A Techno-Economic Framework of Spectrum Combining for Indoor Capacity Provisioning

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***Abstract*—Spectrum combining refers to utilizing multiple types of spectrum authorization options for a wireless network. The approach is considered as an essential ingredient of high-capacity provision in the coming years. This paper presents a techno-economic framework to analyze capacity and cost of different spectrum combining options. We focus on indoor environments where the traffic demand is expected to be extremely demanding. We describe various spectrum options such as licence-exempt, light licensing, and licensed shared access (LSA). Then, we compare various combinations of these options with increasing traffic demand over time. In terms of capacity provisioning, this framework is based on the idea that spectrum combining must be done at the right time, that is when the existing deployment can no longer satisfy capacity demand. For the cost analysis, most relevant cost drivers are included in a cost structure which becomes the backbone of this framework. The proposed framework can help network providers determine the most cost-effective spectrum acquisition strategy which can meet capacity demand in indoor environments.**

***Index Terms*—Spectrum combining, techno-economic framework, indoor capacity**

I. INTRODUCTION

With the development of mobile devices and applications, wireless data traffic has grown substantially and reveals a strong potential for further increase. It is estimated that mobile traffic grows with compound annual growth rate (CAGR) of around 50% between 2012 and 2018 [1]. Considering that 80% of the traffic will be generated indoors [2], it is important to investigate better ways to improve how indoor capacity is provided.

Indoor capacity has been provided by utilizing either licensed or unlicensed spectrum. Unlicensed spectrum has been widely used for indoor wireless service provisioning, e.g. Wi-Fi, which is the most commonly applied solution. Research has also been done on indoor wireless networks operating on licensed cellular spectrum, e.g. femtocell networks with WCDMA or LTE technologies [3]–[5]. However, due to the scarcity of cellular spectrum, high cost of spectrum licences, and spectrum congestion, operators should look for other spectrum options for their indoor networks deployment.

Regulators are actively investigating new options of authorizing and allocating radio spectrum in order to foster more competitions and to provide better business opportunities for service providers. Spectrum sharing options such as light licensing and licensed shared access (LSA) are currently under study [6], [7]. Therefore, an indoor operator needs to know the type of spectrum it should acquire for its network. Furthermore, the operator would need to utilize different types of spectrum at the same time because the available bandwidth for each spectrum option is limited. Due to the tremendous capacity demand in the future, reliance on one spectrum solution will require too many access points (APs) which will complicate the interference situation.

In this paper, we address the problem of choosing and aggregating various spectrum options for indoor capacity provisioning. We coin the term *spectrum combining* to refer to a situation where an indoor network utilizes more than one type of spectrum. This is similar to carrier aggregation concept in LTE, except that the spectrum bands used in spectrum combining may have different licensing regulations. For example, an operator may install a number of APs on the exclusively licensed spectrum, and add more APs on spectrum with light licensing some years later. The challenges imposed on the spectrum combining would include deciding how many APs to deploy for each type of spectrum to meet the capacity demand, and investigating how the choices of the spectrum options could affect the cost.

Literature in indoor wireless networks mostly emphasizes the technical issues such as interference coordination and cell planning. Therefore, we aim at filling the gap by analyzing the subject from a techno-economic perspective. A good foundation for the cost structure and network dimensioning of indoor networks can be found in [8]–[10]. However, there is still a need for a framework for developing a deployment strategy of indoor wireless networks allowing spectrum combining.

Our contribution is the development of a techno-economic framework for choosing the most cost-efficient deployment strategy for indoor wireless networks operating on more than one spectrum type. Our framework is simple for ease of use, yet comprehensive to cover essential cost components and capacity parameters. In particular, this framework could be used to select *which* spectrum bands and licensing types to use for indoor network deployment and *when* to use them.

The remainder of the paper is organized as follows. Section II describes the system model. Section III provides a brief background on spectrum alternatives for indoor networks. Section IV explains our proposed framework in details, including how to formulate the scenarios of deployment strategies and how to calculate capacity and cost. In Section V, we give an example of how our framework can be used by setting numerical parameters. Section VI concludes the paper.

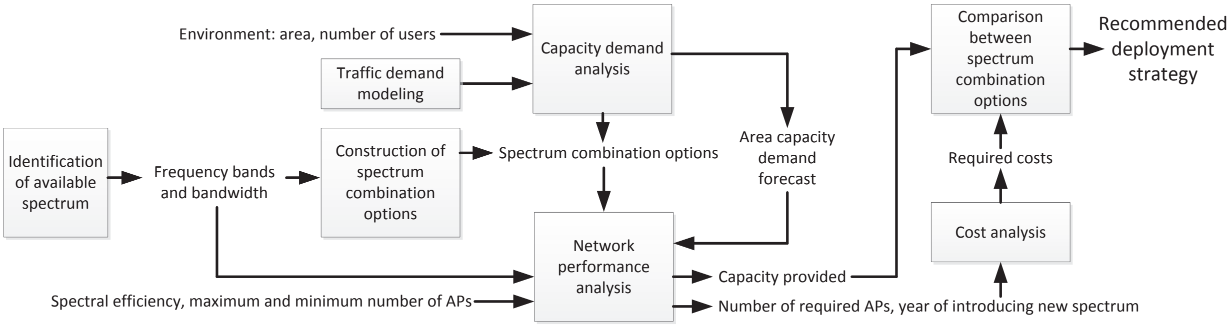

Fig. 1. Flowchart of the proposed framework

II. SYSTEM MODEL

In this study, we look at the indoor deployment in one single building for brevity. Since only one building is considered, performance degradations brought by interference from other buildings, as well as possible cost incurred by coordination between buildings for interference cancellation purposes, are not within the scope of our discussion. When deploying new indoor wireless networks, it is assumed that there are limitations on minimum and maximum number of access points for each spectrum.

A single operator is assumed here. By default, an incumbent mobile network operator (MNO) is chosen as the actor deploying and operating the wireless networks in the building. Choosing MNO as the main actor is motivated by potential integration between macro and indoor networks, enabling seamless service for the users. In addition, the heavy traffic demand could be an incentive for the MNO to offload some data traffic to the indoor networks. However, in the proposed framework, it is possible to choose other actors such as facility owner and new entry operator with a slight modification of cost components.

III. SPECTRUM OPTIONS

We consider emerging spectrum licensing options other than exclusive cellular spectrum for the future deployment of indoor network. This will also avoid interference between the macro-networks. The spectrum options used in our study are categorized into three types according to the state-of-the-art spectrum regulations: licence-exempt, light-licensing, and LSA. The three spectrum options allow different levels of spectrum sharing. On spectrum bands that allow sharing, interference is generally higher, and thus spectral efficiency is lower. We consider spectral efficiency, available bandwidth, and licensing costs as the parameters that differentiate the spectrum options.

A. *Licence-exempt Spectrum*

The licence-exempt frequency bands are considered free-to-use by anyone who fulfils the requirements of hardware configuration. A typical example of the licence-exempt spectrum is ISM band at 2.4 GHz which is now dominated by Wi-Fi technologies.

- Advantages: zero licence fee, relatively large bandwidth
- Disadvantage: low spectral efficiency because of spectrum congestion

B. *Light-Licensed Spectrum*

The idea of light-licensed spectrum is intended as a possible solution of bypassing the traditional spectrum regulation process. In light-licensed bands, users are given bandwidth to use, either free or with a nominal fee, and they may be obligated to follow additional rules given by the administrator of the spectrum bands [6]. This framework will not only simplify the regulations but also give incentives to both regulators and current licence holders in forms of administrative cost savings [7]. In general, this scheme would offer an equal sharing among the users at a lower cost compared to traditional licensed spectrum.

- Advantages: better quality of service (QoS) guarantee than licence-exempt spectrum, lower cost than exclusively licensed or LSA spectrum
- Disadvantage: possible interference from other licensees nearby

C. *Licensed Shared Authorization*

LSA framework focuses on sharing spectrum with a service quality assurance [7]. This scheme grants a LSA licensee an access to spectrum held by LSA incumbent. An important remark to this framework is that the LSA licensee obtains the spectrum according to a mutual agreement between itself and the LSA incumbent which specifies the usage and evacuation conditions. Therefore, it is easy for the licensee to predict the usability of the spectrum in the long term. An example of LSA band would be 2.3 GHz spectrum primarily allocated to military use in some European countries.

- Advantages: higher spectral efficiency than light-licensed and licence-exempt spectrum, lower cost than traditional exclusive spectrum
- Disadvantage: More complex procedure and higher cost than light-licensed spectrum

IV. FRAMEWORK FOR TECHNO-ECONOMIC ANALYSIS

We propose a framework for deciding the best deployment strategy for indoor networks with spectrum combining. An overview is presented in Fig. 1. The first step is identifying the available spectrum options to combine. Then, we decide in which ways the spectrum options can be combined, i.e. we define spectrum combination options. Capacity analysis is carried out to decide when an additional spectrum is necessary as well as how many APs are required by each spectrum combination option to meet the capacity demand. Some spectrum combination options may fail to meet the capacity demand, in which case they should not be considered as a deployment strategy candidate. After the network deployment plan for each spectrum combination option is made, cost analysis will be carried out to acquire information about the cost occurred in each spectrum combining option, serving as the final criteria for evaluating the choices.

A. Spectrum Combination Options

Spectrum combination options are constructed based on the idea that additional spectrum should be introduced to the system only when the already employed spectrum can no longer meet the traffic demand. For example, consider a case where there are three spectrum options for the indoor network deployment: licensed 800 MHz cellular band, 2.4 GHz ISM band, and new spectrum that will be available via LSA. A possible option would be to start with 800 MHz band, and then to use a combination of 800 MHz and ISM bands when the traffic increases beyond the capacity provided. Alternatively, LSA band can be deployed as the additional spectrum instead of ISM band. Another option would be to initially deploy APs operating on ISM band, and then deploy ISM-LSA combination when the traffic increases. This time-dependent approach has two advantages: minimizing over-provisioning of capacity and easing the network administration.

Note that each spectrum option will have different bandwidth, spectrum efficiency, and licensing costs. Recalling that traffic demand is time-varying and that our framework aims to provide just-enough capacity to meet the traffic demand, we expect that the capacity provided by each combining option will be different. Each option will also incur different cost because of different number of APs, prices per AP, and licensing fees.

B. Capacity Demand Analysis

Performance metric used in this framework is area capacity, which is expressed as follows:

$$R_{i,k} = S_k W_k N_{i,k}, \tag{1}$$

where i and k correspond to year and spectrum index, respectively. $R_{i,k}$ is area capacity in year i, provided by APs operating on spectrum k. S_k denotes spectral efficiency of spectrum k in bps/Hz and W_k denotes spectrum bandwidth in Hz. $N_{i,k}$ is the number of APs operating on spectrum k in the year i.

The network must be able to meet current capacity demand as well as estimated capacity demand in the future. Thus, forecast of traffic demand is an important part of this framework. The following equation can be used to model the growth of capacity demand.

$$R_{D_i} = R_{D_0}(1 + CAGR)^{i-1}. \tag{2}$$

R_{D_i} is area capacity demand in year i.

C. Network Performance Analysis

An important output of network performance analysis in this framework is the number of APs required in each spectrum type each year, which in general can be calculated as follows:

$$N_{i,k} = \left\lceil \frac{\max\left(0, R_{D_i} - \sum\limits_{l<k} R_{i,l}\right)}{S_k W_k} \right\rceil . \tag{3}$$

The term $\sum\limits_{l<k} R_{i,l}$ represents area capacity provided by spectrum types previously deployed. Eq.(3) represents the idea that spectrum combining and addition of new access points will only be done when existing deployment cannot meet the capacity demand.

In practice, it is necessary to have minimum and maximum number of APs in a building. The minimum constraint N_k^{min} is due to coverage requirement, whereas the maximum N_k^{max} is mainly caused by the physical limitation of feasible AP locations. Thus, the actual number of APs $N_{i,k}^{\dagger}$ must lie within the range of the constraints.

D. Cost Analysis

The cost of wireless networks is normally divided into two parts: capital expenditure (CAPEX) and operational expenditure (OPEX).

$$C_{total} = C_{CAPEX} + C_{OPEX}. \tag{4}$$

We consider four CAPEX components: spectrum licence fee (C_{lic}), radio equipment cost (C_{rad}), installation and deployment cost (C_{ins}), and backhaul cost (C_{bac}). We assume that spectrum option will affect C_{rad}; for instance, APs operating in LSA band could be more expensive due to a cognitive capability enabling a timely evacuation. This difference is represented by AP price coefficient ω_k. Furthermore, C_{rad} is also scaled by annual depreciation rate α, $\alpha \in [0, 1]$. Installation and deployment cost is assumed to have normalized fee of $\tilde{C}_{ins,i}$ and annual increase rate λ. For the backhaul cost, a backhaul coefficient β is introduced. If backhaul network is self-constructed, $\beta = 1$. If it is leased from a fixed network provider, then $\beta = 0$. Overall, CAPEX for a particular spectrum combination option can be expressed in Eq. (5) where P_{AP} is the price of one AP.

$$\begin{aligned} C_{CAPEX} = C_{lic} + \underbrace{\sum_k \sum_i N_{k,i} P_{AP} (1-\alpha)^{i-1} \omega_k}_{C_{rad}} \\ + \underbrace{\sum_k \sum_i \tilde{C}_{ins,i} max(N_{k,i}) (1+\lambda)^{i-1}}_{C_{ins}} + \beta C_{bac}. \end{aligned} \tag{5}$$

TABLE I
ASSUMED NUMERICAL VALUES

Traffic demand parameters	
CAGR	55%
Initial area capacity demand	5000 Mbps
Deployment years	2013 - 2020
Environment parameters	
Building area	20000 m^2
Number of users in the building	2500
Maximum AP coverage	800 m^2
Maximum AP load	100 users
Maximum number of AP per spectrum	125
Spectrum parameters	
Spectrum options	licence-exempt; light-licensed; LSA
Spectrum bandwidth	80; 70; 30 MHz
Spectral efficiency	6; 8; 10 bps/Hz
AP price coefficient (ω_k)	1; 1; 1.2
Pricing parameters	
Price per AP	240 €
AP price depreciation (α)	10% per year
Spectrum licence fees	0; 0.2; 0.4 €/MHz/user
Installation cost increase (λ)	2.5% per year
Backhaul coefficient (β)	1

The OPEX considers two components: operational and maintenance cost (C_{om}) and backhaul maintenance cost (C_{bcm}). C_{om} is assumed to be proportional to the number of APs, while C_{bcm} is proportional to the provided capacity. Note that C_{bcm} is only calculated when the backhaul is leased. Normalized operational and maintenance cost and normalized backhaul maintenance cost are denoted by $\tilde{C}_{om,k,i}$ and $\tilde{C}_{bcm,i}$ respectively.

$$C_{OPEX} = \sum_k \sum_i (\underbrace{N_{k,i}\tilde{C}_{om,k,i}}_{C_{om}} + \underbrace{(1-\beta)\tilde{C}_{bcm,i}R_{k,i}}_{C_{bcm}}). \quad (6)$$

E. Decision Making

The recommended deployment strategy is the spectrum combination option with lowest total cost accumulated throughout deployment period, given that capacity demand is always met.

V. NUMERICAL RESULTS

In this section, we give an example of how to utilize the framework. Parameters assumed in this section are summarized in Table I. It is important to emphasize that the table is only used for demonstrating the proposed framework. Although we propose a general framework, correct numbers must be inserted to draw a right conclusion. The actual values and the consequent decision will be different depending on specific time and location. Also, notice that the spectral efficiency of LSA is assumed to be the highest among the three options, while that of licence-exempt band is the lowest. This is based on the fact that LSA concept will allow spectrum sharing only in a well planned manner. Furthermore, indicated by ω_k, LSA APs are assumed to be the most expensive. This represents the case when LSA APs are required to have cognitive radio capability which increases the hardware complexity.

TABLE II
SPECTRUM COMBINATION OPTIONS

Combination option	Initial Spectrum	Additional Spectrum
1	licence-exempt	light-licensed
2	licence-exempt	LSA
3	light-licensed	licence-exempt
4	light-licensed	LSA
5	LSA	licence-exempt
6	LSA	light-licensed

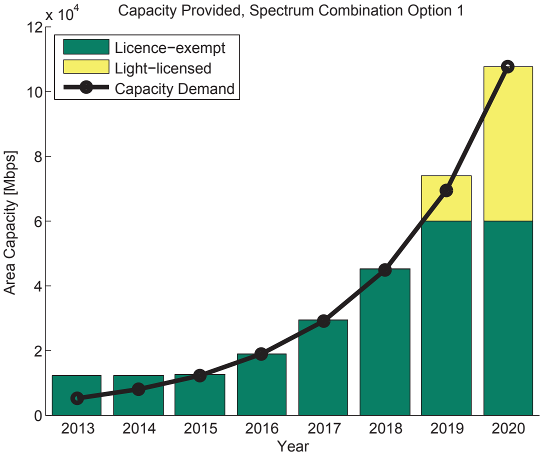

Fig. 2. Capacity analysis of combination option 1

The first step of the decision making is construction of spectrum combination options based on the available spectrum. Consider six combinations listed in Table II, where each of them involves two spectrum options. Assuming capacity demand follows Eq. (2) and performing the capacity analysis in Section III, we can obtain the capacity provided by each spectrum combination option and the corresponding number of APs needed in the deployment. We can also see when the initial spectrum of each combination option fails to meet the capacity demand.

Fig. 2 illustrates an example of this observation. It is observed that, in the first six years, licence-exempt band alone is able to provide the required capacity by gradually adding the number of APs. However, in the year 2017, we can no longer add more APs on this spectrum band, and the second spectrum is introduced. Over-provisioning may happen because there is a minimum number of APs required for each spectrum. Capacity analysis for other spectrum combination options concludes that options 2 and 5 fail to meet capacity demand in the last year. This is caused by less available bandwidth of LSA spectrum and low spectral efficiency of licence-exempt band assumed in this example. Options 3 and 4 introduce the additional spectrum only in the last year, while option 6 will need additional spectrum in 2018.

Based on the number of APs calculated in the capacity analysis, we can start considering CAPEX and OPEX for each spectrum combination options. Spectrum licence fees are annualized. The sum of CAPEX and OPEX yields the total costs for each option as illustrated in Fig. 3. It can be seen

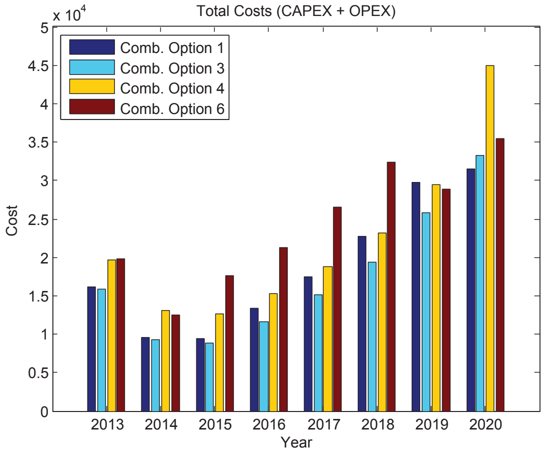

Fig. 3. Costs required for each spectrum combination option, each year

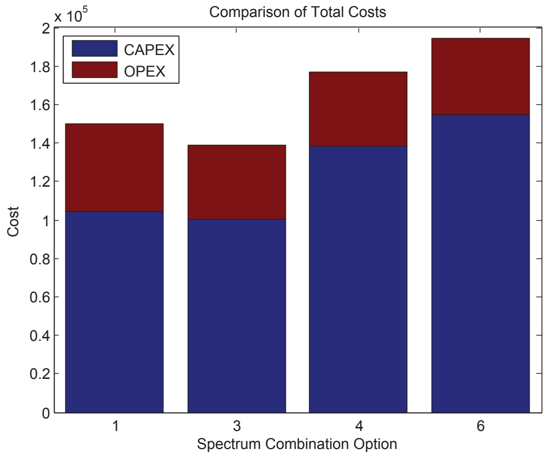

Fig. 4. Total costs required for each spectrum combination option

that total cost in all combination options show an increasing trend in general. However, a decrease in cost in the early years is also observed. It happens because the capacity redundancy brought by the minimum number of APs can result in less investment in the coming year. Depreciation in AP price and normalized backhaul leasing cost can also be the cause.

Since we are interested in the most cost-effective combination option, we sum up all the required costs for each option throughout the whole deployment period. The results are depicted in Fig. 4. It shows that CAPEX for the combination options 4 and 6 are higher than others. This is due to the licence fees required for LSA and light-licensed bands. Expensive AP price assumed for LSA also causes the high CAPEX. By observing Fig. 4, we can make a decision on the best spectrum combination option. By choosing the option with the lowest total costs, we can conclude that option 3 is the best, i.e. the MNO should initially deploy APs operating on light-licensed spectrum, and use a combination of light-licensed and licence-exempt spectrum when the traffic demand increases. Remember that the result is highly dependent on the assumed parameters in Table I. Therefore, it is important to identify relevant parameters tailored to each situation and put them into our framework to draw a valuable business decision.

VI. CONCLUSION

In this paper, we investigated a cost-efficient indoor capacity provisioning by considering the combination of different spectrum licensing options depending on the increasing traffic demand, which we term *spectrum combining*. In particular, we proposed a techno-economic framework which can assist indoor wireless service providers to decide how to implement spectrum combining. In order to make a cost-efficient decision, the framework is designed to follow capacity demand and to employ spectrum combining when it is truly necessary. Important cost drivers such as radio equipment cost, backhaul cost, operation and maintenance cost are taken into account. We demonstrated that the proposed framework is a useful decision making tool with a numerical example. It should be emphasized that the results highly depend on the situation. It is important to insert relevant parameter values into our framework in order to make a right decision.

As a future work, this framework can be extended to a bigger environment, which could be a cluster of buildings. In that case, new cost components such as coordination fee between buildings can be introduced. In terms of technical analysis, this framework can also be improved by taking more detailed propagation and interference models into account.

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