

Srinuan, Chalita; Bohlin, Erik

Conference Paper

A country comparative study of spectrum re-farming: Implication for Thailand

22nd Biennial Conference of the International Telecommunications Society (ITS): "Beyond the Boundaries: Challenges for Business, Policy and Society", Seoul, Korea, 24th-27th June, 2018

Provided in Cooperation with:

International Telecommunications Society (ITS)

Suggested Citation: Srinuan, Chalita; Bohlin, Erik (2018) : A country comparative study of spectrum re-farming: Implication for Thailand, 22nd Biennial Conference of the International Telecommunications Society (ITS): "Beyond the Boundaries: Challenges for Business, Policy and Society", Seoul, Korea, 24th-27th June, 2018, International Telecommunications Society (ITS), Calgary

This Version is available at:

<http://hdl.handle.net/10419/190333>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.

A country comparative study of spectrum re-farming: Implication for Thailand

Chalita Srinuan*, Ph.D.
Faculty of Business Administration and Management
King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand
chalita.sr@kmitl.ac.th
*corresponding author

Erik Bohlin, Ph.D.
Department of Technology Management and Economics
Chalmers University of Technology, Gothenburg, Sweden
erik.bohlin@chalmers.se

Abstract— With the latest advances in mobile broadband brought by UMTS, HSDPA, and LTE, all radio communications make use of a highly regulated resource. Specific portions of that spectrum are allocated for use by competing uses, and it is a scarce and expensive resource. To deal with this scarcity, some countries have changed legislation so that other services can use portions of the spectrum initially allocated to a different service/technology. This is called re-farming: repurposing a frequency that was initially allocated to one technology for another one. Re-farming is a cost-effective way to increase capacity for mobile use without the need for market players to apply for new spectrum. This issue is becoming crucial and important for the national regulatory body in every country including Thailand to manage their scarce resource with fair and clear rule. With the exponential growth in mobile broadband (MBB) services in Thailand, it places enormous demand on the need to expand the capacity of the MBB sites with the available spectrum resources. Most often, there is a dire need to acquire additional spectrum to fulfill the demand in capacity growth. Spectrum auction prices are very expensive in principle; hence operators need to maximize the available spectrum resources for better utilization. To accelerate the 3G&4G network, spectrum re-farming is needed in Thailand. This study aims to explore the similarity and difference of the objective, spectrum target and approach of spectrum re-farming in the selected countries from each region which are USA, Germany, France and Australia. Public consultation documents and related literature were used for data collection in the selected country. Additional qualitative method which was focus group was employed for data analysis in Thailand. Experience of re-farming from selected countries is expected to provide lessons for the Thai national regulatory authority (NRA) in terms of improving quality of service and coverage and create a fair competition environment among service provider.

Keywords— *Spectrum re-farming, Comparative study, Thailand*

1. Introduction

Over the past two decades, mobile telecommunications have significantly changed from the analog systems which carrying only voice to more robust voice and text systems, and enabling to the latest advances in mobile broadband (MBB) brought by various technologies. Mobile services make use of a highly regulated resource with a limited portion of the spectrum. National Regulatory Agencies (NRAs) typically allocate a portions spectrum to use by specific technologies due to it is a scarce and expensive resource for example GSM bands in 800 – 900 MHz and 1800 – 1900 MHz frequencies, UMTS bands are typically within the 1900/2100 MHz frequencies and LTE is found at 700/1900/2100/2400 MHz in the spectrum (Viavi, 2015).

To deal with this scarcity, some NRAs both in developed countries (Bohlin, Blackman, Forge & Renda, 2007; Kwerel & William, 2002; Lundborg, Reichl & Ruhle, 2012, Minervini, 2014) and emerging countries (Sridhar & Prasad, 2011; Hazlett, Giancarlo & Wayne, 2014; Minervini, 2014; Jain & Dara, 2017) have been deregulated the spectrum management process from as administrative to a market regime such as spectrum auction. Though the auctioning of the spectrum allocate spectrum to those who are best able to use it in the highest value, but the case of under-utilized spectrum might be occurred. Thus, the complementary spectrum management such as spectrum refarming recently has been considered by NRAs.

Some countries have changed legislation so that other services can use portions of the spectrum initially allocated to a different service/technology. This is called refarming or repurposing a frequency that was initially allocated to one technology for another one. For example, an operator may have a license to operate on the 900 MHz spectrum for GSM. To better deploy UMTS or LTE, the operator could potentially free some of the GSM capacity and allocate it to LTE or UMTS¹. Therefore, the spectrum mix of a mobile network operator (MNO) can spread over these bands recently as a technology and service neutrality service (Lundborg et al. 2012).

Refarming (re-deployment) is a cost-effective way to increase capacity for mobile telecommunication services without the need to auctioning a new spectrum. MNOs economically provide mobile service over much greater areas and more cost-effectively. However, spectrum refarming also presents challenges. Firstly, the MNOs must have sufficient contiguous spectrum to support the simultaneous operation of two or three technologies in a frequency band. Other challenges include avoiding disruption to existing users on the band/technology that will be refarmed and encouraging them to migrate to new services. The MNOs need to maintain the quality of service as the process takes place, not compromising customer satisfaction, experience and avoiding service degradation. Some handsets and machine-to-machine devices cannot work with multiple bands or must remain on the old technology. This can be a big challenge which importantly affect MNO revenues, spectrum management policy and level of competition.

¹ Directive 2009/114/EC of the European Parliament and of the council of 16 September amending Council Directive 87/372/EEC on the frequency bands to be reserved for the coordinated introduction of public pan-European cellular digital band mobile community. Official Journal of the EU, L 274/25 of 20 October 2009.

In this paper, the spectrum refarming mechanism in selected countries-USA, Germany, France and Australia are critically reviewed together with the re-farming situation and lesson learn for Thailand are highlighted. The objective is to provide lessons learn in spectrum refarming policy for the NRAs in emerging country which are a few literatures covered currently. Findings will be benefited in terms of managing the scare resource with fair and clear rule which enabling the good quality of service and create a fair competition environment in mobile service.

The remainder of this paper is organized as follows. Section II reviews prior studies on spectrum refarming both empirical studies in selected countries and related economic theories. Section 3 presents status of Thailand spectrum liberalization. Section 4 illustrates possibility of spectrum refarming in Thailand. The concluding section summarized the finding followed by policy recommendation.

2. Prior Studies

2.1 Overview of spectrum refarming and international practices

Analysys Mason (2015) reported the MBB in the Asia-Pacific region will grow at a CAGR of 6% while data traffic will grow at 46%. With the exponential growth in MBB services, it places enormous demand on the need to expand the capacity of the MBB sites with the available spectrum resources. Most often, there is a dire need to acquire additional spectrum to fulfill the demand in capacity growth. Spectrum auction prices are very expensive in principle; hence operators need to maximize the available spectrum resources for better utilization. To accelerate the 3G&4G network, spectrum refarming is needed.

Medeisis and Bozsóki (2015) noted that various economic spectrum management tools are by now well established and tested. It can be invoked in three different stages of the spectrum use cycle. Firstly, to increase efficiency of initial spectrum distribution in the licensing process (i.e. auctions). Secondly, to increase efficiency of spectrum use by the license holder (i.e. Administrative Incentive Pricing (AIP)). Last;y, to increase timeliness and efficiency of re-distribution of inefficiently used spectrum (i.e.AIP and re-farming tools). NRAs have been allowed MNOs to refarm their existing frequency band for the new services. The availability of this new spectrum is creating a range of opportunities for incumbent and challenger MNOs alike to improve their competitive market position.

Spectrum refarming is one of national spectrum management instrument which combines administrative, financial, and technical measures aimed at vacating users or equipment of existing frequency assignments either completely or partially from a frequency band. With substantial increase in number of mobile connection and traffic per connection worldwide, spectrum refarming is considered a powerful and innovative approach to manage the spectrum dynamically to make it available for newer applications such as LTE and digital broadcasting etc. These new applications have a tremendous impact on the development of the countries. The frequency band may then be allocated to the same or different radio service(s). The different elements to be considered are (a) National plans on new radio

technology implementations; (b) Obsolete technologies; (c) The best international practice; (d.) Results of public consultation (TRAI, 2010). International practices are reviewed as follows;

2.1.1 France

France presented a success story of operator-driven in refarming of the 900/1800 MHz. All 2G licensee were renewed in their licenses which scheduled to expire in 2006. ARCEP-French NRA launched a public consultation in July 2003 to initiate the renewal process. ARCEP had a policy of promoting equitable spectrum holdings across operators through the refarming process. ARCEP levied fee plus tax on sales for renewal on the new 3G licensees. Renewal applied for 15 years from March 2006. License obligation and roll out were imposed for renewal (NERA, 2011). The new license allows for new technology deployment, but all licensees focused on reuse of 2G for 3G (UMTS) services. Refarming in the 1800MHz band was not implemented as none of the incumbent operator have requested at that time.

In 2013, ARCEP made two decisions. Firstly, authorizing to SFR and Orange France for refarming the 1800MHz band for LTE use from 25 May 2016, if they give some of the spectrum to smaller operator -Free Mobile. Another decision is allowing Bouygues Telecom to start offering 1800MHz LTE from 1 October 2013, while the 5MHz of spectrum it returned was awarded to Free Mobile in December 2014². ARCEP processed this refarming to ensure equality between operators and the conditions for effective competition in the mobile market. At the end, three largest operators (Orange, SFR and Bouygues Telecom) each hold 20 MHz, while smaller rival Free Mobile has 15 MHz³.

The concept of a redeployment fund to compensate spectrum users for having to hand back spectrum was introduced in France. This approach provides several possibilities for implementing redeployment in a shorter time-scale than waiting for the expiry of a licence. A redeployment fund can be funded from several different sources for example: a) the new entrants could pay into the fund collectively, b) all licence holders could pay via part of the licence fee, c) spectrum pricing fees could be transferred to the redeployment fund or d) fees from auctioning of licences or frequency bands could be transferred to the redeployment fund. While a redeployment fund can provide a convenient means to speed up the spectrum redeployment process, it is not a universal remedy. Redeployment funds may not be sufficiently strong to pay for refarming in other than limited cases. The fund will need to be managed and there may be concerns over transparency. Therefore, evaluation of the various cost elements and redeployment principles; a schedule for the redeployment operation; the supervision of the procedure and managing the redeployment fund are the important tasks which the NRA need to be carried out (ITU-R SM.1603-2, 2014)

² <https://www.telegeography.com/products/commsupdate/articles/2015/08/07/arcep-authorises-sfr-orange-to-refarm-1800mhz-spectrum/>

³ <https://www.mobileworldlive.com/featured-content/top-three/french-regulator-green-lights-orange-sfr-spectrum-refarming/>

2.1.2 Germany

Reforming the 800MHz band in Germany was aimed for using the spectrum as a means of providing universal broadband access across the rural areas of Germany which driven by the the government broadband strategy. However, the reforming process was complicated due to the separation regulation responsibility between the broadcasting , which is undertaken by Federal States (Bundesländer) and licensing of spectrum for electronic communications services, which undertaken by the national government and the NRA-BNetzA. It means that BNetzA could only be used this band if the Federal States agreed and the demand for capacity for broadcasting transmissions were satisfied. The Federal States released its broadcast deployment plan earlier in 2008 on deploy six digital terrestrial television (DTT) and one mobile TV (DVBH) multiplexes. It indicated that all spectrum was occupied. Then, the parliament has to take role as the government plan to allocate broadcasting services to mobile services (Aetha, 2011a).

In June 2009, the Federal States adopted the national government's proposals. The 800 MHz band was awarded in May 2010 in a combined auction with spectrum in the 1800MHz, 2.1GHz and 2.6GHz bands, resulting in a total of 360MHz of spectrum being auctioned together (OECD, 2013). A significant coverage obligation is one key aspect of the license for 800MHz spectrum. All the coverage obligations have to be met by 2016 at the latest. The mandated coverage was specified in rural areas of each Federal State, prior to the deployment of such services in the main cities to ensure that the citizens in these rural regions had access to high-speed Internet services (Brugger & Kluth, 2010; Dotecon, 2012). The auction revenue of 800 MHz band was counted as over 80 percent of the total auction revenue. As illustrated by the bidding price, it is considered that 800MHz is an important frequency band for mobile services (BEREC, 2011). Some of auction revenues were divided to the Federal States which reflected as a compensation fee for refarming.

The process of clearing the 800 MHz band not only affects the households and broadcasters on analogue switch-off, but it also affected the use of program-making and special events (PMSE). The compensation was implemented only for the broadcaster and PMSE users, however. The households did not get subsidy on set-top box due to its cost rapidly fall together with aggressive market strategy of the broadcasting transition by the Federal States. So, impact on households was minimized. Broadcasters got financial incentive to analog switch off and use new platform. PMSE users are typically make use of the spectrum on a license-exempt basis and they are not protected from any interference with other authorized (primary) uses in the band. Therefore, the allocation of the 800MHz band for mobile services raised concerns on the frequency interference and this risk was not aware by users. A compensation mechanism for migration cost and criteria were set (GSMA, 2011).

2.1.3 Australia

In Australia, the Radiocommunications (Spectrum re-allocation) declarations (Declaration No.1 of 2011 and No.2 of 2011) which related to the 700 MHz band and 2.5 GHz were proposed by Australian Communications and Media Authority (ACMA) (ACMA, 2012).

Both bands were allocated for issuing as spectrum license. However, there were several different licenses actively operating in these frequency bands. The mechanism used to clear the services in each band depends on the type of license. ACMA has consulted extensively with stakeholders about its plans for the re-allocation of these bands, 700 MHz band including the marketing plan⁴. A variety of communication methods have been used to reach as many stakeholders as possible at each stage of the re-allocation planning process. ACMA began its public consultation in October 2010.

The 700 MHz band was occupied by the commercial, national or community television broadcasting and low interference potential devices. The clearing process began from moving broadcasting services to other channels, which occurred on an area-by-area basis, is referred to as restack. To accelerate the clearing process of 700 MHz band, government provided a financial incentive together with a clear timetable of restack implementation for broadcasting industry to ensure the on timely clearing process with minimal disruption for viewer (ACMA, 2013). At the same time, ACMA made alternative bands available for the apparatus license in 2.5GHz to relocate to. Cancelling all the licensees made the spectrum free for new uses, especially wireless access services (Aetha, 2011b).

ACMA auctioned spectrum in the 700 MHz and the 2.5 GHz band to new licensees using a combinatorial clock auction (CCA) format in April 2013. Four applicants (Optus, Telstra, TPG Internet and Vodafone Hutchinson Australia (VHA) applied to participate in the auction. However, VHA withdrew before the auction. The auction process ran smoothly and resulted in the three remaining bidders, Optus Mobile, Telstra and TPG Internet securing the reallocated spectrum in the auction⁵. The residual 700 MHz band spectrum from the 2013 digital dividend auction was auctioned in 2017. All lots were sold to two successful bidders which are TPG and Vodafone Hutchinson Australia (VHA)⁶.

2.1.4 The United States

Major refarming in the US can be categorized into two events. First is the relocation of 1710-1755 MHz band for commercial use. The Federal Communications Commission (FCC) discussed reallocating several bands for new advanced mobile and fixed communications services, including the 1710-1755 MHz band, which had been identified for transfer from Federal Government to mixed use in 1995, paired with the 2110-2150/2160-2165 MHz bands, which had been identified for reallocation by the Commission under its Emerging Technologies proceeding since 2001 (FCC, 2001a).

The main users of 1710-1755 MHz band were the government agencies. The relocation process started from March 2007 to December 2014. According to the Commercial Spectrum Enhancement Act (CSEA), the Spectrum Relocation Fund (SRF) provides a funding

⁶ <https://www.acma.gov.au/theACMA/auction-summary-700-mhz-residual-lots-april-2017>

mechanism for relocation cost and authorizes to be auctioned for commercial purposes. The Office of Management and Budget (OMB) were responsible for transferring relocation expenses from the SRF to agencies (OMB, 2007). United States Government Accountability Office (GAO) was directly involved for reviewing the costs to relocate federal spectrum users and revenues from spectrum auctions in order to ensure that auction revenues will be exceeded relocation costs and relocation cost estimation is a sustainable approach (GAO, 2013). In 2002, FCC designated the spectrum for Advanced Wireless Services (AWS) and the auction held in 2006 and 2008. The auction revenue was deposited back in the SRF in accordance with the CSEA (Prizker & Strickling, 2015). A portion of the auction proceeds was used to facilitate relocation of FCC systems.

Second refarming event is the relocation of 700 MHz band. In 2002, FCC re-allocated the 698-746 MHz band (Lower 700 MHz band) that was originally used by TV Channels 52-59. The upper band was for TV Channels 60-69 (FCC, 2001b). The lower band is 48 MHz while upper band is 60 MHz. Of the total 60 MHz, 24 MHz of the spectrum is reserved for public safety, while rest is going to be auctioned off. The U.S. House of Representatives approved a budget for analog switch-off in 2006. In March 2008, the FCC auctioned spectrum in the 700 MHz block or known as Auction 73, which had previously been allocated to analog television. Auction generated \$19.6 billion in revenue, nearly double prior estimates and the highest amount for any U.S. spectrum auction (Eisenach, 2011).

During the relocation process, the FCC placed rules on public safety for auction (FCC, 2017) and introduced legislation to reallocate the spectrum from commercial to public safety use and to use the proceeds from and provide funding to support an interoperable public safety network.

From the above international practices, it indicated that initiation of spectrum refarming can be driven by mobile consumer and consumer. NRAs and the governments confront with challenges during the relocation process. Different action and refarming mechanism for refarming are used as shown in Table 1.

Table 1: Key findings of the international case studies

Country	Refarmed Spectrum band	Rational for Refarming	Challenges on refarming	Refarming mechanism
France	800MHz	Clearance for use by mobile broadband	Clearing historic users including PMSE and military.	Redeployment fund implementation. Sources of fund came from government.
Germany	800MHz	Clearance for use by mobile broadband	Clearing historic users including federal state broadcasters. Separation regulation responsibility between the broadcasting and spectrum licensing	Redeployment Funding implementation. Sources of fund came from government and auction.
Australia	700 MHz	Clearance for use by mobile	Clearing historic users including commercial, national or community	Redeployment fund implementation.

Country	Reformed Spectrum band	Rational for Refarming	Challenges on refarming	Refarming mechanism
		broadband	television broadcasting and low interference potential devices Affecting apparatus licenses for commercial, national or community broadcasting services Affecting apparatus licenses for the retransmission of television broadcasting services, temporary delivery of commercial television services in digital mode or delivery of open narrowcasting services Affecting class licenses for low interference potential devices	Sources of fund came from government. Relocation to new frequency
	2.5GHz	Clearance for use by mobile broadband	Apparatus licenses for electronic news gathering and other services	Relocation to new frequency
US.	700 MHz	Clearance for use by mobile broadband	Spectrum Interference	Auction
	1710-1755 MHz	clearance for use by mobile broadband	Time consuming (up to 1 year) for historic user clearance since all of them were government agencies.	Spectrum Relocation Fund

Besides, it is clearly showed that the successful of frequency refarming should align with the national and international frequency plan. NRAs also need to inform and consult industry closely to avoid the delay of relocation. It is reasonable for NRAs to aid existing spectrum holders to migrate their systems and services to alternative bands and technology during a refarming exercise. However, this is usually done by providing adequate migration time and alternative frequencies.

2.2 Economic Theory of Spectrum Refarm

This section refers to two literature which are Cramton et al. (1998) and ITU-R SM.1603-2 (2014). First study showed applying the contract theory in bargaining and another is recommendation to implement the refarming policy.

Spectrum refarming is bargaining game of asymmetric information between incumbent (i.e. the incumbent of the existing service) and entrant (i.e. removing the incumbent) in private spectrum value. Cost of relocating (i.e. relocation of service, terminate service and accommodate service) is occurring in which this value is known by all agent and calculated by third party. Incumbents will not agree if they are not providing share of the gain from reallocation. There are three alternative policies including the right-to-stay (incumbents can continue their existing service according to the terms of license) and the right-to-move with or without compensation (entrants have right to clear the incumbent and is do/not required to compensation). The right-to-move with compensation is efficient policy because it provides

bargaining power to the entrant and focuses on the cost of relocation rather than the spectrum value of the entrant.

FCC applied the delayed right-to-move with compensation in Personal Communications Service (PCS). FCC offered the right-to-stay in limited time first and then imposing the right-to-move with compensation. This policy is desirable in political views in negotiation to the incumbent can get a premium above relocation cost. The policy results in encourage voluntary settlements and keep FCC out of resolving dispute in individual case. To reduce over this premium, however, is shorter the right of stay period.

Another example is the evidence of combining reform and auction together in the FCC Auction 73. This method gives new acquired spectrum to pay when spectrum is available reform and auction together. It gives the new acquired spectrum pay when spectrum is available. Cramton et al. (1998) suggest that the mechanism (called right-to-move with compensation) will make negotiation easily by old right of use and new acquired spectrum being better-off, however, it must to limit inefficiency of transiting the end-user.

Recommendation of ITU-R is practical process on spectrum reform or spectrum redeployment. Spectrum reform is occurring when available for introducing a change in spectrum use. It is necessary to use a supporting mechanism to speed up the reform process. New entrant compensating to existing spectrum user has been used in some country to speed-up the process such as Bulgaria, Finland, France, Israel, Italy, Jordan, the U.K. and The U.S.A. Moreover, the relocation should make known before the auction led to marginal cost be associated with such relocation or with modification accommodate in anticipation if it is necessary. In addition, reform fund in some countries has been established by different source such as new entrant, license fee, spectrum fee, fee from auction. However, there are two concerns on the existence of the fund. Firstly, the transparency may increase the effort and cost. Another one is the size of fund which may distort the market value of the spectrum and then prolong the redeployment process.

France experience is also reported by ITU-R as interesting point in cost of reform. There two methods to apply including residual book value (RBV) and residual economic value (REV). The RBV is consisting of three parts: (1) operating cost of moving (spectrum applied for either existing service or new service/technology) plus (2) capital value on equipment ready for use minus depreciation and minus (3) efficiency value by replacement cost of equipment that equipment ready for use being not modern technology. The REV is likely to RBV but, it should be considering with the fact that life of equipment differs from the life used for accounting purpose. In addition, the cost may not involve the depreciation because it is a part of sunk cost. Indeed, the reform should be incentive to remove by using fair compensation that comparison between cost of move if reform and cost of renewing equipment unless reform.

Specifically, the compensation cost need to be covered the public interest if they are the historical users. It should not limit to only the spectrum right of private use. For example, the switching from analog TV to digital TV of household was compensation by compatible

equipment (or coupon for buying compatible equipment) such as Germany in 2009 and USA in 2008 to limit spectrum refarming inefficiency. The refarm fund in many countries (i.e. France and the US.) was established to avoid insufficient auction revenue for compensation. The budget of compensation could come from many sources such as government budget, spectrum auction (or combination) and direct from incentive auction.

Recent incentive auction of FCC in 2017 applied market mechanism for compensation. Cramton et al. (2015) showed that this auction design give incentive to the broadcaster in participation and to clear spectrum at a cost within plausible revenues. Indeed, no one solution fits all in the spectrum refarm process. Although the main objective is to increase the availability and use of IMT spectrum band but source of spectrum and impact of refarming may different from country to country. However, the compensation process is a must task because it is stakeholder costly affected.

Thus, relevant economic theories revealed the spectrum refarming involves the bargaining theory and asymmetric information theory. Spectrum refarming is not necessarily a simple task and an administration may face several difficulties that can complicate, delay and even disrupt the process. The administration is encouraged to use spectrum monitoring data to supplement other data when considering redeployment. The main problems relating to spectrum refarming occur when insufficient time is available for introducing a change in spectrum use, and it is necessary to use a supporting mechanism to speed up the redeployment process. However, the use of such supporting mechanisms can lead to objections from new or existing users about the consequent expenditure and inconvenience; it may require as much, if not more, management effort than the redeployment process. The benefits of spectrum refarming for improved quality of service and coverage are well understood. However, these benefits need to be weighed against the challenges faced by each mobile operator during the planning and execution of a spectrum refarming activity (ITU-R SM.1603-2, 2014)

3.Current Status of Thailand Spectrum Liberalization

Spectrum refarming is a process of spectrum liberalization. It introduces of technology and service neutrality, gives spectrum users greater flexibility over how to use the spectrum they hold, in terms of the service or technology they deploy. As such it can help to bring spectrum into use for new technologies and applications quicker than regulatory measures requiring more direct intervention. It also gives spectrum users greater freedom to respond dynamically to changes in consumer demand over time, rather than relying on regulatory intervention which can be slow, burdensome and costly.

In Thailand, huge usage of data in mobile service requires more spectrums. Data of use per user increases from less 1 GB per month in 2012 to over 6 GB per month in 2017 as shown in Fig. 1. This trend is similar other countries (GSMA, 2018). However, the spectrum refarm remains an instant policy.

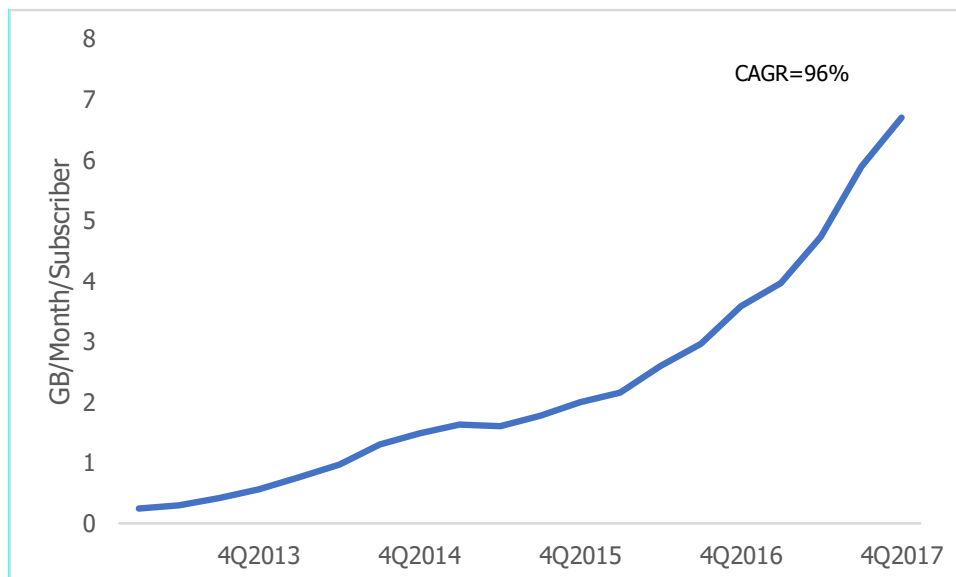


Fig. 1 Average Data per Subscriber of Thailand

Source: GSMA (2018) <https://www.gsmainelligence.com/>

Note: CAGR is annual calculation.

According to ITU-R SM.1603-2 (2014), the total spectrums requiring for two Radio Access Technique Groups including RATG-1 (Pre-IMT system, IMT-2000 and its enhancements) and RATG-2 (IMT-Advanced) are 1340 MHz in lower user density setting (user/km²) and 1960 MHz in higher user density setting. It indicates additional mobile spectrum is needed for Thailand as shown in Table 2. Analysys Mason (2015) and NERA (2017) also confirmed that the amount of the total spectrum assigned for all MNOs in Thailand is significant below among Asia-Pacific countries. It may slow down the deployment of MNOs and the service availability.

Table 2: Spectrum Requirement for Thailand

Setting	Total Spectrum Requirement in the year 2020 (ITU)	Future Spectrum Requirement for Thailand*
Lower User Density Setting	1340 MHz	595 MHz
Higher User Density Setting	1960 MHz	1215 MHz

Source: ITU-R M.2290 (2014), NBTC (2017) and compiled by authors

Note: * Calculation bases on totally possible spectrum for IMT.

Specifically, current usage of spectrum among MNOs can be illustrated as shown in Table3. Table 3 presents that the stated-owned company has offered and collaborated with the MNOs on capacity in order to save their loss instead of return the spectrum to the NRA. The scare of spectrum is an urgent concern for the NRA and the unequally of spectrum holding and usage.

Table 3: Current Usage of Spectrum in Thailand

Operator	After 2nd & 3rd Auction (1800 MHz & 900 MHz)				
	850 MHz	900 MHz	1800 MHz	2100 MHz	2300 MHz
AIS	-	20	30	30	-
DTAC	-	-	90*	30	60** (TDD)
True Mobile	30**	20	30	30	-
TOT	-	-	-	30	-
CAT	20*	-	-	-	-
Total	50	40	150	120	60

Source: NBTC (2017) and compiled by authors

Note: The spectrums subject to current usage. CAT and TOT are stated-owned company.

* Concession spectrum from CAT but, 850 MHz limited for no fully utilized in 1800 MHz first. In addition, it will end of 2018. ** Capacity sharing contract in 850 MHz between TRUE with CAT (2010 to 2025) and DTAC with TOT in 2300 MHz (2018 to 2025)

In Thailand, the National Broadcasting and Telecommunications (NBTC-Thailand NRA) has the duty to responsible for national spectrum plan according to Act on Organization to Assign Radio Frequency and to regulate the Broadcasting and Telecommunications Services (Issue 2nd) B.E. 2560 (2017) (called NBTC act). Spectrum reform is intentionally incorporated in the legislation. This legislation gives authorization for NBTC to reform the spectrum and right to use Broadcasting and Telecommunications Research and Development Fund for the Public Interest (BTFP Fund) for compensation. The part of BTFP fund portion come from spectrum auction revenue. This authorization relies with international experiences.

According to NBTC (2017), there are now 420 MHz in current usage included 800/900 MHz, 1800 MHz and 2100 MHz for 360 MHz in FDD and 2300 MHz for 60 MHz in TDD in 2017 as shown in Table 4. The numbers of licensees are concentrated in VHF band (30-300 MHz) (see Fig.2). Additionally, NBTC (2016) has planned to reform spectrum for IMT in total amount of 270 MHz from 700 MHz for 90 MHz and 2600 MHz for 140 MHz (FDD) and 40 MHz (TDD) which same as the international experiences. Thus, total spectrum may meet lower user density however, it not clear that spectrum will be available within 2020.

Table 4: Current Spectrum for IMT Services

Spectrum Band	Bandwidth (MHz)
700 MHz*	90
800/900 MHz	90
1800 MHz	150
2100 MHz	120 + 15* (TDD)
2300 MHz (TDD)	60 + 40*
2600 MHz*	140 + 40 (TDD)
Total	745

Source: NBTC (2017) and compiled by authors Note: Spectrum is for FDD (excepted TDD in parenthesis) and* The future spectrum release plan is subjected to changed depends on Spectrum Plan of NBTC.

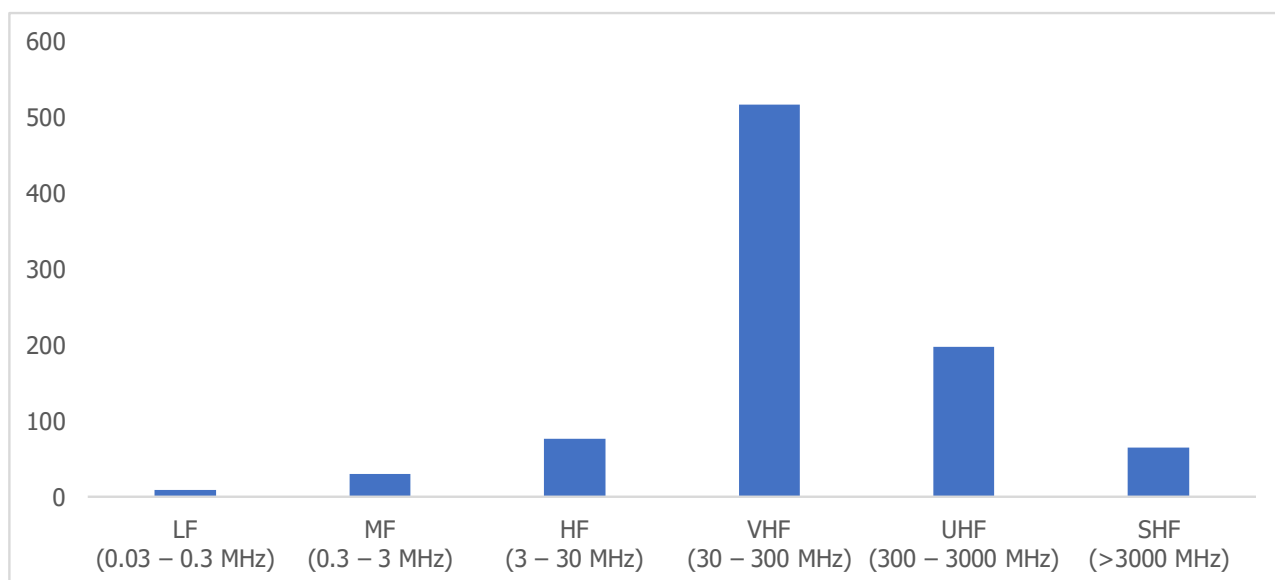


Fig. 2: Number of License in Each Spectrum Band

Source: NBTC (2017) and compiled by authors

The challenge of refarming for NBTC is the licensing system that may not compatible with international experiences. In Thailand, right to use spectrum have distinct licenses between telecommunication and broadcasting led to might be hard to implement. Licenses are authorized by separately commission (i.e. NBC and NTC). The process in meeting and corporate with two commissions before make decision by NBTC takes time. In addition, the right of use in the 700 MHz band is common usage between Digital TV service licenses (Digital TV channels) (ITU, 2015). In 2600 MHz, MCOT which is a state-owned company remain unclear about their rights of using spectrum due to the NBTC panel decision in the 3rd/B.E. 2557 NBTC meeting. Different number and characteristics of current spectrum holders may lead to the delay in refarming.

Malisuwan, Sivarakas & Madan (2013) discussed the updated important action of Thai NRA which relating to the spectrum re-farming activity in 2013 that national table of frequency allocations was scrutinized. Spectrum Refarming Committee had set the criteria and time frame for allocating spectrum band 2300 MHz band for mobile wireless access. However, the process of refarming the 2300 MHz has no progress. Their study clearly indicated that there is a lot of discussion and preparation for BWA band but lack of interest for lower band as 700 MHz which is also important in mobile broadband era.

In April 2018, the business partnership deal between TOT, which is a state-owned enterprise and the 2300 MHz spectrum holder, and DTAC including technical conditions of transmission was approved by the NBTC. Under the agreement, TOT will use a portion of the network capacity to provide its services to customer and support government policy. At the same time, TOT will lease telecommunication equipment, and the other for a domestic roaming service. TOT will receive an annual revenue stream of Bt4.51 billion from DTAC till 2025 according to the rights of TOT (Nation, 2018).

4. Possibility of spectrum refarming in Thailand

Focus group interviews were the main method to explore the possibility of spectrum refarming in Thailand. Focus groups allow probing stakeholder opinions and experiences of spectrum refarming in details. Major stakeholders are spectrum licensees/holders who are invited to participated in three focus groups during January- October 2017. While focus group data is often difficult to interpret, the method stands strong for validity of results. It is possible to interview stakeholders in a social context, and it is relatively easy to elaborate on issues that subjects deem important.

According to Babbie (1998) focus group interviews are particularly suitable for explorative studies. Composition of the group is one of the central issues in studies where data is collected using focus group interviews. Contrary to many other research methods, focus group research relies more heavily on group interaction. Group dynamics, not interviewing, is the main source of data. The focus group discussions was arranged in three phases in order to allow researcher to adjust the interview guide to cover in detail those topics stakeholder felt important in this topic. The focus group interviews were recorded, and the researchers themselves transcribed the recordings to assure the quality of the data. The participants in the focus group are consists of the current spectrum holders of 700 MHz, 2300 MHz, 2600 MHz in Thailand (see Table 5).

Table 5: Current spectrum holders and holding proportion of the 700 MHz, 2300 MHz and 2600 MHz

Spectrum band	Spectrum holders	Holding proportion
700 MHz	BBTV	34%
	Royal Thai Army Signaling Department	33%
	MCOT	25%
	Thai PBS	8%
2300 MHz	TOT	34%
	PTTEP	23%
	Royal Thai Army Signaling	9%
	PTT	7%
	Samart Telecom	6%
	Air Forces Directorate of Communication and Electotrics	5%
	Royal Thai Police	5%
	CAT Telecom	4%
	Royal Thai Army Forces Directorate of Join Communications	4%
	Kasetsart University	2%
	Hydrographic department	1%
2600 MHz	MCOT	91%
	Royal Thai Army Forces Headquarters	6%
	Royal Thai Army Signals Department	3%

Source: Spectrum Management Bureau, NBTC (2017) and complied by authors

Opinions of the current spectrum holders were mapped with the setting criteria to give insight the possibility of spectrum refarming in Thailand (see Table 6) and analyzed reform band prioritization as following.

4.1 The 700 MHz band

The 700 MHz band is occupied by 4 network operators operating 6 digital TV networks as shown in Fig.3. In Thailand, the band 470 – 510 MHz is used for telecom service. So, it is necessary to use the band 700 MHz for digital terrestrial television, especially during the transition period. Therefore, steps to release 470 MHz for digital TV and 700 MHz for IMT in Thailand is very crucial process for re-farming the 700 MHz. According to the concession, BEC (Channel 3) will switch off their analogue television in 2020. However, their analog switch-off (ASO) plan can be shifted earlier depending on the negotiation and the legal process. Under this process, NRA will confront with many challenges. Firstly, to keep the DTV coverage requirement of 95% households, the frequency planning for 6 MUXs is much more difficult with less frequency channels. Secondly, ASO cannot be completed before the end of concession, unless both sides reach agreement. Next, digital TV (DTV) receiving antennas (especially the old models in Thailand) were not designed for the frequency range 470-510 MHz. Fourthly, to re-configure or replace the transmitting equipment of DTV, it will affect to the services. Thus, the broadcasters need to minimize the downtime or provide the redundant system. There is a cost for broadcasters to do so. The sufficient and reasonable compensation is required. Lastly, to re-scan the set-top box and iDTV after frequency re-stacking, the DTV viewers might be confused. So, the communication plan has to be well-prepared and jointly implemented by relevant parties.

4.2 The 2300MHz band

Regarding to the 2300-2400 MHz band, 2300-2400 MHz band users can be categorized into three groups which are TOT, private sector and national security agencies based on the study of spectrum refarming Committee as shown in Fig.4. TOT is a majority of 2003 MHz band holder. TOT mainly has been provided a public service in rural area to support government policy. The 2300 MHz of TOT is underutilized, however.

TOT got approved from the NBTC to use the 60 MHz of this band for LTE broadband from October 2015 till August 2025. If TOT could not manage and set up the service at the end of 2017. TOT needs to return the spectrum to the NBTC. TOT then decided to discuss with DTAC. However, their agreement raised concerned to NBTC that the arrangement might violate some laws, the sub-letting of spectrum. Finally, TOT and DTAC business got released and approved from the NBTC in 2018 on the leasing of telecommunication equipment agreement and domestic roaming service Agreement to launch the 4G LTE-TDD network on the widest bandwidth of 60 MHz in 2300 MHz spectrum. Interestingly, the 2003 MHz band is non-exclusive rights in some areas and TOT is not priority user in that areas. The deployment need to solve this problem.

The second group is the private sector (PTTEP, CAT, SMART, government agencies and university) utilizes the frequency for internal coordination within its organization and for serving its users. Therefore, spectrum refarming could affect end users served by the private firm. Some of them (i.e PTTEP) use frequencies in areas such as Gulf of Thailand and Andaman Sea will not be affected by spectrum refarming in 2300-2400 MHz. Permission for

specific user and area should be considered by the NRA. The last group is national security agency that utilizes 2368-2400 MHz spectrum refarming may result in negative impact on the national security (Malisuwan et al., 2013). If there is a need to enforce this process in a short period, the compensation and creation of benefit is needed to reimburse the users affected.

4.3 The 2600 MHz band

The 2600MHz band currently belongs to MCOT Plc. which is state-owned broadcaster under the supervision of the Office of the Prime Minister. It was registered as a public company limited on August 17, 2004 by mean of the privatization from the Mass Communication Organization of Thailand (M.C.O.T). The 2600 MHz is granted to MCOT since 1999 under the concession scheme. MCOT has owned 184 MHz of bandwidth to provide pay-TV services with the Multichannel Multipoint Distribution Service (MMDS). MCOT has been talked with pay-TV marketing partner Playwork on potential collaboration to launch the service. The MCOT has not started pay-TV business but MCOT could be retained the right to utilize 2600 MHz spectrum (MMDS) to provide the subscription television service for a period of 15 years after the commencement date of service in accordance with the agreement made with the private sector.

In November 2016, MCOT asked for the network code from NBTC for the first time but the broadcasting committee declined to grant to it, citing that the code is only for telecom operators. MCOT also attempted to get permission to import equipment for trail the service joining with the MNOs. NBTC took a long process for considering the request by MCOT. Still, NBTC gave a network code for MCOT in May 2017.

According to MCOT (2017), MCOT discussed with the NBTC and the government regarding to the 2600 MHz . The conclusions were (1) MCOT shall return some portion of 2600-MHz spectrum (MMDS) to the government for 4G wireless auctions in return for some amount of compensation from the NBTC and (2) MCOT shall utilize the remaining portion of 2600-MHz spectrum (MMDS) to provide the subscription television service, which shall become a source of its long-term revenues. For the remaining portion of 2600 MHz spectrum (MMDS), MCOT and Playwork would jointly operate the subscription television service. The contract between MCOT and Playwork has started since 2010 and it will be expired in 2025⁷⁸. The party would make all investments and allocate its revenues to MCOT.

However, technological differences for the provision of subscription television service between 2600 MHz spectrum (MMDS) and fiber optic cable, and the appropriateness of utilizing 2600 MHz spectrum (MMDS) for such service because the audiences now preferred watching contents via on-line platform. Thus, the subscription television service no longer generated a huge amount of income as MCOT expected and made the shareholders concern. Additionally, the attempt of MCOT on testing service with the 2.6GHz may see as a confirmation of its ownership on the spectrum to the NBTC. This would enable MCOT to get compensation from the NBTC.

⁷ <https://ethailand.com/business-news/mcot-seeks-fair-compensation-for-2600-mhz-spectrum-return/1395/>

⁸ <http://www.magawn19.com/2016/01/19-2559-mcot-mmms-lte-mmms.html>

From above evidence, the possibility of spectrum refarming in Thailand and analyze refarm band prioritization can be concluded as shown in Table 5.

Table 6: Relevant Costs and possibility of refarm

	700 MHz	2300 MHz	2600MHz
Expired year of current spectrum holder	2020 for analogue TV broadcaster 2029 for digital TV broadcasters	2025	2025
Current usage	Active use	Active use	Inactive use (as of May 2018)
Possible Costs			
<i>The number of incumbents</i>	***	**	*
<i>The number of incumbent systems</i>	*	*	*
<i>The description of complexity of incumbent systems</i>	*	*	*
<i>The mission criticality or uniqueness of incumbent</i>	***	*	*
<i>The degree to impact service and operation of incumbents from refarm</i>	***	***	*
<i>Global allocation (to require international negotiation to bring about reallocation)</i>	*	*	*
Refarming method	Compensation relocation cost for broadcasters Compensation for new receiver of households	Compensation relocation cost	Compensation cost for initial investment on pay-tv trial business and other declared cost excluding the unused frequency band
Source of refarming fund	BTFP and auction		
Possibility year to refarm	Refarming can be started in 2020 after ASO	Refarming can be started in 2025	Refarming can be started in 2019

Source: partly adopt from Lock (2010) and complied by authors

Note: level of impact severity on cost represents as *marginal refarming cost, **significant refarming cost and *** critical refarming cost, respectively.

The 2600 MHz should be a first spectrum band among three bands to refarm since it has marginal cost of refarming as compared to others. There is only one incumbent and less impact on the current service of the operator. Moreover, refarming will make the spectrum usage of the 2600 MHz align with international standard. This will also help MNOs lay out a spectrum roadmap towards the commercial standardization of 5G technology.

However, the NRA should clearly set out and agree on the approach to reform in advance to avoid the delay of refarming process. The certainty and transparency through long term planning of the spectrum plan need to be considered to gain credibility and stability from the industry. In case of relocation, NRA should aware that incumbent licensees should have right of first refusal. Financial compensation is one of instruments to facilitate the refarming. Therefore, compensation evaluation should consider in a holistic approach.

5. Conclusion

Spectrum refarming is a new but critical process for Thailand. Without spectrum refarming, further development of telecommunications in Thailand could be extremely difficult. NRA should take action as soon as possible by disclose a national frequency table and refarming plan and process

Findings from the literature review and focus group showed that spectrum availability for mobile broadband should be made through spectrum refarming. Spectrum refarming allows the reallocation of spectrum from existing less efficient uses to higher value generating uses, thereby resulting in higher spectral efficiency which will further lead to a more advanced telecommunications industry. Essentially refarming is an administrative technique for changing a spectrum use or users. In some cases, refarming can be implemented relatively quickly and simply (for example where spectrum is liberalized in the hands of an existing user), but in others it can be a complex, lengthy and costly process (for example where it needs to be cleared and awarded).

Regarding to the cost and benefit analysis, 2600 MHz should be the priority band to serve exponential growth of MBB usage in Thailand. Findings indicated that 2600 MHz has currently inefficiency usage. Relocation cost and compensation cost of this band is relatively low compared to the 700 MHz band and 2300 MHz. NRA should set a fund to compensate the allocation and determination of spectrum refarming to support the process of determining and allocation of spectrum refarming with ease and justice according to the regulation of NRA. Also. NRA should finalize the standard to develop and support users that use radio frequencies, so they will collaborate in returning the license to use the frequencies for the benefit of the society and for the development of the Thai telecommunications industry.

Refarming can help to promote competition through the process of making more spectrums available. This can help to promote competition between existing players and/or provide scope to introduce a new entrant into the market. Furthermore, refarming is part of the current scenario of liberalization of services and technologies in which, to the extent possible, it is left to the market to decide which services and technologies are more efficient for each band.

Acknowledge

This study was supported by Spectrum Management Bureau, Office of the NBTC and Faculty of Administration and Management, King Mongkut's Institute Technology Ladkrabang. Author thank all participants in focus group who provided insight and expertise that greatly assisted the study, although they may not agree with all the interpretations/conclusions of this paper. Also, thanks to Mr. Thanwar Phansatarn for the data collection.

References

ACMA. (2012). Draft allocation instruments for the allocation of spectrum in the 700 MHz and 2.5 GHz bands (the digital dividend auction).Information paper. Retrieved March 11, 2018 from <https://bit.ly/2IKiZdf>

ACMA. (2013). AUCTION SUMMARY: 700 MHz 'DIGITAL DIVIDEND' – 2013 . RETRIEVED MARCH 11, 2018 FROM [HTTPS://BIT.LY/2S4EUDA](https://bit.ly/2S4EUDA)

Aetha. (2011a). Case studies for the award of the 700MHz/800MHz band: Germany. Retrieved March 19, 2018 from <https://bit.ly/2xayc5W>

Aetha. (2011b). Case studies for the award of the 700MHz/800MHz band: Australia. Retrieved March 19, 2018 from <https://bit.ly/2LqAil2>

Analysys Mason. (2015). The Impact of Mobile Broadband in the Asia-Pacific Region, and Future Spectrum Need. Retrieved March 11, 2018 from <https://bit.ly/2LkZn0Z>

Bebbie, R. (1998). The practice of social research. 8th ed. Belmont: Wadsworth Publishing Company.

BEREC. (2011). RSPG BEREC Report on Competition: Transitional Issues in the Mobile Sector in Europe. Retrieved February 25, 2018 from <https://bit.ly/2kmzy4n>

Bohlin, E., Blackman, C., Forge, S. & Renda, A. (2007). A Common European Policy: Barriers and Prospects. Retrieved February 18, 2018 from <https://bit.ly/2KR9M3q>

Brugger, R. & Kluth, O. (2010). 800 MHz Auctions and Implementation of the DD in Germany of the DD in Germany. EBU ECS Workshop. Retrieved March 4, 2018 from <https://bit.ly/2LqPhM1>

Cramton, P., Kwerel, E., & Williams, J. (1998,). Efficient Relocation of Spectrum Incumbents. *Journal of Law and Economics*. 41, 647-675.

Cramton, P., Lopez, H., Malec, D., & Sujarittanonta, P. (2015). Design of the Reverse Auction in the Broadcast Incentive Auction. Retrieved March 15, 2018 from <https://bit.ly/2J71zuR>

- Dotecon. (2012). Spectrum value of 800MHz, 1800MHz and 2.6GHz. A DotEcon and Aetha Report for Ofcom. Retrieved March 15, 2018 from <https://bitly.com/>
- Eisenach, J. A. (2011). Spectrum Reallocation and the National Broadband Plan. *Federal Communications Law Journal*. 64 (1) p. 88-133.
- FCC. (2001a). Notice of Proposed Rule Making. Retrieved March 04, 2018 from <https://bit.ly/2ILkr2T>
- FCC. (2001b). Reallocation and Service Rules for the 698-746 MHz Spectrum Band (Television Channels 52-59). Notice of Proposed Rule Making. Retrieved February 18, 2018 from <https://bit.ly/2KTqq2v>
- FCC. (2017). 700 MHz Public Safety Spectrum. Retrieved February 18, 2018 from <https://www.fcc.gov/700-mhz-public-safety-narrowband-spectrum>
- GAO. (2013). Spectrum Management: Federal Relocation Costs and Auction Revenues. Retrieved February 18, 2018 from <https://www.gao.gov/assets/660/654794.pdf>
- GSMA. (2018). The Mobile Economy 2018. GSMA Intelligence. Retrieved February 18, 2018 from <https://bit.ly/2oTFrsl>
- Hazlett, T., Giancarlo, I., & Wayne, L. (2007). Property rights to radio spectrum in Guatemala and El Salvador: An experiment in Liberalization. *Review of Law & Economics*, 3(2), 437–484.
- ITU-R M.2290-0. (2014). Future Spectrum Requirements Estimate for Terrestrial IMT. ITU-R. Retrieved February 25, 2018 from <https://bit.ly/2IHMPwv>
- ITU-R SM.1603-2. (2014). Spectrum Redeployment as a Method of National Spectrum Management. ITU-R.
- ITU. (2015). Implementing digital terrestrial television in Thailand. Retrieved February 25, 2018 from <https://bit.ly/2kmYQ23>
- Jain, R. & Dara, R. (2017). Framework for evolving spectrum management regimes: Lessons from India. *Telecommunications Policy*, 41(5-6), 473-485.
- Kwerel, E. R., & Williams, J. (2002). A Proposal for a Rapid Transition to Market Allocation of Spectrum. Federal Communications Commission, Office of Plans and Policy. Retrieved February 5, 2018 from <https://bit.ly/2yQ6mf6>
- Locke, G., & Strickling E., L. (2010). Plan and Timetable to Make Available 500 Megahertz of Spectrum for Wireless Broadband. U.S. Department of Commerce. Retrieved February 5 from <https://bit.ly/2x6rduJ>
- Lundborg, M., Reichl, W. & Ruhle, E. (2012). Spectrum Allocation and Its Relevance for Competition. *Telecommunications Policy*, 36(8), 664-675.

- Malisuwan, S., Sivaraks, J. & Madan, N. (2013). Broadband Wireless Access (BWA): Spectrum Refarming in Thailand. *International Journal of Computer and Communication Engineering* 2(4), p.446-119
- MCOT. (2017). The Minutes of the 2016 Annual General Meeting of Shareholders. Retrieved April 20, 2018 from <https://bit.ly/2IOOnJOI>
- Medeisis, A. & and Bozsóki, I. (2015). Spectrum Management Trends: Toward 2020. Retrieved March 11, 2018 from <https://bit.ly/2s9QKNJ>
- Minervini, L. F. (2014). Spectrum Management Reform: Rethinking Practices. *Telecommunications Policy*, 38(2), 136–146.
- Nation. (2018). TOT, TeleAssets and dtac TriNet join forces for first 4G LTE-TDD network Retrieved April 20, 2018 from <https://bit.ly/2FawUXn>
- NBTC. (2014). Future spectrum requirements of estimate for terrestrial IMT. Spectrum Management Bureau, Office of NBTC. Retrieved April 20, 2018 from <https://bit.ly/2J05Kbx>
- NBTC. (2016). Spectrum Refarming Roadmap. Retrieved April 20, 2018 from <https://bit.ly/2KSQn1X>
- NBTC. (2017, December 12). Focus Group on Spectrum Caps in Thailand.
- NERA. (2011). 900 MHz and 1800 MHz Band Refarming Case Study: France. Retrieved March 20, 2018 from <https://bit.ly/2IHCenD>
- NERA. (2017). Spectrum Auction Risks Leaving Thailand Stranded in a Mobile Data Slow Lane. Retrieved April 25, 2018 from <https://bit.ly/2ILhL1p>
- Prizker, P. & Strickling, L. (2015). Relocation of Federal Radio Systems from the 1710-1755 MHz Spectrum Band. Retrieved March 20, 2018 from <https://bit.ly/2s6iV0V>
- OECD. (2013). OECD Communications Outlook 2013. Retrieved March 20, 2018 from <http://www.oecd.org/sti/broadband/2-13.pdf>
- OMB. (2007). Commercial Spectrum Enhancement Act Report to Congress on Agency Plans for Spectrum Relocation Funds. Retrieved March 11, 2018 from <https://bit.ly/2INOVXx>
- Sridhar, V., & Prasad, R. (2011). Towards a New Policy Framework for Spectrum Management in India. *Telecommunications Policy*, 35(2), 172–184.
- TRAI. (2010). Recommendations on Spectrum Management and Licensing Framework. Retrieved March 11, 2018 from <https://bit.ly/2kmaq74X>
- Viavi Solution Inc. (2015). Spectrum Refarming Benefits, challenges, and solutions (White paper) Retrieved March 11, 2018 from <https://bit.ly/2kk3y0u>