Energy Savings in Wireless Access Networks Through Optimized Network Management

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***Abstract* - The energy consumption of wireless access networks amounts for more than 55% of the whole communication sector and for a non negligible part of the operational costs of mobile operators. In this paper we consider possible energy savings through optimized management of on/off state and transmission power of access stations according to traffic estimates in different hours of the day or days of the week. We propose an optimization approach based on a ILP model that minimizes power consumption while ensuring coverage of the active users and enough capacity for guaranteeing quality of service. Proposed model is solved to the optimum on a set of randomly generated instances that show the effect of system parameters on optimal power consumption.**

I. INTRODUCTION

During last decade, energy consumption of information and communication technologies (ICTs) sector has become a key issue, from both economic and environmental perspective [1]. ICT alone is responsible of a percentage which varies between 2% and 10% of the world power consumption [3, 6]. ICT also contributes with 2% to 2.5% of a global greenhouse gas (GHG) emissions annually [4]. These percentages are likely to grow in next years as ICTs become more widely available [8]. Although mobile radio networks, as one part of the ICT sector, contributes a rather small portion of the global GHG emissions (0.2%) [7], energy consumed by this sector is not negligible. Reported energy consumption of mobile telephony operators in Italy equals to 0,7% of total national electric consumption [9]. This is equivalent to 55% of energy consumed by all communications sector. Therefore, with rising demand for wireless communication services, serious challenges with respect to the energy needs of mobile radio networks are expected in the future.

Furthermore, economical reasons such as possible minimization of capex and opex impose cellular network operators and other owners of wireless network devices to consider reducing the energy consumption of their networks. Currently over 80% of the power in mobile telecommunications is consumed in the radio part of the wide-area access network, more specifically the base stations (BSs) [7]. Also, the number of enterprise deployments and the average number of access points (APs) in each enterprise wireless local area network (WLAN) is increasing exponentially every year. Although energy consumption of the BS is much higher compared to the AP, vast number of WLAN network devices installed worldwide contributes to enlargement of the energy consumption in wireless access networks.

Mentioned reasons necessitate development of a new energy saving approaches which can be accomplished on a micro or macro level of the access network. Improvements of individual network devices on the micro level are based on the use of more energy efficient and load adaptive hardware components as well as software modules [5]. In this paper we consider potential macro level advances which take into account management strategies of whole wireless network through optimal selection of active network devices. Such energy-efficient resource management strategies must enable wireless access networks to scale power consumption with the number of active users and corresponding traffic demands. This topic has attracted the attention of the research community very recently and some initial ideas and results appear in [2], [3], [5] and [6].

Wireless access networks are mostly dimensioned for peak demands using dense layers of cell coverage in order to ensure sufficient capacity in areas where large numbers of users are expected to be simultaneously active. Although mobile users benefits redundant capacity during times of peak demands, it is known that peak demand rarely occurs. Additionally, reduction of the traffic in some areas of wireless network is due to combination of the typical day-night behavior of users and daily movements of users carrying their mobile devices from residential to office areas and back.

Therefore, we believe that significant energy savings can be achieved if parts or all components of some wireless network devices are powered off when traffic is low, and powered on based on the volume and location of user demand. To achieve this for large-scale wireless networks without hampering coverage and/or client performance, a centralized network management approach based on traffic estimations of different hours of the day and days of the week seems to be the most appropriate. Network management architectures of the current wireless access system already provide to mobile operators full control of network elements and tools for measuring traffic statistics with rather fine granularity.

In this paper we propose an optimization approach for managing the network based on mathematical programming. To the best of our knowledge, this is the first paper that uses principles of *integer linear programming* (ILP) in order to minimize energy consumption of wireless access network. Our goal is to develop general energy optimization models which will be applicable for different wireless access technologies (WLAN, WiMax, 2G/3G/4G).

The rest of the paper is organized as follows: Section 2 emphasizes the influence of changes in transmit power on consumed power, transmission rates and cell coverage considering WLANs as an example. In Section 3, proposed linear mathematical model for optimization of power consumption is presented. Instance generator used for generation of solver input data is described in Section 4, while obtained numerical results have been discussed in Section 5. Finally, Section 6 gives some concluding remarks.

II. POWER CONSUMPTION MODEL

In order to define input parameters for developed mathematical models, we consider as an example the energy consumption of IEEE 802.11b/g WLAN networks with APs and user devices working in infrastructure mode. Similar considerations can be done for other wireless technologies, including 3G, WiMax, LTE systems. We start from the assumption that average electric power consumption of wireless network device depends on the level of the transmitted power of wireless signal [7]. Two components, fixed and variable contributes to the average power consumption of wireless network device. Fixed component (AC/DC conversion, signal processing, filtering, cooling) does not depend on a radiated power and is constant in time. Hence, even if the radio interface does not transmit signal of any power, wireless network device still consumes power, and this *baseline power consumption* is denoted as P_b (W). On the other hand, *variable component of power consumption* P_k (W) due to power amplifier, feeder losses and cooling depends on the radiated power P_{Tk} (mW, W or dBm) and is higher when radiated power increases. Accordingly, power consumption of a wireless network devices can be expressed as function of transmitted power. If wireless network device transmits radio signal with the transmit power P_{Tk}, baseline power consumption P_b increases for amount of P_k resulting in instantaneous (average) power consumption equal to

$$P(k) = P_b + P_k \qquad \text{[W]} \qquad (1)$$

where $k=\{1,...,L\}$ is one of L possible levels (values) of the transmitted signal power P_{Tk}. Correlation between level k of the transmitted power P_{Tk} and additional electric power P_k consumed by WLAN AP can be assumed as shown in Table 1.

Changes in the transmit power also influence on channel condition estimates used for adaptive selection of the best rate out of multiple available Physical Layer (PHY) rates defined by IEEE 802.11g standard. Because of that, for different transmit power levels P_{Tk} of wireless device (AP), users allocated at the distance d from AP have different transmission rates as presumed in Table 1. We assume different number of coverage rings $r=\{1,...,D\}$ corresponding to the different coverage areas of every AP as shown on Figure 1a). Fixation of number ($D=3$) and coverage ring borders with $r=1$ ($0 \leq d \leq 40$ m), $r=2$ (40 m $< d \leq 80$ m) and $r=3$ (80 m $< d \leq 120$ m) simplifies specification of PHY rates in coverage area around AP. Therefore, every user allocated in *r-th* coverage ring will have the same PHY rate, which can be treated as average transmission rate of corresponding coverage area. Maximal coverage of 120 m is typical for moderately obstructed indoor environments. In real scenarios coverage areas are not circular as channel attenuation does not depend on distance only but it also influenced by other effects like obstacle shadowing.

The log-distance path loss model [10, 11] considering log-normal fading expressed as

$$P_{pl}(d) = \overline{P_{pl}}(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \qquad \text{[dB]} \qquad (2)$$

is propagation model used for characterization of WLAN radio environment. In relation (2), $\overline{P_{pl}}(d_0)$ is average value of path loss at close-in reference distance d_0, n is path loss exponent and X_σ is zero-mean Gaussian distributed random variable having standard deviation σ. Summery of all values used for calculation of received power given by

$$P_r(d) = P_{Tk} - P_{pl}(d) \qquad \text{[dBm]} \qquad (3)$$

at Euclidean distance d between transmitter and receiver are shown in Table 2. Furthermore, increase of transmit power results in enlargement of coverage area size. To add additional simplicity to the graphical presentation of coverage areas, it is assumed that no geometric changes of the coverage radii will be visible as a result of transmit power scaling. This effect will be inherently considered in such way that changes of the coverage areas due to changes of transmit power will be taken into account by scaling PHY transmission rates. Connection can be obtained in the third ($r=3$) coverage ring only if a level of receive signal strength is below power sensitivity threshold: $P_r(d) \leq P_{rth}$. This is the reason why for the lowest transmit power level ($k=4$, P_{Tk}=25 mW) in the third ($r=3$) coverage ring, connection between user terminal and AP can not be establish. Although IEEE 802.11 PHY mandates scaling of sensitivity values base on the used PHY rate, for further simplification, constant receiver sensitivity (P_{rth}) of the -83 dBm will be considered for all PHY rates. Selected sensitivity value is characteristic for most of the new WLAN cards.

III. MINIMIZING ENERGY CONSUMPTION

The problem of managing the energy of a wireless access network is similar to that of network design where however we reduce the capacity of the network by switching off or adjusting the power of some devices. A simple and common way to model the radio coverage in the service area (SA) is to consider possible positions of user terminals called test points (TPs) and all positions of the APs called coverage sites (CSs). Let:

TABLE I Average Power Consumption and Transmission Rates for Different Levels of Transmit Power

Level of transmitted power k	Baseline power consump. P_b (W)	Additional power consump. P_k (W)	Average power consumption $P(k)$(W)	Transmit power P_k (mW/dBm)	Distance (coverage rings)/Average PHY rates $r=1$ (0 m-40 m) R_{jkr} (Mb/s)	$r=2$ (40 m-80 m) R_{jkr} (Mb/s)	$r=3$ (80 m-120 m) R_{jkr} (Mb/s)
1	5	7	12	100/20	R_{j11}=54	R_{j12}=48	R_{j13}=36
2	5	5	10	75/18.8	R_{j21}=54	R_{j22}=36	R_{j23}=18
3	5	3	8	50/17	R_{j31}=48	R_{j32}=24	R_{j33}=11
4	5	1	6	25/14	R_{j41}=36	R_{j42}=18	R_{j43}=5,5(N/A)

TABLE III Parameters Used in: Path-loss Model, Setup of Simulation Network and Definition of Demand Values

Path-loss model values (λ =0.122 m, f=2.4 GHz)		Simulation network parameters	Type of CDV ($\mathbf{d}_i^{p,v}$) (%/No. of active TPs)	Version of CDV ($\mathbf{d}_i^{p,v}$) Mb/s (distribution)
X_σ=6.23 dB	σ=13 dB	SA size: 1200x1200	$\mathbf{d}_i^{1,v}$ = Low (15/30)	$\mathbf{d}_i^{p,1}$ = 1 (uniform for all TPs)
d_0=1 m	$\overline{P}_{pl}(d_0)$=40 dB	Total CSs no.: 200	$\mathbf{d}_i^{2,v}$ = Medium (55/110)	$\mathbf{d}_i^{p,2}$ = 0.3-3.5 (random for all TPs)
n = 2.7	$P_{rtr}(d)$=-83 dBm	Total TPs no.: 70	$\mathbf{d}_i^{3,v}$ = High (100/200)	$\mathbf{d}_i^{p,3}$ = 0.3-1.4, 1.5-2.5, 2.6-3.5(random)

- $j \in J=\{1, ..., m\}$ be the set of CSs hosting APs and
- $i \in I=\{1, ..., n\}$ denote the set of TPs where user terminals are placed.

The *j-th* CS consumes power P_{jb} when it is powered on and additional power P_{jk} if transmits using *k-th* power level P_{Tk}. For the sake of simplicity we assume all APs have the same power consumption and transmission power levels with $P_{jk}=P_k$ and $P_{jb}=P_b$, however the model can be easily generalized. Figures 1a) and b) presents plots of an example network with TPs and CSs positions. Straight lines between TPs and CSs on Figure 1b) defines which TPs can be potentially connected to corresponding CS(s) based on the distance and sensitivity restrictions. The problem is to find a set of APs with minimal power consumption satisfying capacity demand d_i (in Mb/s) of all active TPs. Measurements show that number of the users and corresponding capacity demands in wireless access networks significantly varies depending on the period of the day [2].

Therefore, these two factors contribute to the considerable variations of traffic pattern on daily or weekly bases. Influence of these two factors on network resources will be expressed in the form of *capacity demand vector* (CDV) $\mathbf{d}_i^{p,v}=\left[d_1^{p,v}......d_n^{p,v}\right]^T$. Index $p=\{1,...,c\}$ refers on different *types of demand vectors* determined with percentage of the active users and index $v=\{1,...,s\}$ states *version of demand vector,* taking into account different distributions of the user capacity demands. Introduction of different types p of the CDVs enables variations in number of active users that are characteristic for specific period of a day. In numerical results we use three ($c=3$) different types of the CDVs, corresponding to the *low* (night), *medium* (afternoon) and *high* (day) user activity (Table 2). Also, with different versions v of the CDVs, random or uniform distribution of user demand values can be modeled. Percentages of active users for different p and v of the CDVs are shown in Table 2.

The problem of finding the subset of powered CSs with minimal energy consumption that ensures coverage and capacity demand of all TPs is a combination of the: minimum set covering problem and capacitated facility location problem. Such problem can be formulated using three different binary decision variables: y_j, x_{jk} and w_{ijk}. First fundamental decision variables y_j are, as in any covering problem, those selecting which subsets of CSs (APs) are part of the solution:

$$y_j=\begin{cases}1 & if\ an\ AP\ is\ powered-on\ at\ j-th\ CS\\ 0 & otherwise.\end{cases}$$

Transmissions of *j-th* CS using *k-th* transmit power level (P_{Tk}) will be defined with second decision binary variable x_{jk} equal to:

$$x_{jk}=\begin{cases}1 & if\ aditional\ power\ P_k\ is\ spent\ by\ j-th\ CS\\ 0 & otherwise\end{cases}$$

Also, binary decision variables explicitly indicating assignment of the TPs to the CSs are defined as

$$w_{ijk}=\begin{cases}1 & if\ TP\ i\ is\ assigned\ to\ j-th\ CS\\ & transmitting\ at\ k-th\ power\ level\\ 0 & otherwise.\end{cases}$$

Based on the verification of distance and receiver sensitivity criteria, *0-1 incidence matrix* containing coverage information will be derived for each triple TP *i*, CS *j* and *k-th* transmit power level P_{Tk} in the form of a binary parameter expressed as

$$a_{ijk}=\begin{cases}1 & if\ TP\ i\ is\ covered\ by\ CS\ j\\ & spending\ aditional\ power\ P_k\\ 0 & otherwise.\end{cases}$$

Furthermore, two subsets are defined as:

- $I(j,k) \subseteq I$ which is the set of the TP(s) in coverage area of *j-th* CS transmitting with *k-th* Tx power level and
- $I(j,k,r) \subseteq I$ as the set of TP(s) allocated in *r-th* coverage ring for every *(j,k)* combination.

In order to optimize power consumption taking into account different throughput rates R_{jkr} (Table 1.) at different distances from every CS, we propose the following *Integer Linear Programming* (ILP) model:

$$\text{Min} \sum_j P_b y_j + \sum_j \sum_k P_k x_{jk} \tag{4}$$

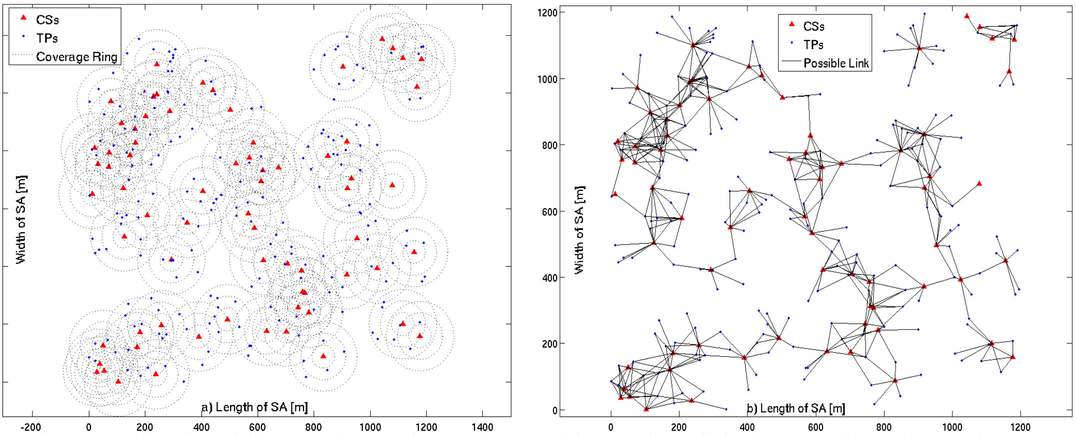

Figure 1a) Allocation of all TPs and CSs within SA, b) Potential connections (links) between allocated TPs and CSs

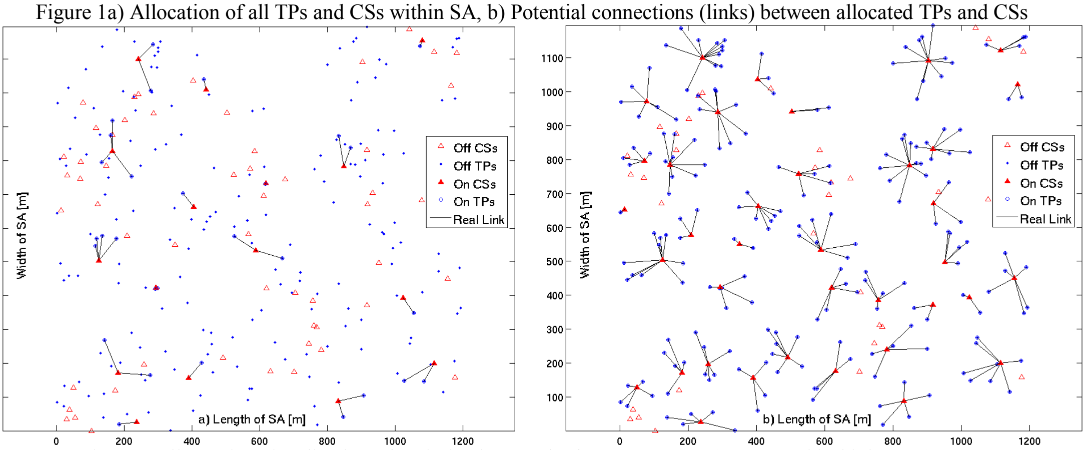

Figure 2. Illustrative visualization of optimization results for: a) Low ($p=1$) CDV and b) high ($p=3$) CDV

S. t.

$$\sum_{k} x_{jk} \le y_j \qquad \forall j \in J = \{1,\dots,m\} \tag{5}$$

$$\sum_{j} \sum_{k} a_{ijk} x_{jk} \ge 1 \qquad \forall i \in \{1,\dots,n\}: \quad d_i \ne 0 \tag{6}$$

$$x_{jk} \sum_{r\in R} \sum_{i\in I(jkr)} d_i / R_{jkr} \le 1 \quad \forall j \in \{1,\dots,m\}, \forall k \in \{1,\dots,l\}: I(j,k,r) \ne \{\phi\} \tag{7}$$

$$x_{j_b k_b} + \sum_{h=b+1}^{B} w_{ij_h k_h} \le 1 \quad \forall i \in \{1,\dots,n\}: d_i \ne 0, \quad \forall b: 1 \le b \le B \tag{8}$$

$$w_{ij_h k_h} \le x_{j_b k_b} \quad \forall i \in \{1,\dots,n\}: d_i \ne 0, \quad \forall b: 1 \le b \le B, h = b \tag{9}$$

$$\sum_{h=1}^{B} w_{ij_h k_h} = 1 \quad \forall i \in \{1,\dots,n\}: d_i \ne 0, \quad s.t.: h = b \tag{10}$$

$$\sum_{i\in I(j,k)} w_{ijk} \le N \quad \forall j \in \{1,\dots,m\}, \forall k \in \{1,\dots,l\}: I(j,k) \ne \{\phi\} \tag{11}$$

$$y_j \in \{0,1\} \qquad \forall j \in \{1,\dots,m\} \tag{12}$$

$$x_{jk} \in \{0,1\} \qquad \forall j \in \{1,\dots,m\}, \forall k \in \{1,\dots,l\} \tag{13}$$

$$w_{ijk} \in \{0,1\} \qquad \forall i \in \{1,\dots,n\}, \forall j \in \{1,\dots,m\}, \forall k \in \{1,\dots,l\}. \tag{14}$$

Objective function (4) provides the total instantaneous power consumption of active network devices (CSs) in the WLAN. Constraints (5) are *coherence constraints* stating that in each CS at most one transmit power level can be used. *Coverage constraints* (6) ensure that all TPs are within service area of at least one CS and *connection constraints* (10) states that every TP i must be connected to only one CS. Since total capacity of each activated CS must be shared between connected TP(s), *capacity constraints* (7) prevent that overall TP demand(s) in *r-th* coverage ring exceed the PHY rate R_{jkr} of that ring. *Best-power selection constraints* (8) make implicit assignment of TPs to the best active CS in terms of signal strength. In order to satisfy best-power connection criteria, the pairs of CSs and corresponding (Tx) configurations that would allow connection with *i-th TP* are sorted in a decreasing order of the signal strength, creating for each TP i set of pairs:

$$JK(i)=\{(j_1, k_1),\dots,(j_b, k_b),\dots,(j_B,k_B)\}.$$

Index B represents maximal number of a CS-configuration pairs for each set $JK(i)$ defined as $b=\{1,\dots,B\}$. *Configuration constraints* (9) mandates that a TP i can be assigned to a CS j only if that CS is active and configured with *k-th* transmit power level. In order to eliminate huge number of TPs connected to active CS, *excessive number constraints* (11) limit the overall number *(N)* of TPs than can be simultaneously connected to the CS. Finally, constraints (12), (13) and (14) are *integrality*

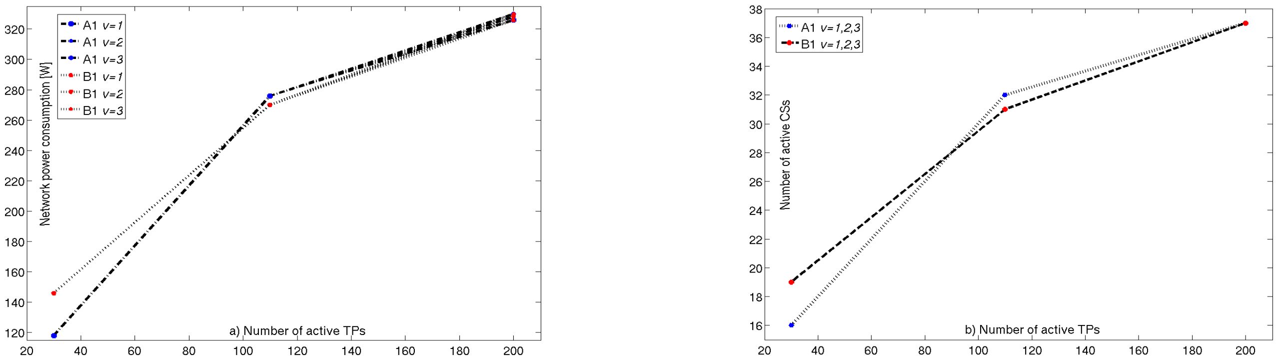

Fig. 3a) Dependence of power consum. on number of active TPs, b) Dependence of powered CSs on number of active TPs

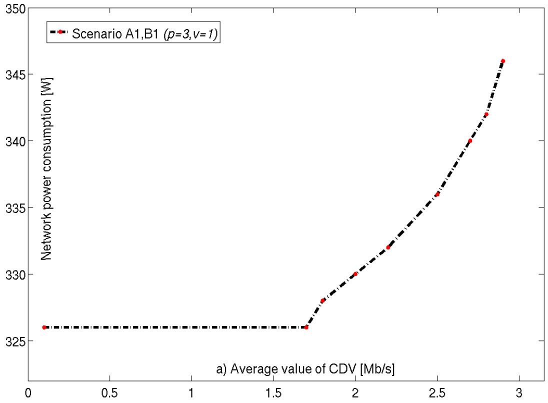

Fig. 4a) Consumed power-average CDV value dependence

constraints for decision variables y_j, x_{jk} and w_{ijk}, respectively. The ILP model proposed can be solved to the optimum using state-of-the-art solvers like CPLEX for reasonable size instances.

IV. INSTANCE GENERATOR

In order to test the effectiveness of proposed optimization model, we have developed an instance generator (IG) that provides realistic wireless networks that are used as input data for the CPLEX solver. The IG takes the following entry parameters: *edges of the simulated SA, number of TPs and CSs allocated in SA, minimal number of CSs covering single TP, number of coverage ranges (rings) of each CS, threshold value of received power at TPs locations (dBm), CS rates (Mb/s) offered to the TPs in each coverage ring, value of CSs transmit power levels (dBm), baseline (*P_b*) and variable (*P_k*) power consumption (W) for every of transmit power levels (k), different groups of TPs having diverse distributions of demand values, ranges for definition of CDV values (Mb/s) in each TPs group.*

For our numerical results, generation of input data is performed for two *test scenarios: A1 and B1,* differing in a way IG creates demand values of the TPs and selects active (having nonzero demand) TPs in specific CDV. Scenario A1 can be seen as nondeterministic approach corresponding to the completely random activation of users in wireless networks. Scenario B1 can be characterized as deterministic since active users in the previous CDV continue to have the same traffic demand value if they remain active in the emerging CDV.

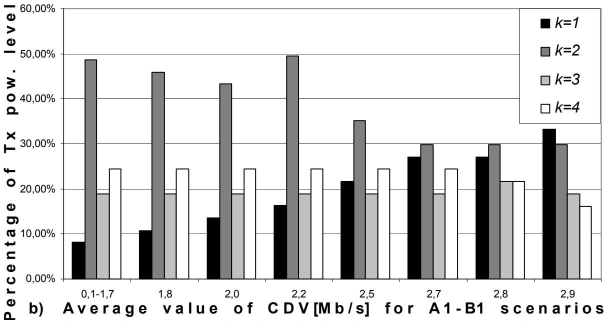

Figure 4b) Tx pow. level statistics for average CDV values

For every of the test scenarios, three different versions ($s=3$) of demand vector v are considered (Table 2). Distribution of TPs demand values for the first ($v=1$) version of CDV is uniform, resulting in fixed and equal demand values of all active TPs for every *p-th* CDV. For the second ($v=2$) and third ($v=3$) version of CDVs, distribution of demand values for every *p-th* CDV type is random, with demand values selected within some predefined range. In the third version of CDV different ranges of demand values for different groups of TPs are defined, while in the second version all active TPs belong to the single group. Selected demand values for all versions of CDVs are shown in Table 2.

V. NUMERICAL RESULTS

Three different types of the CDVs having three distinct versions of demand distributions result in nine different CDVs for every test scenario (A1, B1). All of them have been generated using the IG. The SA size expressed in meters and number of TPs and CSs randomly generated on squared SA are defined in Table 2 and depicted on Figure 1a) and 1b). Optimization of power consumption has been performed for every CDV of each test scenario using mathematical model presented in Section 3. Visualizations of optimization results obtained for low and high CDVs for the example network are shown in Figures 2a) and 2b), respectively. Graphical presentation of obtained results can be seen on Figures 3 and 4. Instantaneous power consumption of the network increases with augmentation of active TPs in CDV. This is shown on Figure 3a) where energy consumption for all three versions ($v=1,2,3$) of the low, medium and high demand vector has been presented and compared for the different test scenarios. In order to satisfy increased number of the TPs and corresponding demands, higher number of activated TPs imposes higher number of CSs to be active. Figure 3b) confirms this behavior, since increase in the number of active TPs belonging to the corresponding CDVs results in enlargement of the number of active CSs.

Furthermore, for every CDV type *p* (low, medium, high) of single test scenario, equal power consumption for all versions *v* of CDVs has been obtained. Because of this, results for every version *v* of each test scenario are presented with only one line on Figures 3a) and 3b). This shows that distribution of demand values has influence on power consumption only if we take into account average demand of CDV on entire network resources, expressed as: $\overline{D}_v = \sum_{i=1}^{N} d_i / N$ [Mb/s]. Although different distributions *v* of TPs demand values have different average capacity demands $\overline{D}_v$ for different types *p* of CDV, variations in values of average demands are very similar (1 Mb/s $\leq \overline{D}_v \leq$ 2.29 Mb/s) for both test scenarios. Hence, for the same number of active TPs in CDV, similar average demand values $\overline{D}_v$ of the CDV will result in equal energy consumptions (Fig. 3a).

But, with enlargement of average demands of the CDVs, instantaneous power consumption tends to increase as presented on Figure 4a). These results have been obtained by varying demand values of the first version (*v=1*) of the high (*p=3*) CDV ($\mathbf{d}_i^{3,1}$). Since this type and version of the CDV has all of TPs active with equal demand values, influence of the overall capacity demand on the power consumption will be the most evident. On Figure 4a), we can see that network power consumption will remain unchanged until average demand reaches some *lower bound value* (1.7 Mb/s). This is because up to the lower bound value, lower average demand of the CDVs does not invoke activation of additional network resources (powering new CSs and transmitting at the higher Tx power levels). Additionally, we are forced to keep part of the network on, in order to meet coverage constraints. More in general we can reduce power consumption only when the system has redundant resources to meet capacity constraints that can be switched off when traffic is low.

Despite increase in the number of active CSs, augmentations of energy consumption for demands above the lower bound will be also dedicated to the enlargement of CSs transmit power, as presented on Figure 4b. It can be noticed that percentage of CSs transmitting at highest power level (*k=1*) increases as the values of average demands becomes larger. With enlargement of the transmit power, CSs will compensate increase in average demand values of the CDVs, since higher PHY rates can be achieved with higher transmit power levels.

VI. CONCLUSION

In this paper we have considered the problem of minimizing the power consumption of wireless access networks through switching on and off and adjusting the emitted power of access stations based on different traffic profiles that can be experienced by the network. We have proposed an ILP model that allows to select the optimal network configuration in terms of power consumption and to guarantee coverage and enough capacity to serve active users in the SA. Numerical results show that proposed approach is actually able to modulate instantaneous power consumption of the network based on the traffic needs. In the case of peak user activity, higher PHY rates guaranteed to the users have been pursued with upgrowth of the network power consumption.

We are currently working to extend proposed model to consider the negative impact that large variations in network configuration from one period to next one may have on signaling overhead and perceived service quality. Moreover, we are also considering the need to keep network element active during some periods to ensure their reliability.

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