital terrestrial TV DTT was discussed given that younger people tend to less use linear TV and use dominantly streaming services. Data on TV usage behaviour was published e.g. in the plum study [21]. However, a broadcast network is a cost efficient system and can serve as fallback for communication in case cellular networks and wireless internet collapses e.g. with disasters and catastrophic scenarios. Recent events like the flood disaster in the Eifel region in Germany have shown that broadcast systems are needed and that cellular systems will collapse to a large extent. Then broadcast systems of High Power High Tower will be key. In these Corona times personnel operating TV stations stayed at the towers 24/7 to ensure availability of broadcast system. Broadcast based on “high power high tower” is seen as critical infrastructure that needs to be protected.

The cultural and creative industry is dependent on PMSE to work. CCI has a large societal relevance. It also serves for societal integration and cultural development aside of support for business events. This was also highlighted in the RIFEL study [22].

Given societal and economic relevance of each UHF uses, the complete palette of options for growths needs to be looked at. This palette of options for growths goes beyond the simple scheme of taking away spectrum from one UHF user and handing it to another one.

MIMO, massive MIMO, true SDMA (Spatial Division Multiple Access) and network densification can bring much larger capacity gains than other options like source coding (compression) or further evolutions in channel coding or new physical layer schemes. Furthermore, outphasing of less spectrally efficient cellular systems like 3G/UMTS/W-CDMA and 2G GSM and their substitution by more feature rich and spectrally efficient systems like 4G LTE and 5G can bring further capacity gains.

6 UHF spectrum situation

6.1 Digital Dividends

The following figure 7.1 shows the spectrum situation at UHF (470...960 MHz). With digital dividends I and II already 44% of UHF spectrum no longer can be accessed for PMSE use.

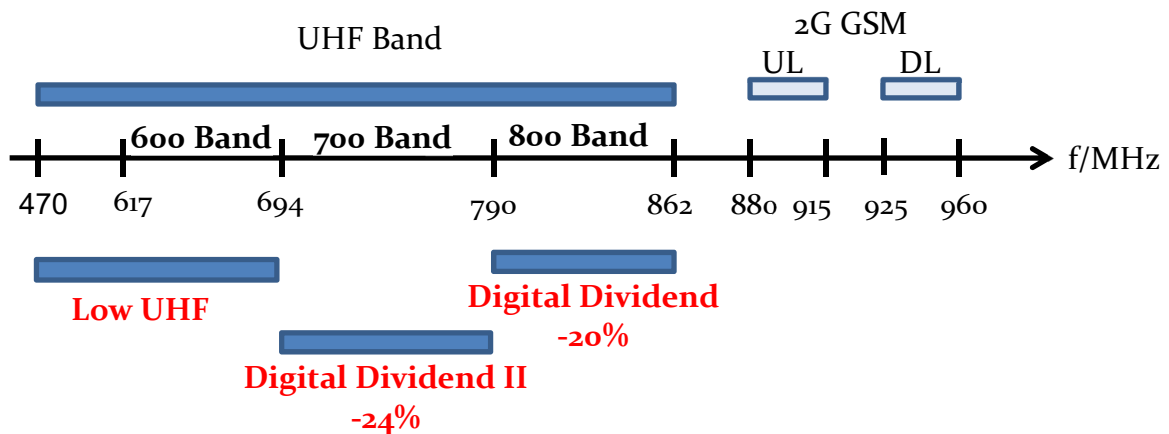


Figure 6.1: UHF spectrum situation

Currently there is a discussion going on regarding the future use of the frequency range 470...694 MHz, called the “low UHF” range. The cellular industry is proposing supplementary downlink use or use for cellular based broadcast like FeMBMS (Further evolved MBMS, Multimedia Broadcast Multicast Service) or 5G broadcast. There is also some support from the broadcast side as this would give the TV and radio broadcasters more reach, especially towards mobile smartphone users. In addition, a combination of dedicated and broadcast links is proposed, whereby if data packets are lost with the broadcast distribution, these lost packets can be requested via dedicated links on an individual basis. Such a combination makes broadcast also attractive for mobile use. There have been tries on DVB-T and DVB-T₂ reception mobile, e.g. in cars, but fading robustness is not that good with DVB-T/T₂. A combination of cellular MBMS broadcast with dedicated links will definitely perform better. But it will also lead into further spectrum consumption.

Although the cellular industry positions MBMS mainly as a tool that in future could not only complement but also replace DVB-T/T₂ and pave a way to mobile IPTV and further Multimedia services, the MBMS system can also be used for other purposes. A cellular broadcast system

can also distribute software updates to cars. This implies that an argumentation MBMS would simply replace DVB-T/T2 is not true. Market opportunities beyond classical TV and radio are opened.

As stated above, PMSE has lost already access to 44% of UHF spectrum, where there was a well understood coexistence with DTT in the past. It is unclear what will happen with the low-UHF range in the future. However PMSE is dependent on UHF due to body worn equipment. This was discussed in section 2.5 above. In low-UHF band the wavelength (about 60 cm) is larger than a human body's diameter, which prevents directivity of body worn antennas and in consequence unreliable PMSE links. A loss of PMSE frequencies at UHF cannot be substituted by assignments at higher frequencies even if bandwidth would be larger.

Also for PMSE to advance in radio transmission like e.g. through WMAS systems, large chunks of spectrum are preferred, e.g. chunks of 6, 8, 10, 20 MHz, like they are common with 4G/LTE and DTT carrier sizes.

Historically PMSE was based on narrowband radio systems (200 kHz) similar to what is used with FM radio, however wideband carriers of 6...20 MHz inherently offer frequency and interference diversity. Based on equal treatment, all systems DTT, cellular and PMSE must be given the possibility to profit from wideband physical layer techniques.

6.2 Spectrum for cellular communication

In the following, an analysis of spectrum assigned year over year to cellular in Germany is conducted.

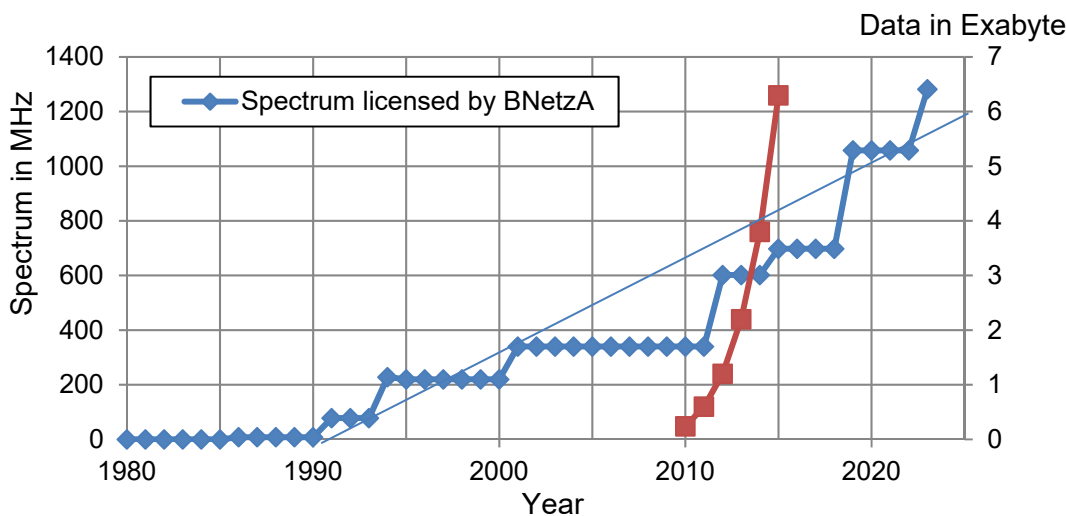


Figure 6.2: Spectrum assigned to cellular in Germany

From above figure, it can be concluded that spectrum assignment to cellular cannot keep track with the evolution in wireless data amount. As the Cisco law (see section 4.3) says that there is an exponential growth in wireless data amount of nearly a doubling per year, this would imply if no other scheme is followed aside spectrum grants, that also spectrum assignment would have to grow in exponential fashion. The rate of exponential growth can be debated somehow, but it is clear that an exponential growth of data amount would have to be accompanied also by exponential spectrum grant. However as UHF spectrum is finite this is no sustainable approach. Assuming a rate of wireless data amount doubling year over year, this would mean that next year 2600 MHz are needed and overnext year 5200 MHz. The complete UHF range anyhow is only $960-470=490$ MHz.

Looking at the spectrum assignments conducted so far, this had more the flavour of a linear assignment. But a linear assignment cannot satisfy an exponential growth. The consequence of this is that granting more spectrum is no sustainable way. It is no solution into the future. Even if low-UHF would be assigned to cellular, this would only provide a short term relief with no outlook for the future. This would simply shift the problem one or two years out. However it would come at pulling the base for PMSE and the Cultural and Creative Industry CCI, which are dependent specifically on low-UHF spectrum due to body worn antennas.

Therefore, a radical new approach is needed offside from more UHF spectrum grants to cellular. Options on how to offer more capacity in cellular networks without requesting more spectrum are discussed in section 7.1 . These mainly reside in network densification, MIMO, massive MIMO, distributed MIMO and cell free MIMO coming along with network virtualization.

6.3 Spectrum auctions and smart antenna solutions (MIMO)

Network densification and MIMO antenna arrays or more generally called smart antenna solutions They are the only realistic way to offer more capacity at UHF aside of new spectra in mm wave, which somehow cannot give good coverage. UHF frequencies are attractive thanks to good cell reach and good coverage properties.

Network densification has the problem that new base station sites need to be acquired, but this is difficult due to long lasting approval processes and pushback from the public for new sites. MIMO can be treated as an upgrade to existing base station sites. Adding new frequency bands can also be treated as an upgrade of existing base station sites.

When adding new spectrum it is preferred to add lower frequencies to an existing site rather than higher frequencies. The issue here is that lower frequencies have larger cell reach. If adding higher frequencies it could happen that cell radius becomes too short that further base station sites in-between existing ones are needed to avoid coverage holes. This problem will never arise when adding lower frequencies. Cell radius is always larger, so there is no risk that new base station sites are needed between existing ones. This is also the direction the digital dividends have progressed. The trend is always towards lower frequencies.

Digital Dividend I was lower than GSM900, Digital Dividend II again is lower than Digital Dividend I and yet again the push on low-UHF (470...694 MHz) reflects a spectrum lower than Digital Dividend II.

Regarding MIMO and smart antenna solutions an important point has to be considered. The raise in capacity does not scale with the number of antennas and transceiver chains. 4G LTE uses 2x2 MIMO as a minimum set, which explains why it is about factor 2.4 better than 3G W-CDMA. Factor 2 comes due to MIMO. Factor 1.2 comes due to improvements at physical layer.

In 2x2 MIMO the capacity gain is nearly 2, which does not hold, when going much larger in antenna count, especially if the MIMO arrangement gets asymmetric like e.g. 2 antennas at terminal side and 64 at base station. However the costs scale with the number of active transceiver chains. This is the reason why actually cost efficient implementations of MIMO are being researched, like hybrid analogue-digital beamforming (HADB).

On the opposite if transceiver chains are added for offering further frequencies there is an immediate reward in terms of capacity. By today costs scale better with addition of new transceivers for new frequencies than adding transceivers for more antenna branches with MIMO. This is also highlighted by qualitative Figure 6.3.

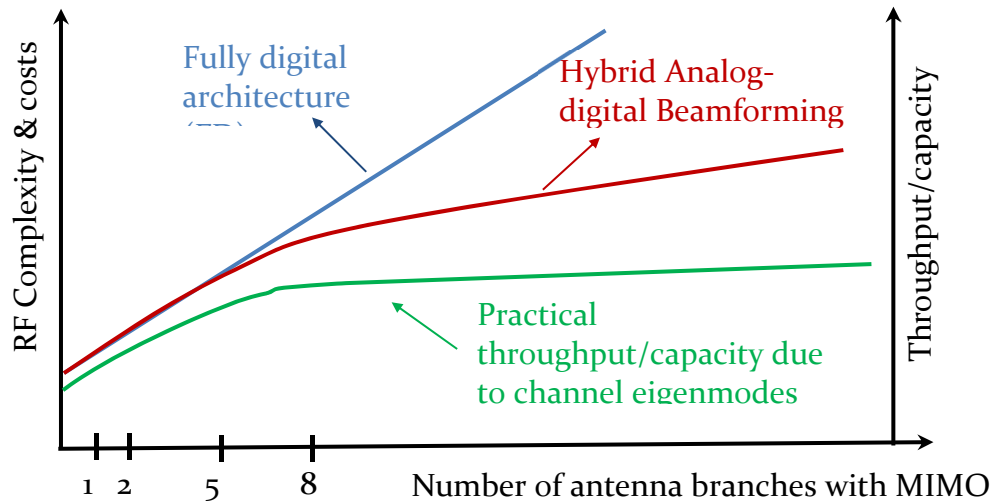


Figure 6.3: Cost Scaling with MIMO

The underlying information theoretical background is the following. Throughput of a radio link scales according to the number of channel eigenmodes, also named number of layers or parallel streams. It does not scale necessarily with the number of antenna branches. Just consider an example of 8 antennas at terminal and 64 antennas at base station. There is potential for 8-fold raise of link capacity in such a case, but if the channel only supports 5 eigenmodes than throughput may raise by factor 5. Nevertheless this would already be a factor of 2.5 in comparison to today's minimum set of 2×2 MIMO. On top of MIMO gain there is spatial multiplexing gain by SDMA (Spatial division Multiple Access), which is scenario dependent.

Massive MIMO faces issues with more signalling overhead and need for more pilots (pilot contamination problem) which is addressed in ongoing research.

The worse cost scaling with MIMO in comparison to adding new frequencies is the reason why MNOs (Mobile Network Operators) prefer investing in new frequencies over investing in MIMO. However research is addressing the cost challenge of MIMO implementations by complexity and cost reduced hybrid analog digital beamforming (HADB) MIMO architectures.

Cost is a serious issue for the MNOs. Under the assumptions that subscribers will pay constant monthly fees and data volume nearly

doubles year over year, this means that the cost to transport one bit must support a price erosion of 50% year over year, which is difficult to meet.

The fact that MNOs prefer going more spectrum rather than MIMO of higher order means that spectrum is sold too cheap. If spectrum would be more expensive then MIMO would be cost wise more attractive for the MNOs. This finding is backed by an analysis what happened about smart antennas and spectrum auctions, which is depicted in Figure 6.4.

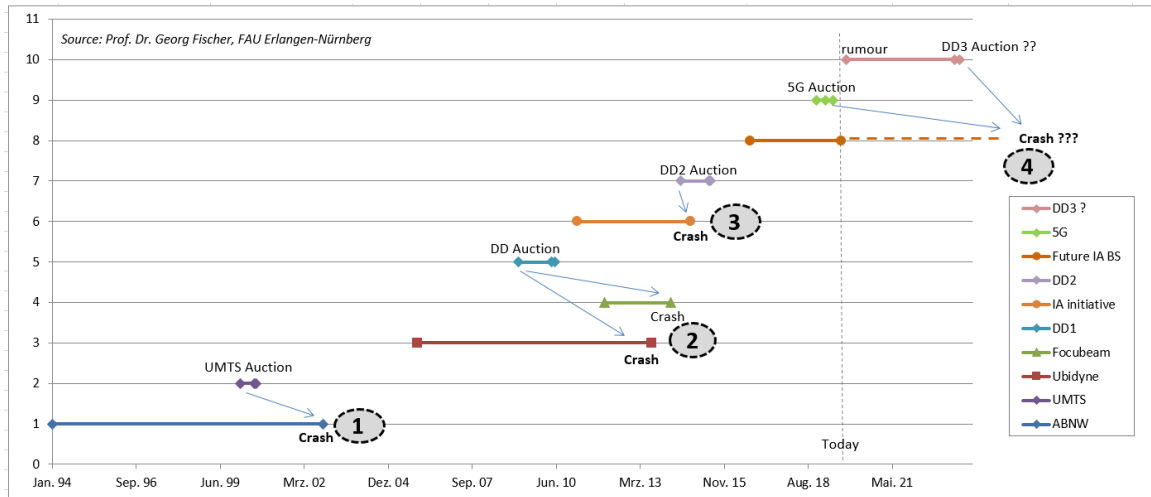


Figure 6.4: Spectrum auctions and Smart antenna activities in Germany

From Figure 6.4 it can be derived that activities in smart antennas always stopped after a spectrum auction. Companies offering smart antenna IPR (Intellectual Property Rights) and solutions got bankrupt after spectrum auctions. Regulators position themselves as innovators, stimulating advancements by new technology. Indeed the opposite happened, more or less three times. Whenever new spectrum was auctioned, infrastructure suppliers and MNOs lose their interest in smart antenna technology.

After UMTS auction company “A Brand New World ABNW” of Sweden got bankrupt. After DD I auction companies Ubidyne and Focubeam went bankrupt. After DD II an initiative inside a big infrastructure supplier was stopped as no business was seen with MNOs.

This means that spectrum auctions hinder innovation in smart antennas, especially for the UHF frequency range.

6.4 Analysis of spectrum auction results in Germany

Experience tells us, if there is shortage of certain goods or services, then prices will raise. Accordingly, a study on the prices per MHz of spectrum was conducted based on the past auctions in Germany. This study is depicted in Figure 6.5.

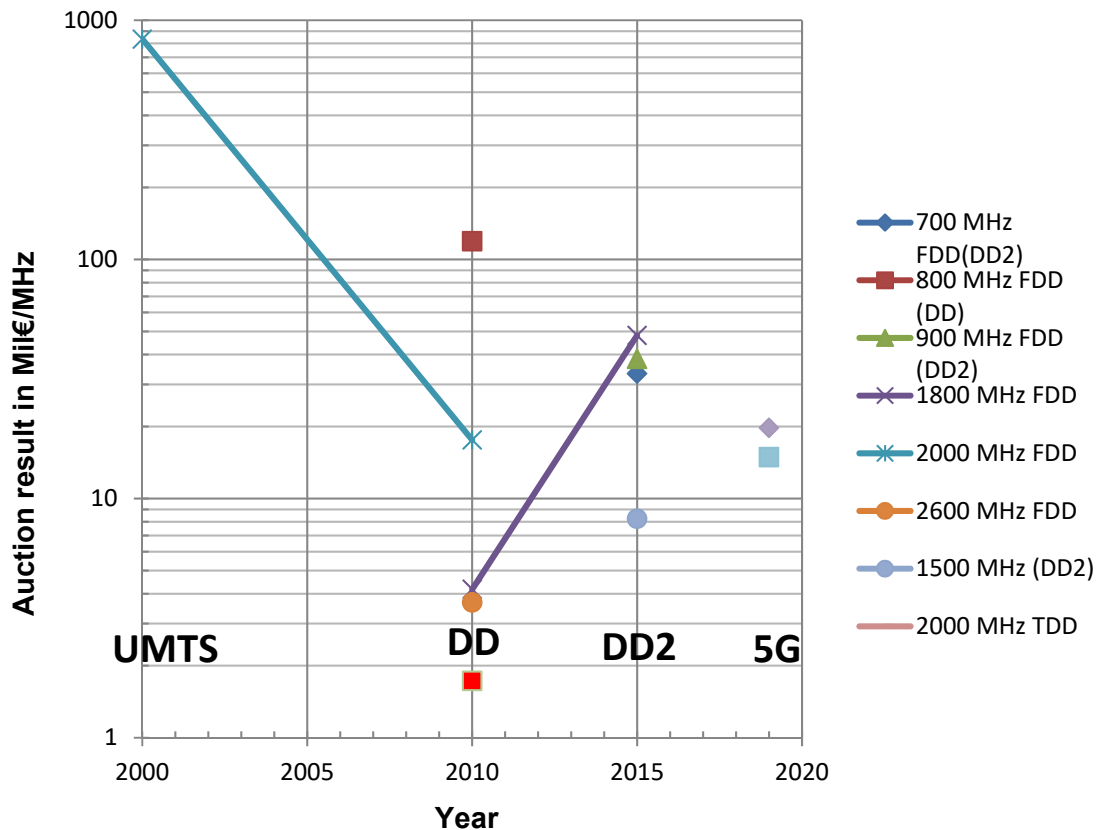


Figure 6.5: Auction results in Germany

From above graph it can be concluded that prices per MHz go down, although it is complained from cellular side that there is a shortage of spectrum. This is inconsistent. If there really are shortage and no other ways of coping with the wireless data traffic growth, prices would have to go up, based on the assumption of competition between multiple MNOs.

Aside of falling prices in general, there is one case, where prices raise. This happened about 1800 FDD spectrum. It can be speculated that there was strong interest in expansion of GSM1800 capacity.

In consequence this means that aside of more spectrum there are further options for managing the increased traffic, which are network densification and MIMO at its various flavours.

6.5 What is spectral efficiency?

The term “spectral efficiency” is used very often and systems are compared in terms of their spectral efficiency. Can this term be clearly defined? The following definitions are recovered from Prof. Friedrich Jondral of KIT who is a well-known expert in SDR.

6.5.1 Spectral efficiency of a point to point connection

- Number of bits transported within a second and within a given bandwidth
- Measured in bit/s/Hz
- Increase by:
 - Higher order modulation e.g. 256-QAM, 512-QAM
 - MIMO multi antenna systems
 - Not by source coding / compression, e.g. Digital: MP3, Analog: Comander !!

6.5.2 Spectral efficiency of a wireless communication system

- Number of bits transported within a second and within a given bandwidth summed over all users normalized to area
- Measured in bit/s/Hz/km² (aggregated over all users)
- Increase by:
 - Smaller cells, more dense placing of base stations

6.5.3 Efficiency of spectrum use, sometimes also called short “spectral efficiency”

- Number of bits totally transported within a second and within a given bandwidth summed over all users and systems normalized to area
- Measured in bit/s/Hz/km² (aggregated over all users and all systems)
- Increase by:

- Implementation of co-primary and secondary systems, that make use of resources currently not in use by primary systems, opportunistic access

6.5.4 Implications of spectral efficiency definitions

These different meanings of the term spectral efficiency are often mixed up and not clearly differentiated. Source coding, thus compression techniques implemented through ever improved codecs are not a tool for enhancing spectral efficiency, although this is often stated wrongly.

MIMO raises the spectral efficiency of a wireless communication system as both the MIMO and the spatial multiplexing gain are explored. Capacity gains of a network are drawn by orthogonalizing users in space leading into SDMA (Space Division Multiple Access).

There is a fundamental difference between classical beamforming in the way that beamforming aims at illuminating a small sector, whereas MIMO aims at illuminating a spot around a target user at a certain distance. In beamforming the closer the user to the base station the stronger the received signal. In MIMO it is natural that the received signal gets weaker, when a user comes closer to the base station as constructive superposition of a multitude of reflected waves only happens at the illuminated spot. This is the reason why MIMO works best in highly refractive environments like in towns. Simultaneously in towns there is the highest capacity demand. This coincides nicely. In rural areas where MIMO gains reduce there is anyhow lower traffic demand.

The regulator mainly aims at the efficiency of spectrum use, which is improved by flexible and dynamic licensing schemes, where spatio-temporal usage patterns are explored.

6.5.5 Source coding, compression and spectral efficiency

As stated above source coding/compression is not a scheme for raising spectral efficiency. This can be explained by the following example in Figure 6.6.

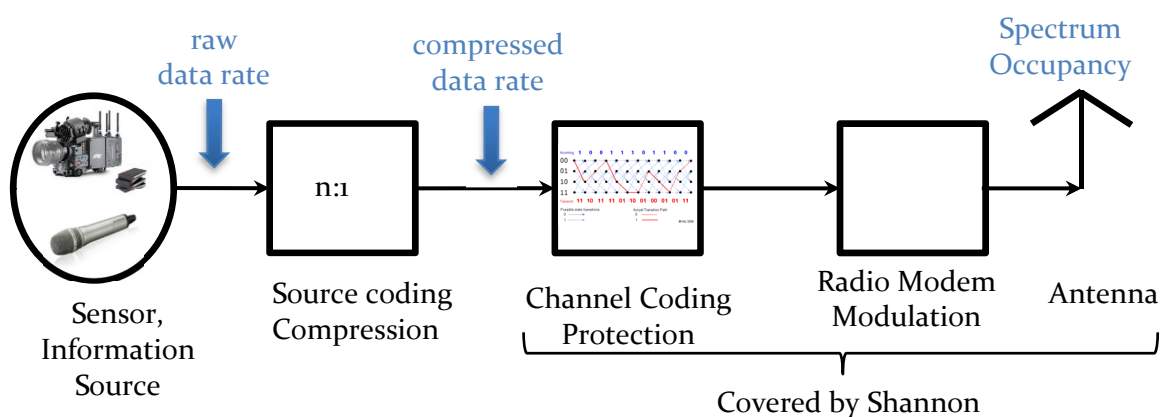


Figure 6.6: Audio/Video transmitter

If one takes an ever higher resolution sensor, e.g. camera chip with ever higher raw data rate but at the same side adjusts compression in a way so that the compressed data rate stays constant so that occupied spectrum also stays constant then a definition of spectral efficiency relating raw data rate to occupied spectrum would ever grow without any improvement in quality of experience QoE with the users.

New codecs for compression are advertised as a tool for enhancing spectral efficiency. But this is wrong according to Shannon theory as spectral efficiency should only relate compressed data rate after source coding to spectrum occupied. Also the separation theorem of information theory holds, which states that it is always possible to split source and channel coding.

Nevertheless, improved codecs can help in placing more services in a given spectrum. Experience tells us that codec research has given us codecs that deliver the same QoE but at higher average compression. Then indeed more services can be placed in a given spectrum. But higher compression rates typically come at larger latency and typically VBR (Variable bit rate), which means the benefits show up in a statistical sense if multiple services are bundled in a multiplex, which is only the case with wideband systems.

6.6 Rebound effect

Especially with video transmission Rebound effects are observed. It means that codec advancements have been made that allow for higher compression at identical QoE, but this was used as an argument to select a higher resolution sensor, so that net wise the compressed data rate

raised, leading into a demand for more spectrum. One can e.g. see that 4k videos with recent codecs are offered on smartphones, although display size is small. This leads to additional spectrum occupation.

7 How to deal with increasing demand in Cellular, DTT and PMSE?

7.1 The Case of Cellular

7.1.1 Capacity versus Coverage demand

In the discussions about spectrum need for cellular, the various demands by the cellular industry are mixed up.

A capacity problem means that users have enough signal strength when receiving base stations, but the base stations cannot serve the traffic requested by users. This happens from time to time at so-called hotspots, where many users at an event at the same time and the same location want to access the internet or want to phone.

A coverage problem arises if the next base station is too far away that the received signal is so weak, that it cannot be received by the users. This often happens in rural areas.

Now it is argued that the low-UHF frequencies are needed to overcome the coverage problems in rural areas. Indeed the lower the frequencies the less base stations are needed to cover the same area thanks to larger cell radius at lower frequencies. Lower frequencies lead into less investments to cover rural areas. But it is not impossible to cover rural areas with existing medium UHF frequencies. If further spectrum would be more expensive for the MNOs than installing more base stations at the frequencies they already own, then low-UHF spectrum would not be requested by MNOs.

It is clear: ***Where there is no coverage, there is no capacity problem.*** This implies that an argumentation “*new frequencies are needed to serve the capacity demands in rural areas*” is inconsistent. If there is large capacity demand then more base station sites are economically feasible.

The interest in low frequencies by MNOs is more motivated by new business opportunities e.g. for broadcast services, not only for TV and radio but e.g. fleet management services (see above) at moderate invest for good coverage.

The 3G business case failed initially due to the fact that the frequency at 2 GHz was too high. In the beginning of 3G many base stations had to

be set up to fill coverage holes due to small cell radius, but at the same time traffic demand was low, so the tremendous capacity offered by 3G base stations was not drawn practically. Thus there was barely a strong return of invest.

On the opposite, 2G GSM started at 900 MHz and later expanded into 1800 MHz for capacity reasons. This is also backed by above analysis that the price for 1800 MHz raised in contrast to the general trend.

In an ideal case a base station is operated in a way that by the traffic generated inside its coverage area its capacity limit is nearly reached. Then the ROI (return of invest) is excellent. Operators prefer to set up new base stations or upgrade base stations when the capacity limits are reached, not for the purpose of offering coverage at low to negligible traffic. In rural areas with its low traffic per area, this ideal operating point is better reached at low frequencies. This means the interest in low frequencies is motivated by more attractive business case not by spectrum shortage, which is also backed by above analysis on the price per MHz with passed auctions.

7.1.2 Adding more spectrum

As discussed already above the MNOs are more interested in expanding their spectrum towards lower frequencies as this avoids the need for new base station sites when upgrading the network with further higher frequencies.

The frequency range 470...694 MHz accounts for additional 224 MHz. In relation to today's assigned spectrum of about 1300 MHz this is marginal on the order of +17% in relation to the capacity gains that could be obtained by network densification or MIMO or refarming like switching off 3G at 2 GHz and substituting by 4G/5G technology. Meanwhile during the course of this study 3G was switched off in Germany

7.1.3 Adding mm-wave

Capacity problems can be well addressed by mm-wave communication. At mm-wave large frequency spans are available offering large capacity. Also thanks to higher frequency and thus shorter wavelength, MIMO arrays are more compact at mm-wave. In contrast, cell ranges at mm-wave are much smaller, therefore it is not suited for giving large coverage. mm-wave would not be selected to cover rural areas. mm wave is attractive with hot spots, like shopping malls.

7.1.4 Network densification

Network densification follows the general cellular approach as invented by Bell Labs and published in 1947 the first time [23]. In the early days of 1G analogue cellular networks, there were just 8 base stations to cover whole Germany. Then in 2G GSM times 10,000 to 20,000 base stations were considered to cover whole Germany. Now in 4G there are even more. MNOs simply must keep on going this route to serve the capacity demands.

Network densification gives arbitrary capacity gains when cells get smaller and smaller, however it struggles with acquiring new sites, backhauling and more signalling traffic for handover. Nevertheless, if capacity problems are in place it can provide relief. Problem with backhauling can be addressed by in-band mm-wave backhauling or microwave backhaul links.

7.1.5 MIMO, Massive MIMO

MIMO is the only way to get beyond the classical one-dimensional Shannon bound and indeed a minimum set of 2x2 MIMO was standardized into 4G. This can be stretched further to higher order MIMO schemes. The throughput gain scales with the smaller antenna number at terminal and base station side. 4 antenna branches are very realistic on smartphones, on laptops 16 antenna elements e.g. on the backside of display are also not unrealistic. On the base station side research on massive MIMO arrays between 64...1024 can be observed.

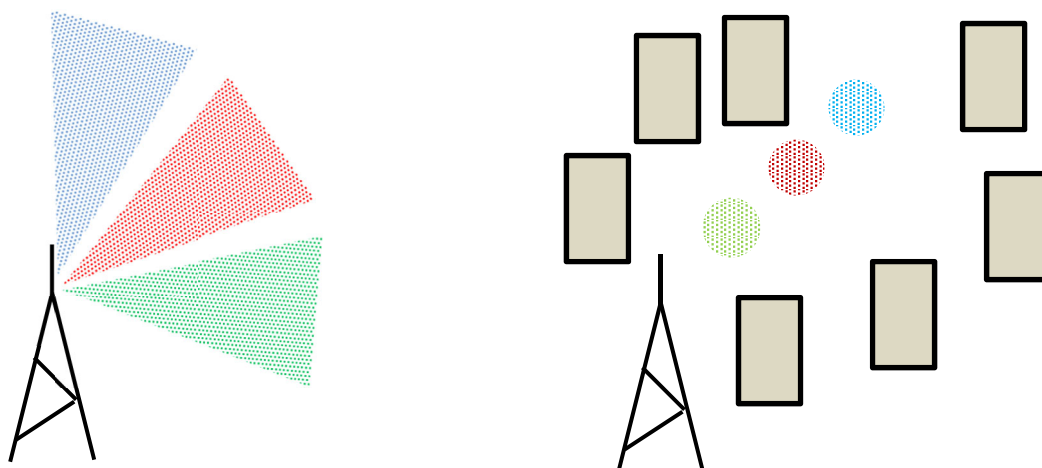


Figure 7.1: Illumination through Beamforming (left) versus MIMO (right)

MIMO must clearly be distinguished from beamforming. Beamforming illuminates a small sector, whereas MIMO illuminates a spot at a desired location. This is highlighted in Figure 7.1.

Beamforming therefore cannot provide that much SDMA (Spatial Division Multiple Access) gains as MIMO can do. However, MIMO requires a rich scattering environment to enable constructive and destructive

superposition of reflected waves, which typically is the case in urban areas, where also capacity demands are large.

The spots by MIMO are a consequence of the constructive superposition of multiple reflections at the spots. Even closer to the base station, the signal is weaker due to destructive superposition. The multitude of spots use the same radio resources. They are distinguished by the precoding at the base station side matching the orthogonal Eigenmodes of the radio propagation environment. Multiple spots could also exist in a row, one behind another. Such a scenario could never be served simultaneously by beamforming.

Research by Fraunhofer society on SUDAS (Shared UE side Distributed Antenna System) [24] aims at providing large MIMO gains with compact smartphones. The SUDAS approach is based on distributed small “Shared UE-side Distributed Antenna Component” (SUDAC devices). They can be seen as some sort of Remote Radio Heads for Smartphones. The SUDAS system translates a spatial domain vector into a frequency domain vector at higher frequencies. It thereby converts the signals at each SUDAC into different frequencies on the link to the smartphone, which relaxes the number of transceivers needed at the smartphone. This in consequence means that the smartphone can run large scale MIMO with many branches, although itself it has only a few branches. In summary, it can be said that SUDAS is a technology easing the use of large scale MIMO at the terminal side. Instead of going the direction of Carrier Aggregation (CA) for higher throughput, a terminal could go the direction of higher order MIMO, whereby less spectrum is occupied.

7.1.6 Higher Order Modulation

Selecting higher order modulation schemes like 512, 1024, 2048, 4096 QAM can also increase throughput and provide additional capacity. The problem however is that the higher the modulation scheme and data rate, the higher the required Signal to Noise Ratio (SNR). This means

that highest schemes can only be used in excellent propagation conditions nearby the base station. At large distance from the base station the benefits from higher order modulation vanish. On the opposite, the MNOs would like to give minimum service guarantees. Here Higher Order Modulation schemes do not help in raising minimum service guarantees.

Highest peak data rate with highest order modulation are good for advertisement and glossy brochures, but for user satisfaction, mainly the minimum rate experienced counts. This has led the MNOs to focus on techniques that homogenize the data rate in the coverage area. CoMP Coordinated Multipoint is an example for addressing this wish for homogenization.

7.1.7 HARQ, retransmit, incremental redundancy

Hybrid ARQ schemes allow to request a retransmission of not successfully received packets. In incremental redundancy coding different puncturing schemes of a channel code can be requested if needed. It is common to both schemes that the increase in robustness of radio transmission comes at the cost of an increased latency, which turns this feature unusable for PMSE. However with file download, email or web browsing, where latency is less critical as service are non-realtime, this is a way to go and indeed it is used in today's cellular systems. But the retransmission or transmission of another puncturing of channel code also leads into additional radio resource consumption, say spectrum occupation.

7.1.8 Quality scaling

During Corona times, when people had to stay at home a raise in usage of video streaming services was detected leading to an increased server and network load. Netflix reacted on this and reduced resolution from 4k/UHD to HD and SD to prevent overload. The impact on QoE is moderate, however the loading of servers and network could be reduced significantly.

It has to be questioned whether it is really necessary to stream 4k videos to smartphones. An MNO may downscale video size to reduce the traffic loading of its network. In some networks data of videos and pictures is compressed based on characteristics of end device.

7.1.9 Virtualization of Radio Access Networks - VRAN

In cellular network architectures, a trend towards more and more virtualization can be observed. It means that classical network elements become services in a cloud. Running services in a cloud is attractive as capacity can be scaled more easily by instantiating further network element services in the cloud.

Driving Virtualization further implies that classical base stations no longer exist. Instead Distributed Radio Heads are connected to the cloud via fast links and precoding gets a service in the cloud. This allows for large scale distributed MIMO. With extremely distributed radio heads forming a MIMO array the classical term “cell” no longer makes sense. Therefore people talk about “cell free MIMO”.

As Radio heads operating at different frequency bands can be part of such virtualized networks, the selection of frequency bands can be handled very dynamically based on terminal needs. Terminals farer away from the radio head may be better served by lower frequencies. And terminals close-by, but demanding higher throughput may be better served at higher frequencies.

In summary, it can be said that VRANs can also provide capacity and coverage gains for MNOs, especially if multiband radio heads are used.

7.2 The case of DTT

7.2.1 Statistical Multiplex

TV broadcasters typically assemble several programs e.g. 4...6 in a multiplex. The reason for using multiplexes is that benefits from statistical multiplexing can be drawn. As said above, higher average compression ratios with source coding are obtained if Variable Bitrate codecs (VBR) are used. Then it is very unlikely that all codecs of all TV programs at the same time produce their peak data rate. The radio resources i.e. the spectrum assigned to a multiplex is dynamically partitioned between the TV programs.

7.2.2 “More reach” by cellular

TV broadcasters not only want to reach users with classical TV sets or Internet users at home. They also want to reach mobile users. There have been experiments with using DVB-T in a mobile way. However, initially

DVB-T was not designed for mobile use. In the past there was also a derivate DVB-H (handheld), but it did not commercially succeed. The intention behind DVB-H was to define a slim standard at less complexity that could be implemented easily in phones. Thanks to Moore's law complexity with DVB-T no longer is a big hurdle. But still DVB-T receivers are not common in Smartphones.

Nevertheless, the interest by TV broadcasters to reach the mobile users is still high. The Broadcasters see the low-UHF frequency range together with MBMS service via cellular as a great and realistic chance to achieve this desire to reach into mobile users. Furthermore, cellular will provide them with a back channel, allowing for more interactivity, which is also in their interest.

As mentioned above, a combination of broadcast and dedicated logical channels inside cellular will allow to ask for retransmission of lost packets. This will give the users a great QoE. This individual retransmission of lost packets for each user will also lead into additional spectrum occupation.

If in future identical TV content is transmitted in parallel via DVB-T/T2 and via MBMS over cellular, this would constitute a waste of attractive UHF spectrum.

7.3 The case of PMSE

7.3.1 Narrowband Digitization of PMSE

The STRATIX study [5] addressed the question what benefits could be drawn from digitization of PMSE. There was large expectation by the Dutch regulator as the contract giver that the move from analogue to digital could result into less spectrum demand by PMSE. However, the study revealed that no real gains could be drawn. The reasons were manifold. The comparison took place between analogue and digital PMSE, but both narrowband.

Analogue PMSE makes use of some sort of analogue compression and pre-/de-emphasis, which can be seen as some sort of analogue source coding. Analogue not per se is spectrally inefficient. For example analogue Single Sideband Transmission (SSB) is 0dB at the Shannon bound. There cannot exist any system that does better. Narrowband digital PMSE uses source coding on the order of 2:1 compression, which is comparable with the analogue compander system.

Aside of the fact that narrowband analogue and narrowband digital PMSE both use compression techniques with comparable compression factors, it is obvious that both narrowband schemes miss the benefit from frequency diversity, which is inherent to wideband systems.

With digital transmission it was also found that the “digital cliff” comes into play, whereas analogue systems show graceful degradation. When receive level falls below the digital cliff with fading channels, then a dropout is faced, which may take long time due to need for resync.

There are also digital PMSE systems that offer a “robust mode”. Here higher compression is selected with source coding producing a lower compressed data rate, which allows to apply more channel coding that in consequence will lead to a more robust system, but at the cost of a moderately degraded QoE. For high performance events and capturing audio in an archive, this quality is insufficient.

In conclusion, it means that running all PMSE links in robust mode is not an option for growth in PMSE.

7.3.2 Transmitter intermodulation management

PMSE transmitters that are close to each other will generate intermodulation products that occupy additional spectrum. This implies that the required spectrum grows over-proportional with number of PMSE links, see PMSE system reference document [25, Fig A.2].

The problem can be addressed by RF-circulators, however these do not cover large tuning ranges, which implies that high end wireless microphones contain a bank of circulators that are switched [5].

Today’s spectrum assignment for PMSE is pretty fragmented into many small spectrum pieces, which leads into huge effort, complexity and costs for circulators. In order to manage transmitter intermodulation more efficiently large chunks of spectrum should be assigned to PMSE. Large spectrum chunks also allow for operation of wideband PMSE systems, with bandwidths of 5 / 6 / 8 / 10 / 20 MHz, like WMAS (see below). Wideband systems in general have less problems with transmitter intermodulation.

In summary, this means that large spectrum chunks for PMSE are the more efficient way of managing transmitter intermodulation than fragmented assignments.

7.3.3 Wideband Digitization of PMSE - WMAS

Wireless Multichannel Audio Systems WMAS are a new approach for PMSE. The physical layer is of wideband nature, thus it provides frequency and interference diversity, which makes the PMSE system more robust. Furthermore, WMAS systems allow to configure the QoE for each link individually and dynamically during use.

With artists, the same PMSE hardware is used for talkback before going on stage and afterwards, as PMSE equipment is part of the artist's costume. Now WMAS also allows to dynamically alter the QoE depending on current usage. Not all PMSE links require highest QoE at the same time. The mix of low and high QoE links will provide capacity gains. The prerequisite however is the availability of large spectrum chunks. Natural channel raster are TV channel sizes of 6 or 8 MHz and the widths used in cellular of 10 and 20 MHz.

7.3.4 Will 5G provide relief?

It has been asked whether PMSE could be handled inside 5G networks? Private 4G/5G networks now also have become feasible, which would allow for operating a dedicated wireless PMSE network [32, 33]. 5G promises Ultra Reliable Low Latency Services URLLC, which would meet the needs by PMSE.

However 5G in mainstream is not yet there as needed. There is still work to be done. Practical trials in standard 5G equipment reveal round trip latencies beyond 5 ms, which is too much for PMSE. Only specially tweaked 5G system demos have shown to meet the needs of PMSE, e.g. the demo by NOKIA and Sennheiser at Mobile World Congress in Barcelona [26].

Low latency is achieved if dedicated radio resources are reserved for PMSE. VBR codecs would imply a dynamic reservation of radio resources, which leads to additional signalling load and latency, which compromises the main goal for low latency.

In consequence it means that low latency does not come for free. The price to pay is spectrum. Following the fluctuating compressed data rate produced by a VBR codec by dynamically scheduling radio resources suffers from additional latency and signalling load. A fixed reservation of radio resources (persistent scheduling) according to peak data rate

produced, questions spectrum savings by VBR and any benefits from statistical multiplexing of multiple PMSE links.

A reservation of radio resources would allow meeting the latency constraints but leaves aside benefits in spectral efficiency from VBR. It gets more or less equivalent to classical circuit switched services. From this perspective CBR codecs avoid problems in dynamic Radio Resource Scheduling to cope with fluctuating capacity demand.

7.3.5 Network Slicing in 4G/5G cellular

Network slicing is seen as a way to secure QoS guarantees for certain services. One could reserve a slice for PMSE services. Slicing in itself is a very flexible tool for MNOs to assign radio resources to certain service classes of different QoS. However it reflects somehow a partitioning of spectrum, which prevents truncation gains between multiple services of different kind.

So far there is no cost model dependent on QoS guarantees in cellular. Rulings of equal treatment prevent such models. Network slicing is a way to circumvent this limitation. Nevertheless regulatory problems need to be solved.

7.3.6 Exploring Tempo-Spatial Usage Patterns of PMSE

PMSE usage often is characterized in a way that PMSE is only used in limited areas and for limited times. Given this tempo-spatial usage patterns of PMSE dynamic licensing schemes could be of help.

With 5G auctioning a new licensing scheme was introduced in Germany which allows for 5G campus networks, thus wireless networks operating in a limited area.

However what is problematic is that with large scale events high usage in PMSE goes along with high usage in cellular, which implies that benefits from spectrum sharing between PMSE and cellular wouldn't be in place. High capacity demands in PMSE are typically coincident with high capacity demands in cellular.

7.4 Summary of options for growth

The following Table 7.1 gives a rating of the options for each system operating in UHF to grow in capacity.

Table 7.1: Options for growth at UHF depending on system (Cellular, DTT, PMSE)

	Cellular	DTT	PMSE
More spectrum	☹ Spectrum is a naturally limited resource, barely available	☹ Spectrum is a naturally limited resource, barely available	☹ Spectrum is a naturally limited resource, barely available
Source coding / compression	☺ High compression ratios reduce QoE, however in distribution of multimedia content this is acceptable, e.g. 4k video on smartphones	☹ DVB-T used high compression but QoE was only moderate, users wanted more quality, e.g. HDTV, thus DVB-T2 was introduced	☹ As PMSE is used on production, high compression cannot be accepted, an archive requires highest quality to later derive any quality level from it, cascading high compression on production and distribution leads to artefacts, spatial sound is compromised with compression as audio phase fronts are not maintained
MIMO, Massive MIMO	☺ A realistic option, given network virtualization and remote radio heads, see cell free MIMO, distributed MIMO. Also a realistic option for terminals, see SUDAS	☹ Users will barely accept Rooftop MIMO antennas or large number of antennas at set-top boxes	☹ PMSE equipment is body worn and part of costume, PMSE equipment should be small size and battery constrained, MIMO less possible, max 2 at terminal side
Channel width	☺ 3G/4G/5G all wideband	☺ Wideband, multiplex of several TV programs	☹ Traditional narrowband 200 kHz ☺ in future wideband by WMAS systems

8 Introduction to Spectrum scanning for PMSE usage analysis

8.1 Organisational challenges

Scanning spectrum usage by PMSE in the field is subject to various challenges. With every event allowance for scanning must be obtained upfront from the organizer of the event. Although scanning is a receive only process without transmission, sometimes concern was raised when additional electronic equipment is brought into an event.

Typically, there are stringent restrictions where to put up a broadband antenna to scan a wide frequency range. The additional antenna on one hand should not be obtrusive and harm the “performance” but on the other hand, it should be placed at a location where all PMSE signals can be captured.

As users of PMSE might walk around like stage/backstage or reporters might follow a politician from inside to outside building not every antenna location is suited. In order to overcome such problems the used scanning method allows for fusing scanning results of up to three scanning locations.

Sometimes it was also observed that in an event frequencies got used that are no longer regulated for PMSE. Partially also large deviations from initial coordination plan have been seen. This all happens if sudden problems have to be overcome. It is obvious that some operators of PMSE equipment do not want to see public documents from which it is obvious that they operate outside regulatory limits and outside assigned frequencies. On the other hand, such cases are especially interesting as they are a proof of spectrum shortage in such an event.

Furthermore, with a multichannel IEM transmitter, large spectral regrowth by transmitter intermodulation was observed. It can be speculated that for securing stable PMSE links, total transmit power had to be increased. The intermodulation products implied larger spectrum occupancy.

8.2 Technical challenges with scanning

The whole setup by antenna gain plus eventual LNA gain and antenna cable plus filter losses must be calibrated to ensure that a proper signal level at air interface is recorded.

As UHF signals typically have very good propagation properties and as also TV stations and base stations are operating in UHF, the scanning receiver is exposed to large dynamic range, facing very strong signals aside weak ones. Receivers of high linearity (low intermodulation) are needed. Typically, test & measurement equipment like a Rohde&Schwarz FSUP is used, which offers high intermodulation robustness.

Recently also overreach of TV stations was observed in spectrum scans.

A special AGC algorithm (Automatic Gain Control) is used to prevent overdrive of receiver. The optimization of the AGC with its attenuator is the result of a longer research activity. However switching in an attenuator on one hand is beneficial as it avoids overdrive, but at the same time it also makes the receiver less sensitive, so that weak signals are not captured.

Very strong signals can turn the receiver blind. This is called blocking. As was shown in the Doctoral thesis by Johannes Brendel [27], a scanning grid also is a good countermeasure to this problem, as it is unlikely that all receivers of a scanning grid are blocked simultaneously. This significantly reduces the probability that PMSE signals are overlooked. But not at all events it is possible to setup multiple antennas and scanning receivers to facilitate a scanning grid.

8.3 Scanning method

This study is based on the analysis of a sequence of scanning reports presented to and reviewed by VDE DKE AK731.0.8 "Professionelle Funkmikrofonsysteme und Veranstaltungstechnik" [28] since 2007. These reports have served as basis for input papers from Germany to ECC CEPT European Conference of Postals and Telecommunications Administrations – European harmonization, ITU International Telecommunications Union - international regulation and ETSI Standardisation.

8.4 Final goal with analysing scanning results

Statistical tools are applied to the scanning reports to provide confidence intervals on metrics like used spectrum and allow for extrapolations into the future.

The final goal with the analysis of scanning reports year over year is to derive trend laws that reflect how available spectrum for PMSE at UHF has changed year over year and how spectrum usage has evolved year over year. The intention here is to derive growth laws similar to those present with microelectronics and telecommunications as presented in Chapter 3.

However there are only a few events that take place year over year in the same format. These are for instance the ESC (European Song Contest), Wacken Open Air and regional state Elections in Germany.

It is the aim to clarify on the spectrum need by PMSE, how it has evolved over time and what prognosis can be done for the future.

8.5 Merits of result interpretation

The set of scanning reports constituting the base of this detailed study in the following Chapter 9 is limited, as scanning is always a tremendous effort. One may ask whether the results are representative and whether the statistical base is sufficiently large for deriving growth laws, conclusions and recommendation to politicians and regulatory bodies. Thus, in order to comply with scientific quality standards, uncertainty modelling is applied.

Other aspects to consider with the interpretation of the results are the organisational and technical challenges discussed above. They constitute a bias towards less spectrum usage.

The study is further biased towards lower spectrum need as art directors already by now face spectrum shortage and thus do not realize performances in a way that would need more PMSE links. They limit the artistic performance due to lack of spectrum.

Limits in terms of available spectrum are already in place today as frequency coordinators tell. This may lead into wrong conclusions of less spectrum need for PMSE.

In summary the conclusions will not reflect the full truth regarding PMSE spectrum demand and will be biased towards lower need. They can be considered optimistic in the sense of less demand.

9 Data analysis on the spectrum needs by the event industry

9.1 Events Germany 2007-2020

9.1.1 Analysis base - Key data

Table 9.1: Germany - Analysis base

Event type	Different
Period	March 2007 – March 2020
Recorded frequency range	470 MHz - 862 MHz (total scanning bandwidth 392 MHz)
Other participants in the frequency band	Broadcast stations, cellular (DD1 & DD2), other event productions PMSE
Coordination information	Mostly present. If not present, then 1.5 times the detected PMSE links was assumed.
Size of the data set	40 recordings from 38 events 36 without Wacken Open Air (WOA) 2015 & 2016

9.1.2 Analysis results - Basic stochastic parameters

Table 9.2: Germany - Analysis results

Expectation value on spectrum need	102 MHz
Standard deviation	36.6 MHz
Slope of the regression line	0.0065 MHz/day (increasing)

	2.31 MHz/year (increasing)
Maximum frequency need	191 MHz (Wacken Open Air)

9.1.3 Estimation of the available spectrum

Table 9.3: Germany - Available Spectrum

Designation	Range in MHz	Total Bandwidth in MHz	Comment
UHF professional, bottom	470 – 608	138	Not subject to registration, shared with TV
UHF professional, top	614 – 694	80	Not subject to registration, shared with TV
LTE II duplex gap, professional	733 – 758	25	Subject to registration, may be dropped in the future
LTE I duplex gap, private	823 – 832	9	Private use
EU band	863 – 865	2	Private use, EU-wide
LTE II, Uplink	603 – 733	30	Occupied by cellular
LTE II, Downlink	758 – 788	30	Optional additional capacity for PMSE
LTE I, Uplink	791 – 822	30	Occupied by cellular
LTE I, Downlink	832 – 862	30	Occupied by cellular

In the administrative regulation for frequency allocations in Non-Public Land Mobile Radio VVnömL [30], the federal network agency regulates the use of radio microphones and in-ear monitoring systems and divides the users of radio systems into two groups: private and professional. The classification of the frequency range relevant for the PMSE sector in the past, present and future can be seen in above Table 9.3. This shows that frequencies previously allocated to PMSE were allocated to mobile radio through Digital Dividend I (LTE I) and Digital Dividend II (LTE II).

In the table, the frequency allocation was deliberately divided into three sections:

- a) The range that can be used professionally by the PMSE sector (UHF, LTE II duplex gap),
- b) The private range (LTE I duplex gap, EU band) and
- c) The range occupied by mobile radio (LTE I & II).

The private sector is only suitable to a limited extent for professional applications and planning for the following reasons:

- Equipment for this frequency range often is designed for private use
- Relatively narrowband (7 radio channels LTE I duplex gap, 4 channels EU band)
- Susceptible to interference from unregistered private users (smaller bands)
- Susceptible to interference from mobile communication (LTE I duplex gap)

It is not considered as available spectrum for PMSE in further considerations.

Another critical frequency range is the LTE II duplex gap (733 – 758 MHz). This is also exposed to interference from the adjacent mobile radio bands and has further disadvantages such as a registration obligation. In addition, it can be assumed that this will be further restricted by technical progress in the mobile radio sector. Nevertheless, according to the current status, it can be used at least for less critical applications such as personal radio and event coordination and is assigned to the usable PMSE spectrum for further consideration. However, if SDL Supplementary Downlink is implemented more widely in the assigned range 738 - 753 MHz, this range will get unusable for high

quality PMSE in future due to unpredictable interference by highly dynamic resource scheduling. For large-scale events, it can be expected that this range will be intensively used to support larger download data rates by the cellular users.

This division results in a spectrum of 243 MHz theoretically available for the PMSE sector. In this range, broadcasting (DVB-T2) is the primary radio service and must not be interfered by wireless systems. In Germany, 6 DVB-T2 transmitters are currently active and thus require 48 MHz (6x8 MHz) of bandwidth. For technical reasons, these transmitters are broadcast to different broadcasting stations at different channels in order to avoid interference in peripheral areas or areas with overlapping. This sometimes results in a significantly higher local demand from broadcasting. For example, in Frankfurt at the "Prolight+Sound" event in 2013, a spectrum requirement of 152 MHz was measured for broadcast. This is certainly an exception, but the local broadcasting demand must be included in the planning for each event in advance.

From the data provided, an average broadcasting demand of 56.2 MHz with a standard deviation of 23.8 MHz was determined. The average value is assumed as a measure of broadcasting demand for the following consideration and must be subtracted from the available spectrum for PMSE applications.

As already mentioned, interferences occur regularly during an event. They can be caused by neighbouring events, private users or incorrectly used equipment. During the measurements at the events, in addition to the links coordinated by the organisers, uncoordinated links were also recorded and detected. These can be caused by the above-mentioned interferers, but also due to event-related or technically-related spontaneous re-coordination by the organisers themselves. Even if it cannot be identified from the data for what reason these links are active, they do give a measure of how much buffer an organiser must plan for, in order to be able to react to unforeseeable problems at an event. Therefore, this buffer must also be subtracted from the available spectrum. The data showed an average demand of 16.2 MHz for the uncoordinated links.

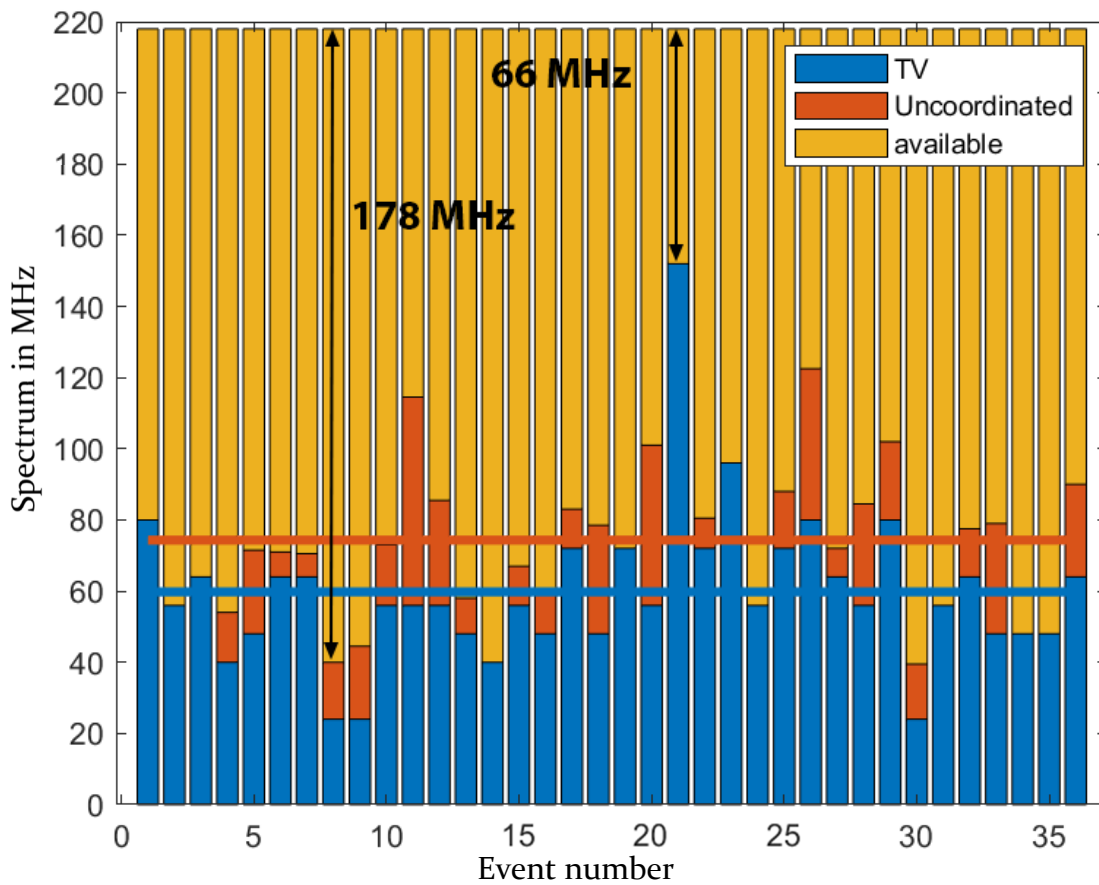


Figure 9.1: Available spectrum after subtraction of need by TV and uncoordinated links

Figure 9.1 clearly shows how much the available spectrum at the recorded events is restricted by uncoordinated links and broadcasting. In some cases, this goes so far that at some events less than 100 MHz was available for planning the event. For the further considerations, we nevertheless want to assume the average values and thus obtain an average available spectrum of 170.6 MHz.

9.1.4 Linear regression of the coordinated links

To look at and analyse the spectrum needs of the event industry, we will use the coordinated links of the event organisers as a basis. The data set provided to us contains this information for most of the events included. For those events, where the coordination information is not available, we assumed 1.5 times the number of links recorded. Furthermore, it should be mentioned at this point that the data mostly contains events with a medium or large event structure.

The spectrum demand of the coordinated links is shown in Figure 9.2. Here it can be seen that the data can mainly be assigned to medium and larger events. In addition to the data points, a linear regression of the data was carried out and the corresponding regression line drawn until 2025. This results in a clear increase in demand of approx. 2.3 MHz per year.

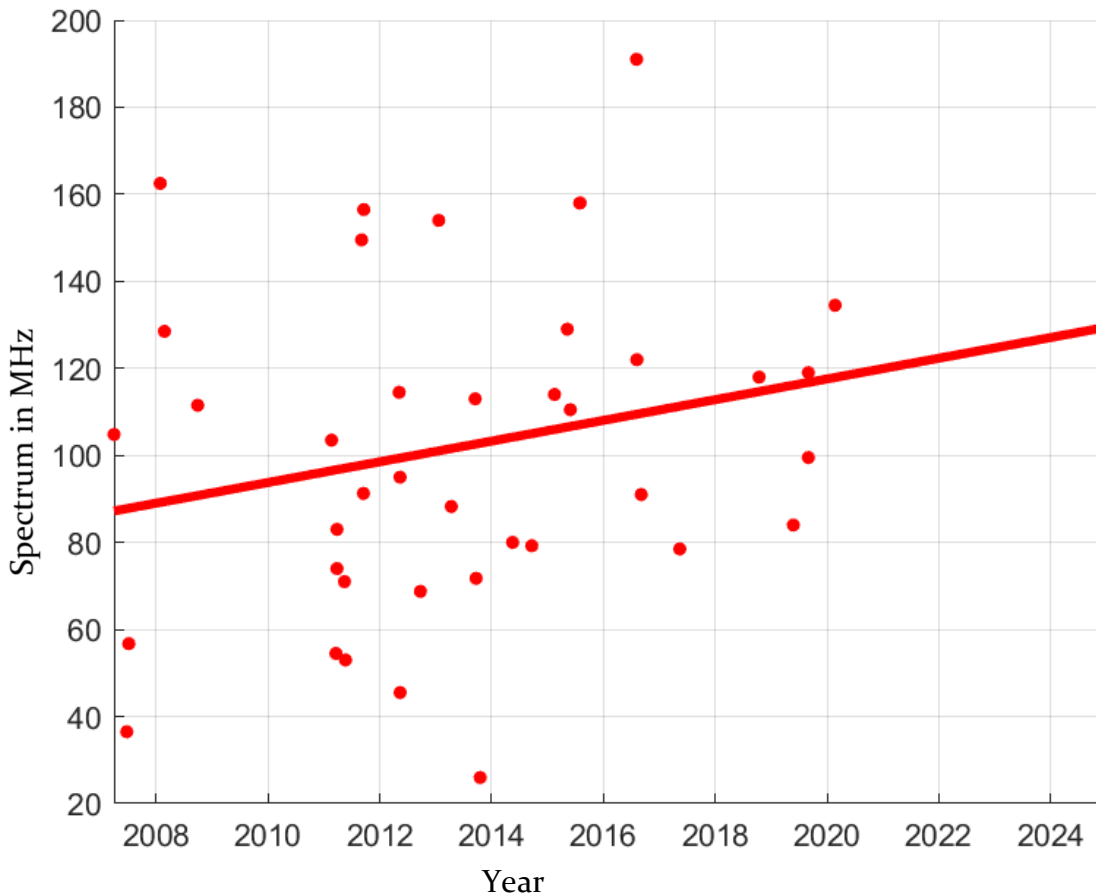


Figure 9.2: Linear regression of the spectrum demand of the coordinated links

When looking at Figure 9.2, the data point in the middle of the year 2016 stands out with a very high spectrum demand. This belongs to the "Wacken Open Air" (WOA) 2016 event, which must be seen as an exceptional event with particularly high requirements due to its size and structure.

Figure 9.3 clearly shows by drawing in the single (green) and double standard deviation (blue) that this event also represents an exceptional event stochastically. It is therefore to be expected, and is also shown in

Section 9.2, that the data from these events disproportionately influence forecasts for future spectrum requirements.

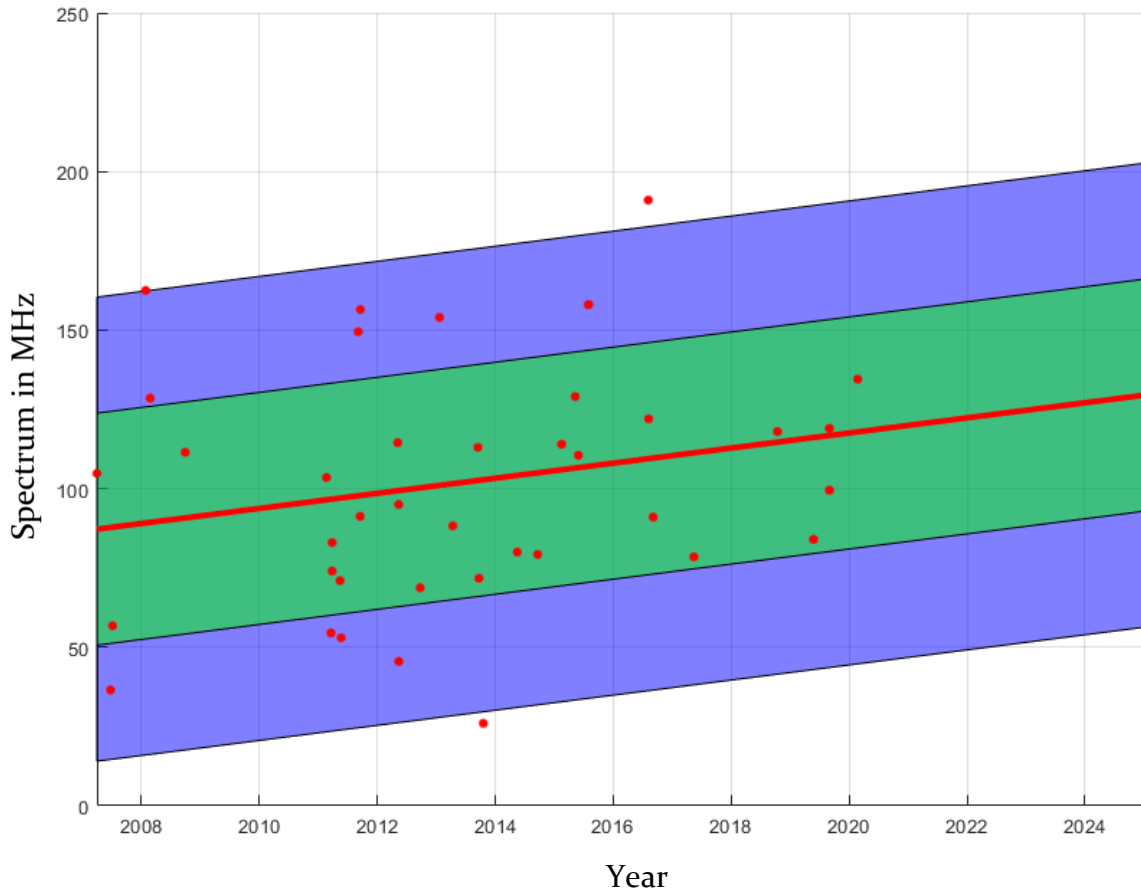


Figure 9.3: Linear regression with plotted standard deviations, $\pm\sigma$ green, $\pm 2\sigma$ blue

Thus, due to their structure but also based on stochastic considerations, these events are to be considered separately and are removed from the data for the following calculations. The data set contains 4 events of this type, so that the total number of events is reduced from 40 to 36 in the following.

9.2 Events in Germany 2007 - 2020 without Wacken Open Air

9.2.1 Germany Analysis base - Key data

Table 9.4: Germany - Analysis base

Event type	Different
Period	03.2007 – 03.2020
Recorded frequency range	470 – 862 MHz (total scanning bandwidth: 392 MHz)
Other participants in the frequency band	Broadcast stations, cellular (DD ₁ & DD ₂), other event productions PMSE
Coordination information	Mostly present. If not present, then 1.5 times the detected PMSE links were assumed.
Size of the data set	36 from 36 Events

9.2.2 Analysis results - Basic stochastic parameters

Table 9.5: Germany - Analysis results

Expected value	99.86 MHz
Standard deviation	33.23 MHz
Slope of the regression line	0.0031 MHz/day 1.2 MHz/year
Maximum frequency requirement	162.5 MHz (Lower Saxony state election 2008)

9.2.3 Linear regression of the coordinated links

On the same basis as in subsection 9.1.4, a linear regression is applied to the restricted data set to develop a forecast for the average spectrum demand in the future. Figure 9.4 shows the resulting regression line with associated single (green) and double standard deviation (blue) of the data. In addition, the upper limit of the spectrum available for the PMSE industry described in subsection 9.1.3 has been plotted (red).

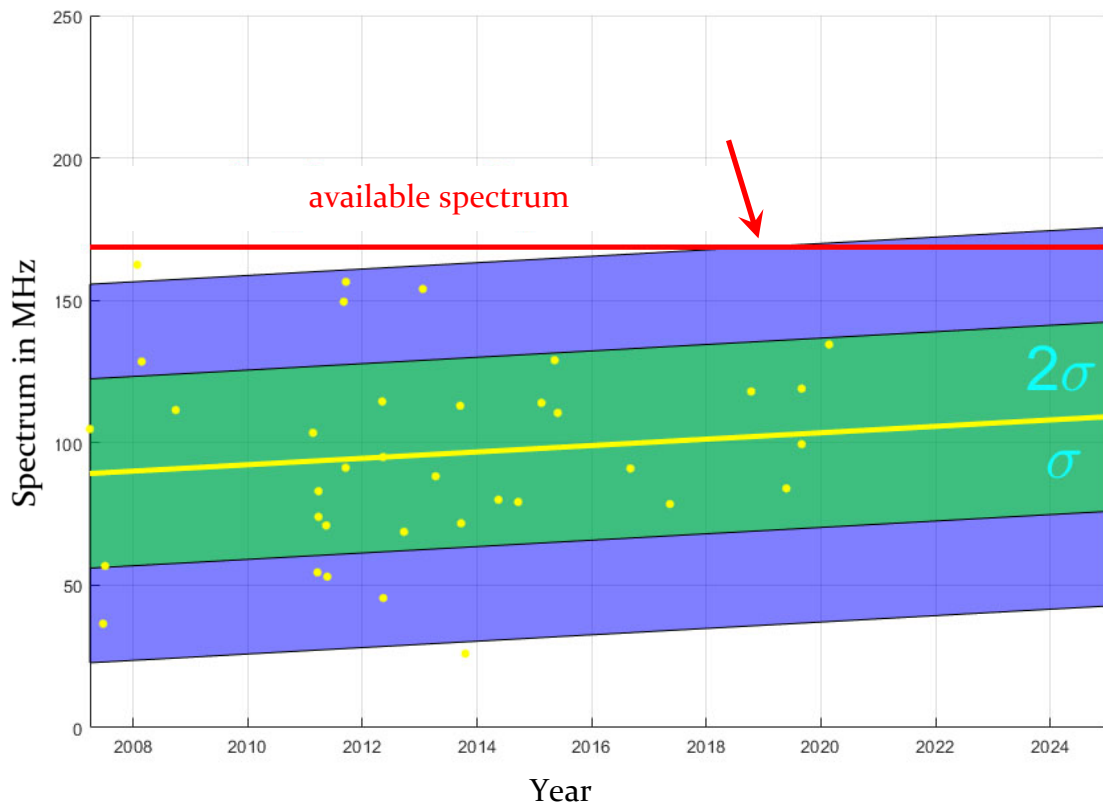


Figure 9.4: Linear regression of the coordinated spectrum compared in relation to the currently average available bandwidth, available spectrum in red

Here, despite the significantly lower increase in spectrum demand of approximately 1.2 MHz per year, an intersection between the upper limit and double the standard deviation can be seen in 2019. This means that a significant proportion of events from 2019 onwards will exceed the upper limit and thus on average will not be able to take place as planned. In addition, the available spectrum for many scenarios/locations is still significantly smaller, which leads to further problems. In the engineering discipline of machinery and automation, serious planning is based on the so-called “6-sigma design technique”, which considers a safety margin of $\pm 3\sigma$ (6σ design technique).

A spectrum need exceeding available spectrum can clearly be seen in the example of the Wacken Open Air 2016, described in subsection 9.1.4. An event of this format can only take place in this form because it is not hosted in a conurbation and can be organised in a relatively isolated manner. In an environment such as Frankfurt, a significantly higher demand by the broadcasters and a significantly higher level of interference from cellular and external events would have to be expected, so that the event would already be subject to severe restrictions at the current time. In numbers, a coordinated spectrum requirement of 191 MHz would stand opposite to an available spectrum of less than 100 MHz. There is a non-negligible “overbooking” of factor 1.9.

9.2.4 Forecast: Plannability of major events

Based on the results from the last section that large events such as the Wacken Open Air would not be plannable under certain conditions even at the current time, we want to take a stochastic look at the current and future plannability of large events in this chapter.

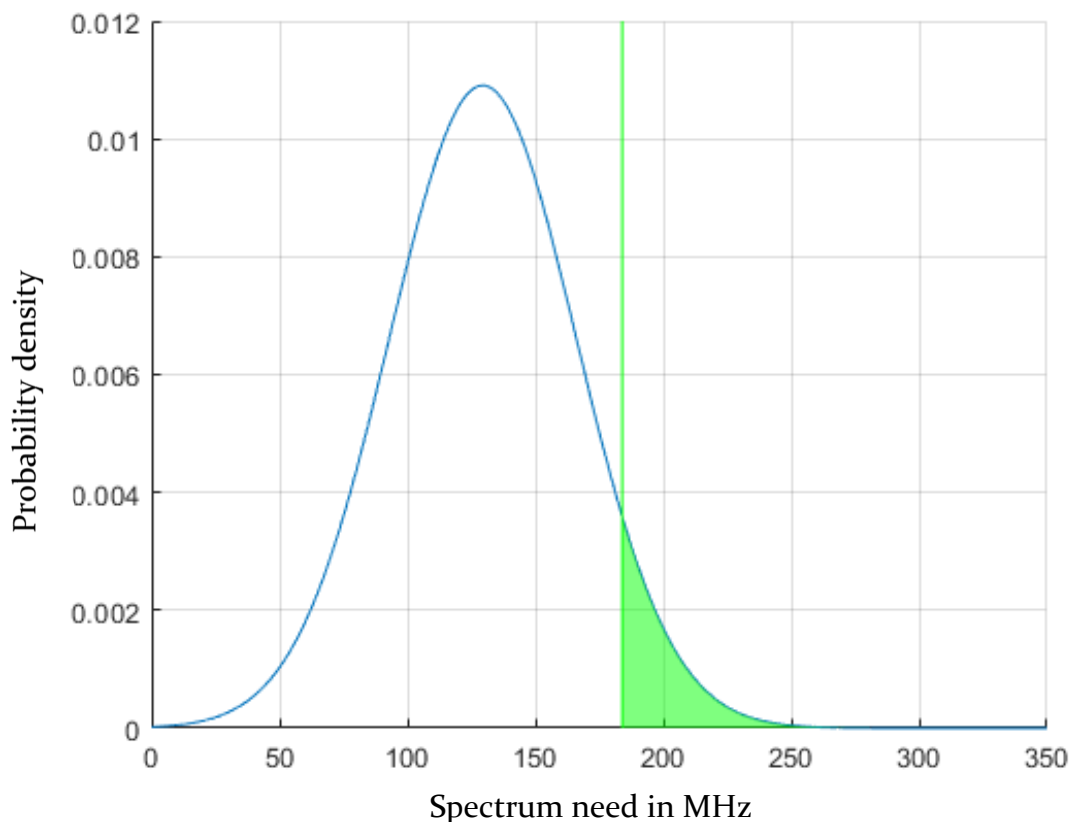


Figure 9.5: Probability above threshold 170 MHz (green)

The basis of our consideration is the assumption that the spectrum demand $X(t)$ for a randomly chosen event at time t is normally distributed:

$$X(t) \sim N(\mu(t), \sigma^2),$$

with expectation value $\mu(t)$ and variance σ^2 . We choose the root of the empirically determined variance of the entire data set as the standard deviation of the distribution. The expected value at time t results from the regression line as determined from the data set in Subsection 9.2.3.

By making this assumption, we are able to calculate the probability of having to plan an event that exceeds the upper limit of 170 MHz for any given point in time on the basis of the data set provided (cf. Figure 9.5).

For the period from 2007 to 2025, there is an expected rising curve of probability, as can be seen in Figure 9.6.

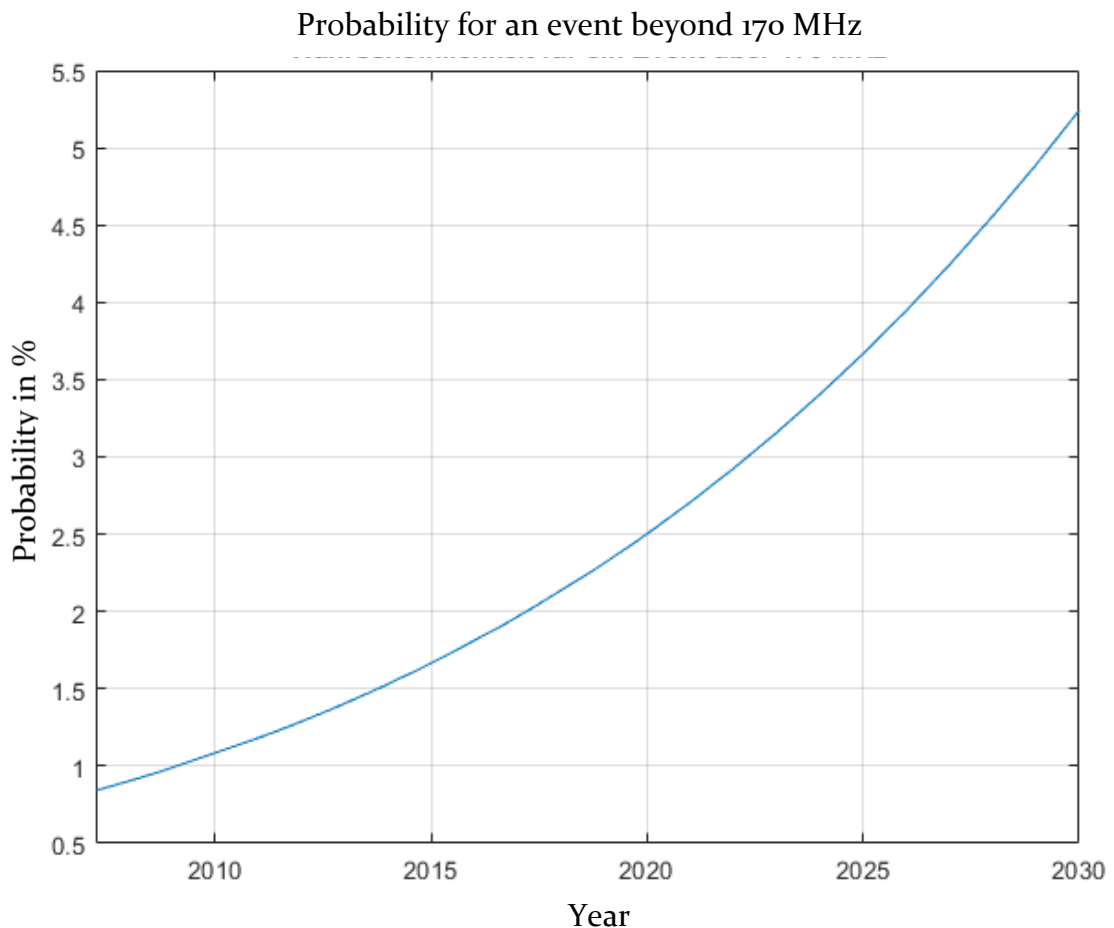


Figure 9.6: Probability of an event with planned spectrum requirements above the 170 MHz limit

While the proportion of events that cannot be planned was still less than 1% in 2007, it is already over 3% at the current time. With the emerging further development of the demand for spectrum due to ever larger events with further increasing technical equipment and desired level of audio quality and immersion, it is to be expected in 10 years that more than 5% of the events cannot take place as planned. This corresponds to every 20th event.

Through representing the spectrum demand by a stochastic random variable, it is also possible to make a statement about the plannability of events should the available spectrum continue to decrease. For this purpose, a certain time t is fixed and the upper limit is reduced step by step.

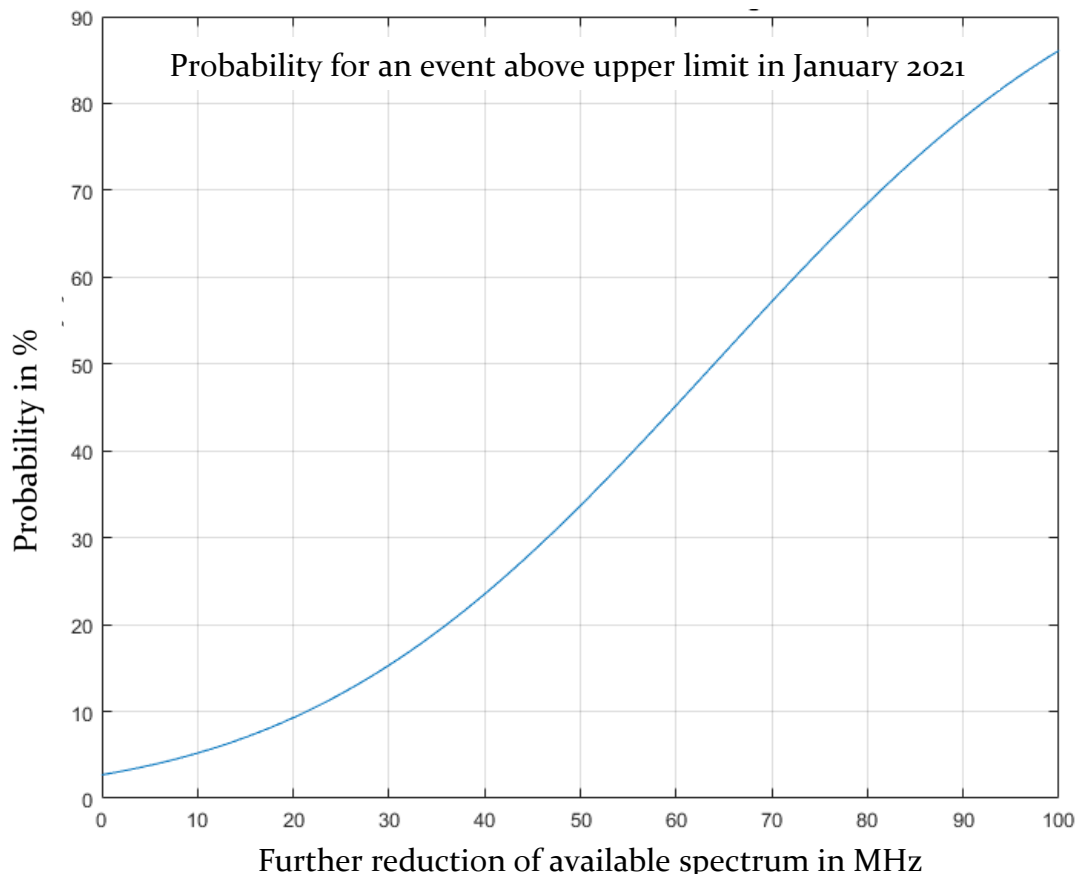


Figure 9.7: Probability of unplannable events with further reduction of the available spectrum

Figure 9.7 shows the result of this methodology for theoretical events around January 2021. Here, the zero value of the x-axis describes the status at January 2021 with an average available spectrum of 170 MHz. A probability of approx. 2.7% can be seen, as already determined in Figure

9.6. Any further restriction of the available spectrum (x-axis) inevitably leads to restrictions in event planning.

Already 25 MHz less spectrum, which would correspond to the elimination of the LTE II duplex gap, leads to the fact that at more than every 10th medium and large event, the organisers' creative possibilities are limited because there is not enough bandwidth available. Organisers in conurbations are already confronted with this fact today. Experience in Frankfurt area already shows that there is higher demand by broadcasting. As a result, a reduction of the available spectrum by 20...40 MHz can be assumed in conurbations, which in turn leads to restrictions for approx. 10...25% of all events.

The current considerations to allocate another 60 MHz in the UHF range to cellular in the future would inevitably lead to the fact that almost every second event would be restricted in its planning due to insufficient available spectrum. Large events such as music festivals would hardly be feasible in this constellation, even in rural areas. Events in large cities such as city festivals with a multitude of events organised in parallel would be almost impossible.

9.3 Restrictions

The calculations and estimates in sections 9.1 and 9.2 were made under certain assumptions and on the basis of a limited data set. However, the data set and the assumptions made from it are exclusively related to Germany. The demand of other participants in the frequency bands of the PMSE sector and the allocation of the frequencies themselves is completely different in other regions. Due to the event structure of the data set provided, the statements made in the previous chapters are not generally valid and must be understood in part in the correct context. Furthermore, the data set provided is limited to 40 events over 13 years and therefore only offers a limited insight into the totality of all events. In detail, the following limitations have to be considered.

9.3.1 Available spectrum

The available spectrum shown in section 9.1.3 refers exclusively to the current situation in Germany. In other countries and regions, a different constellation has to be considered. In addition, the estimation of demand by broadcasting is based exclusively on the 40 data points provided, which are partly located in the same way. Thus, from a

stochastic point of view, the broadcasting landscape in Germany is probably not fully represented by the data. Since technically a minimum demand of 48 MHz is given by broadcasting, it can be assumed that an average demand of 56.2 MHz is a suitable assumption. In addition, due to the insufficient measurement technology, it can be assumed that the interference from uncoordinated links tends to be underestimated. Especially in conurbations and at large events, it can be assumed that the interference factor is significantly higher than described by the data set.

9.3.2 Structure of the events

The data set made available to us reflecting Germany mainly contains events of medium and large structure. Thus, the data set is not representative for the entirety of all events in Germany. This can be illustrated by another data set provided, consisting of smaller and very large events from Switzerland. The key data of the Swiss data set are described in the following table:

Table 9.6: Swiss - key data

Period	06.2013 – 03.2020
Recorded frequency range	470...862 MHz (total scanning bandwidth 392 MHz)
Size of the data set	33 Events
Expected value: coordinated spectrum	64.48 MHz

Here, too, an increase in spectrum demand can be observed after classifying the data into large and small events, even if the expected value of the data is approx. 35 MHz lower than in the German data.

Nevertheless, the German data in itself represents a compact representative group. The statements in the first two sections of this chapter only need to be understood in the correct context of medium and large events. In particular, the statements about the plannability of large events in subsection 9.2.4 are only affected in their value by the event structure of the data.

9.4 Background information to statistical methodology

The methods applied in the previous sections are based on statistical views and commonly used statistical methods to abstract from specific events. Limits of the study and merits were mentioned. Outliers were excluded in determining trend lines for prognosis into future.

It was also justified why there is a bias that the spectrum need by PMSE is estimated too low. Thus the conclusions ignore that PMSE might realistically need even more spectrum.

Therefore, the conclusions drawn refer to a best case view. In reality the case might be worse, to what is forecasted.

9.5 Evaluation of the Swiss data

9.5.1 Swiss Analysis base - Key data

Table 9.7: Swiss - analysis base

Event type	Different
Period	June 2013 – March 2020
Recorded frequency range	470...862 MHz
Other participants in the frequency band	Local TV, IMT, other events
Coordination information	Mostly present. If not present, then 1.5 times the detected PMSE links were assumed.
Size of the data set	33 Events

9.5.2 Swiss analysis data - Basic stochastic parameters

Table 9.8: Swiss – stochastic results

Expectation value	64.48 MHz
Standard deviation	42.85 MHz
Slope of the regression line	-0.0023 MHz/day -0.81 MHz/year (decreasing)

The case for Swiss shows a slight decrease over time. However such a conclusion is barely justified due to massive spectrum refarmings going on and new assignments that took place during the years recorded.

9.5.3 Estimation of the available spectrum

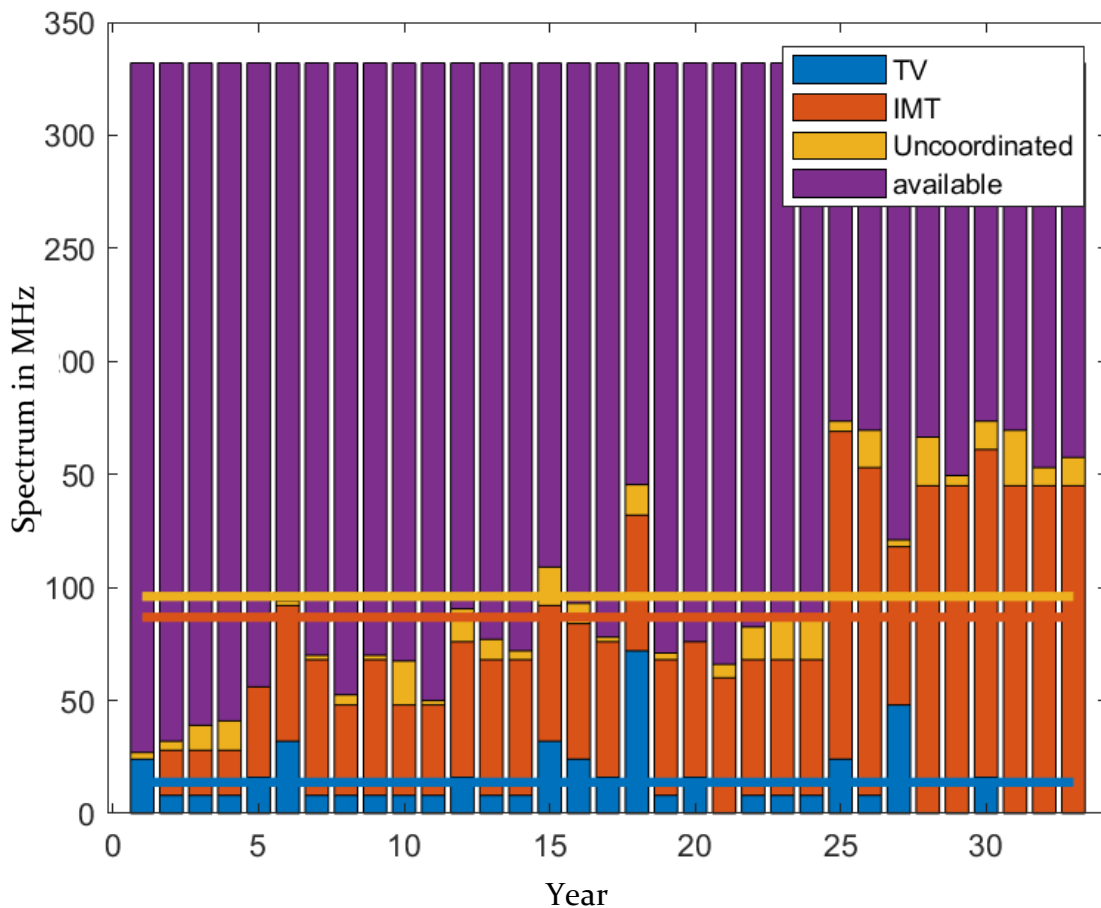


Figure 9.8: Frequency requirements of the other participants and the resulting available bandwidth for PMSE. In addition, average lines have been plotted

A linear regression of the spectrum demand of the other spectrum users does not make sense at this point, as due to local conditions there has

been a large increase in the spectrum taken up by cellular in recent years. It is very unlikely that the spectrum demand of cellular will continue to increase in this way.

9.5.4 Linear regression of the coordinated spectrum demand

Using the same methodology as for the data set of events in Germany, a linear regression was also carried out for this data set. The result can be seen in Figure 9.9.

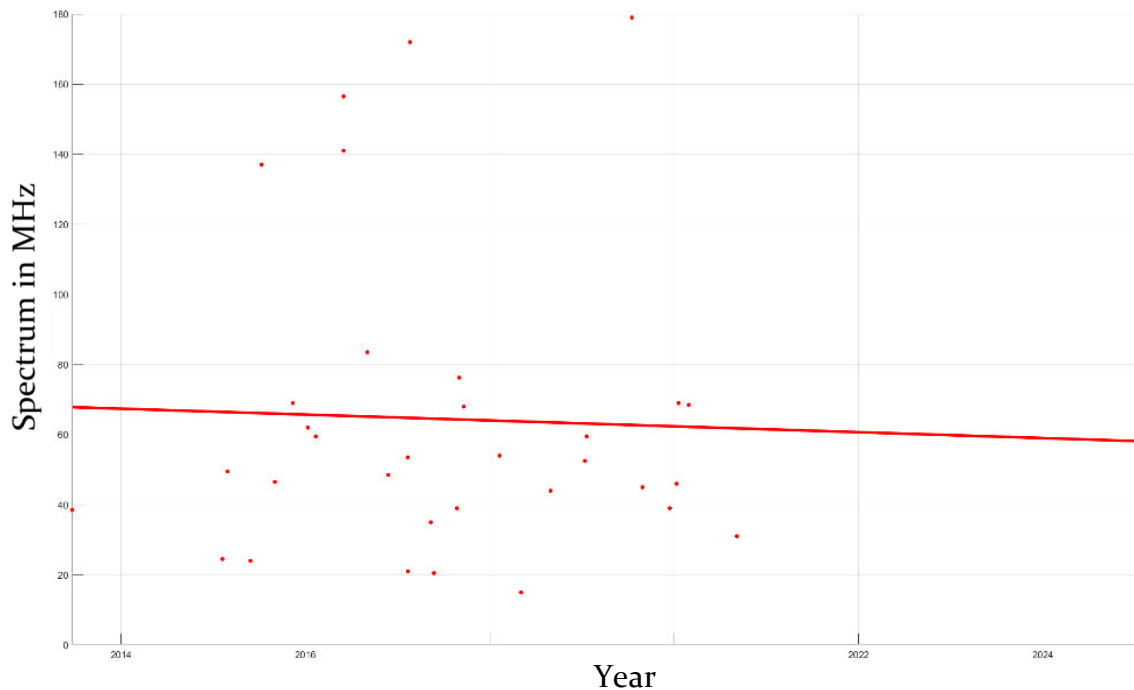


Figure 9.9: Linear regression of the coordinated spectrum for all Swiss events

Unfortunately, it becomes clear here that the data set for Switzerland is too small and too diverse. It can be assumed that the data is not representative.

- 1) The linear regression shows decreasing behaviour. This is due to the absence of large events with increased spectrum demand from February 2017 onwards, with the exception of a single event in 2019. An examination of the data set without large events can be found in the following section.
- 2) Large events and small events can be clearly classified in the data set. Events with medium demand are not present.

- 3) The mass of small events compared to large events is disproportionately large. Therefore, the data set does not take a balanced view. This statement is also backed by the average spectrum requirement of approx. 64 MHz compared to 100 MHz with German data.

9.5.5 Linear regression of data without major event

In the last subsection, it was determined during the data analysis that the data set is not representative in its entirety. The reason for this is the insufficient availability of data from large events, which is why a further analysis can only be made on the data of the small events.

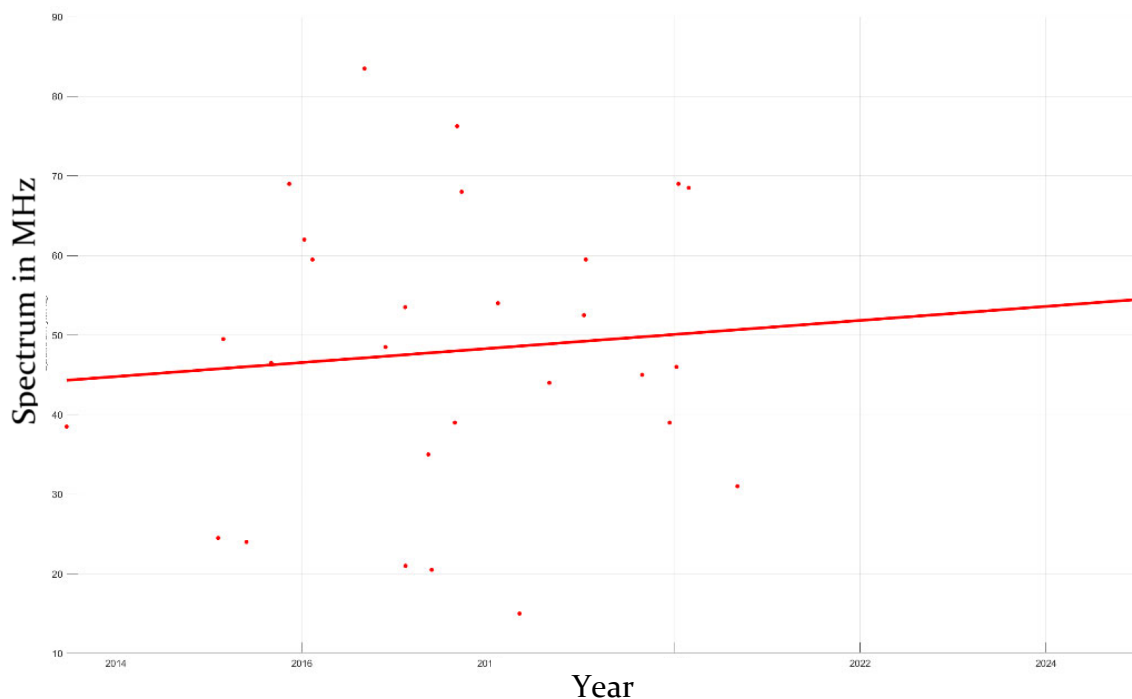


Figure 9.10: Linear regression of the spectrum demand of the Swiss small events.

Figure 9.10 shows the linear regression of the data where the expected increase in demand can be seen. In addition, the following stochastic key data emerge:

Table 9.9: Analysis results for small events

Expected value	47.94 MHz
Standard deviation	17.61 MHz
Slope of the regression line	0.0024 MHz/day 0.86 MHz/year (increasing)

10 Interpretation of PMSE spectrum situation

Based on analysis of spectrum scans from 2007 to 2020 in Chapter 9 it can be concluded that for Germany there is a growth in PMSE spectrum need by 1.2 to 2.3 MHz/year.

For Swiss a growth in PMSE spectrum need for small events of about 0.86 MHz/year was observed.

For Germany, it was deduced that already by Januar 2021 2.7% of events cannot take place as planned. A further reduction of PMSE spectrum by 25 MHz would lead to the situation that every 10th event cannot take place as planned.

If further 60 MHz would be assigned to other services like e.g. cellular assignment in 470...694 MHz, this would lead to the case that every second event cannot take place as planned. In conclusion, a further loss of UHF spectrum around 470...694 MHz would be a disaster for the event industry.

Large scale events like Olympic games, soccer games and ESC would no longer be possible in Germany. The event industry respective the Cultural and Creative Industry (CCI) would lose its ground.

The CCI has increasing need for spectrum. The event industry is growing economically and has already superseded the financial industry and needs more spectrum for sustained growth. Pulling spectrum away from the event industry would hinder economic growth.

Frequencies in UHF range cannot be substituted by frequencies at other bands as discussed in Section 2.5. Lower frequencies face large electromagnetic noise. Higher frequencies imply larger losses and directivity of antenna patterns with body worn equipment, which hinder movement of subjects and objects with wireless PMSE equipment. Therefore, UHF and especially the low-UHF range of 470...694 MHz cannot be given up for PMSE.

Above statement is also backed by a recent study at Berliner Hochschule für Technik [37, 38, 39]. The author of the study, the Bachelor student Mr. F. Glaß reports on interviews he conducted with PMSE frequency coordinators. The finding in the study is that the low-UHF frequency range 470...694 MHz is the most important frequency range for PMSE thanks to its superior radio propagation characteristics and availability

of a large contiguous chunk. These findings are consistent to the statements made in this study that the low-UHF range is of ultimate need for the PMSE community.

11 Summary and Recommendations

With the next sections, recommendations to politicians, to cellular infrastructure and phone suppliers, to PMSE equipment suppliers and regulators are provided. They represent the views of the authors based on this study findings.

11.1 To politicians

Spectrum Scans do not reveal the full situation of spectrum shortage in PMSE. Already today, artists are hindered in their artistic performance and excellence due to limited spectrum for PMSE. The problem of PMSE spectrum shortage is in place already today.

Instructors of large scale events cannot turn their creative ideas to reality due to limited number of available PMSE links. They downsize artistic performance of events in order not to run out of spectrum.

UHF Spectrum (DD₁₊₂) was sold too early. Selling spectrum is like “selling silver spoons” – it is impossible to satisfy exponential growth of cellular traffic with linear spectrum assignment. We need to take a radically different approach than releasing more spectrum to cellular. And we definitely shouldn't continue in this way as we did so far.

There are other ways for cellular to cope with increasing capacity demand. Relief can be provided by: MIMO, Massive MIMO, higher order modulation, codec/compression switch depending on terminal, small cells with network densification and mm-wave. Currently it takes too much time to set-up a new cellular base station. Approval processes for new base station sites need to be sped up.

MIMO and Massive MIMO by far have the highest potential in coping with exponential traffic growth in cellular. SDMA (Spatial Division Multiple Access) as offered by MIMO is the only way to serve increased traffic density (bit/s/Hz/km²).

The term “Digital dividend” is misleading. Money was earned on lowering QoE (Quality of Experience) for TV spectators, the end consumers. Watching Football games on DVB-T is worse compared to analogue TV especially with fast movements of ball and players.

IA (Intelligent Antenna) / MIMO / massive-MIMO solutions have a bad cost scaling. Research on efficient implementation of massive MIMO is

needed (see e.g. single RF MIMO Architectures). European and national funded research projects are needed. Politicians should support research in the area of HADB architectures (Hybrid Analog-Digital Beamforming).

5G is not the answer to PMSE needs. 5G mainly happens at higher spectrum 3..4 and 28 GHz, which is not suited for body worn PMSE equipment.

5G even at lower frequencies is not the solution yet for PMSE. Latency requirements of PMSE cannot be met with mainstream 5G equipment. Only in specialized tweaks of 5G equipment, PMSE requirements are met. But then more spectrum is needed for PMSE. Radio resource reservations are needed. Thus, satisfying stringent latency constraints of PMSE comes at the cost of additional spectrum.

Dedicated wideband radio solutions for PMSE like WMAS uses spectrum more efficiently than tweaking 5G for PMSE. PMSE therefore needs a long term perspective on large spectrum chunks to advance further. Trials in this direction can be observed already today, when looking at WMAS demos for PMSE. WMAS needs large spectrum chunks of 6, 8, 10 or 20 MHz to provide its full benefits. Large contiguous spectrum chunks are needed to draw high radio link robustness from frequency and interference diversity.

11.2 To cellular infrastructure providers

There is another option for meeting increased data demand and lowered costs for transporting data than more spectrum. Efficient implementations of MIMO and Massive MIMO, like Single RF MIMO [31] and HADB architectures have the potential to provide more capacity in the spectrum owned already.

Infrastructure suppliers need to work on cost reduction schemes for MIMO / mMIMO implementation based on architectural innovations with base stations.

11.3 To cellular smartphone providers

Instead of going to ever more complex schemes of intra and interband carrier aggregation (CA), higher order MIMO schemes should be implemented in smartphones, tablets, laptops. More antenna elements

will allow for more throughput and capacity due to exploring more parallel streams (Layers, Eigenmodes).

Fold Smartphones like getting more commodity also offer more space to implement more antennas.

It is unacceptable that in some Laptops second antenna port of modem module is left open and is not used for connection to further antenna.

New phones should support new 5G frequency bands 3.5 GHz and 28 GHz. This will offload traffic from UHF band.

Smartphone suppliers should be open to new ideas. If size constraints do not allow for more antenna elements with smartphones, remote radio heads for terminals like offered through the SUDAS approach of Fraunhofer IIS can provide relief.

11.4 To PMSE equipment providers

PMSE equipment should be designed for scalable QoE. In some cases like e.g. backstage communication and talkback lower QoE is sufficient. A dynamic in-situ adjustment of QoE will allow for dynamic adjustment of spectrum need. If used with large number of links trunking gains can be drawn. Variable QoE setting will allow for flexible radio resource consumption.

The event industry, resp. Cultural and Creative Industry is demanding solutions for advanced artistic performance and increased immersion. Future production tools must support this.

WMAS bears the potential to simplify work flows and enhance efficiency of spectrum use.

It is advisable to engage further frequency ranges and systems for side needs, e.g. DECT for work organization, security of events.

11.5 To standardization

Support for higher order Modulation and higher order MIMO schemes must become obligatory in cellular smartphones and base stations to enforce efficient spectrum use. Demanding that 4G equipment must at least support 2x2 MIMO was a good start, but this has to be extended to higher order schemes.

11.6 To regulators

Regulators cannot continue the way they have acted in the past. The exponential growth of cellular data traffic implies that spectrum to be released must also grow exponentially, which is unrealistic. There is not so much UHF spectrum left.

The linear assignment of spectrum to cellular as done so far by regulators is a lost game already today in light of exponential data traffic growth.

Spectrum still is licensed too cheap. Spectrum license costs for operators broken down to monthly subscriber tariffs are just on the ballparks of cents. If spectrum would be more costly than demand for advanced antenna architectures like MIMO and massive MIMO would raise. Advanced antenna options would be more cost attractive than more spectrum.

Regulators claim that the way they act is supporting innovation. Indeed as this study shows, the opposite happens. The way spectrum is licensed hinders innovation. As shown in Section 6.3 interest in advanced antenna solutions always vanishes after a spectrum auction.

Cellular and DTT are based on wideband physical layers allowing to profit from statistical multiplex of multiple media streams. PMSE must be given the same opportunity through deploying WMAS in large spectrum chunks. The traditional way of assigning small spectrum pieces to PMSE here and there is hindering innovations with PMSE radio equipment.

In order to make WMAS profit from frequency and interference diversity as a means for gaining robustness of transmission, sufficiently wide spectrum assignments are needed, e.g. 6, 8, 10, 15, 20 MHz as common with cellular and Broadcast.

For fairness reasons all systems whether cellular, DTT or PMSE must be given the chance of wideband physical layers.

The fact that the Cultural and Creative Industry has overtaken the financial sector in terms of gross value backs its economic relevance. This justifies assigning large spectrum chunks to PMSE at primary state.

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