Management of Network and Energy Resources in Cognitive and Self-Organizing Wireless Networks

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Abstract. The reduction of the consumed energy in modern self-organizing communication systems in a dense urban environment is a challenging task that requires coordination in management operations for the most effective use of network resources. Configuration and performance optimization tasks affect energy consumption of specific components and energy-related metrics of different devices. We propose a novel approach for energy saving and resource management in a wireless urban environment. Central to our approach is the organization of WLAN access points into clusters to facilitate local management and coordination. In each cluster, a cluster head access point monitors the energy consumption changes during the transmission and reception, at both the access point and user equipment sides, and decides on the appropriate adaptation action. The energy consumption reduction and performance improvement attained under the proposed solutions, at both the network and the user equipment sides, is evaluated via simulation.

Keywords: network management, wireless networks, resource management, energy saving, self-organization, cognition

1 Dissertation Summary

Contrary to common belief, information and communication technologies contribute a significant portion both to world energy consumption (2-4%) and environmental pollution (2-2.5% of greenhouse gas) [1]. Wireless network energy efficiency plays a primary role in reducing the impact of communication systems on energy consumption and environmental pollution [2]. Apart from

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an environmental responsibility, energy saving is important for the reduction of communication networks operational costs.

In the last decade, there has been a continuous increase in the number of wireless access points (AP) installations (e.g., IEEE 802.11) in private and public places to cope with user mobility and capacity requirements for emerging and future Internet services. Such APs are often not part of the same administrative entity, and the configuration of their locations and operational features are not necessarily planned for the “network welfare”. This unstructured network environment results in dense AP topologies, especially in urban areas, with high coverage and frequency overlapping. The above in conjunction with users’ varying traffic volume and service requirements, create optimization opportunities in energy saving and wireless resources.

The need to cope with complexity that derives from the interaction of hundreds or even thousands of network devices for the identification and realization of optimization opportunities calls for a distributed and localized solution. Self-organizing networks (SON) is considered as one of the most promising approaches for the management of networks that operate in highly dynamic and dense environments [3], [4].

For the deployment of a SON, each AP incorporates a Cognitive Network Manager (CNM), where energy saving as well as Coverage and Capacity Optimization (CCO) algorithms are placed [5]. In the context of this dissertation we present two types of a CNM a) simple CNM that is referred to as Network Element Cognitive Manager (NECM) and b) domain CNM entitled Network Domain Cognitive Manager (NDCM) [6]. NECM implements the cognitive cycle at the network element level, providing an intelligent adaptation layer to the conventional control plane. Management problems that cannot be addressed directly at the network element level, due to computational or communicational constraints, are escalated to the respective NDCM level. The NDCM incorporates the required cognitive capabilities to identify optimization opportunities and solve problems that require a greater view of network status. The distributed software architecture of cognitive managers is described [7], [8]. We implemented the distributed cognitive framework (software agents and artificial intelligence algorithms) that is deployed in access points and base station of a real heterogeneous access network composed of a Broadband Worldwide Interoperability for Microwave Access (WiMAX) BS and WiFi AP. Interference management and load balancing through channel reselection and vertical assisted handover algorithms respectively are the management tasks of the NECM and NDCM in this experimentation phase. Useful findings and the recommendations from the deployment of the cognitive network management architecture in a real life implementation are provided (average utilization of processing resources, memory usage, and delay of cognitive cycle phases) [9].

Central to our approach is the organization of WLAN APs into clusters to facilitate local management and coordination. Clusters are organization structures used for the collaborative tackling of network management problems, and they are formed following a common known scheme. Clusters facilitate the cooperation and the coordination of a group of network nodes for identifying and solving network management problems. In the literature, there are several clustering algorithms, which are mainly targeting wireless sensor networks or mobile ad-hoc networks, but the majority of them are application-specific (e.g., energy-efficient, mobility-aware). We propose SYSTAS algorithm, for the distributed discovery and establishment of clusters among network nodes, based on the features of the physical network topology. The density of the network graph and the preferential attachment model are used in order to form logical topologies [10]. The application of the proposed algorithm leads to the election of the head and the specification of the borders of the clusters through the allocation of the member nodes to the elected heads. The number of elected heads defines the number of the formed clusters. Clusters are non-overlapping and consist of two types of nodes:

- Simple member node
- Head node.

The head node of each cluster has the role of a NDCM, while simple member nodes instantiate the NECM. Both types of nodes implement CCO and energy saving management tasks. The simulation results, using various network graphs, show the effective cluster formation and the resulted high modularity.

In each cluster, the elected cluster head monitors usage of resources as well as the energy consumption changes and decides on the appropriate adaptation action (Fig. 1). In this dissertation, we propose a novel approach for energy saving and wireless resources management in a WLAN urban environment, where dependencies among different types of nodes and components are taken into account. CCO adapts network connectivity at all desired locations and provides bandwidth according to the communication needs of the users, avoiding the overutilization and underutilization of network resources.

The Capacity Usage Ratio (CUR) of a cluster network area with n APs is defined as the fraction of the available capacity that is actually being used:

$$CUR = \frac{\sum_{i=1}^{n} C_i}{\sum_{i=1}^{n} C_i^{\max}} \quad (1)$$

where C_i and $C_i^{\max}$ is the used (uplink and downlink) capacity and the maximum available (uplink and downlink) capacity, respectively, of AP *i*.

For the calculation of the degree of coverage overlap in a cluster we introduce the overlapping factor (OF), which is based on the clustering coefficient (CC) [11]. The correlation of the CUR with the OF of the APs in a cluster area allows for more effective interpretation of the information that CUR provides, by taking into account the overlap level of the offered bandwidth. For this reason we use the composite metric of Coverage Optimization Opportunity (COOP) introduced in [12]:

$$COOP = CUR^{OF} \tag{2}$$

The COOP metric is useful for the identification of optimization opportunities for low load situations, where less capacity needed, as well for high load situations, where more capacity is required. A low COOP value means that too much capacity is provided in a very dense area, while a too high COOP value indicates an overloaded network area, where more resources are needed.

Energy consumption is measured at both the AP and the User Equipment (UE) side, focusing on the communication component (transmission, reception). CCO is applied via a novel scheme for the dynamic deactivation or reactivation of APs. This scheme aims at the rational usage of the radio resources according to traffic intensity and network density. The mechanism for UE load balancing after the de(re)-activation of an AP is also provided. The effect of an AP deactivation on UE and other APs energy consumption is assessed, triggering an additional adaptation action in the case that an energy efficiency problem has been detected. A scheme for multi-hop relay communication mode is proposed for the energy saving of UE transmission phase, exploiting local networking opportunities [13], [14], [15]. In addition, a novel channel reallocation scheme is introduced for the reduction of energy consumption during data reception phase. CCO and energy saving algorithms in a SON WLAN have been evaluated using OPNET simulation environment.

A novel scheme for the management of the interactions of various optimization or configuration problems in a SON is proposed. We identify and resolve conflicts on metrics and parameters (i.e., configuration actions), which arise from the deduction phase of the cognitive managers that are placed in a SON, in the context of the same or neighboring devices. The proposed scheme consists of three steps. Firstly, a time series-based mechanisms is used in order to avoid checking a configuration action (adaptations) that is triggered by a performance metric, which value appears continuous variations due to temporary changes of the network area. This phase helps a SON to act proactively on conflicts and dependencies resolving, avoiding the trigger of adaptations that appear high uncertainty. In the next step, we check for conflicts on the triggered configurations actions. Only one “direction” per configuration action is prioritized, according to the severity and the priority of the performance metrics that trigger the corresponding configuration action. Finally, the impact of non-conflicting configuration actions on the other performance metrics is analyzed using a cost-benefit analysis scheme. The goal is to select the highest priority configuration action that creates fewer conflicts among available configuration actions and has the minimum possibility to deteriorate other (high priority) performance metrics. The proposed scheme for the coordination of various SON problems has been tested using OPNET simulation environment addressing CCO, energy saving, and interference tasks.

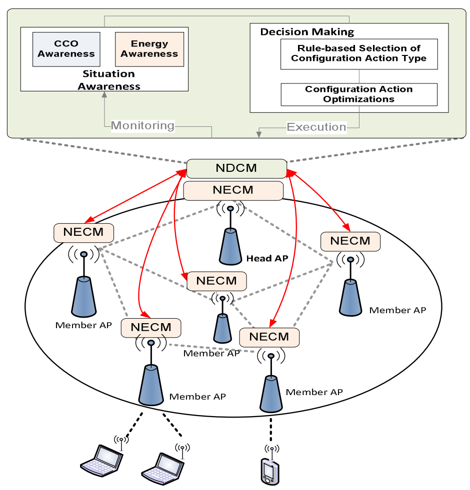


Fig. 1. Cluster head management tasks

In addition, an algorithmic framework for the extension of cognitive capabilities in network management has been described, facilitating performance management tasks. This framework is used for the improvement of Voice over IP (VoIP) QoS in a congested WiMAX network [16]. Despite the WiMAX related introduction, the proposed algorithmic framework solution is not access technology specific, but is equally feasible to other wireless network technologies as well, such as WLAN. The proposed algorithmic framework consists of the decision making, the execution and the learning phase. The decision making part includes the scheme for the identification of the most appropriate action for the packet loss reduction of VoIP service; selecting between a) the change of VoIP flows priority at the WiMAX base station, exploiting Medium Access

Control (MAC) features, and b) the change of VoIP flows selected codec, exploiting service level features. The solution and the quantification of the derived action (e.g., number of VoIP flows, the type of codec transition) is achieved using either a history-based scheme that takes advantage of previous events, or a heuristic approach for un-classified (i.e., unknown) situations. A k-Means learning algorithm is introduced to process the accumulated knowledge from all applied actions and evolve the decision making scheme [17], [18]. The performance and feasibility evaluation of the proposed solution has been tested using FIRE Panlab WiMAX experimental facility.

2 Results and Discussion

The proposed solutions for the effective utilization of network resources and energy saving have been deployed evaluated using both a simulation environment as well as real WiFi/WiMAX infrastructure.

2.1 SYSTAS: Algorithm for Cluster-based Structure of a Self-Organizing Wireless Network

The distributed algorithm for the organization of APs control loops in clusters has been evaluated in different topologies (sparse, dense, and real). In the literature, there are several clustering algorithms, which are mainly targeting wireless sensor networks or mobile ad-hoc networks, but the majority of them is application-specific (e.g., energy-efficient, mobility-aware). The results show efficient discovery of clusters and resulted modularity [19], comparing with algorithms from the area of data mining and graph clustering algorithms.

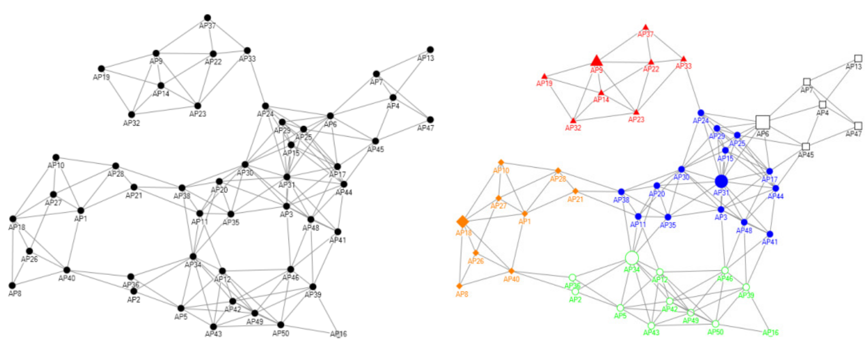


Fig. 2. Sample Topology of 50 Nodes (a) Graph visualization, (b) Formed clusters visualization

2.2 Energy Saving and Efficient Utilization of Wireless Resources in a cluster-based Self-Organizing Network

After the formation of the cluster structures and the activation of NECM and NDCM, the head AP retrieves topological, performance, and energy consumption information from the member APs. Moreover, the head receives monitoring data that the associated UEs provide to the All these data allow the head to build its situation awareness, which includes energy and CCO awareness of the cluster. They both are the input for the decision-making phase, which consists of two steps. Firstly, the head uses a rule-based scheme in order to evaluate the existing the situation awareness and select the appropriate adaptation. Then, the deduced configuration is resolved.

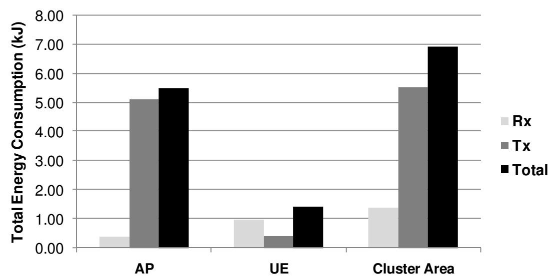
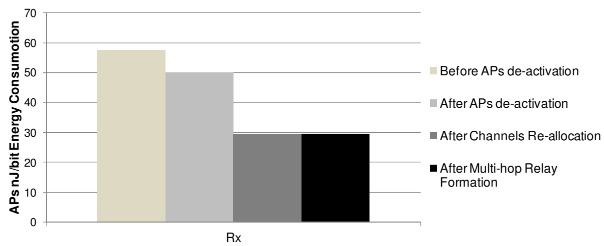


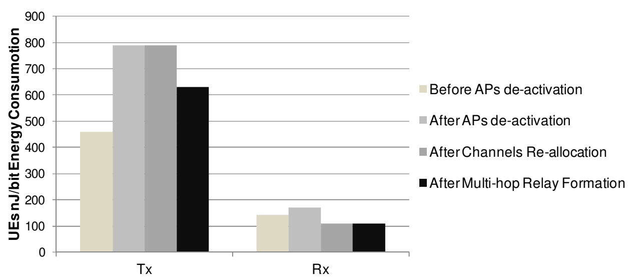
Fig. 3. Total energy consumption – Disabled energy saving and CCO

In this dissertation, we have focused on the communication component (Rx, Tx) of both APs and UEs in a dense WLAN network (Fig. 3) [20]. The decomposition of energy consumption into device and component levels facilitates the analysis and the identification of their dependencies.

From the obtained simulation results it is evident that coverage and capacity optimization is a tool for achieving energy efficiency. However, the extend of energy reduction as well as the impact on other system components (Rx, Tx) or nodes depends on the specific network topology, the network configuration features and traffic conditions. The simulation results for the selected topology configuration, show that an AP deactivation action, reduces cluster level EC_{AP}, mainly due to the reduced energy spent for packets reception (13% decrease) and processing. However, it increases the energy consumption of UEs for the reception and the transmission phase (EC_{UE}^{Tx} , EC_{UE}^{Rx}) under specific topology and traffic conditions (e.g., high overlap of frequency channels, UL/DL ratio). On the other hand, the consumed energy of UEs for the reception and the transmission phases increases after APs deactivation. The change of the selected channels in the cluster leads to the reduction of the energy that UEs consume for the sensing of data packets that come from neighboring cells. APs gain also benefit from this adaptation. EC_{UE}^{Rx} and EC_{AP}^{Rx} measured in nJ/bit are improved by 35.7% and 40.5%, correspondingly. Furthermore, the handover of a UE to a more distant AP leads to an increase of the energy used for transmissions (EC_{UE}^{Tx}), especially for a UE with high UL traffic. In this case, the formation of UEs multi-hop relays improves the energy consumption in the data packet transmission phase by 20% (Fig. 4).



(a)



(b)

Fig. 4. Energy consumption in nJoules/bit (a) APs Rx, (b) UEs Tx and Rx phases

2.3 Coordination of Conflicts and Dependencies in Self-Organizing Networks

In the conducted experiments that described above, the degradation of a performance metric, after the enforcement of a re-configuration is addressed by using an additional optimization action. However, in the case that two or more configurations actions are triggered concurrently it is important for the SON to identify and resolve conflicts on metrics or parameters, so as to assure the stability of the communication network. The goal of the introduced algorithmic scheme is to select, solve and apply the most appropriate configuration action in a cluster area taking into account a) problems severity, b) the total performance improvement of the network nodes of the cluster, c) and the number of reconfigurations or system's oscillations. Simulation results show that the proposed scheme for the coordination of the self-optimization functions of thye different cognitive cycles improve the performance of the system (throughput BER, network side energy consumption), according to the defined priorities.

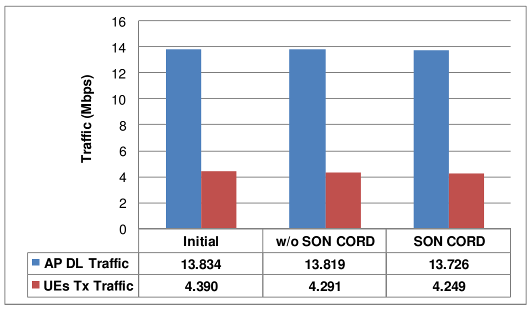


Fig. 5. Cluster-level throughput (UL/DL)

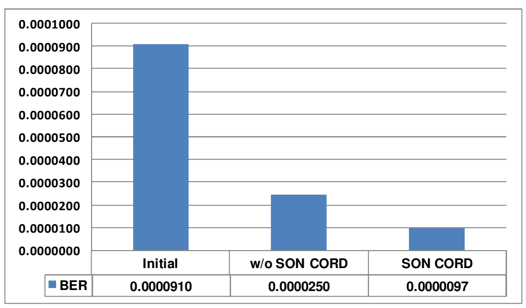


Fig. 6. Cluster-level BER

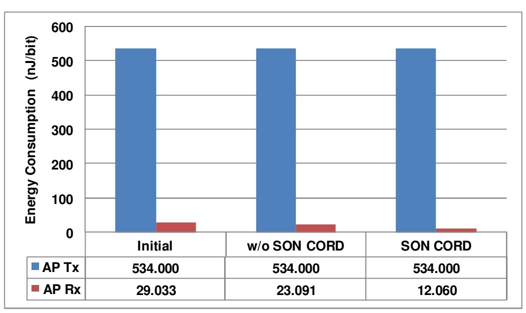


Fig. 7. Cluster-level AP energy consumption (nJ/bit)

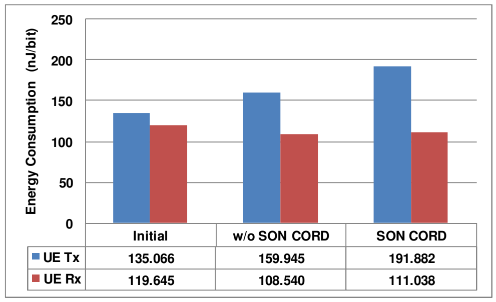


Fig. 8. Cluster-level UE energy consumption (nJ/bit)

2.4 Cognitive Capabilities for a Service-aware Self-Managed Network

The proposed architecture and the introduced algorithmic framework for the extension of cognitive capabilities in a self-managed network system have been deployed and evaluated for the improvement of VoIP QoS (packet loss, delay, jitter) in a congested WiMAX network. The conducted experiments, using FIRE Panlab and CORE facilities, prove the feasibility and the strengths of our work. Both network and service side adaptation actions improve the detected packet loss level. However, the change priority of VoIP flows at WIMAX BS cannot reach the target PL threshold (<1%) for high PL events; although service continuity is always satisfied. On the other hand, the VoIP codec modification is more drastic (Fig 9.).

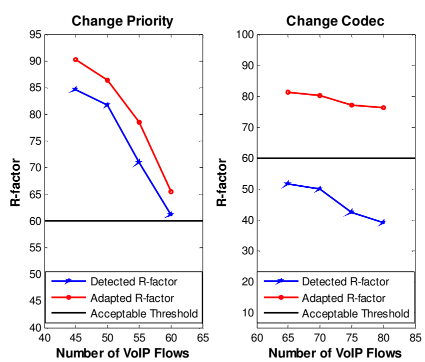


Fig. 9. R-Factor after Change Priority and Change Codec adaptation

The utilization of the history of previous adaptations reduces the transitory period and the iterations that a heuristic scheme requires for QoS improvement. The results of the learning phase show that the accuracy of the decision making scheme is improved, avoiding adaptations that are not effective. Finally, we have showed that other QoS metrics such as delay, jitter and R-factor are also improved by the proposed solution (Fig. 10).

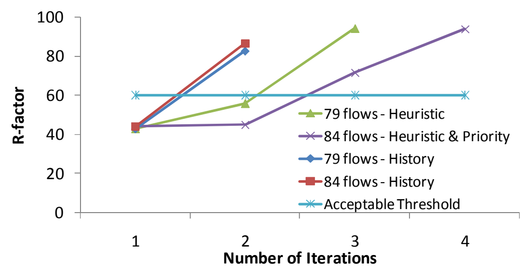


Fig. 10. R-factor vs. Number of Iterations

3 Conclusions

The efficient usage of network resources and the reduction of the consumed energy in modern communication systems that operate in a dense urban environment are challenging tasks, due to the complexity and the spatio-temporal dynamics of wireless networks. Self-organization is considered as one of the most promising paradigms for the management of networks that operate in highly dynamic and dense environments. In this thesis a novel approach has been proposed to dynamically control the size and configuration of a wireless network for the effective utilization of network resources and energy saving. The energy consumption reduction and performance improvement (BER, throughput, QoS) attained under the proposed solutions, at both the AP and the user equipment sides, is evaluated via simulation.

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