Network Planning for Indoor Joint LTE and WLAN Networks

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***Abstract*—This paper presents a formulation of the network planning problem which effectively models the indoor deployment of joint LTE and WLAN small cells as an optimization problem. This problem determines the position, frequency and bandwidth allocation of the network by maximizing the capacity and coverage, and minimizing the interference as well as the cost of the network. The additional frequencies available to the network are incorporated into the model, and measures are taken to avoid the size of the problem from getting too large. By including the choice of frequency as a degree of freedom causes the interference buffer to halve per additional LTE frequency. The formulation considerably decreases the interference in the network when compared to other network designs.**

***Index Terms*—WLAN, LTE, interference management, network planning, indoor, bandwidth allocation.**

I. Introduction

To support the increase in volume of indoor traffic, small cells with WLAN and LTE capabilities can be deployed, and WLAN technology can be used for traffic offloading [1]. By using existing technologies in this way, the capacity of networks can be increased without requiring the complete overhaul of existing networks.

In [2], interference management for LTE networks is extensively investigated. It introduces a planning algorithm which finds the optimal placements of LTE transmitters, outdoors, taking the interference of neighbouring transmitters, and macro cells into consideration. There is increased interest in LTE and WLAN networks coexisting [3] and the first step in this process is designing a planning algorithm which can support multiple frequencies and locations. For example, in [4] the authours consider a heterogeneous LTE network, with macro and small cells used for OFDM-based cellular networks. Here the frequencies are assigned to the access points, and the paper discusses interference considerations. However, the paper does not deal with determining the locations of the transmitters. Likewise, [5] and [6] start with existing WLAN networks and in the first case, are adding an LTE network which transmits in the unlicensed spectrum, thus interfering with the WLAN network, and in the second case, allowing the network to self-plan.

As far as we known, no papers in the literature have allowed the frequency to be chosen alongside the location and bandwidth allocation in a network. As the joint deployment of LTE and WLAN indoors is of high interest, a joint optimization of these technologies is of increased importance. The work in this paper does this by extending the model in [2]. The choice of frequency is introduced using the so-called frequency attribute, which is an additional dimension on the decision variables over which we are optimizing. The addition of the frequency attribute enables us to consider the advantage of network operators allowing customers to share frequencies, for example using licensed shared access (LSA). A new degree of freedom also means that the search space is larger, this is stifled by introducing the harmony matrices, which indicate which access points can use which frequencies, and which users are covered by which frequency. One way the harmony matrices can be used is to take into consideration the technology, WLAN or LTE, used by the users equipment. Then the optimization problem will choose the optimal position and frequency of the access points such that both types of customers are reliably covered. The model presented in this paper can be used to represent various scenarios, which makes it a good candidate to compare offloading, or data aggregation techniques with one another for a specific scenario. This supports the network planning process as the complex nature of indoor planning makes it difficult to predict which technique is most appropriate for a given environment.

Using small cells presents interference considerations which are solved using intelligent planning and interference management schemes. For simulation, we apply a model of the path loss behaviour in an indoor environment. The planned network is considered a successful candidate when all demand nodes are effectively served, at the lowest cost to the network operator. To evaluate the network, all the added features in this approach were compared to networks without these features added. For example, we allow multiple frequencies to be selected, so we compared this to a setup where only one LTE frequency is allowed to be used. We also demonstrate that the interference is successfully considered for the optimal network, and that choosing otherwise intuitive positions and frequencies for the access points results in suboptimal solutions.

Paper Organization: Section II describes the system used and the assumptions made in more detail. Next, in Section III the optimization problem is introduced, after which the results

TABLE I
NOTATION

Symbol	Description
$\mathcal{S}$	Index set for transmitters, with indices $s \in \mathcal{S}$
$\mathcal{T}$	Index set for demand nodes, which model the traffic distribution, with indices $t \in \mathcal{T}$
$\mathcal{F}$	Index set for frequency band used, with indices $f \in \mathcal{F}$
$e_{sft} \in \mathbb{R}_{\geq 0}$	Spectral efficiency from access point s, using frequency band f, to demand node t
$e_{\min} \in \mathbb{R}_{>0}$	Minimum required spectral efficiency
$r_t^{\text{eff}} \in \mathbb{R}_{\geq 0}$	Effectively served data rate at demand node t (depending on signal quality and allocated bandwidth)
$c_s, c_{sf} \in \mathbb{R}_{\geq 0}$	Cost of access point deployment per location s and at frequency f
$y_{sf} \in \{0, 1\}$	Binary decision variables indicating the selection of transmitter site s, at frequency f
$z_{sft} \in \{0, 1\}$	Binary decision variables indicating the assignment of demand node t to transmitter s, at frequency f
$y_s, z_t \in \{0, 1\}$	Auxiliary binary decision variables indicating if access point s is deployed or demand node t is assigned to a transmitter, respectively
b_{sft}	Bandwidth allocation variable indicating the bandwidth assigned from transmitter s to demand node t at frequency f
$r_t \in \mathbb{R}_{>0}$	Requested data rate for demand node t
$B_{sf} \in \mathbb{R}_{\geq 0}$	Total available bandwidth per transmitter s at frequency f
$\mathcal{H}^{\mathcal{SF}} \in \{0,1\}^{\|\mathcal{S}\| \times \|\mathcal{F}\|}$	Harmony matrix representing feasible transmitter-frequency pairs, $\mathcal{H}^{\mathcal{SF}} = (h_{sf})_{s \in \mathcal{S}, f \in \mathcal{F}}$
$\mathcal{H}^{\mathcal{FT}} \in \{0,1\}^{\|\mathcal{F}\| \times \|\mathcal{T}\|}$	Harmony matrix representing feasible frequency-demand node pairs, $\mathcal{H}^{\mathcal{FT}} = (h_{ft})_{f \in \mathcal{F}, t \in \mathcal{T}}$
$r_t^{\min} \in \mathbb{R}_{\geq 0}$	Minimum required data rate if demand node t is to be served
$p_t \in \mathbb{R}_{\geq 0}$	Priority level of demand node t
$q_{ss'ft} \in [0, 1]$	Interference impact factor, see (1j)
$d_{st} \in \mathbb{R}_{\geq 0}$	Distance between access point s and demand node t

are discussed in Section IV to demonstrate the capabilities of the problem formulation introduced here.

II. SYSTEM MODEL AND ASSUMPTIONS

The goal is to determine the optimal location $s \in \mathcal{S}$ and frequency $f \in \mathcal{F}$ at which to deploy access points (also referred to as transmitters or small cells) in order to maximize the coverage and capacity with the lowest possible monetary cost. This is done with interference taken into consideration. To assess coverage and capacity, we introduce demand nodes $t \in \mathcal{T}$ representing the variable requirements for the scenarios under investigation. To achieve this goal, the following steps must be completed: a channel model is established, the system model is described and assumptions stated, and using these as a guide, an optimization problem is formulated. For this purpose, Table I summarizes all the variables, sets, and values that are used to describe the problem.

A. System Model

In this work, the set of frequencies contains both WLAN and LTE frequencies. The WLAN network can be used for individual users as well as an offloading technique for the LTE network. To enable the choice of frequency, as well as location, the binary decision variables y_{sf} and z_{sft} have a dimension to indicate the frequency choice. This frequency attribute allows every combination of multiple frequencies at a single transmitter to be considered, while keeping the problem size reasonable. Applying the method introduced in [2] (page 35) to this problem, the set $\mathcal{S}$ needs to include all possible combinations of the frequencies resulting in a set of cardinality $|\mathcal{S}| \cdot 2^{|\mathcal{F}|}$ where $|\cdot|$ denotes the cardinality. The method used in this paper decreases the size of the feasible set to $|\mathcal{S}| \cdot |\mathcal{F}|$.

To avoid the problem from getting too large, and in order to reflect other limitations, this paper introduces the harmony matrices $\mathcal{H}^{\mathcal{FT}}$ and $\mathcal{H}^{\mathcal{TS}}$. All frequencies (and thus, the distinction between WLAN and LTE) which are suitable for a demand node t are indicated with a 1 in the matrix $\mathcal{H}^{\mathcal{FT}}$. Similarly, the harmony matrix $\mathcal{H}^{\mathcal{SF}}$ specifies which access point locations can accommodate which frequencies.

There are two types of interference to be considered, inter-cell (co-tier) interference and cross-tier interference. Inter-cell interference is between neighbouring small cells and cross-tier is between different tiers of communication within the same spectrum. To address inter-cell interference, when a frequency is reused in the network, a bandwidth buffer b_{sf}^{itf}, for transmitter s at frequency f, is calculated. This bandwidth is then blocked from the available bandwidth to ensure that when interference inevitably occurs in the network, it can be dealt with by the network. It also ensures that the network of chosen transmitters interfere as little as possible.

B. Assumptions

In the simulation, cross-tier interference is assumed to be uniform, from surrounding macro-cells, and thus, a uniform power reduction of 5dB is included in the channel model.

Another important element in planning the network, is modeling the received signal strength at the demand nodes. In this work, this is accomplished by using the empirical channel model known as the dual slope model, which is recommended by [7] for indoor shopping malls. The attenuation of signals due to materials, such as walls, is also considered using the multi-wall model. However, the channel model can easily be replaced, either with a different model, or with measurements.

The signal-to-interference-and-noise-ratio (SINR) which is calculated through the above mentioned channel model, is then converted to a spectral efficiency e_{sft} between each access point and demand node, at each frequency. These lookup tables were procured from [2] and [8].

The small cells are assumed to have both WLAN and LTE capabilities, the cost of installation for a single small cell is c_s and for each frequency that it can transmit at, an additional cost of c_{sf} is considered. These values don't necessarily represent a numerical cost, they reflect the cost which ensures that it is not of interest to install all possible frequencies at one station. The value of c_{sf} should be set relatively small compared to c_s.

The demand nodes themselves are assumed to approximate a representative distribution of customers in the shopping complex. Appropriately chosen demand nodes ensure that the network designed in this paper is robust to changes in the traffic.

III. Problem Formulation and Optimization

In order to reduce the interference between neighbouring access points, the positions and frequencies of the transmitters can be intelligently planned using an appropriate optimization model. The goal of the optimization should be to maximize coverage C_1 and capacity C_2, while reducing the cost C_3 of the system, and thus, the required number of access points, and to ensure a certain quality of service (QoS) (1g). To achieve this goal, the following optimization problem is defined

$$\max_{y_{sf}, y_s, z_{sft}, z_t, b_{sft}} \quad \lambda_1 C_1 + \lambda_2 C_2 - \lambda_3 C_3 + \lambda_4 R - \lambda_5 P \tag{1a}$$

$$\text{s.t.} \quad z_t = \sum_{f \in \mathcal{F}} \sum_{s \in \mathcal{S}_{ft}} z_{sft} \leq 1, \quad \forall\, t \in \mathcal{T}, \tag{1b}$$

$$y_s \geq \frac{1}{|\mathcal{F}|} \sum_{f \in \mathcal{F}} y_{sf}, \quad \forall\, s \in \mathcal{S}, \tag{1c}$$

$$z_{sft} \leq y_{sf} \leq h_{sf}, \qquad \forall\, (s,f,t) \in \mathcal{R}_{\mathcal{SFT}}, \tag{1d}$$

$$z_{sft} \leq h_{ft}, \quad \forall\, (s,f,t) \in \mathcal{R}_{\mathcal{SFT}}, \tag{1e}$$

$$b_{sft} \leq \frac{r_t}{e_{sft}} z_{sft}, \quad \forall\, (s,f,t) \in \mathcal{R}_{\mathcal{SFT}}, \tag{1f}$$

$$r_t^{\text{eff}} = \sum_{s \in \mathcal{S}} \sum_{f \in \mathcal{F}_{st}} e_{sft} b_{sft} \geq r_t^{\min} z_t, \quad \forall\, t \in \mathcal{T}, \tag{1g}$$

$$\sum_{t \in \mathcal{T}_{sf}} b_{sft} + b_{sf}^{\text{itf}} \leq B_{sf} + (1 - y_{sf}) \cdot B_{\infty}, \quad \forall\, s \in \mathcal{S}, f \in \mathcal{F}, \tag{1h}$$

$$b_{sf}^{\text{itf}} = \sum_{\substack{(s',f,t) \in \mathcal{R}_{\mathcal{SFT}} \\ s' \neq s, f = f'}} q_{ss'ft} b_{s'ft}, \quad \forall\, s \in \mathcal{S}, f \in \mathcal{F}, \tag{1i}$$

$$q_{ss'ft} = \beta_s \min\left\{ \frac{e_{sft}}{e_{s'ft}}, 1 \right\}, \quad \forall\, s, s' \in \mathcal{S}, f \in \mathcal{F}, t \in \mathcal{T}. \tag{1j}$$

A. Objective Function

To ensure that there is a sufficient link quality $e_{\min}$, define feasibility regions:

$$\begin{aligned}
\mathcal{R}_{\mathcal{SFT}} &= \{(s,f,t) \in \mathcal{S} \times \mathcal{F} \times \mathcal{T} : e_{sft} \geq e_{\min}\}, \\
\mathcal{S}_{ft} &= \{s \in \mathcal{S} : (s,f,t) \in \mathcal{R}_{\mathcal{SFT}}\}, \\
\mathcal{T}_{sf} &= \{t \in \mathcal{T} : (s,f,t) \in \mathcal{R}_{\mathcal{SFT}}\}, \\
\mathcal{F}_{st} &= \{f \in \mathcal{F} : (s,f,t) \in \mathcal{R}_{\mathcal{SFT}}\}.
\end{aligned}$$

The objective function (1a) contains a weighted sum of the following terms:

- Coverage:

$$C_1 = \frac{\sum_{t \in \mathcal{T}} p_t z_t}{\sum_{t \in \mathcal{T}} p_t}. \tag{2}$$

Maximizing this term maximizes the weighted sum of demand nodes covered. The priority levels p_t act as weights for users or areas that are more important. The priority levels can be used for stores using WLAN at their checkout for secure transactions, for example. Dividing by $\sum_{t \in \mathcal{T}} p_t$ normalizes the coverage term.

- Capacity:

$$C_2 = \frac{\sum_{t \in \mathcal{T}} r_t^{\text{eff}}}{\sum_{t \in \mathcal{T}} r_t}. \tag{3}$$

This term ensures that the demand nodes are getting the highest possible effective data rate as a ratio of the maximum possible data rate, $\sum_{t \in \mathcal{T}} r_t$.

- Cost:

$$C_3 = \frac{1}{\sum_{t \in \mathcal{T}} r_t} \sum_{s \in \mathcal{S}} (c_s y_s + \sum_{f \in \mathcal{F}} c_{sf} y_{sf}). \tag{4}$$

The cost of the access points is divided into the installation costs of a transmitter c_s and any potential extra cost incurred per frequency at which it can transmit c_{sf}. The cost is normalized by the total rate term from above $\sum_{t \in \mathcal{T}} r_t$. This means that the value can be greater than one, however the weight on this term λ_3 can be used to regulate this.

- Reward:

$$R = \frac{1}{|\mathcal{T}| e_{\max}} \sum_{f \in \mathcal{F}} \sum_{s \in \mathcal{S}} \left(\min_{t \in \mathcal{T}_{sf}} z_{sft} e_{sft} \right), \tag{5}$$

rewards access point locations which maximize the minimal covered spectral efficiency. The maximum spectral efficiency $|\mathcal{T}| e_{\max}$ acts as the normalization term.

- Penalty:

$$P = \frac{1}{d_{\max}} \sum_{f \in \mathcal{F}} \sum_{s \in \mathcal{S}} \left(\max_{t \in \mathcal{T}_{sf}} z_{sft} d_{st} \right), \tag{6}$$

where d_{st} is the Euclidean distance between s and t and $d_{\max}$ is the maximum distance between an access point and a demand node in $\mathcal{R}_{\mathcal{SFT}}$. In the case where two or more access points are equally optimal in terms of coverage, capacity, and cost, this penalty ensures that the access points are located in such a way that the demands nodes are more robustly covered. Access points which minimize the maximal distance are preferred. This way, the solution is a bit more robust to changes in the demand node locations and their requested data rate. In a radially symmetric case this corresponds to the more centrally located access point. Dividing this term by $d_{\max}$ normalizes the term.

The full objective function is presented in (1a). The weights $\lambda_1, \dots, \lambda_5$ can be used to put more weight on objective terms which are more important for the particular network that is being planned. The normalization of the terms enables these weights to be reused for different scenarios, even as the sizes change. Which also means it allows the comparison of different scenarios through the objective terms.

B. Constraints

For the realistic implementation of the optimization problem, a number of constraints are introduced. First, (1b) ensures all demand nodes t are assigned to at most one access point s, at a certain frequency f. For the auxiliary variable y_s to represent which access points are deployed, (1c) is used. Equation (1d) reflects that only deployed access points and their frequencies are available for demand node assignment.

The harmony matrices $\mathcal{H}^{\mathcal{SF}}$ and $\mathcal{H}^{\mathcal{FT}}$ denote when a given pair can be deployed simultaneously. Here, $h_{sf} = 1$ only when transmitter s has the capability to transmit at frequency f. Similarly, $h_{ft} = 1$ only when a demand node t can be served by frequency f. Constraints (1d) and (1e) use this concept such that only transmitters with certain frequency capabilities are deployed, and all demand nodes are covered by one of the correct frequencies. For a requested data rate r_t, the required bandwidth for downlink transmission is given by $b_{sft} = \frac{r_t}{e_{sft}}$, where e_{sft} is the spectral efficiency between s and t at frequency f. Following from this definition, (1f) ensures that the bandwidth for each link is bounded by the bandwidth that is required to serve the data rate. Constraint (1g) ensures that the effectively served data rate of each demand node exceeds a QoS related minimum threshold $r_t^{\min}$.

Finally, the bandwidth buffer is defined in (1h). The bandwidth buffer b_{sf}^{itf} reserves some bandwidth for interference mitigation, if there is some access point s' that is using bandwidth on the same frequency as s which affects t. The interference impact factor $q_{ss'ft}$ determines this impact, which scales with the quality of the interfering link e_{sft} and the reciprocal of the quality of the desired link $e_{s'ft}$, (1j) where the frequency reuse factor β_s is the rate at which frequencies can be reused in a network. This is implemented in constraint (1h), where B_∞ is a large number that ensures that non-deployed transmitters are ignored and is implemented as a number larger than $\sum_{f\in\mathcal{F}}\sum_{s\in\mathcal{S}} B_{sf}$. The constraint ensures that the sum of bandwidth links cannot exceed the total available bandwidth from the access point.

The resulting optimization problem is a convex mixed integer linear program, which is solved using the Gurobi solver for CVX [9], [10].

C. Modeling different scenarios and avoiding conflicts

The optimization problem can be applied in a number of different ways to model different scenarios. For example to model carrier aggregation, if the system is supposed to allow two or more access points (or frequencies) serving one demand node, then two or more demand nodes can be placed in the same location, together making up one user. Instead of seeing a demand node as a full user, it can be seen as a more granular entity to allow the bandwidth to be split across different frequencies and access points.

TABLE II
PARAMETERS USED FOR RESULTS.

Channel model	ABG with mall parameters from [7]
Area	The path loss was calculated per 65cm by 65cm square of a 100m by 100m square indoor area with nine rooms and a surrounding margin of 15m
Set of transmitters $\mathcal{S}$	Every 10 meters there is a transmitter in the centre of the 100 m^2 square
Set of frequencies $\mathcal{F}$	Wi-Fi standard 802.11 channels 1, 5, 9, and 13, and LTE frequencies 791, 821, 1805 and 1880 MHz
Set of demand nodes $\mathcal{T}$	13 WLAN, 13 LTE distributed around the building, represented using $\mathcal{H}^{\mathcal{FT}}$, totaling in 520 people
Antenna	Omnidirectional
Priority levels p_t	All equally important
Rate requested per demand node	30Mbps, which corresponds to 20 people using 1.5Mbps (the recommended rate for streaming video)
Minimum rate per demand node	$r_t^{\min} = 25$Mbps
Total bandwidth per transmitter	15 MHz
Costs c_s, c_{sf}	50 and 15 respectively
Frequency reuse β_s	$\frac{1}{3}$
Optimization weights	$\lambda_1 = 0.3, \lambda_2 = 0.6, \lambda_3 = 0.1,$ $\lambda_4 = 0.0125$ and $\lambda_5 = 0.012$
Normalization terms for reward and penalty	$d_{\max} = 118.81,\ e_{\max} = \max_{s,f,t} e_{sft} = 4.8$

If the set $\mathcal{F}$ includes overlapping frequencies which cannot be jointly deployed, the possibility exists to include an additional constraint, in the form of a conflict graph. All conflicting pairs are included in the graph $(f, f') \in \mathcal{G}^{\mathcal{F}} \subseteq \mathcal{F}^2$ where $\mathcal{G}^{\mathcal{F}}$ is the conflict graph, and f and f' are a conflicting pair. Then the constraint $y_{sf} + y_{sf'} \leq 1, \forall s \in \mathcal{S}, (f, f') \in \mathcal{G}^{\mathcal{F}}$ ensures that no overlapping frequencies are jointly deployed, limiting the inter-cell interference. The same can be done if, instead of an interference buffer, neighbouring transmitters that are too close to one another should be restricted from being deployed simultaneously. This only works when the attenuation is radially symmetric. Then, similarly as above, conflicting positions are represented as $(s, s') \in \mathcal{G}^{\mathcal{S}} \subseteq \mathcal{S}^2$ for conflicting locations s and s'. This conflict graph can also be used when two configurations are considered of the same transmitter. Then, since not both configurations can be deployed at the same location, each distinct configuration would be in conflict with the others, at the same location.

IV. Results and Discussion

Results are depicted below for the conditions specified in Table II. The spectral efficiency is generated through a combination of the dual slope model and the multi-wall model. The dual slope model divides the path loss prediction into two regions, with unique path loss exponents. The region closer to the access point, and before the breakpoint, is characterized by a slower weakening of the signal. The path loss in the second region is a composite of the previous path loss and an addition term with a higher path loss exponent.

The path loss P is a function of d and f which denote the distance from the access point, in meters, and the frequency used, respectively. The motivation in using a dual slope model is that there are many unaccounted objects in stores which would make ray tracing and other deterministic models too complex, while an alternative empirical model may be too forgiving. Here, the alpha-beta-gamma (ABG) model is used,

$$P(f,d) = \begin{cases} 10\alpha_1 \log_{10}(d) + \beta + 10\gamma \log_{10}(f), \\ \qquad 1 < d \leq d_{\mathrm{BP}} \\ 10\alpha_1 \log_{10}(d_{\mathrm{BP}}) + \beta + 10\gamma \log_{10}(f) \\ \quad +10\alpha_2 \log_{10}(\frac{d}{d_{\mathrm{BP}}}), \qquad d > d_{\mathrm{BP}} \end{cases}$$

where $\alpha_1, \alpha_2, \beta$, and γ are parameters which were experimentally obtained for certain indoor environments [7]. This channel model was implemented in the open-source software introduced in [11]. The software has predefined attenuation parameters for classical building materials and so the attenuation of the waves through walls is taken into consideration.

The weights used in the optimization problems are chosen to improve coverage and capacity, with less focus on cost. The penalty and reward terms are meant to only discern between otherwise optimal solutions, and are therefore given much smaller values compared to the other weights. In fact, they are set to $0.0001 \cdot |\mathcal{T}|e_{\max}$ and $0.0001 \cdot d_{\max}$ respectively.

The figures show the SINR for two of the WLAN frequencies which were chosen. In total, for this setup, seven access points were deployed, each transmitting at two or three frequencies each, with a total of 18 pairs of frequencies and access points, ten of which were LTE frequencies. Although other frequencies were also deployed, these figures were chosen to demonstrate the successful implementation of the interference buffer. In Figure 1 the seven access points are denoted by the red circles, the demand nodes are in gray, where the circles denote LTE and the triangles WLAN. The two figures show two of the frequencies used for WLAN, channels 1 and 9, respectively. In the top figure one can see transmitters 3 and 7 are deployed at this frequency and are covering the blue crosses and triangles, respectively. Due to the walls, there is strong interference in the bottom rooms. To avoid this interference affecting the performance of the system, the bottom figure shows that different frequencies are used to cover this area, demonstrating that it went beyond alternating frequency reuse, and chose frequencies based on the environment. In the bottom figure it is also visible that access point 2 has a weaker SINR due to the interference with access point 5 and thus is only assigned to one demand node at this frequency.

Table III has the numeric results of the objective terms, coverage, capacity, cost, reward and penalty term, as well as the bandwidth reserved for interference, for six networks. The first four networks are optimized with increasing numbers of LTE frequencies available for use. In other words, the first network, 1 LTE band, has no frequency choice for LTE as it can only chose the first band, while the second network

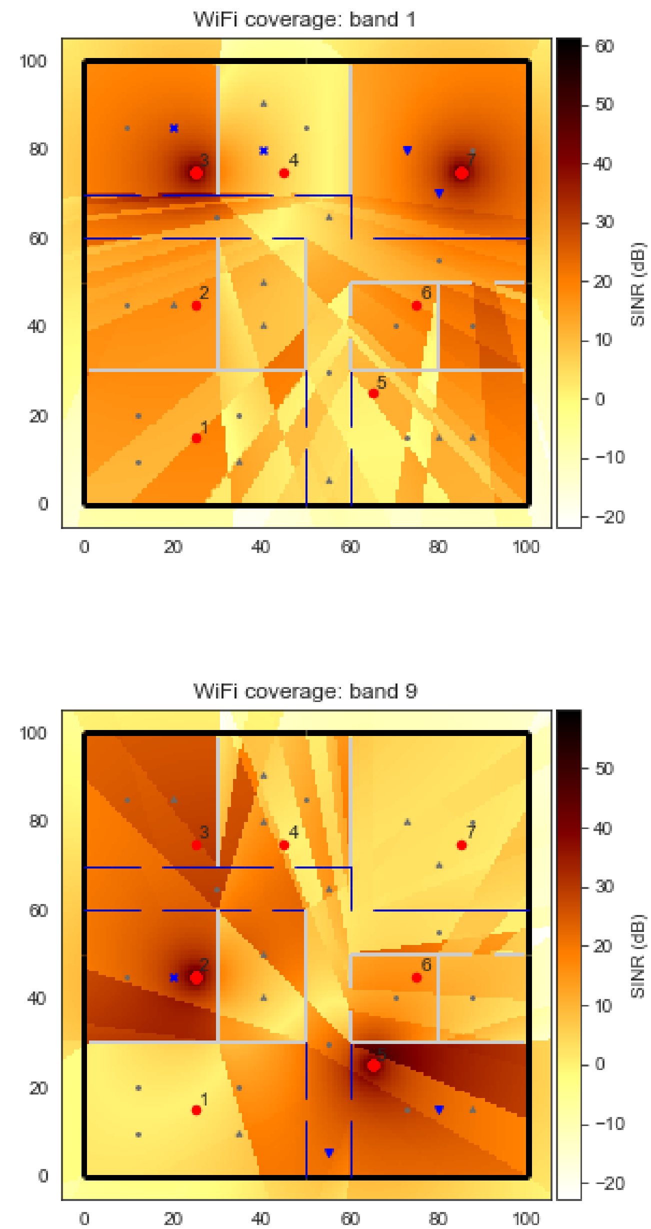

Fig. 1. Simulation results for WLAN network, channels 1 and 9. Deployed access points denoted by red circles, demand nodes by grey circles and triangles for LTE and WLAN, respectively. Top figure: access points 3 and 7 are deployed at WLAN channel 1 and assigned to blue crosses and triangles, respectively. Bottom figure: access points 2 and 5 are deployed at WLAN channel 9, and assigned to blue cross and triangles, respectively.

had 2 LTE frequencies available, and so on. These are set using the harmony matrices $\mathcal{H}^{\mathcal{FT}}$ and $\mathcal{H}^{\mathcal{SF}}$. Networks 1 and 2 are ascertained from an abridged version of the optimization problem, for which the locations and frequencies are fixed and the optimal bandwidth allocation is determined by the algorithm. In network 1 an access point is placed into the centre of each room, with the frequency chosen to accommodate the demand nodes in the room, and with no two consecutive access points

TABLE III
SUMMARY OF RESULTS.

Network	Coverage (C_1)	Capacity (C_2)	Cost (C_3)	Reward (R)	Penalty (P)	b^{itf}_{sft} / MHz
1 LTE band	1	1	0.99	0.93	1.40	12.07
2 LTE bands	1	1	0.84	0.87	1.84	6.96
3 LTE bands	1	1	0.84	0.84	1.84	3.70
4 LTE bands	1	1	0.84	0.84	1.84	1.54
Network 1	1	0.94	0.96	0.83	1.77	6.80
Network 2	1	0.90	0.96	0.77	2.45	6.25

using the same frequencies. Network 2 also has one access point per room, however these access points are placed closer to the edge of the building so as to reduce the interference between the access points.

All six networks manage to cover all of the demand nodes. The optimized network, with access to all LTE frequencies, drastically outperforms the other networks in terms of interference. Networks 1 and 2 not only have significantly more interference, they are also more expensive at 0.96 cost per rate, without managing to provide full capacity to the demand nodes. This shows that the behaviour of indoor reflections is too erratic for otherwise intuitive network setups to be effective.

To demonstrate the advantage of the frequency attribute, the first four rows in table III contain the results for networks where fewer LTE frequencies are available for use. These results show that per additional frequency the interference buffer is approximately halved. Not only is it important for a network planner to be able to model the choice of frequencies, we also show that it is important for LTE networks to use more than one frequency. This means that schemes which allow LTE operators to share frequencies would be beneficial to implement in indoor networks. Using these models allows the network planner to put a number to that benefit.

V. CONCLUSION

In order to address the interference in LTE and WLAN networks, an optimization problem has been proposed which determines the optimal location, frequency, and bandwidth allocation for an indoor network where the operator can ensure that both technologies are available for use. This type of network will see a rise in implementation to handle the increase in indoor traffic. The method suggested in this paper allows a new degree of freedom in the planning through the use of the frequency attribute. Allowing the frequency to be a variable in the optimization problem considerably reduced the bandwidth loss due to interference.

ACKNOWLEDGMENTS

This research is funded by the German Federal Ministry of Economic Affairs and Energy through the BIC-iRaptor project (project number 16KN052730). The authours would also like to thank Till Rexhausen for his work on the channel model implementation and producing the graphics.

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