Heuristic Approach for Optimized Energy Savings in Wireless Access Networks

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Abstract: Energy consumption of wireless access networks is in permanent increase, what results with higher operational expenditures of network operators and negative impact on environment. In this paper we consider possible energy savings of wireless access networks through development of ILP model based on energy efficient network management. To cope with the problem of high computational time characteristic for ILP model, we have developed own heuristic algorithm based on greedy methods and local search. Although heuristics results have been up to 10% higher in comparison to the ones obtained for ILP model, heuristic algorithm ensures minimization of network energy consumption in reasonable amount of time. This makes heuristics algorithms applicable for practical implementation in real network management systems.

1. INTRODUCTION

Power consumption of Information and Communication Technologies (ICT) sector has become a key issue in the last few years, due to rising energy cost and serious environment impacts on green house gases emissions. Pollution and energy savings are keywords that are becoming more and more of interest of people and of governments, and the research community as well is more sensible toward these topics in the last years. As important part of the ICT consumption, the energy consumption of wireless access networks is rapidly increasing and in some countries it amounts for more than 55% of the whole communication sector [1]. Such increase also accounts to a non negligible part of the operational expenditures (OPEX) of network equipment owners. Growth of data rates in wireless networks by a factor of roughly 10 every 5 years and increase in the number of users, results in a doubling of the energy consumption of wireless networks infrastructure every 4-5 years [2].

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) [3]. Also, the number of enterprise deployments and overall number of individual access points (APs) in small and medium size wireless local area networks (WLANs) increases 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.

Due to afore-mentioned reasons, development of new generation of wireless access networks that will be more energy efficient becomes necessity. This topic gain attention of research community very recently and some initial results can be found in [4], [5], [6], [7]. First attempt for adoption of resource on-demand (RoD) WLAN strategies that can reduce energy consumption of centrally managed WLANs was published in work [4]. Authors in [5] develop analytical model for assessment of the effectiveness of RoD strategy introduced in [4]. Although energy wasted in large-scale and high-density WLANs is a new and serious concern, according to both papers, ample room for possible energy savings exists.

In our positioning paper [6], for the first time principles of integer linear programming (ILP) are used for minimization of instantaneous power consumption of real size WLAN. We extended obtained results in work [7] through development of new ILP models, indicating significant reductions in monthly energy consumption on the level of complete WLAN. Actually, we manage to modulate energy consumption of WLAN according to the realistic traffic pattern, also considering important factors like: full coverage of service area, negative effect of frequent variations in activity of network devices, influence of interference among network elements and capacity limitations of network devices. Obtained energy savings have been realized through implementation of intelligent network management. Such energy-efficient management adopts on/off activity of APs and corresponding transmitted (Tx) power in accordance with number and location of active users.

Although optimization approach based on ILP models presents powerful tool for modeling possible energy savings in wired and wireless networks [6], [7], ILP approach is not without drawbacks. Due to NP-hardness of optimization models proposed in our recent work, computational time of some mathematical models becomes very long. Since long computational time reduces possibility for practical implementation of ILP models in real-time management systems, in this paper we present novel heuristic algorithm for energy savings in WLANs. Moreover, we make comparison of optimization results and computational time of heuristic approach with those obtained by ILP model.

The rest of the paper is organized as follows: in Section 2, structure of the analyzed WLAN with proposed ILP model has been presented. Section 3 contain details of developed heuristic algorithm. Obtained numerical results have been discussed in Section 4. Finally, Section 5 gives some concluding remarks.

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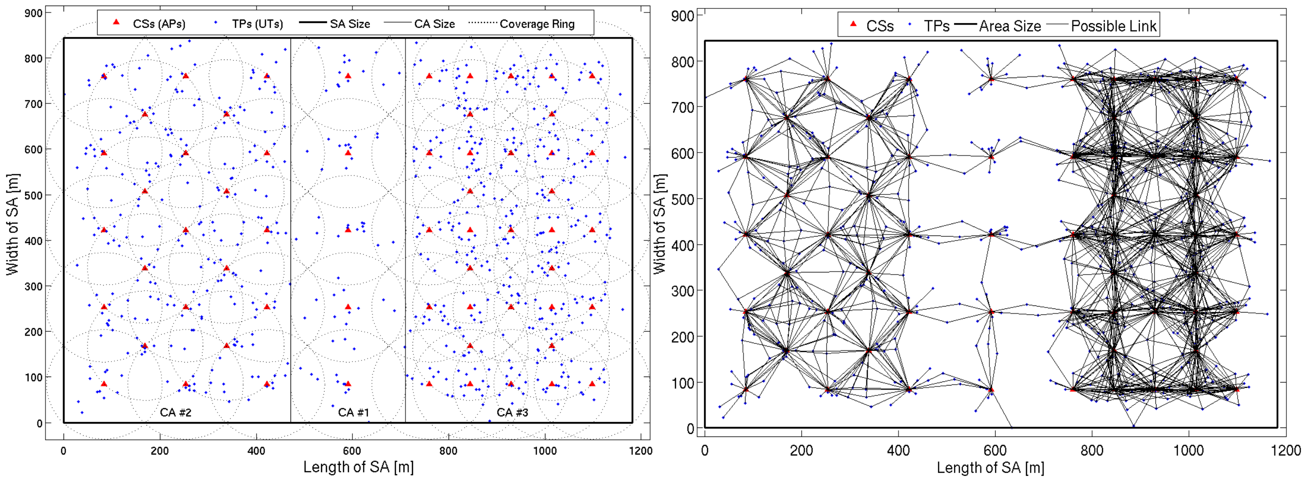
[*] Research activities on this subject are supported by Unity through Knowledge Fund (UKF) based on grant agreement No. 57 ("Green Networking" project). Furthermore, these materials are based on work financed by the National Foundation for Science, Higher Education and Technological Development of the Republic of Croatia.



a) b)

Figure 1. a) Allocation of CSs and TPs inside medium size WLAN, b) Potential wireless links between TPs and CSs

Table 1. Average power consumption and distance-PHY rates dependence

Level of Tx power k	Baseline pow. cons. P_b (W) -	Additional pow. cons. P_k (W) -	Average pow. cons. $P(k)$ (W) -	Tx power P_{Tk} (mW/dBm)	Distance (coverage rings)		
					$r=1$ (0 m-40 m)	$r=2$ (40 m-80 m)	$r=3$ (80 m-120 m)
					Average PHY rates		
					R_{jkr} (Mb/s)	R_{jkr} (Mb/s)	R_{jkr} (Mb/s)
1	5	7	12	100/20	$R_{j11}=54$	$R_{j12}=36$	$R_{j13}=18$
2	5	5	10	75/18,8	$R_{j21}=48$	$R_{j22}=24$	$R_{j23}=12$
3	5	3	8	50/17	$R_{j31}=36$	$R_{j32}=18$	$R_{j33}=9$
4	5	1	6|	25/14	$R_{j41}=24$	$R_{j42}=12$	$R_{j43}=6$ (N/A)

Table 2. Time periods for traffic aproxim.

Time period t	T_t [h]	T_{t+1} [h]	$\Delta T_t = T_{t+1} - T_t$ [h]	% of active users
1	00	09	9	20
2	09	12	3	100
3	12	15	3	70
4	15	18	3	85
5	18	24	6	55

2. NETWORK STRUCTURE AND ILP MODEL

For testing the energy management strategy introduced in the paper through ILP model and heuristic algorithm derived later on, we tried to emulate the topology of a realistic IEEE 802.11g WLAN. Figure 1a) presents analyzed medium size WLAN instance consisted of 61 APs working in the infrastructure mode and 671 user terminals (UTs) allocated inside service area (SA) of 1200 m × 900 m. Such network can correspond to travel terminal like airport building, having different allocation densities of APs in three different coverage areas (CAs). Similar to real network topologies, higher number of APs is allocated inside those CAs where higher number of UTs is expected. On Figure 1b), with straight lines possible wireless connections between APs and UTs are presented. For characterization of WLAN radio environment and for calculation of possible wireless connections we use long distance path loss model with log-normal fading [2].

Furthermore, we assume that instantaneous average power consumption of wireless network devices can be expressed as function of Tx power (P_{Tk}). If wireless network device transmits radio signal with the Tx power P_{Tk}, baseline power consumption P_b increases for amount of P_k resulting in instantaneous (average) power consumption equal to $P(k)$. Considered values of baseline P_b and additional power consumptions P_k for different Tx power levels P_{Tk} have been presented in Table 1. Additionally, we considered three coverage rings around APs with borders $0 \le d \le 40$ m, 40 m $< d \le 80$ m and 80 m $< d \le 120$. All users located in some coverage ring will have the same PHY rate, which can be treated as average transmission rate R_{jkr} of corresponding coverage area. Table 1 presents values of PHY rates in each coverage ring for different Tx powers. Values are selected according to practical measurements of 802.11g AP rates.

To mathematically model the radio coverage in the SA, we consider possible positions of UTs called test points (TPs) and all positions of the APs called coverage sites (CSs). Let:

- $j \in J = \{1, ..., m\}$ be the set of CSs hosting APs,
- $i \in I = \{1, ..., n\}$ denote the set of TPs where user terminals are placed,
- $k \in K = \{1,...,l\}$ is the set of l different levels (values) of the Tx signal power P_{Tk},
- $r \in D = \{1,...,e\}$ be the set of circular coverage rings which corresponds to different coverage areas around each AP,
- $t \in H = \{1,...,p\}$ denote the set of different time periods during one day,
- $s \in S = \{1,...,u\}$ is the set of measurement points (MPs) virtually allocated inside SA.

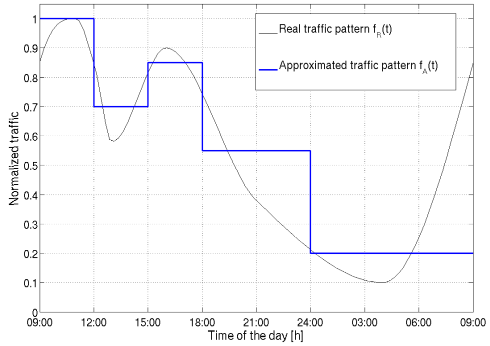


Figure 2. Approximation of real traffic pattern during one day

To simulate changes in user activity, discrete function $f_A(t)$ presented in Figure 2. is used for approximating normalized daily traffic pattern $f_R(t)$ of a some realistic WLAN. According to Figure 2, approximation is done using five different time periods *t*. Time periods are expressed in hours (h) as time difference between ending (T_{t+1}) and starting time (T_t) of time period *t*. Percentage of active users in each time period with corresponding durations can be found in Table 2.

The problem is to find a set of CSs with minimal power consumption satisfying capacity demand d_{it} (in Mb/s) of all TPs, active during specific time period *t*. To solve such problem we define three binary decision variables as:

$$y_{jt} = \begin{cases} 1 & if \;\; an \;\; AP \;\; is \;\; powered-on \;\; at \;\; j-th \;\; CS \\ & during \;\; time \;\; period \;\; t \\ 0 & otherwise \end{cases}$$

$$x_{jkt} = \begin{cases} 1 & if \;\; aditional \;\; power \;\; P_k \;\; is \;\; consumed \;\; by \;\; j-th \\ & CS \;\; during \;\; time \;\; period \;\; t \\ 0 & otherwise \end{cases}$$

$$w_{ijkt} = \begin{cases} 1 & if \;\; TP \;\; i \;\; is \;\; assigned \;\; to \;\; j-th \;\; CS \;\; transmitting \\ & at \;\; k-th \;\; power \;\; level \;\; during \;\; time \;\; period \;\; t \\ 0 & otherwise \end{cases}$$

Furthermore, 0-1 incidence matrix containing coverage information of all TPs is defined as

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

In order to assure full coverage of the SA with WLAN signal during all time periods, we introduce concept of measurement points (MPs). Introduction of virtual points (MPs) regularly allocated in the grid manner with 10 m x 10 m distance enables mathematical modeling of full SA coverage. These virtual points serve as a sort of probe points in which received signal strength must be above minimal sensitivity threshold set to -83 dBm. Hence, we introduce one additional 0-1 incidence matrix containing information's about coverage of each MP as:

$$b_{sjk} = \begin{cases} 1 & if \;\; s-th \;\; MP \;\; is \;\; covered \;\; by \;\; j-th \;\; CS \\ & transmiting \;\; with \;\; k-th \;\; power \;\; level \\ 0 & otherwise \end{cases}$$

Optimization problem can be mathematically modeled as:

$$\text{Min} \left[\sum_t \sum_j P_j y_{jt} (T_{t+1} - T_t) + \sum_t \sum_j \sum_k P_k x_{jkt} (T_{t+1} - T_t) \right] \times C \qquad (1)$$

S. t.

$$\sum_k x_{jkt} \le y_{jt} \quad \forall (j,t) : j \in J = \{1,...,m\}, \forall t \in H = \{1,..., p\} \qquad (2)$$

$$\sum_j \sum_k a_{ijkt} x_{jkt} \ge 1 \;\; \forall (i,t) : i \in \{1,...,n\}, \forall t \in H = \{1,...,p\} \wedge \forall d_{it} \ne 0 : a_{ijkt} \ne 0 \qquad (3)$$

$$\sum_{r \in D} \sum_{i \in I(jkrt)} \frac{d_{it} w_{ijkt}}{R_{jkr}} \le 1 \;\; \forall (j,k,t) : j \in \{1,..., m\}, k \in \{1,..., l\}, \forall t \in \{1,..., p\} \qquad (4)$$

$$x_{j_b k_b t} + \sum_{h=b+1}^{B} w_{ij_h k_h t} \le 1 \forall (i,t) : i \in \{1,...,n\}, t \in \{1,...,p\}, d_{it} \ne 0, s.t. \forall b : 1 \le b \le B-1 \qquad (5)$$

$$w_{ij_h k_h t} \le x_{j_b k_b t} \forall (i,t) : i \in \{1,...,n\}, t \in \{1,...,p\}, d_{it} \ne 0, s.t. \forall b : 1 \le b \le B, h = b \qquad (6)$$

$$\sum_{h=1}^{B} w_{ij_h k_h t} = 1 \;\; \forall (i,t) : i \in \{1,..., n\}, t \in \{1,..., p\}, d_{it} \ne 0, h = b \qquad (7)$$

$$\sum_j \sum_k b_{sjk} x_{jkt} \ge 1 \forall (s,t) : s \in S = \{1,..., u\}, \forall t \in H = \{1,..., p\} \qquad (8)$$

$$y_{jt} \in \{0,1\} \qquad \forall j \in \{1,...,m\}, \forall t \in \{1,..., p\} \qquad (9)$$

$$x_{jkt} \in \{0,1\} \qquad \forall j \in \{1,..., m\}, \forall k \in \{1,..., l\}, \forall t \in \{1,..., p\} \qquad (10)$$

$$w_{ijkt} \in \{0,1\} \quad \forall j \in \{1,..., m\}, \forall k \in \{1,..., l\}, \forall t \in \{1,..., p\} \qquad (11)$$

where *objective function* (1) minimizes monthly energy consumption of complete WLAN. Since billing unit of consumed energy is kWh, constant C=0,03 1/month in objective function is used for transformation of daily energy consumption to the monthly energy consumption. Constraints (2) are *coherence constraints* stating that each CS (AP) can use in any moment at most one Tx power level. *Coverage constraints* (3) assure that all TPs are within coverage area of at least one CS and *connection constraints* (7) states that every TP *i* can be connected to only one CS at any time. Since total capacity of each powered on CS is shared between connected TP(s), *capacity constraints* (4) prevents that overall TP demand(s) d_{it} in the *r-th* coverage ring exceed PHY rate R_{jkr} of that ring. *Best-power selection constraints* (5) make implicit assignment of TPs to the best active CS in terms of the signal strength. According to *configuration constraints* (6), TP *i* can be assigned to a CS *j* only if that CS is active and configured with *k-th* transmit power level. Since *full coverage constraints* (8) mandate that every MP be covered with the radio signal received form at leas one CS during each time period, with those constraints complete coverage of the SA is assured.

Finally, constraints (9), (10) and (11) are the *integrality constraints* for decision variables y_{jt}, x_{jkt} and w_{ijkt}, respectively. All described constraints must be satisfied for each time period *t*. It's easy to see that presented optimization problem belongs to NP-hard category, since it includes the Capacitated Facility Location Problem, known to be NP-hard, as a special case.

3. HEURISTIC ALGORITHM

Another approach for solving the problem of energy efficient network management is based on development of heuristic algorithm. Heuristics are important in practice because efficiency is often a high priority. An efficient heuristic algorithm is the one which determines a solution within reasonable time using reasonable resources. For the types of problems considered in this work, a typical reasonable time frame is a few hours and a typical reasonable resource is a high-end personal computer (server).

Our heuristic approach has been spatially tight to the problem tackled by previous ILP (mathematical) model, focused on energy consumption minimization in WLANs. Given an instance with a set of CSs, TPs and corresponding traffic demands, the aim of heuristics is to build up a solution that offers the lowest energy consumption of the network in each time period. During this process, heuristics must take into account different constraints. Proposed heuristic algorithm is composed of the two phases. In the first one, we adopt a *greedy approach* in order to build up a feasible solution S. In the second phase, *local search* (LS) starts with an initial solution S and iteratively moves to the best candidate within the current neighborhood until no further improvement can be achieved. If this happens, we memorize this solution; otherwise we keep the greedy solution. The *generic structure* of the proposed heuristic algorithm is the following:

```
PROCEDURE Heuristic(I,J,K,P)
      S=∅;
   BuiltUpSolution(I,J,K,P,MM,S)
   LocalSearch(S);
   RETURN(S)
END Heuristic
```

where meaning of the sets: *I, J, K,* and corresponding indexing are the same as the ones introduced in previous section. With **P**, we denote set of all TPs and for each TP we define set of (j, k) combination(s) covering that TP. In the **P,** for each TP, (j, k) combinations P_(j, k) are sorted in decreasing order of the signal strength received by that TP. The MM has the same meaning as **P,** but instead of TPs the MM is related to MPs. Therefore, MM defines for every MP, (j, k) pairs that can assure coverage of that MP with wireless signal. Additionally, S is the set of (j, k) combinations, with $j \in J$ and $k \in K$, that belongs to a final solution S. Therefore, (j, k) combinations in S define which CS j transmitting at Tx power k will be powered on during some time period t.

Each of the two phases of heuristic algorithm are characterized with the related generic function. The *BuiltUpSolution* function in the greedy phase develops, after sequence of iterations, a feasible starting solution. The pseudo code of the greedy phase is:

```
PROCEDURE BuiltUpSolution(I,J,K,P,MM,S)
       Covered_TPs = ∅;
       Covered_MPs = ∅;
 WHILE Covered_TPs!=ALL_TPs || Covered_MPs != ALL_MPs
           Best_Pair = BestPairselection(J,K,P,S);
    S = S U Best_Pair;
    Covered_TPs = Covered_TPs U Tps_PairToAdd
     Covered_MPs = Covered_MPs U MPs_PairToAdd
     TPs_Association(S,P);
  Try_Decrease_Power(S);
END BuiltUpSolution
```

At the beginning of the greedy phase, *BuiltUpSolution* creates and puts to null the set of TPs and MPs that are covered with the current solution S. Then it invokes *BestPairSelection* function to look for the (j, k) pair that covers the highest number of not yet served TPs which must be added to the solution S. The *BuiltUpSolution* function repeats this search until solution S can satisfy all TP demands and until all MPs have been covered, adding at each step a new (j, k) pair. When *BuiltUpSolution* adds a new (j, k) pair in the solution S, algorithm invokes *TPs_Association* function. This function enables, for every TP in solution S, connection with the (j, k) pair from which TP receives the best power. In order to reduce Tx power of (j, k) pairs in S and to more efficiently explore CSs capacity, greedy phase ends with *Try_Decrease_Power* function. This function tries to decrease the selected power level *k*, keeping satisfied the same constraints about capacity (4) and best received power (5). Due to space shortage, pseudo code of *BestPairSelection*, *TPs_Association* and *Try_Decrease_Power* function have not been presented in the paper.

During second phase, *LocalSearch* function is used to improve the feasible starting solution S obtained at the end of greedy phase. The LS starts from an initial solution S and moves to a better solution in its neighborhood until it finds a local optimum, i.e., a solution that does not have a better neighbor. A neighborhood is simply a set of solutions that are found by applying an appropriate transformation (move) to the current solution. In other words, LS chooses an initial solution S and searches for a set S' in solution space Q(S) with f(S')<f(S). If none exists, LS stops and S is a local optimum solution. Otherwise it sets S=S' and repeats its search. We have indicated with S' a set of (j, k) pair(s) that are developed from S through addition of a CS(s) that are near to existing CS j in S, and through removal of this CS j. Solution space Q(S) is the set of all possible neighborhood so that Q(S)={S':S'=S U {j} for j in J\S}U{S':S'=S\{i} for i in S}. In our case, a neighbor of a CS in the solution S is a CS or CSs which can cover some of its coverage area.

The group of all possible neighbors for every CS is calculated before LS phase and is denoted with **N**. For every CS j, the subset of all possible neighbors have been indicated as N(j). The pseudo code of the LS is:

```
PROCEDURE Local_Search(S,N,K)
  DO FOR j in S
    Counter=0;
    DO FOR jj in N(j) until Counter<NearMax
       DO FOR k in K
               G(S) = $S\setminus\{(\underline{j},\underline{k}):\underline{j}=j\}U\{(jj,k)\}$
         S' = BuiltUpSolution2(G(S));
         IF S' feasible
      IF Energy_Consump (S')<Energy_Consump(S)
             S = S';
             TPs_Association(S);
           FI
           ELSE
             QUIT FOR k
         FI
       OD
       Counter=Counter+1;
    OD
  OD
END Local_Search
```

As input, the LS takes the previous solution S obtained at the end of the *BuiltUpSolution* function, the set of all possible neighbors **N** and the set of power levels K. At the beginning, LS adds a neighbor and removes the corresponding CS from the solution S. Since such move has changed the solution and the possible association with TPs, it is necessary to update connections. After the move, LS selects the highest power level for the added CS j, in order to create solution S with the (j, k) pairs equal to the previous one. To do this, we have developed *BuiltUpSolution2* function, which is similar to the previously described *BuiltUpSolution.* The difference between the two functions can be found in the way *BuiltUpSolution2* chooses (j, k) combination when creates S'. Instead of choosing among all possible (j, k) pairs, the *BestPairSelection2* function explores only (j, k) pairs inside G(S). With G(S), we indicate the subset of possible (j, k) pairs generated starting from S and by applying the move that we have described before. G(S) is generally different from S', because at this point, we do not know which (j, k) will be included in S', what Tx power level newly added CS had and is this kind of solution feasible. Every time the LS needs to calculate solution S' from G(S), it has to satisfy the traffic demand of TPs and also coverage of MPs.

If there is further energy consumption improvement, LS memorizes the configuration of this (j, k) pair until it reaches the minimal Tx power level. At that point, LS saves the feasible configuration of (j, k) that improves energy consumption and stops the construction of a new solution. This search is repeated for every CS inside the set of neighbors. Once LS reaches last member of the neighbor set **N**, it presents the final solution for the selected time period and heuristic proceeds with finding a solution for another time period until all time periods have been analyzed.

4. NUMERICAL RESULTS

In order to verify the effectiveness of the proposed heuristics, we have compared results of heuristic approach with optimization results obtained for the previously introduced optimization model. Moreover, examinations of heuristic and ILP model effectiveness have been performed on three additional network instances, dimensions of which are presented in Table 3. These network instances are named as *small, large* and *extra large* instances, due to significantly lower or higher SA size (number of TPs and CSs) in comparison with *medium size* instance introduced in Section 2. While results of the ILP model have been obtained at the output of CPLEX solver, results of the heuristics approach are generated following phases of the previously described pseudo codes.

Table 3. Characteristics of analyzed network instances

Size of netw. instance	Number of TPs	Number of CSs	Dimensions of SA (m x m)
Small	143	13	506 x 506
Medium	61	671	1.182 x 844
Large	1672	152	1.689 x 1.689
Extra large	3069	279	2.196 x 2.196

Based on values of initial parameters, analyzed network instances are generated using an instance generator (IG). We have developed the IG in order to provide information's about realistic wireless networks that are used as input data for the: CPLEX solver and heuristic algorithm. The code of IG and heuristic algorithm has been programmed in C++ programming language. Efficiency of heuristic algorithm has been tested using INTEL-Core 2 E8400 processor with Kubuntu 8.04 OS and its integrated gpp as compiler.

Obtained results presented on Figure 3 for the case of *medium* instance show that for both, ILP model and heuristic approach, we actually manage to modulate instantaneous power consumption of the network according to the realistic traffic pattern (Figure 2). Additionally, on Figure 4 we can notice that higher energy savings can be obtained during time periods of lower user activity (t=1, 5) and vice versa. Results of power consumption during some time periods are for heuristic approach up to 10% higher in comparison with results obtained for ILP model. This is reflected on coefficient of average energy savings which is somewhat lower for the case of heuristic algorithm.

Generally, Figures 3 and 4 indicate inferior results obtained by heuristics in comparison with results obtained by optimization model. But for reaching final solution, heuristics needs significantly lower computational time in comparison with optimization model. This is confirmed on Figure 5 for medium size instances, where suboptimal solution has been obtained due to termination of optimization process after 24 hours. Therefore, less optimal solution obtained by heuristics is compensate with a lower computational time.

Additionally, we experiment with some modifications related to derived heuristics. This result with development of *modified*

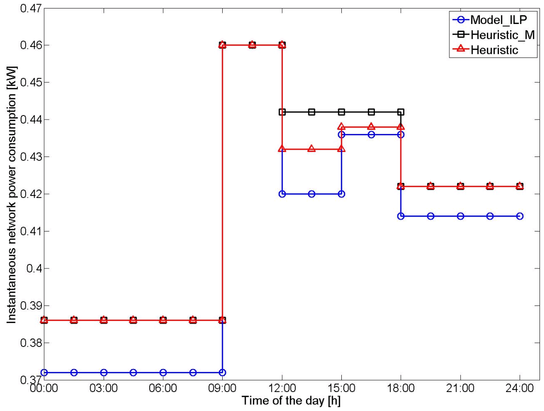


Figure 3. Instantaneous network power consumption during one day

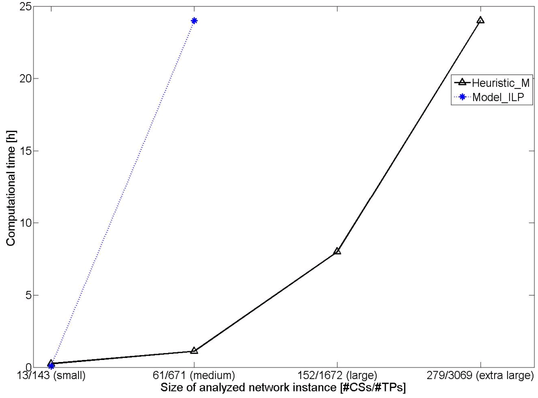


Figure 5. Comparison of computation time for heuristic and ILP model

versions of heuristics denoted as heuristic_M. Generally, greedy phase of modified heuristics_M is the same as for the previously presented heuristic, only differing in the way heuristic_M performs selection of neighbor CSs during LS phase. Instead of analyzing, for every CS in S, all possible neighbors that are not members of S, algorithm of heuristic_M randomly selects only one neighbor for every CS in S. Due to narrower scope of neighbor exploration, on Figure 3 and 4 can be observed that heuristic_M generally obtains equal or worse results if compared with heuristic introduced in Section 3. On the other hand, reduced exploration complexity of the heuristic_M offers final solution for medium network instance in reasonable amount of time (Figure 5). Such computational time is even lower then computational time of developed heuristic in the case of same network instances. Therefore, heuristic algorithms must have a good balance between computational complexity and computational accuracy. In practical implementations, somewhat lower computational accuracy can be accepted at the expense of acceptable computational time.

5. CONCLUSION

In this paper we have considered the problem of optimizing the energy consumption of WLAN through switching on and off and adjusting the emitted power of access stations based on realistic traffic pattern. We have proposed ILP optimization model and heuristic algorithm that allows selection of the optimal network configuration in terms of energy consumption. Energy efficient network management embedded in both approaches can guarantee coverage and enough capacity to serve active users inside the SA. Numerical results show somewhat inferior results of proposed heuristic approach in terms of energy savings. Nevertheless, heuristic algorithms can be valuable alternatives to exact algorithms due to possibility of offering "good" solution in reasonable amount of time. We are currently working to extend proposed ILP model and heuristic algorithm to consider possible energy savings in wide area wireless networks like 2G/3G/4G networks.

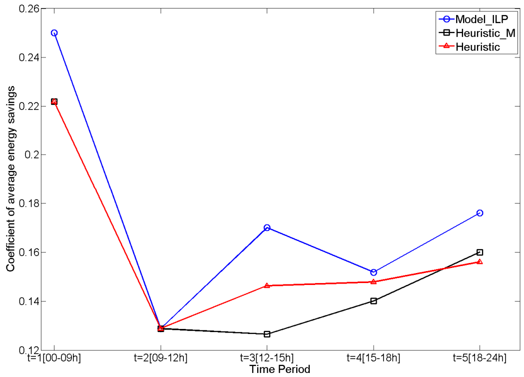


Figure 4. Changes in trend of average energy savings coefficient

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