Opportunistic Network Creation Schemes for Capacity Extension in Wireless Access and Backhaul Segments

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Abstract. It is expected that the wireless world will migrate towards an era that will comprise more local/temporary structures which, for instance, can be called Opportunistic Networks (ONs). Operator-governed ONs are dynamically created, temporary, coordinated extensions of the infrastructure. This paper presents an approach for exploiting such ONs in order to extend the capacity in wireless access and backhaul segments for efficient application provisioning, as well as an evaluation of an indicative test case as a proof of concept of the aforementioned approach.

Keywords: Opportunistic Networks, Functional Architecture, Cognitive Management Systems, Future Internet.

1 Introduction

The vision of Future Internet (FI) seems to drive the research in many aspects of today's Information and Communication Technologies (ICT) [1]. One of the great promises that FI needs to fulfill so as to live up to its potential, is the efficient provisioning of emerging and new applications, through a wide range of Internet-enabled devices. New applications, services and content will require a truly ubiquitous network capacity [2] capable of handling the amplified data traffic volumes transmitted by internet enabled devices. Such an increasingly demanding landscape motivates the quest for technological solutions that will offer improved efficiency in resource provisioning and provide users with high quality services anywhere, anytime. Efficiency can be generally coupled with targets like: (i) the higher utilization of resources, (ii) the reduction of transmission powers and energy consumption (in general, having decisions with a "green" footprint) or (iii) the reduction of the total cost of ownership, which is assumed here to comprise the operational expenditures (OPEX), capital expenditures (CAPEX), and costs associated with the management of customer relations.

K. Pentikousis et al. (Eds.): MONAMI 2011, LNICST 97, pp. 201–216, 2012.

The solution proposed in this paper (Fig. 1) is based on dynamically created, operator-governed and coordinated, temporary extensions of the infrastructure, called Opportunistic Networks (ONs). ONs are governed by operators through the provision of policies, e.g. upon resource usage, as well as context/profile information and knowledge, which is exploited for their creation and maintenance. They are dynamically created in places and at the time they are needed to deliver application flows to mobile users. Moreover, they comprise various devices/terminals, potentially organized in an ad hoc mode, as well as elements of the infrastructure itself.

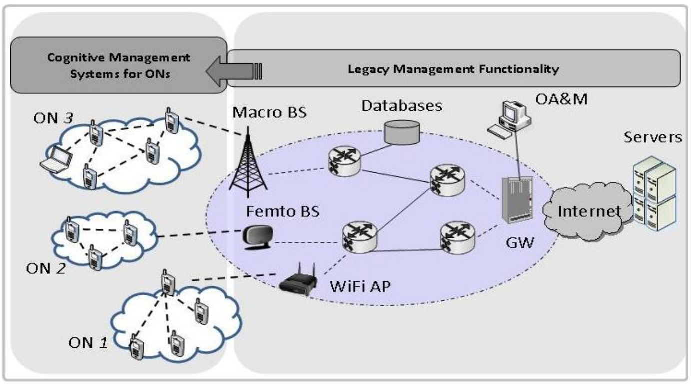


Fig. 1. High level view of the proposed solution: Opportunistic Networks and Cognitive Management Systems

Furthermore, because of the highly dynamic nature of the environment, including traffic and applications issues, as well as the potential complexity of the infrastructure, a solution that incorporates self-management and learning mechanisms is deemed essential. Self-management enables a system to identify opportunities for improving its performance and adapting its operation without the need for human intervention. Learning mechanisms are important so as to increase the reliability of decision making. Learning mechanisms also enable proactive handling of problematic situations, i.e. identifying and handling issues that could undermine the performance of the system before these actually occur.

In this respect, Cognitive Management Systems (CMSs), comprising both self-management and learning capabilities [3] seem appropriate for ensuring the fast and reliable establishment of ONs. CMSs can be located in both the network infrastructure and the terminals/devices. Moreover, it is envisaged that the coordination between CMSs and the exchange of information and knowledge can be realized by appropriate control channels, conveying the necessary cognitive information. Such control channels may be logical channels transporting information on top of a physical network architecture.

Several scenarios of exploiting this concept of combining ONs and CMSs for efficient application provisioning can be considered [4][5]: (i) opportunistic coverage extension, to serve devices that are out of coverage of the infrastructure or are not capable of operating at the provided Radio Access Technology (RAT); (ii) opportunistic capacity extension, where ONs are exploited to offload service areas with high traffic; (iii) infrastructure supported opportunistic ad hoc networking exploiting the closeness of location of application end-points so as to reduce application traffic; (iv) opportunistic traffic aggregation in the radio access network where a sub-set of ON terminals exchange data with the infrastructure; (v) opportunistic resource aggregation in the backhaul network where backhaul bandwidth is aggregated to match the bandwidth of wireless access technologies towards the user. It is assumed for all cases that terminals participating in an ON are those terminals that are made available by their users for such use/creation. For brevity reasons, the rest of this paper focuses on opportunistic capacity extension in the wireless access and backhaul segments.

This paper is structured as follows. In Section 2 a high-level functional architecture is presented encompassing CMS entities on the infrastructure and terminal side. The scenarios on opportunistic capacity extension in the wireless access and backhaul segments are presented in detail in Sections 3 and 4, respectively. Finally, results derived from simulations of indicative test cases are presented in Section 5 in order to provide a proof of concept of the proposed solution. Finally, the paper is concluded in Section 6.

2 Architecture Aspects

In order to meet the requirements for improved efficiency in resource provisioning and providing users with high quality services anytime, anywhere through the combination of ONs and CMSs new management and control functionalities for ONs need to be added to network management architectures. In this direction, this section gives an overview of a corresponding Functional Architecture (FA), which is an extension of an existing architecture, namely the "Functional Architecture for the Management and Control of Reconfigurable Radio Systems" as defined by the European Telecommunications Standards Institute (ETSI), Reconfigurable Radio Systems (RRS) Technical Committee (TC) in the Technical Report (TR) 102 682 [6], [7]. The resulting FA proposed here, comprising mechanism for the management of ONs through CMSs is depicted in Fig. 2.

The infrastructure governed Opportunistic Networks Management is divided into two building blocks, namely the "Cognitive management System for the Coordination of the infrastructure" (CSCI) and the "Cognitive Management system for the Opportunistic Network" (CMON). The CSCI is mainly responsible for the activities before an ON created. This includes ON opportunity detection and ON suitability determination. The CSCI is in charge of the context acquisition and processing and the determination whether or not right conditions are in place for creating the ON. When the CSCI has made a decision that an ON is suitable, the decision is sent to the CMON. The CMON controls the life cycle of the ON from creation to termination. This includes the execution of the creation procedures as well as maintenance and termination of a given ON.

Apart from the CSCI and CMON other main building blocks of the functional architecture which act on top of existing Radio Access Technologies (RATs) include:

- The Dynamic Spectrum Management (DSM) which provides mid- and long-term management (e.g. in the order of hours and days) of the spectrum for the different radio systems;
- The Dynamic, Self-Organizing Network Planning and Management (DSONPM) which provides mid- and long-term decisions upon the configuration and reconfiguration of the network or parts of it. The DSONPM decides for example on the configuration of a base station and then instructs the Configuration Control Module (CCM) to execute the reconfiguration;
- The Joint Radio Resources Management (JRRM) which performs the joint management of the radio resources across different radio access technologies. It selects the best radio access (Access-Selection & Handover Decisions) for a given user based on the session's requested Quality of Service (QoS), radio conditions, network conditions like cell load, user preferences and network policies. The JRRM also provides Neighborhood Information which can then be distributed via Cognitive Control Channels (CCC) or a Cognitive Pilot Channel;
- The Configuration Control Module (CCM) which is responsible for executing the reconfiguration of a terminal or a base station, following the directives provided by the JRRM or the DSONPM.

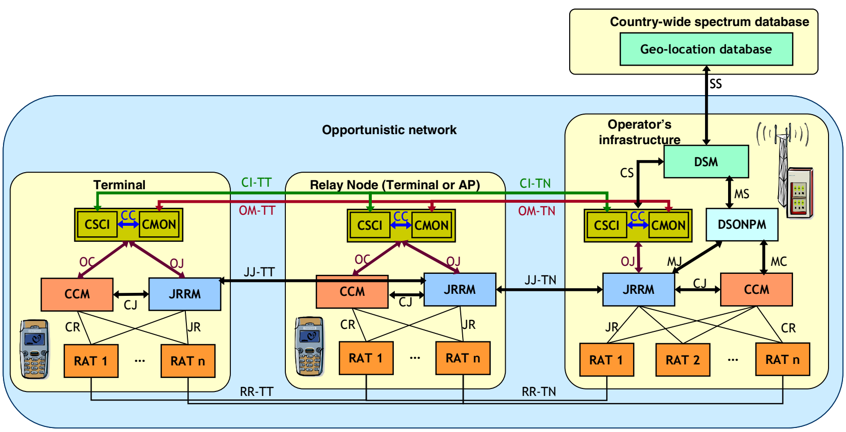


Fig. 2. Functional Architecture for the Management and Control of infrastructure governed Opportunistic Networks as an evolution of the ETSI RRS FA [8]

As previously presented, the CSCI is responsible for the detection of situations where an ON may be useful as part of the ON suitability determination phase. The Suitability Determination is a centralized process, with the decision making located typically in the infrastructure but in some cases (e.g. out-of-coverage scenario) located inside a device. The decision making is based on infrastructure-level information provided by functional entities in the network and user/device-level information provided by the CSCI entities from a selected set of devices. The Suitability Determination runs before the creation of an ON but also during the lifetime of the ON in order to check that context changes and ON reconfigurations (information from CMON) have not cancelled the suitability of the ON.

The CSCI comprises context awareness, operator policy derivation and management, profile management and knowledge management which provide the input to the decision making mechanism for the ON suitability determination. Cognition relies on the fact that knowledge management encompasses mechanisms for learning on context, profiles, policies and decision making in order to reach better decisions in the future, and faster according to the learned results. The CSCI delegates the actual creation, maintenance and termination of a given ON to the associated CMON functional entity and it is located in both the operators' infrastructure and the terminal side, respectively.

The CMON is responsible for the creation, maintenance and termination of the opportunistic network, according to the result of the suitability determination and policies obtained from the CSCI. The CMON is also located in both the operators' infrastructure and the terminal side. Similarly to the CSCI, the CMON in both the operators' infrastructure elements as well as the terminals involves context awareness, policy acquisition, profile management as well as knowledge management which provide the input for the decision making mechanism on the creation, maintenance and termination processes.

The exchange of information and knowledge between the CMONs and CSCIs relies on control channels (information, signaling flows and protocols) that can be built through the integration and evolution of two concepts: the cognitive pilot channel (CPC) [9] and the cognitive control radio (CCR) [10]. The CPC is a (logical and optionally in part a physical) channel, which provides information from the network to the terminals, e.g., on frequency bands, available Radio Access Technologies, and spectrum usage policies. Therefore, the CPC will be the basis for the coordination between infrastructure and opportunistic networks, i.e., the communication between CSCIs and CMONs. The CCR is a channel for the peer-to-peer exchange of cognition related information between heterogeneous network nodes (e.g., between terminals). Therefore, it will be the basis for the exchange of information/knowledge between the nodes of the opportunistic network, i.e., the communication between CMONs. The integration and evolution of the two concepts is the product of the C4MS. Evolutions involve the specification of supplementary information, signaling flows and protocols (data/packet structures and exchange strategies) required for the support of the ON suitability determination, creation, maintenance and termination processes.

For the proposed approach to be recognized and accepted by networks operators, specific demands for security and trust establishment should be addressed. Three potential implementation options to meet the security requirements of the proposed approach are [8]:

- An implementation based on the existing mechanisms specified in 3GPP RAN and EPC [11][12] for providing services to "native" 3GPP mobile devices and users.

- An implementation based on existing mechanisms specified by 3GPP to deal with untrusted non-3GPP accesses [13][14] to the EPC services by devices/users typically making use of operator-managed WLAN Access Points.
- An overlay of security, built for the management of ON and making no assumption on underlying provided by RATs.

It should be noted that further details on security and trust aspects are out of the scope of this paper.

3 Capacity Extension in the Wireless Access

In general in the opportunistic capacity extension scenario (Fig. 3), it is assumed that a specific area which experiences traffic congestion issues can be offloaded with the creation of an ON in order to re-route the traffic to non-congested Access Points (APs). This scenario enables devices to maintain the required level of QoS for a wireless communication link even though a congestion situation occurs. In particular a system operating in a licensed/ unlicensed band is assumed to be overloaded and cannot guarantee the provision of the required QoS anymore. In this case, the traffic can be re-distributed to neighboring uncongested cells (which can use different RATs).

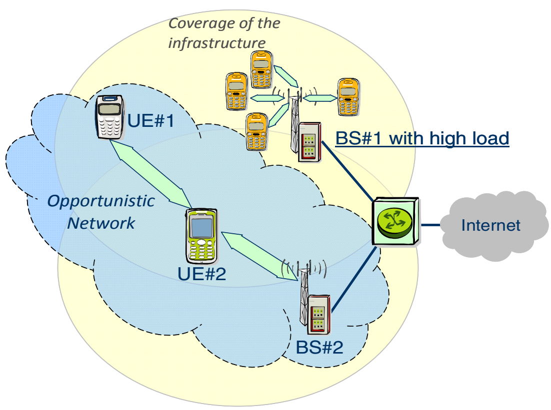


Fig. 3. Capacity Extension Scenario [8]

The approach followed here for the creation of an ON is based on the Ford-Fulkerson flow control algorithm [15]. An overview of the overall process and the corresponding interactions between the various FA entities is depicted in Fig. 4, with 3 main phases. Particularly, the procedure starts when a Base Station (BS) identifies a congestion situation, through its CSCI entity. This is depicted in the "Problem identification" phase of Fig. 4. As soon as an infrastructure element starts experiencing congestion issues it reaches a warning level where reconfiguration is imminent. The congested BSs send a notification to the DSONPM entity in order to inform it about the problematic situation. DSONPM indicates the BS that will solve the problem (selected BS), which will also populate the set of terminals that will be moved from the congested area to alternate BSs ("Suitability determination" phase of Fig. 4). All non-congested BSs in the vicinity are identified.

For both the congested as well as the uncongested BSs information on the respective terminals is acquired through the CMON entities ("Creation" of Fig. 4). Such information includes the BS to which each terminal is currently connected, the capacity of each terminal, and its neighboring terminals. The information from all terminals is collected by the selected BS CMON entity in order to obtain information on all potential paths from terminals in the congested area to alternate BSs, through other terminals in the non-congested or congested area. Each path comprises a set of nodes (BS or terminal), the capacity of these nodes, and the cost of the links between the nodes. The aim is to find the most appropriate paths (a subset of all available paths) to re-route the terminals in the congested area to alternate BSs. As an outcome, each terminal should be provided with a path to a BS, allowing it to obtain the required QoS.

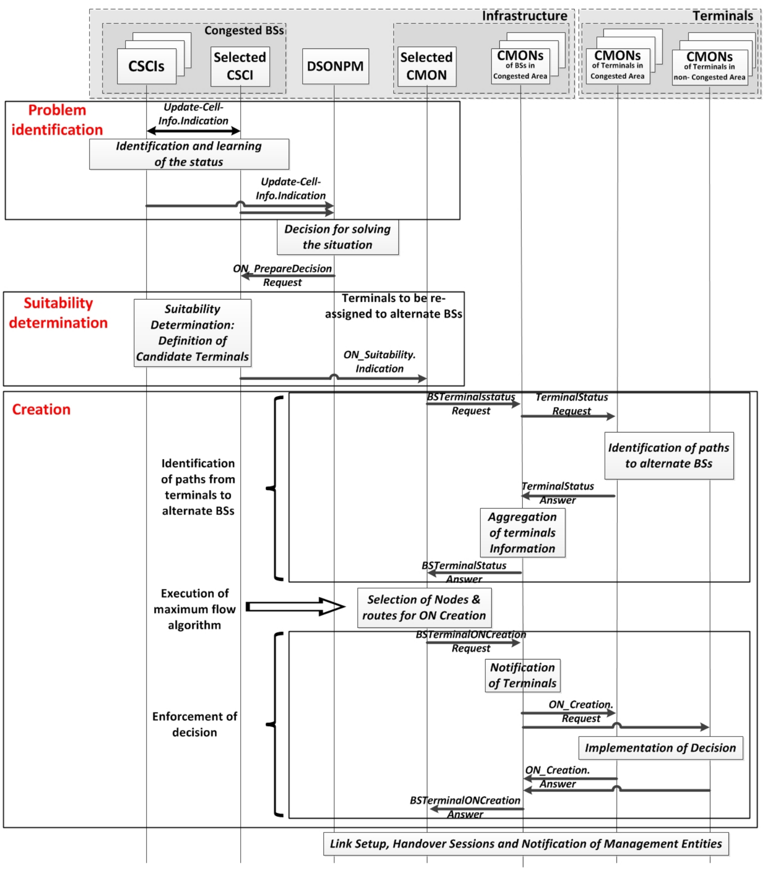


Fig. 4. Message Sequence Chart for Capacity extension

4 Capacity Extension in the Backhaul

In this scenario an ON is created across multiple APs (infrastructure access nodes) in order to provide means to share backhaul bandwidth among them. The primary objective of the proposed backhaul bandwidth aggregation is to match the access bandwidth of modern wireless technologies with the adequate transport bandwidth in the backhaul/core network (CN). The second objective concerns the need for creation of the bandwidth pools that can be deployed in emergency situations when a particular backhaul link is either highly congested or malfunctioning. Moreover, the same ON can be used to pull together processing or storage resources across multiple APs in order to condition the multimedia content and relieve pressure on the bandwidth resources needed for its transmission or the storage.

The two objectives mentioned above can be also presented in terms of two distinctive use cases: The first use case describes the situation when available backhaul link bandwidth equals or exceeds maximum available access bandwidth. In this case the backhaul bandwidth aggregation provided by the ON is used for resolving the problems of resource utilization through means of efficient load balancing. With this approach it is possible to resolve the problems of highly congested or broken backhaul links. ON creation is triggered when problems like malfunction or high congestion on particular backhaul links is detected. ON will enable multi-path routing for the purpose of traffic load balancing across the access nodes. ON will be created by troubled APs and a number of their neighbors whose backhaul links have enough vacant capacity to receive excessive traffic from APs with problematic backhaul (see Fig. 5).

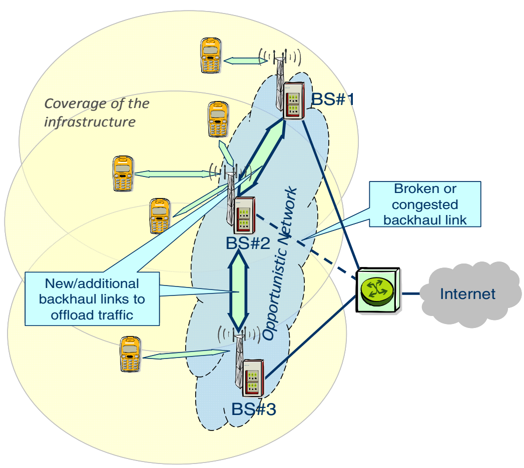


Fig. 5. Resolving a problem of congested/broken link of BS 2 by ON creation [8]

To achieve better system performance and meet the QoS and Quality of Experience (QoE) requirements cognitive packet forwarding mechanisms are considered. These mechanisms will classify traffic based on application and user profiles. Packets originated by different applications/users will be sent over different auxiliary paths based on their requirements (delay, jitter, packet loss, total bandwidth…). Moreover, contextual information gathered during regular network operation will be included in order for the management system to have a clear picture about the status of backhaul links of all APs. These data will be used for estimating backhaul traffic patterns for all APs and for anticipating possible problems with backhaul links. This contextual information will be used for selection of the most appropriate APs which are to participate in an ON creation. During the ON lifecycle contextual information about system performance will be gathered in order to later evaluate ON performance and improve cognitive management of other ONs created under similar circumstances. When all concerned backhaul links start working properly, then the bridging ON will be terminated and every infrastructure access node will continue to route its access traffic over its own backhaul link.

The second use case relates to the backhaul bandwidth aggregation when network access nodes have backhaul link capacity less than that of the RAT used for the access. This situation is common in WLAN networks where APs are connected to internet links of limited bandwidth (e.g. through Digital Subscriber Line - DSL or cable modems). Equally, the networks comprising femto BSs connected to the wired backhaul of limited capacity are likely to suffer from the same symptoms. In this case, backhaul link capacities can be aggregated to ensure that total backhaul bandwidth can match the access bandwidth needs. Backhaul bandwidth aggregation is possible only if access traffic of some APs is less than corresponding backhaul capacity. Then excessive access traffic from some APs can be shared among APs with spare backhaul bandwidth.

Wireless mesh networks (WMN) are especially susceptible to the backhaul links management described in this paper. In this type of network technology, the backhaul links between APs are wireless and often of the same capacity as the capacity of the access link and shared between multiple APs. This makes WMNs especially challenging when it comes to backhaul capacity management. On the other hand, creating ONs for cognitive management of backhaul capacity within a given WMN can drastically improve its performance. A single wireless backhaul link in WMN topology is frequently shared between several access points. Backhaul links closer to gateways have greater chance to become congested so intelligent bandwidth resource management by means of multi-path routing and load balancing should be used in order to achieve better resource utilization and system performance. By gathering and analyzing contextual data relevant for the backhaul and access traffic we would be able to understand behavioral patterns of the system and able to detect problems in backhaul links before they become acute. These behavioral patterns will act as triggers to create and manage an ON in such way to enable usage of multi-path routing algorithms in order to locally deploy load balancing and bandwidth aggregation for more efficient backhaul resource utilization.

Mesh gateways are mesh APs that are directly connected to the wired infrastructure and further onto the internet. These devices are likely to face a situation in which they do not command enough resources to allow for smooth traffic flow between wired and wireless portion of the network. In this case, backhaul bandwidth aggregation should be done on the wired side of the network. Multi-path routing algorithm as a solution for the backhaul bandwidth aggregation includes metrics, for the link cost determination, which comprises WMN environment characteristics (multi channel, shared medium, inter/intra-flow interference…) and are used to determine different values of the link cost for packets originated from applications of different profiles. Application cognitive multi-path routing will ensure the desired QoS requirements are met per application type. Contextual information about network environment should include:

- Status of network links (available capacity of link, channel used, interference levels, expected delay, jitter, packet drop…);
- Operator policies (required resource utilization levels, required QoS levels for different applications and groups of users, security for protection of data, end users and network…);
- Traffic patterns (most used gateways, spatial and time distribution of traffic…);
- Application profiles and corresponding QoS requirements.

The contextual information will be processed by APs and/or some centralized management entity like a wireless controller. When problems in backhaul links (congestion, uneven traffic flows, broken links…) are detected, suitable nodes and radio paths for an ON will be identified and selected. During the ON lifecycle system performance will be measured and gathered data will be used to further improve the decision making algorithms. Fig. 6 *(a)* depicts a WMN where one link in wireless backhaul suffers congestion. The solution is to enable AP2 to send part of its access traffic to GW1 and part of it to GW2. This process of multi-path routing for purpose of load balancing will be done by ON created among WMN APs as shown in Fig. 6 *(b)*. Links in figures are shown in different thickness to depict different traffic loads on them.

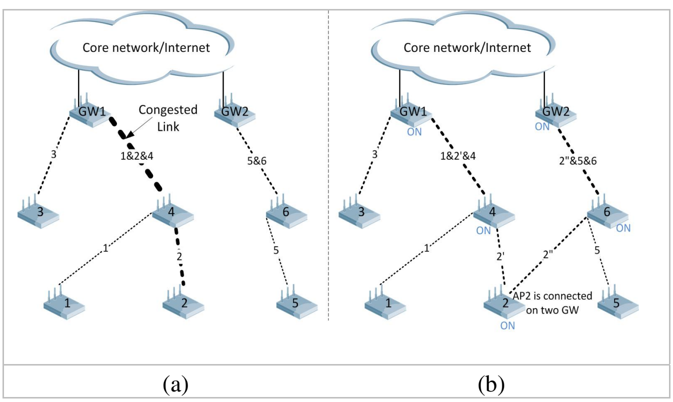


Fig. 6. a) WMN with poor load balancing, b) Backhaul link congestion resolved with properly configured ON

The link between AP4 and GW1 is used for transferring access traffic from AP4, 1 and 2. Since AP2 is under heavy load on access side, the link AP4-GW1 will suffer congestion and the only solution in this case is to configure WMN in a way that will enable AP2 to send part of its traffic towards the GW1 and the other part towards GW2. This load balancing through means of multi-path routing will be application cognitive which means that packets will be differentiated by profile of application from which they originated and sent over appropriate path. Suitable multiple paths will be detected and appropriate ones will be selected and ON will be created over APs belonging to these paths (as shown in Fig. 6 *(b)*). Since multi-path routing imposes greater signaling overhead, more demanding management and higher risk of local interference ON will be terminated as soon as the backhaul links in that portion of WMN start operating normally. The same solution is applicable when the wired link of GW1 suffers congestion. In this case it is crucial to detect APs with the biggest access loads and to start load balancing process away from GW1.

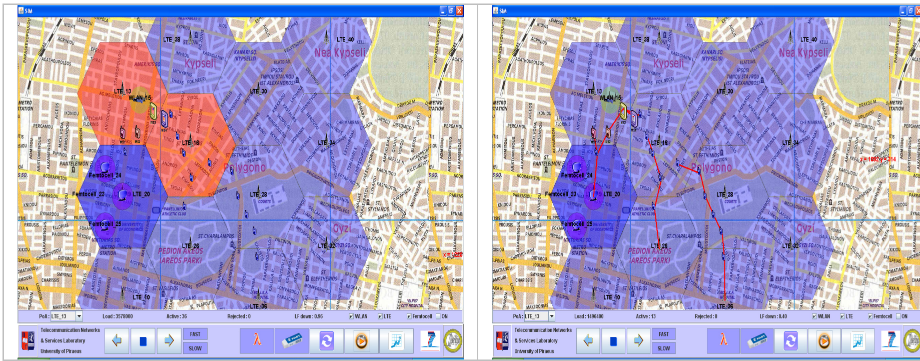
5 Results and Proof of Concept

This section discusses on the simulations and experimental test bed that have been setup in order to validate the creation schemes for capacity extension in wireless and backhaul segments and give some evidence on the potentials arising from the exploitation of ONs.

Scenario 1 – Capacity Extension

In order to obtain a first proof of concept of the CSCI and CMON functionalities for ON management, corresponding prototypes have been implemented (based on Java and the JADE agent platform). These have been integrated into a wider platform which comprises a network traffic simulator used to simulate various traffic load conditions (e.g. congestion) in a certain service area or network, diverse (actual and emulated) network elements, several user devices, self-management functionalities and corresponding Graphical User Interfaces (GUIs) [16].

An indicative network topology which consists of 8 LTE Macro BSs and 25 terminal devices (which are capable of creating an ON, thus they can be re-directed to alternative, available BSs) is being investigated. Each terminal is assigned to a BS. Terminals may use two types of services namely, Voice and Video conference. Voice service requires a data rate of 12.2 Kbps. Video conference service can be offered at 4 quality levels i.e., 512, 256, 128 and 64 Kbps. Moreover, each BS, apart from the assigned terminals serves an extra number of simulated users i.e., each service and each quality level as indicated previously is being provided to 15 initial simulated users. Each terminal of an ON is connected to each other with an IEEE 802.11b/g interface.



(a) (b)

Fig. 7. View of service area for the indicative test case *(a)* prior to ON creation *(b)* after the ON creation

As already introduced, in the capacity extension scenario ONs are exploited so as to address problems of infrastructure elements. All Macro (BSs) operating in the area are initially depicted as blue hexagons in the corresponding GUI (Fig. 7). Two hotspots are created (through the traffic simulator) depicted as red hexagons in Fig. 7 *(a)*. The occurrence of congestion has as a result that a proportion of users will have to move to neighboring BSs in order to relieve the congested ones, through the process described in section 3. Red lines in Fig. 7 *(b)* denote the paths that are created in order to re-route traffic from the congested BSs (red hexagons in Fig. 7 *(a)*) to alternate BSs via intermediate terminals (ON nodes). As soon as the congestion situation is resolved, traffic allocation statistics are available through the demonstration platform in order to prove that traffic was successfully re-assigned to neighboring infrastructure elements. In order to evaluate our approach the following metrics are considered: *i)* normalized load and *ii)* active users.

Fig. 8 *(a)* depicts the normalized load which refers to the current load of the BS divided by the maximum supported capacity. As this figure illustrates, the normalized load in the congested BS gradually increases until it reaches an alarming level (threshold 0.7) and the aforementioned ON set-up procedure is triggered. Eventually, the normalized load decreases as a proportion of users have moved to neighboring BSs. Fig. 8 *(b)* depicts the active users which reflect to the number of active sessions that are currently in use. This metric increases until the solution mechanism is triggered. After the solution enforcement a gradual decrease is observed.

On the other hand, the normalized load of a neighboring non-congested BS tends to increase as it receives a proportion of the users from the previous congested area as Fig. 9 (a) illustrates. Also, the number of active users of the same BS tends to increase as well (Fig. 9 (b)).

Through the capacity extension scenario apparently the congested BSs are relieved as traffic is re-routed into neighboring infrastructure elements. Moreover, the non-congested BSs that acquired traffic did not reach the threshold so as to become congested. Therefore, the users experience better QoS as the problematic BSs are not congested anymore.

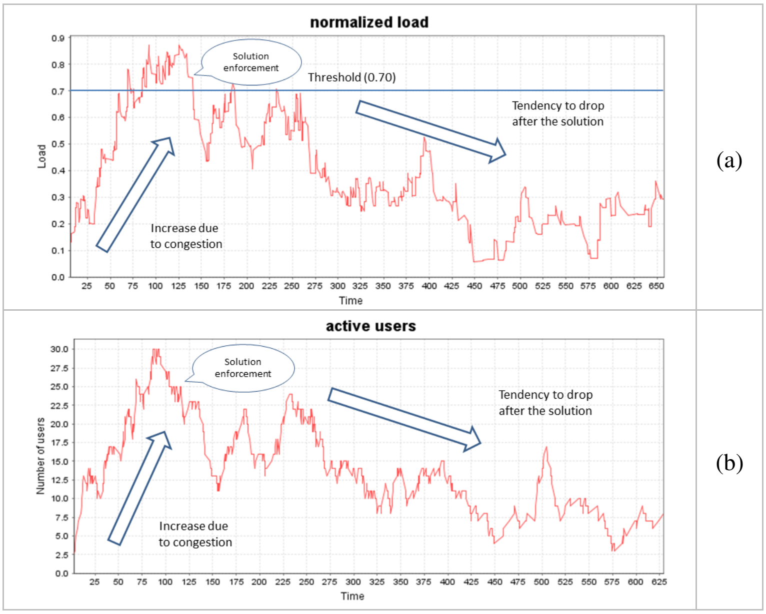


Fig. 8. Normalized Load and Number of Active users in a congested BS

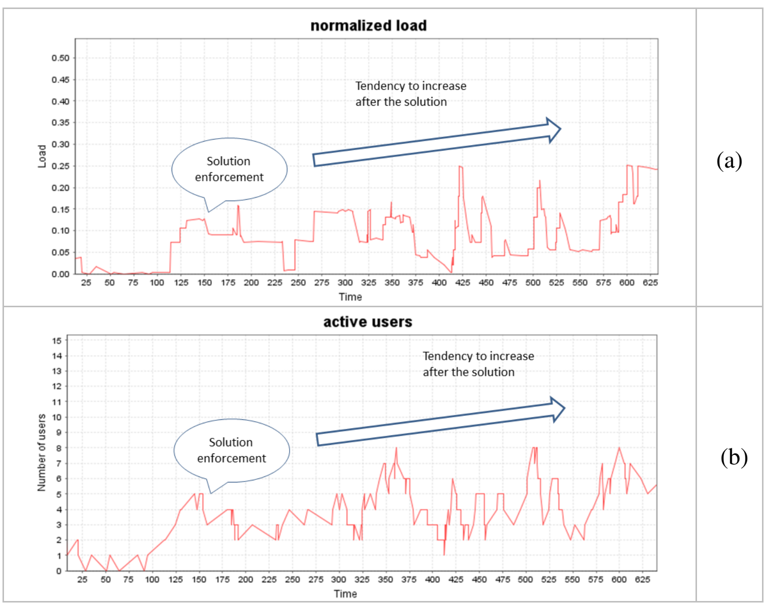


Fig. 9. Normalized Load and Number of Active users in a non-congested BS

Scenario 2 – Backhaul bandwidth management

Regarding backhaul capacity aggregation and management, experiments are done with MikroTik Router Boards (RB) 800 configured as open platform mesh APs. Fig. 10 shows the experimental setup for backhaul bandwidth management. Three APs are configured as mesh gateways and connected to internet links with different capacity. One AP is connected to all three gateways and provides internet access to mobile users.

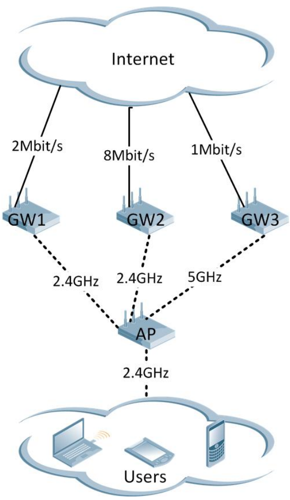


Fig. 10. Experiment setup for backhaul capacity management

With this experimental environment concepts of backhaul bandwidth aggregation and intelligent load balancing are tested. The first preliminary experiment confirmed the concept of backhaul bandwidth aggregation. With proper configuration of the experimental network the AP provided aggregated bandwidth of internet connections of all three gateways on its access (AP provided internet access of 11Mbit/s to its users). The second experimental setup of the network from Fig. 10 provided initial insights in application cognitive load balancing in the WMN backhaul. With proper configuration of open platform APs, load balancing is done between AP and all three gateways. By using packet inspection techniques, the experimental network can be configured in a way that will enable all traffic which belongs to one internet service/application to be sent over one backhaul link (gateway) and the rest of the internet traffic to be transferred over remaining links. The experimental WMN environment enabled all traffic belonging to You Tube service to be sent and received over one gateway only and corresponding wireless backhaul connection with AP.

Preliminary experiments have proven the concepts of backhaul capacity management in WMN environment. Further work will focus on development and tests of algorithms and protocols which will enable automation of bandwidth management processes based on context awareness and knowledge derivation. These algorithms and protocols will enable the concept of opportunistic networking targeting backhaul resource management.

6 Conclusions

This paper proposed a solution for efficient application provisioning in the wireless world. The solution is based on the combination of ONs and CMSs. ONs are assumed to be coordinated extensions of the infrastructure, which are temporarily created in order to serve a specific region and certain application needs, according to the policies dictated by the operator (operator governed). It is claimed that the proposed ON-based solution can prove beneficiary in various scenarios and this is supported through a set of indicative test cases evaluated by means of simulation.

Acknowledgment. This work is performed in the framework of the European-Union funded project OneFIT (www.ict-onefit.eu). The project is supported by the European Community's Seventh Framework Program (FP7). The views expressed in this document do not necessarily represent the views of the complete consortium. The Community is not liable for any use that may be made of the information contained herein.

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