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SON for LTE-WLAN access network selection: design and performance

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Abstract

Mobile network operators (MNOs) are deploying carrier-grade Wireless Local Area Network (WLAN) as an important complementary system to cellular networks. Access network selection (ANS) between cellular and WLAN is an essential component to improve network performance and user quality-of-service (QoS) via controlled loading of these systems. In emerging heterogeneous networks characterized by different cell sizes and diverse WLAN deployments, automatic tuning of the network selection functionality plays a crucial role. In this article, we present two distinct Self-Organizing Network (SON) schemes for tuning the ANS between the Long-Term Evolution (LTE) and WLAN systems. The SON functions differ in terms of availability of inter-system information exchange and internal algorithm design for traffic load control. System level simulations in a site-specific dense urban network show that the proposed schemes improve significantly the user quality of service (QoS), and network capacity over the reference scheme when offloading to WLAN is performed simply based on signal coverage.

Keywords: LTE, Self-Organizing Network, WLAN, Network selection, Network optimization

1 Introduction

The explosive growth in data traffic [1, 2] and the limited availability of new licensed spectrum burden mobile network operators (MNOs) with great challenges to fulfill growing quality of service demands and increase competitiveness by reducing operational and capital expenditures (OPEX and CAPEX). The MNOs are continuously under pressure to seek for more cost-effective radio access technology and deployment solutions and to optimize their use of the unlicensed frequency bands.

The Long-Term Evolution (LTE) and LTE-Advanced (LTE-A) technologies standardized by the 3rd Generation Partnership Project (3GPP) are built to support MNOs in serving high traffic demands. For instance, capacity expansion of the LTE networks can be achieved by deploying different cellular layers, e.g., micro/pico/femto layers overlaid to the macro layer. In addition, there is a trend in the mobile communication industry to make operator-controlled Wireless Local Area Network (WLAN) an integral part of operators' networks to compensate for limited availability of licensed spectrum. The fact that most mobile devices today support both cellular and WLAN radio modes makes this trend accomplishable. The emerging deployments of heterogeneous networks (HetNets), comprising multiple LTE layers complemented by WLAN networks, require intelligent and automatic traffic management between LTE and WLAN in order to optimally exploit available resources and avoid network congestion. In this paper we address in particular the class of mechanisms which handle call assignment to a network during the call admission phase and denote this by access network selection (ANS).

2 State of the art

The configuration and optimization of ANS is a challenging task given the increasing complexity of heterogeneous networks and diverse WLAN deployments. Most of the currently deployed network selection functions have severe limitations: they are either proprietary, autonomously controlled by the user's device, or static and do not adapt to dynamically changing radio environments and radio access traffic load. Inherently, these approaches cannot optimally exploit HetNets' potential in terms of optimal radio resource utilization and hence lead to suboptimal or degraded end user QoS. In several academic

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studies, network selection was modeled as a single or multidimensional decision-making problem that was solved either by maximizing a utility function [3, 4] or minimizing a cost function [5]. Some solutions operate on a global level aiming at providing balanced system loads or optimum collective measures, e.g. concerning user satisfaction (throughput, latency), battery lifetime and OPEX by having a central network entity involved in making decisions for all the mobile devices [4, 5]. Other methods give control to individual mobile devices assisted by information from the network, and target at local performance optimization for each end user [3, 6, 7].

As it has been concluded in [7], the network-based mechanisms can provide optimal system-wide performance only if the mechanisms are able to adapt to network conditions, e.g., user distribution and radio access load. To this end, the Self-Organizing Network (SON) approach is a fully adaptive solution which addresses network configuration and optimization by continuous and automated adjustment of network control parameters to account for changes in the (HetNet) environment [8]. The application of the SON approach to LTE-WLAN ANS has been investigated recently and its effectiveness in improving user QoS was proven with simulation studies [9, 10].

The abovementioned solutions require, to a different extent, the exchange of information between radio access networks and user devices to assist the ANS decisions. The support from industry standards to enable dynamic and SON-based ANS mechanisms has been rather limited in the past; however, there have been some promising developments in recent years. Some existing solutions [3, 5, 6] rely on IEEE 802.21 Media Independent Handover (MIH) [11] for event reporting, information exchange, and handover control. However, its support from network equipment and mobile devices vendors is still very limited today. Furthermore, the WLAN standardization community has been working on the improvement of the interworking between 3GPP and WLAN networks. A recent Wi-Fi Alliance (WFA) certification is CERTIFIED PasspointTM, which incorporates functionalities from Hotspot 2.0 (HS2.0) [12]. To enable network discovery and selection, a set of WLAN network information is made available for 3GPP RAN nodes to access. HS2.0, however, does not provide support for direct and standardized signaling of information related to ANS between a WLAN access point (AP) and a user equipment (UE) over the air-interface.

The 3GPP has specified the Access Network Discovery and Selection Function (ANDSF) framework that defines policies to assist devices in network discovery, network selection, and traffic steering in both 3GPP and non-3GPP radio access networks [13]. In order to enable dynamic control in ANS, 3GPP has recently defined Radio Access Network (RAN) assistance parameters and policies to support dynamic and bi-directional ANS between 3GPP and WLAN networks in Release 12 [14]. While the parameters can be signaled to the UE by the RAN in broadcast or via dedicated messages, the policies can be provisioned both via RAN mechanisms or enhanced ANDSF (eANDSF).

Currently, no standardized interface between the 3GPP RAN and WLAN networks has been specified yet. The definition of such direct interface is expected to be accomplished in the near future by 3GPP within the recently formed work item called “LTE-WLAN Radio Level Integration and Interworking Enhancement” [15] following the conclusions of the recently finalized study item of “Multi-RAT Joint Coordination” [16] and the “Study on WLAN-3GPP radio interworking” [17], to which we have also contributed based on the work presented here. The work item is expected to allow also further RAN control of the ANS decisions.

This paper builds further on findings published in [9, 10]. We describe in detail the step-by-step design and thorough evaluation of several new ANS SON functions by exploring the use of two different monitoring key performance indicators and signal threshold update mechanisms. The resulting simulations below show that the adoption of SON provides remarkable gains compared to the baseline scenario, which results in WLAN congestion. Any proposed SON algorithm yields to a more balanced loading across the layers/systems and thus improves the QoS of end users.All potential ANS solutions require, to a different extent, the exchange of information between systems and devices to assist the access selection decision. The exchange of assistance information can be exploited to achieve higher performance, however, at the price of increased signaling overhead and complexity of the network selection functions. In this paper, we evaluate several ANS algorithms and provide recommendations accounting carefully for such trade-offs.

The remainder of this paper is organized as follows. In Section 3, we introduce the SON concept and several ANS architecture alternatives to realize an ANS SON function. Following a description of selected control parameters and key performance indicators as basic components of the SON function, the proposed SON algorithms for ANS between LTE and WLAN are explained in details. Section 5 describes the adopted system modeling and network-specific simulation scenario comprising a realistic urban environment and HetNet deployment. The performance of the proposed SON functions are summarized and analyzed in Section 6 based on extensive simulation results. The paper is finalized with conclusions and recommendations for future work.

The terms system and network are used interchangeably throughout this paper. An LTE eNB is referred to as an LTE macro cell; an outdoor LTE small cell as a micro cell and a WLAN cell is also referred to as WLAN Access Point (AP). The term cell will be used to refer to both LTE and WLAN radio access nodes, i.e., WLAN AP's and LTE macro and micro cells.

3 SON function design

3.1 Fundamental SON concepts

In the context of this paper, a SON function is the realization of a self-organizing functionality inside a radio access network comprising the required capabilities for the correct operations [8]. The analyzed ANS SON functions can be broken down into several functional blocks, as illustrated in Fig. 1:

1. *KPI monitoring*: This sub-function periodically, at a short time scale of seconds or below, monitors a key performance indicator (KPI) of interest, such as cell load at the LTE and WLAN air interface. In this study, the monitored KPIs of the proposed SON functions are either originating from one network only, i.e., LTE or WLAN, or from both networks. The elaboration of the adopted KPIs is provided in Section 3.4.
2. *ANS SON algorithm*: This sub-function realizes the actual SON algorithm, which is able to automatically adjust key parameters, referred herein to as control parameters, which influence the ANS behavior. The adjustment follows dynamic changes in traffic, radio signal level, and radio interference situations. The sub-function is comprised of the Trigger block, which determines whether any adjustment of the control parameters is beneficial in the current time interval, and the control parameter adjustment block, which performs the actual adjustment. The control parameters adopted in this study are further discussed in Section 3.3, whereas the ANS SON algorithm is described in detail in Section 4.
3. *ANS execution*: This sub-function takes care of the actual execution of the ANS decision. The execution can be either made at the UE side assisted by information provided by the network (UE controlled ANS) or can be controlled directly by the network (network-controlled ANS). In the former case the updated control parameters proposed by the ANS SON algorithm, should be signaled to the UE, on which basis the UE determines the network selection according to pre-configured ANS rules, which are explained in Section 3.3. In the latter case, the ANS rules should be evaluated at the network node that controls the SON function, and an explicit steering command has to be sent to the UE, e.g., to perform a handover from LTE to WLAN.

3.2 ANS architecture

A distributed SON architecture was selected for this study, where the SON functionality responsible for tuning network selection parameters is implemented in the individual LTE cells or WLAN APs. This is considered preferential over a centralized architecture in order to be able to timely process the triggers and adjust the control parameters in response to the dynamic changes in traffic and radio interference situations. Several distributed architectures could be envisioned for ANS between LTE and WLAN technologies. Figure 2 illustrates the distributed SON architectures considered in this paper with indication of the information exchange which may be available according to the state-of-the-art. Each of these architectures supports a specific method to achieve load balancing, referred to here

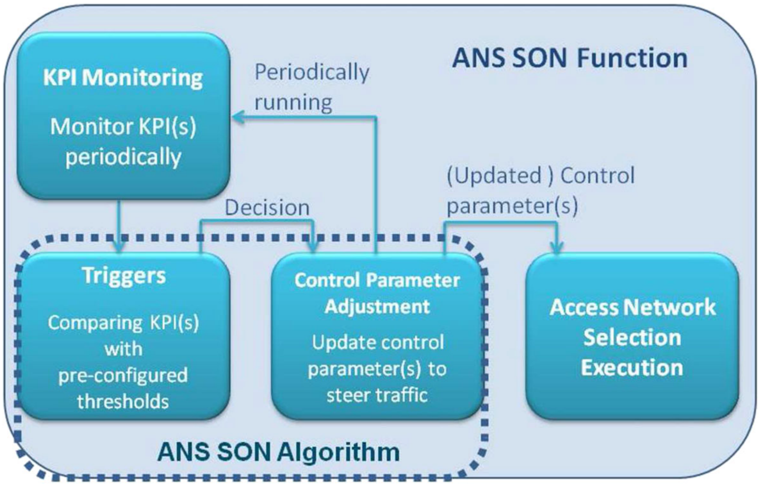

Fig. 1 Illustration of the internal functional components of the ANS SON function

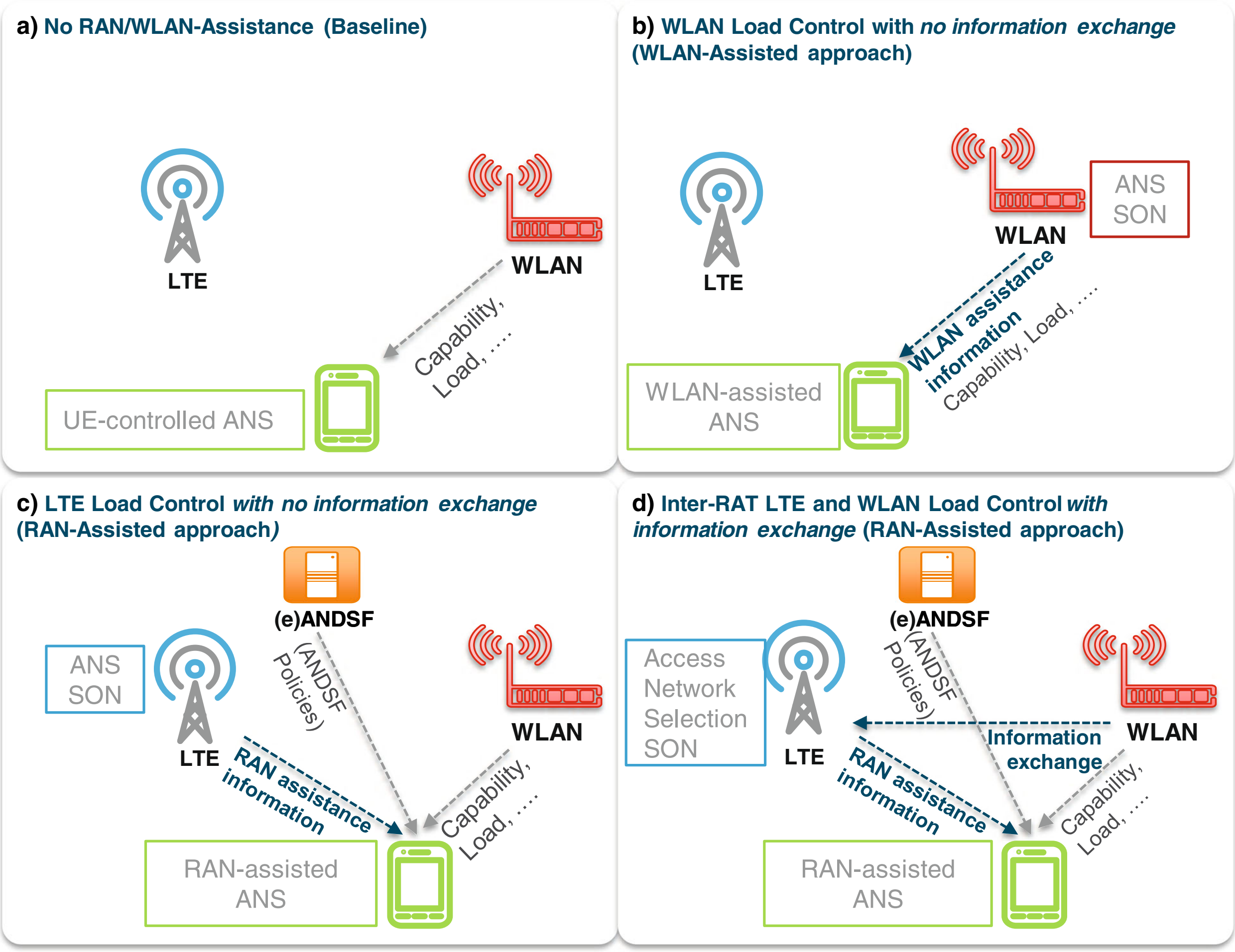

Fig. 2 Illustration of the investigated distributed SON architectures and corresponding load control policies

as a load control policy or LC policy. The description of the considered architecture alternatives is provided below:

1. *No WLAN/RAN-assistance approach (baseline)*: This approach reflects today's typical UE behavior where WLAN network discovery, selection, and access are largely user-controlled. It will be considered as the baseline for the study presented in this publication.
2. *WLAN load control policy without information exchange (WLAN-assisted approach)*: The SON function runs on the WLAN side. Each WLAN AP determines the adjustment of the control parameters related to network selection independently, in an uncoordinated fashion, and without any kind of information exchange between the LTE and WLAN systems. That is, the SON function uses only the monitored KPIs from the WLAN system. The WLAN assistance information is sent directly from the serving WLAN AP to the UEs.
3. *LTE load control policy without information exchange (RAN-assisted approach)*: The SON function runs in the LTE cell. Each LTE cell determines the adjustment of the control parameters related to network selection independently, in an uncoordinated fashion, and without any kind of information exchange between the LTE and WLAN systems. That is, the SON function uses only the monitored KPIs from the LTE system. The RAN assistance information is sent from the serving LTE cell to the UEs. LTE load control (LC) refers to the case where the SON functions is running in both the macro and the micro cells at the same time, which is considered to be the default case. The terms Micro LC and Macro LC are used when the SON function is running only on the LTE micro or macro level, respectively.

4. *Inter-RAT (IRAT) load control policy with information exchange (RAN-assisted approach)*: This approach relies on a tighter coupling between the LTE and WLAN systems and requires that a small amount of information related to the WLAN AP, referred to as information exchange, e.g., WLAN AP load levels, is collected by an LTE cell, which is strategically paired with the WLAN AP, as will be discussed later. The SON function runs on the LTE side. The exchanged information is processed by the LTE cell, in addition to the local (LTE radio related) information, to determine a possible adjustment of the ANS control parameters. The information exchange between the LTE and WLAN systems may rely on UE terminals as relays, on proprietary or a standardized signaling interface between the paired WLAN AP and LTE cell. The latter is the most promising approach when considering air interface signaling overhead, UE battery consumption, and multi-vendor interworking. The RAN assistance information is sent from the serving LTE cell to the UEs.

3.3 Access network selection thresholds and rules

This study targets a SON ANS functionality, which determines the most suitable access network from a user QoS point of view. The radio link quality experienced by the UE together with the cell load level determines the achieved QoS performance (UE throughput in this study). Therefore, to improve the end-user QoS, while limiting the network complexity, the control parameters used in this study are updated based only on the estimated cell load level. The metrics to calculate the cell load level are discussed later in Section 3.4. An alternative approach, where the ANS decision is based directly on the estimation of the UE throughput that could be achieved in the two access networks, is not covered in this study.

The control parameters that are signaled to the UE are thresholds for the UE received radio link quality. It is these thresholds that comprise the WLAN/RAN assistance information. Specifically in this study, the Reference Signal Received Power (RSRP) [18] and Received Signal Strength (RSS) [19] are adopted as UE measurements for LTE and WLAN, respectively. However, the proposed ANS SON concept could be easily extended to adopt radio link quality metrics as well such as LTE Reference Signal Received Quality (RSRQ) [18] and WLAN Received Signal to Noise Indicator (RSNI) [19]. The adopted thresholds related to the above mentioned UE measurements are the WLAN RSS Threshold and the LTE RSRP Threshold. These thresholds define the required level of the UE measurement in order to select a given network.

To understand how the thresholds can be used, it is important to first define the location of the cells. This paper studies SON functionality in a HetNet scenario and therefore assumes that a deployment of outdoor WLAN APs is introduced into an LTE network, which contains both LTE macro and outdoor micro cells. The network operator can place the WLAN APs co-located with LTE cells or on new non-co-located positions. As the transmission range of LTE macro cells is much larger compared to WLAN APs, a WLAN AP will almost always reside within macro cell coverage. Therefore, most of their coverage areas will overlap, even if the macro cell and WLAN AP are not co-located, which means UEs connected to the macro cell can be steered to WLAN. In case the LTE cell is not co-located with the WLAN AP, it is best to use an ANS rule where LTE macro cell edge UEs can be steered to WLAN APs in their proximity, where they will probably experience improved throughput.

If a WLAN AP is not co-located with a micro cell, then their coverage areas will not completely overlap or might not even overlap at all. In those cases, not all UEs connected to the micro cell can be steered to WLAN, which limits the potential of performing ANS. In case an LTE cell is co-located with the AP, to which its UEs could potentially be steered to, it is best to use an ANS rule, which will result in UEs close to the AP being connected to WLAN. This is because, in a WLAN AP, a cell edge UE with poor throughput would cause the throughput of all other UEs connected to this AP to reduce drastically. LTE, on the other hand, can simply assign more resources to the cell-edge UEs that have a lower SINR. This approach has a much smaller impact on the throughput of the other connected LTE UEs.

To summarize, the decision of the UE to which cell to connect, is made according to the following ANS rules:

- *RSS-based ANS rule*: A UE selects the detected/connected WLAN AP if the measured WLAN RSS towards it is above the given RSS threshold; otherwise, the LTE cell is selected. This rule results in UEs in good radio propagation conditions towards the AP being steered to WLAN.
- *RSRP-based ANS rule*: A UE selects the detected/connected WLAN AP if the measured LTE RSRP towards the detected LTE cell is below the given RSRP threshold and the measured RSS towards the AP is above a minimum RSS level, otherwise the LTE cell is selected. This rule results in LTE macro cell edge UEs being steered to WLAN, but only if they are in acceptable WLAN coverage.

The following actions are assumed to be taken by the UE prior the start of a new data session:

1. First, the UE periodically monitors the LTE cell providing the best RSRP value and the WLAN AP providing the best RSS value. The LTE cell can be

either a macro or micro cell. A simplified intra-LTE load balancing is assumed in this study where micro cell range extension is enforced.

2. Second, if SON-enabled ANS functionality is running in either the LTE or WLAN network, the UE will receive either the RAN or WLAN assistance information respectively, through broadcasting by that cell.
3. The UE then determines the cell it will connect to, based on the combination of the signal strength threshold included in the assistance information it received and the RSRP and RSS values it measured according to the RSS/RSRP based ANS rules defined above.
4. Finally, the UE initiates connection to the determined cell and start the data session.

In this study, we assume that WLAN APs are always co-located with LTE micro cells, which maximizes the potential of performing ANS. In such a scenario, the network operator also does not need to find new suitable locations and would probably save on extra site rental costs, which further justifies this decision. Figure 3 shows an example scenario where both the RSRP and RSS rules are being used.

It should be noted here that the RSS-based rule could also be achieved with an RSRP threshold, towards the co-located LTE micro cell. For example, when WLAN LC is combined with the RSS-based rule, the ANS SON functionality could also use an RSRP threshold to enforce it. In that case, UEs with an RSRP value higher than the RSRP threshold are steered to WLAN. From performance point of view, there should not be any difference compared to the RSS-based rule as long as the UE measurements—RSS on WLAN or RSRP on LTE—have similar accuracies. In our study we assume this is the case and we do not investigate the use of the RSRP threshold for WLAN LC.

The proposed ANS SON functionality employs one of the ANS rules—RSS based or RSRP based—combined with one of the LC policies introduced in Section 3.2. When the SON functionality is running on the WLAN side or in the LTE micro cell {WLAN LC, Micro LC, IRAT LC}, the RSS rule will be selected. In case the SON functionality is running in the LTE macro cell {Macro LC}, the RSRP rule will be selected. This means that there is now a 1-to-1 mapping between LC policy, threshold rule, and threshold type. All the available combinations are summarized in Table 1. Notice that LTE LC is simply the combination of Micro LC and Macro LC.

These LC policies have different levels of controllability over the ANS between LTE macro cells and WLAN layers. The first option is to deploy only Micro LC or IRAT LC, which allows for load balancing between the micro cell and the co-located WLAN AP. However, if a UE is camping/connected to an LTE macro cell, there are no applicable ANS rules available; hence, no macro users can be steered to WLAN. We will specifically refer to such a case as "no Macro offloading." The second option is to deploy WLAN LC. Then, UEs can be steered to WLAN, as long as they are in WLAN coverage and if their RSS value is higher than the RSS threshold, regardless of whether they are in LTE micro or macro coverage. A third approach, is to deploy Micro LC or IRAT LC, while also signaling the threshold determined on the LTE micro level to the macro UEs, by relaying the assistance information over the X2 interface. Then, UEs camping/connected to an LTE macro cell can also be steered to WLAN. Both the second and third approach, however, do not allow for separate steering control of micro and macro UEs. In the last alternative, both Micro LC and Macro LC can be deployed

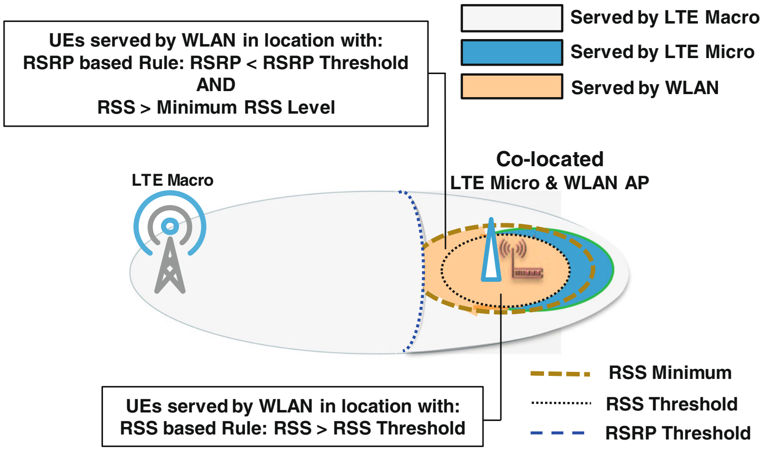

Fig. 3 Illustration of the investigated distributed SON architectural frameworks and corresponding load control policies

Table 1 Investigated load control policies, with the respective threshold rule and threshold type

LC policy	Threshold rule	Type	ANS between LTE micro layer and WLAN	ANS between LTE macro layer and WLAN
Micro LC (No macro offloading)	RSS-based ANS rule	RSS	Supported based on the load level of the micro layer.	Not supported.
Micro LC	RSS-based ANS rule	RSS	Supported based on the load level of the micro layer.	Supported based on the load level of the micro layer.
Macro LC	RSRP-based ANS rule	RSRP	Not supported.	Supported based on the load level of the macro layer.
LTE LC = Micro + Macro LC	Micro layer: RSS rule Macro layer: RSRP rule	RSS & RSRP	Supported based on the load level of the micro layer.	Supported based on the load level of the macro layer.
WLAN LC	RSS-based ANS rule	RSS	Supported based on the load level of the WLAN system.	Supported based on the load level of the WLAN system.
IRAT LC (No macro offloading)	RSS-based ANS rule	RSS	Supported, accounting for both the LTE and WLAN load level.	Not supported.
IRAT LC	RSS-based ANS rule	RSS	Supported, accounting for both the LTE and WLAN load level.	Supported, accounting for both the LTE and WLAN load level.

and separate macro and micro user ANS control is realized with separate RSRP thresholds signaled to the macro and micro UEs. Even though Macro LC is listed as a separate entry in Table 1, it is never deployed on its own in this study. Macro LC does not allow to perform ANS between LTE micro cells and WLAN, which is not considered worth investigating. LTE LC will be considered the default single RAT LC policy based on LTE cell load.

3.4 Monitored KPI selection

Monitored KPIs are network KPIs that are used as feedback information by the ANS SON algorithm to update the RSS and RSRP thresholds and thus influence the network selection of UEs between LTE cells and WLAN APs. The monitored KPI should reflect for each cell whether sufficient (radio) resources are available to maintain or establish a connection to the cell. By adjusting the RSS and RSRP thresholds based on this monitored KPI, load balancing can be achieved, which, in turn, should optimize the connected UEs' throughput and thus their QoS. We have investigated the use of two distinct metrics as monitored KPI.

First, the average LTE or WLAN radio resource utilization (RU) was considered as monitored KPI with the intention of high performance impact and limited complexity. For LTE, RU is defined as the percentage of the average utilization of physical resource blocks (PRBs) over a certain period of time. For WLAN, it is defined as the percentage of average channel busy time of a WLAN AP and is based on the basic service set (BSS) load element information certified by the Hotspot 2.0 specification [12]. The channel is considered as busy if there is at least one active connection associated to the AP and the AP or a UE is transmitting.

Both LTE RU and WLAN RU, however, are less adequate to provide relevant information about the real cell load level when the user traffic is full buffer-alike, i.e., a single UE is capable of utilizing all the available cell resources. Under full buffer traffic conditions, this RU metric will indicate that the cell load reaches 100 % and thus ignores the level of satisfaction/saturation which would be achieved if more users connect to the same cell. Furthermore, the definition for RU is not the same for the two different technologies and therefore they cannot be compared directly to each other. Nevertheless, the RU metric is still considered a viable candidate, because it is very easy to calculate and because it is already available in WLAN APs.

In order to have a KPI that resolves the limitations of RU and is applicable to both LTE and WLAN, a new cell load metric is proposed: the cell saturation ratio (CSR). This metric assumes a reference throughput for each user in the downlink, similar to what the LTE composite available capacity (CAC) [20] measure does, and indicates to which extent the cell is able to satisfy the served users, by comparing the data rates of the connected UEs to the given reference throughput value. The CSR of a cell is calculated as follows:

$$\mathrm{CSR} = \sum_{i=1}^{N} \frac{\text{Reference Throughput}_i}{\text{Datarate}_i} \cdot 100\ \%$$

Here, N equals the number of UEs connected to the cell, Reference Throughput represents a preferred minimum average throughput an operator would like a UE to achieve, and Datarate is the achievable data rate of a UE in the current time interval assuming it is served with all available resources. A CSR level of 100 % indicates that the cell needs all the available resources in order to provide at least the preferred reference throughput to the served UEs. A CSR level higher than 100 % indicates that at least one of the served UEs is not able to get the reference throughput. On the contrary, a lower level of CSR indicates that the cell could meet the preferred minimum reference throughput demands of all the served UEs, without requiring all of its resources, and is thus still capable of serving additional UEs.

Finally, the monitored KPI provided as input to the ANS SON algorithm is the time-filtered version of the measured metric value (RU or CSR). This prevents large and sudden changes of the monitored KPI from having an unnecessary impact on the thresholds and increases stability of the ANS SON algorithm. This filtering is achieved with a simple weighted averaging filter, as presented below:

$$\mathrm{load}_t = (1-\alpha)\cdot \mathrm{load}_{t-1} + \alpha \cdot \mathrm{load}_{\mathrm{measured}}$$

Here α is the filtering factor. Further on, the monitored KPI will also be referred to as the LTE or WLAN cell load.

4 SON algorithms for updating ANS thresholds

A SON algorithm is used to update the ANS thresholds based on the input of the monitored KPIs. We propose two methods for the ANS threshold update, i.e., fixed step size and variable step size. As presented in this section, while both approaches are effective in load control, the variable step size algorithm provides better controllability with a cost of higher algorithm complexity.

4.1 SON algorithm with fixed threshold step size

The flowchart of the proposed ANS SON algorithm, which tunes dynamically a selected ANS threshold per cell, with a fixed step size, is illustrated in Fig. 4 on the left, for the different LC policies.

The following algorithm parameters are defined:

- WLAN or LTE Load High (*WLAN_LH* or *LTE_LH*): load level above which a cell is considered to be in a high load condition;
- WLAN or LTE Load Low (*WLAN_LL* or *LTE_LL*): load level below which a cell is considered to be in a low load condition;
- RSS or RSRP Step (*RSS_Step* or *RSRP_Step*): a static delta RSS or RSRP value with which the RSS or RSRP threshold is updated by the SON function.

At the start of the SON algorithm, the RSRP threshold (*RSRP_Thr*) or RSS threshold (*RSS_Thr*) parameter is initialized to its default value. In the subsequent algorithm iterations (over time), the employed threshold value is updated (incremented or decremented) using a fixed step size, *RSRP_Step* or *RSS_Step*, based on the outcome of the cell load check sequence.

In this flow chart, the SON algorithm with no information exchange mechanism is achieved by using only the LTE load (for LTE LC policy) or only the WLAN load (for WLAN LC policy) check procedures. For the SON algorithm with information exchange (for IRAT LC policy), both LTE load and WLAN load check procedures are performed, sequentially. Whenever a threshold value is updated, the algorithm also ensures that it remains within a desired range to maintain system stability. Then, the updated threshold value is signaled to the UEs located within the coverage area of a given cell to be used for ANS.

Figure 5 illustrates the ANS threshold and cell load variation in an LTE cell when deploying Micro LC combined with an RSS threshold with fixed threshold step size. Note that the LTE CSR cell load measure can be higher than 100 % as explained in Section 3.4 to indicate an overload condition. In this example, the following parameter values were used: *LTE_LH* and *LTE_LL* are 85 and 70 % respectively and *RSRP_Step* is set to 1 dB.

4.2 SON algorithm with variable threshold step size

The SON algorithm proposed in Section 4.1 adapts the ANS thresholds continuously with a fixed step size in order to influence the ANS decision. As shown in Fig. 5, at time stamp 93, the LTE cell load reaches 100 %, but an additional UE selected the cell in the next second due to the slow adjustment of the RSRP threshold. Simply increasing the step size, on the other hand, may cause system instability. Therefore, a SON algorithm with variable threshold step size has been developed with the aim of blocking additional connections when a cell is already overloaded.

The following algorithm parameters are defined:

- Cell state (*CS*): A cell can be in one of the two states: "*protected*" or "*un-protected*." In the "*Protected*" state, the SON function will block additional connections to this cell; while in the "*Un-protected*" state, the SON allows additional users to be connected to the cell, as long as their signal strength satisfies the current threshold and rule;
- WLAN or LTE Load High (*LH*): load level above which a WLAN or LTE cell is considered to be in a high load condition;
- WLAN or LTE Load Low (*LL*): load level below which a WLAN or LTE cell is considered to be in a low load condition;
- RSS or RSRP Fallback Threshold (*RSS_FbThr* or *RSRP_FbThr*): a static RSS/RSRP threshold value high enough to prevent any additional user from connecting;
- RSS or RSRP Step (*RSS_Step* or *RSRP_Step*): a static delta RSS/RSRP value with which the threshold is adjusted by the SON function;
- RSS or RSRP Threshold Store (*RSS_ThrSto* or *RSRP_ThrSto*): a variable that stores the current

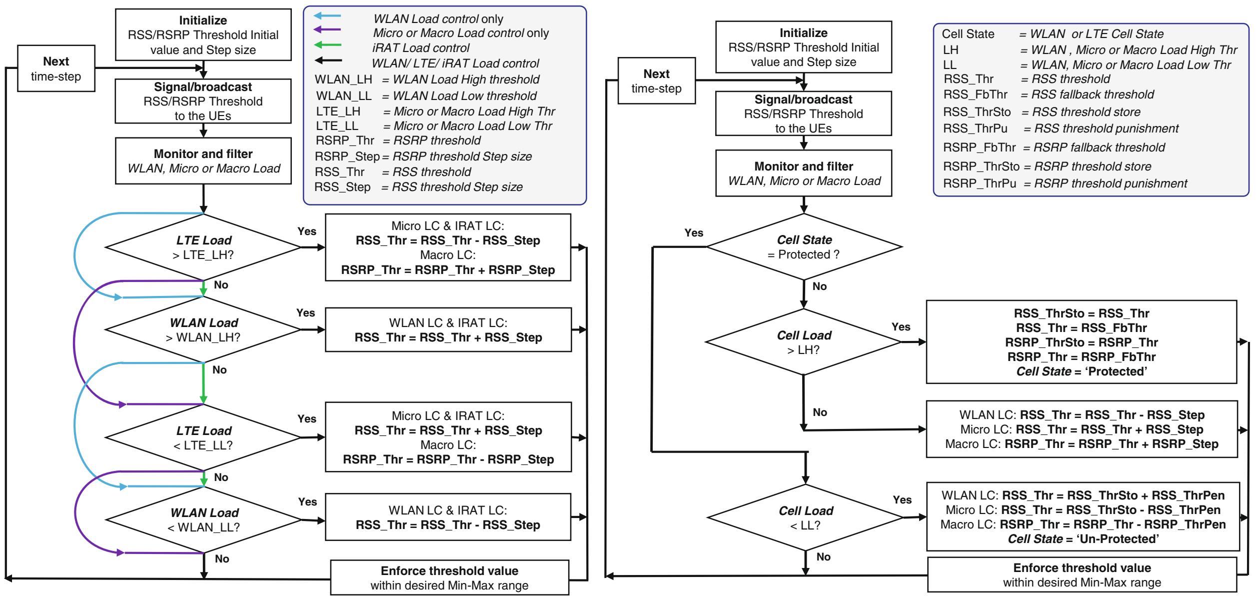

Fig. 4 Flowcharts of the investigated SON algorithms for ANS with fixed (*left*) and variable (*right*) ANS threshold step size

RSS/RSRP threshold value when a cell switches to the "*protected*" state;

- RSS or RSRP Threshold Penalty (*RSS_ThrPen* or *RSRP_ThrPen*): a static delta RSS/RSRP value that is subtracted from or added to ThresholdStore, when a cell switches to the "*un-protected*" state;

The SON algorithm flowchart is illustrated in Fig. 4 on the right. We use WLAN LC as an example to explain the ANS SON operation with variable threshold step size. Initially the cell is considered to be in the "*un-protected*" state. If the cell load is below the LH value, the RSS threshold will be decreased by *RSS_Step* (dB) to attract more users to the WLAN AP. When cell load becomes higher than LH value, the RSS threshold is immediately increased to *RSS_FbThr* to avoid additional connections and the CS is set to "*protected*."

In the "*protected*" state, the RSS threshold remains equal to *RSS_FbThr*, unless the cell load goes lower than the LL value. In that case the RSS threshold is reset to *RSS_ThrSto* + *RSS_ThrPen* and the cell state is reset to "*Un-protected*." The *RSS_ThrPen* addition is defined to avoid that the threshold value goes back too fast to a level that caused the cell to become highly loaded. Whenever the threshold value is updated, the algorithm also ensures that it remains within a desired range to maintain system stability. Then, the updated threshold value is signaled to the UEs located within the coverage area of a given cell to be used for ANS. Note that this variable threshold step size algorithm can only be used for a single RAT load control policy, and not for IRAT LC, because the algorithm cannot take into account the load of the other RAT. It needs to be able to close off the cell, irrespective of the load of another RAT.

Figure 6 illustrates the ANS threshold and cell load variation for WLAN LC with an RSS threshold after deploying the proposed ANS SON algorithm with variable threshold step size. In this simulation, the following parameter values are used: *WLAN_LH* and *WLAN_LL* are 85 and 70 % respectively, *RSS_Step* is set to 1 dB, *RSS_ThrPen* equals 10 dBm, and *RSS_FbThr* equals −20 dBm. As shown in the figure, once the WLAN AP load becomes higher than *WLAN_LH*, no more users get connected to the AP. Only after the load goes below *WLAN_LL* again, an immediate drop of the threshold is enforced to allow connections of additional users.

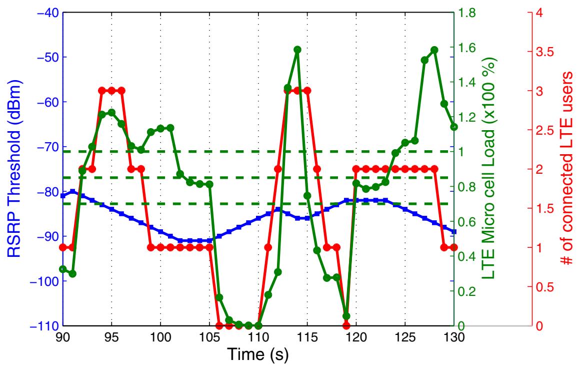

Fig. 5 Plot showing threshold adaptation over time for LTE load control-based policy using the SON algorithm with fixed threshold step size

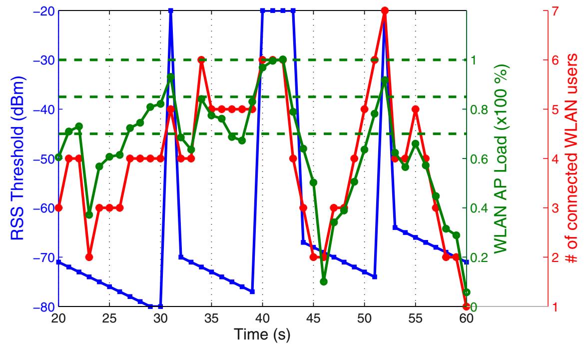

Fig. 6 Plot showing threshold adaptation over time for WLAN load control policy using the SON algorithm with variable ANS threshold step size

5 Performance evaluation

5.1 Scenario and modeling

The proposed SON functions were evaluated by system level simulations, using the SONLAB simulation environment (introduced in Section 5.2), with a realistic heterogeneous network topology. This was achieved by making an exact copy of the radio access infrastructure present in the city of Hannover, Germany [21]. It is covered by three network layers, consisting of 28 co-located outdoor LTE micro cells and WLAN APs in addition to 195 LTE macro sites. The simulation scenario focuses on an outdoor traffic hotspot, which is located in a shopping street area in the city center, as depicted in Fig. 7. User traffic is generated by User Datagram Protocol (UDP) downloading from stationary users with 5 MB file size.

It should be observed that the realistic traffic density applied to the investigated scenario is highly nonhomogenous, as can be seen by the 400 user locations marked with black dots, which are significantly concentrated in the center of the hotspot. The arrival rate of data sessions at those UE locations follows a Poisson process which reflects a bursty data traffic scenario. Thus, a high load scenario indicates in practise that only a subset of LTE micro cells and WLAN APs, truly suffer from those load high levels, while the load levels of other cells might be significantly lower. The LTE system modeling is fully compliant with the 3GPP LTE Release 8 specifications. The system has 20-MHz system bandwidth in the 1.8-GHz carrier frequency band. The macro and micro layers operate on the same carrier frequency band with transmission power of 46 and 33 dBm.

The WLAN system modeling is based on the 802.11n PHY/MAC layer specifications with 20-MHz system bandwidth and 15 channels available at 5 GHz. The transmission power is 24 dBm. The antenna configuration in both systems is 2×2 multiple input multiple output (MIMO). The WLAN throughput was modeled based on the conclusions of [22]. LTE throughput was modeled using a truncated Shannon formula combined with validated parameters provided in [23].

5.2 SONLAB simulation environment

The SON laboratory (SONLAB), developed by atesio [24], provides a simulation platform for scalable, distributed, multi-party simulations of realistic radio network scenarios. SONLAB is designed to be extended

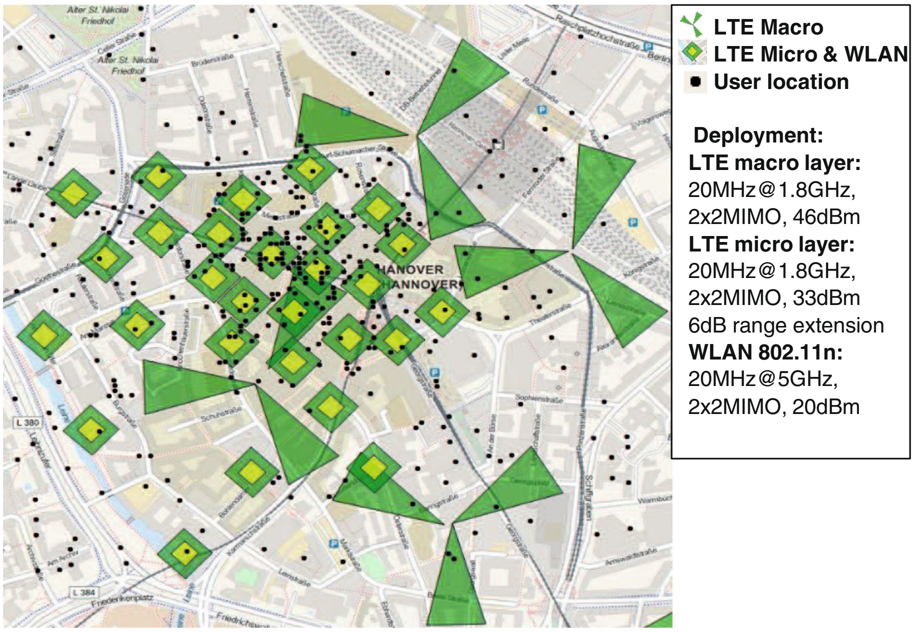

Fig. 7 Outdoor hot zone scenario without mobility: schematical visualization of network deployment layout and user location

by simulation clients, which can add or refine functionality when needed, such as RAT-specific features or SON functions. The SONLAB kernel functionality and default clients are implemented in C and Python and are capable of handling large-scale realistic environments featuring multi-RAT and multi-layer networks, high-resolution radio signal predictions and real-world or realistic traffic data. SONLAB data structures and algorithms are designed to perform network performance analysis, such as load and SINR computations for a large amount of users and cells, within a few seconds.

5.3 Algorithm configuration

The proposed SON algorithms are configured by setting the algorithm parameters listed in Table 2. In order to decide on the SON configuration parameters, i.e., load filtering factor and step size adjustment of the ANS threshold, simulations with different SON parameter values have been performed. For these simulations, a *P_SON* and *P_LTE/P_WLAN* equal to 1 s was used as a starting point. Initial investigation indicated that the combination of a filtering factor of 0.8 and a step size of 1 dB yields the best results, compared to other evaluated combinations. Similar behavior was observed for all the evaluated SON functions with fixed step size and at any offered traffic load level.

6 Numerical results and discussion

In the following, we discuss the observations obtained from the numerical analysis of the proposed SON enabled ANS schemes described in Sections 3 and 4 when using the system parameters provided in Table 2. For all SON functions validated in this section, the simulated mean arrival rate of data sessions ranges from 8 to 16 sessions per second per UE in the entire simulation area. The selection of the arrival rates has been made in order to evaluate the following offered traffic scenarios: low cell load (8 sessions/s), medium cell load (10-12 sessions/s), high cell load (14 sessions/s) and very high cell loads (16 sessions/s). The main KPI depicted is average user session throughput, which is the average throughput of a user's session averaged over all sessions in the simulation.

6.1 Effectiveness of SON approach

To validate the overall effectiveness of the proposed SON functions, we evaluate their performance compared with that of the baseline scheme for the load control policies of LTE LC, WLAN LC, and IRAT LC, described in Section 3.2. The baseline scenario assumes the typical current UE behavior, namely the simple access selection principle of "WLAN if coverage," where a UE selects WLAN whenever it detects WLAN radio coverage, i.e., meeting a bare minimum RSS level of −92 dBm. The analysis in this section assumes fixed step size SON algorithm design, described in Section 4.1.

Figure 8 shows the average and 10th percentile user session throughput as well the average session percentages per layer of the different LC policies and the baseline. Significant performance improvement is achieved with any

Table 2 Summary of adopted simulation parameters related to the SON algorithms and baseline

Parameter	Description	Setting
P_SON	Periodicity of SON algorithm execution	1 sec
P_LTE / P_WLAN	Periodicity of load calculation	1 sec
α	Load filtering factor ("forgetting factor")	0.8
micro_range_extension	Static offset added to RSRP measurements from micro cells	6 dBm
{*WLAN_LL, WLAN_LH*} for CSR	WLAN load thresholds used in threshold updating algorithm	{70 %, 85 %}
{*WLAN_LL, WLAN_LH*} for RU	WLAN load thresholds used in threshold updating algorithm	{60 %, 80 %}
RSS_Step	Step size of RSS threshold adjustments (up or down)	1 dBm
RSS_Initial	Initial value of the RSS threshold	−82 dBm
{*RSS_Min, RSS_Max*}	Minimum and maximum values of the RSS threshold	{−86 dBm, −45 dBm}
{*LTE_LL, LTE_LH*} for CSR	LTE load thresholds used in threshold updating algorithm	{70 %, 85 %}
{*LTE_LL, LTE_LH*} for RU	LTE load thresholds used in threshold updating algorithm	{60 %, 80 %}
RSRP_Step	Step size of RSRP threshold adjustments (up or down)	1 dBm
RSRP_Initial	Initial value of the RSRP threshold	−70 dBm
{*RSRP_Min, RSRP_Max*}	Minimum and maximum values of the RSRP threshold	{−110 dBm, −40 dBm}
Reference Throughput	Reference throughput for the CSR calculation	12 Mbps unless differently specified
{*RSS_ThrPen, RSRP_ThrPen*}	Threshold penalty used in SON algorithms with variable step size	10 dBm
{*RSS_FbThr, RSRP_FbThr*}	Threshold fallback used in SON algorithms with variable step size	−20 dBm

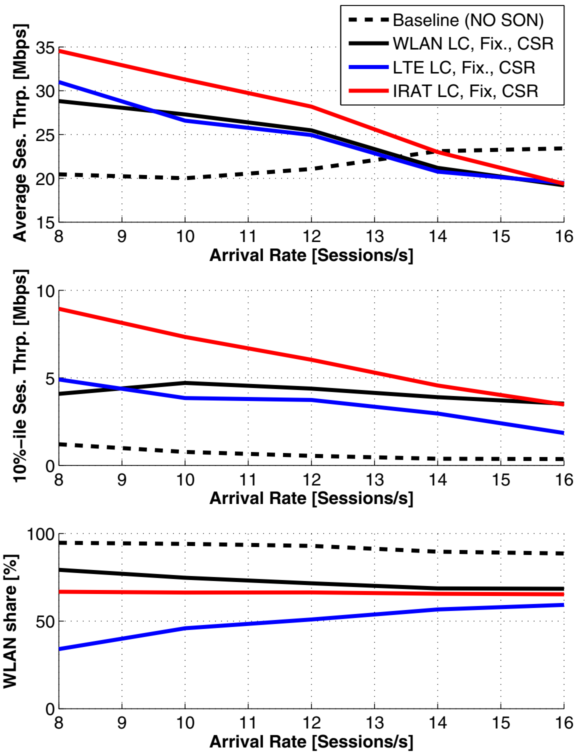

Fig. 8 User session throughputs and percentage of WLAN sessions for different session arrival rates with fixed and variable threshold step size for single-RAT load control

of the proposed load control schemes compared to the baseline, particularly by the IRAT LC.

The baseline shows severe WLAN congestion and underutilization of the LTE macro and micro layers. This is reflected by the very high percentage of user sessions served by the WLAN network, which results in a rather low 10th percentile user session throughput. This outcome is expected in the selected scenario due to the dense WLAN deployment where most of the UEs can detect a WLAN AP. When SON ANS is enabled, it dynamically controls the system load in LTE, WLAN, or both systems—depending on the selected load control policy—with the end effect of a more balanced loading across the layers/systems as shown by the average session percentage per layer. Note that the curve representing the average throughput of the baseline increases at the higher load levels. This is caused due to the simulator's employment the typical principle of session dropping, i.e. sessions arriving for users that are still handling an active session are dropped. Thus, overall, there will be a smaller percentage of sessions with a low throughput, resulting in a higher average session throughput. This, however, barely influences the 10th percentile throughput. The amount of sessions dropped was close to zero, except for the baseline case.

A further observation is that, when the amount of offered traffic to the network reaches a certain level (mean data session arrival rate of 15–16 sessions/s in our scenario), the performance difference between the SON functions becomes minimal. This is because, in the end, the total network capacity remains fixed and limited. The SON solutions allow load balancing between the LTE and WLAN systems and use network resources more efficiently. However, once both systems are highly loaded at the same time, ANS SON can only offer minimal help. Different solutions would be required to address this situation such as enabling additional capacity for the existing network or by means of a denser deployment of LTE small cells and APs. Thus, larger gains can be found at lower and medium load levels, where ANS SON has more freedom to operate. On the other hand, the 10th percentile throughput is still sensitive to differences in SON schemes, even at very high load situations, particularly for the case of LTE LC. By providing protection against congestion limited to the LTE network, at high offered load levels, LTE LC based ANS pushes too much traffic to be served by WLAN. This causes WLAN throughput performance to suffer drastically due to the MAC design which is based on contention-based random access and suffers from inevitable collisions and back-offs.

Further analysis of the configuration and optimization of the proposed SON functions is discussed in the following sections. Further analysis of the load control policies is presented in detail in Sections 6.4 and 6.5.

6.2 Fixed vs. variable step size SON algorithm

In Sections 4.1 and 4.2, the SON algorithms with fixed and variable threshold step size were introduced, respectively. In this section, the performance of single-RAT load control SON functions WLAN LC and LTE LC is compared for the cases of variable and fixed threshold adjustment step sizes. As explained in Section 4.2, IRAT LC was not designed in combination with the variable step size SON algorithm and therefore is not part of this evaluation.

Figure 9 presents user session throughputs (average and 10th percentile) as a function of different session arrival rates. The following can be observed: (a) For all load levels, the variable threshold step size adjustment results in improved average session throughput compared to the cases where fixed step size is used for any of the load control policies; (b) The 10th percentile session throughput also improves for the cases of variable step size adaptation in certain load conditions.

The results in the first observation can be explained as follows. The ANS threshold when changed in a variable fashion completely prevents that new sessions are served by a highly loaded cell. This protection is then maintained by setting the cell state to the protected status.

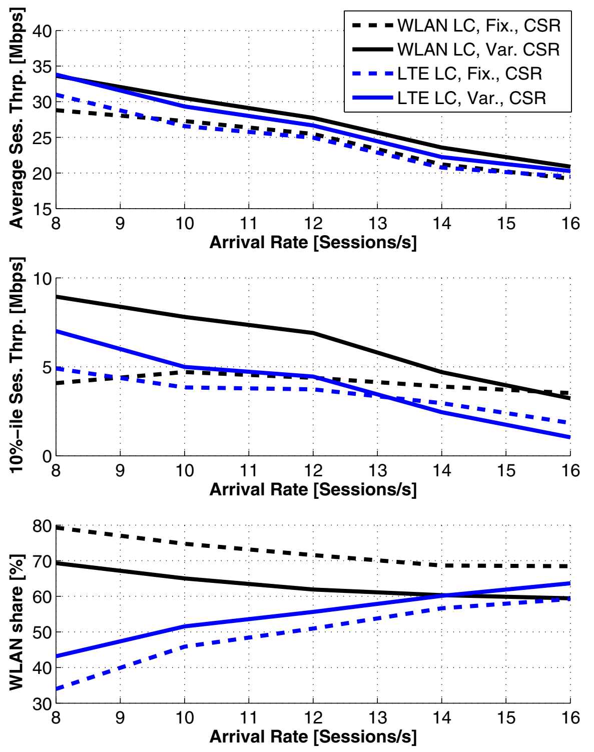

Fig. 9 User session throughputs and percentage of WLAN sessions for different session arrival rates with fixed and variable threshold step size for single-RAT load control

This differs in the fixed step size design, where the start of new sessions in a highly loaded cell can only be minimized, by increasing the RSS or RSRP threshold to be met for entering the cell, however it cannot be avoided completely.

The second result is valid for any arrival rate up to 16 sessions/s in the case of WLAN LC and up to 14 sessions/s in the case of LTE LC. The WLAN LC based SON protects the WLAN layer from overload by monitoring when an AP exceeds the high load threshold and redirects excess traffic to LTE. When the variable step size SON algorithm is used, 10 % more sessions are served by LTE compared to the case of using fixed step size. This results in a severe overload of the LTE layer and causes the crossing point between variable and fixed step SON algorithms to occur at around 16 sessions/s load level. In case of the LTE LC based SON, the variable step size algorithm protects the LTE macro and micro layers and at highest load levels pushes too many sessions, around 60 % or more, to be served by WLAN and congesting the WLAN system at around 14 sessions/s.

The crossing point for LTE LC occurs earlier (in load domain) compared to the WLAN LC because the WLAN capacity is lower and is therefore reached sooner.

6.3 Monitored KPI comparison

In this section, the performance of WLAN and IRAT load control SON functions is compared for the cases of using the RU or CSR load measures as the monitoring KPI.

Figure 10 shows the obtained user session throughput results as a function of different session arrival rates and for the selected SON load control functions and monitoring KPIs. The results for the WLAN LC with CSR load measure (fixed or variable step size) are the same as presented in the previous section.

First of all, it is worth highlighting that, in general, the 10th percentile session throughput performance is much more impacted by the choice of the SON load control function, load measure and control parameter used, compared to the average session throughput performance. Comparing the IRAT LC SON functions using different load measures shows that using CSR as the load measure for both RATs results in the best 10th percentile session throughput for the widest range of user arrival rates. A second conclusion is that, in general, the use of the CSR load measures improves the performance of all SON functions when compared to the use of RU load measure, with the only notable exception of the WLAN LC with fixed step size. This is because an RU measure is much more suited as WLAN radio air-interface load measure (non-scheduled, best effort) when no additional

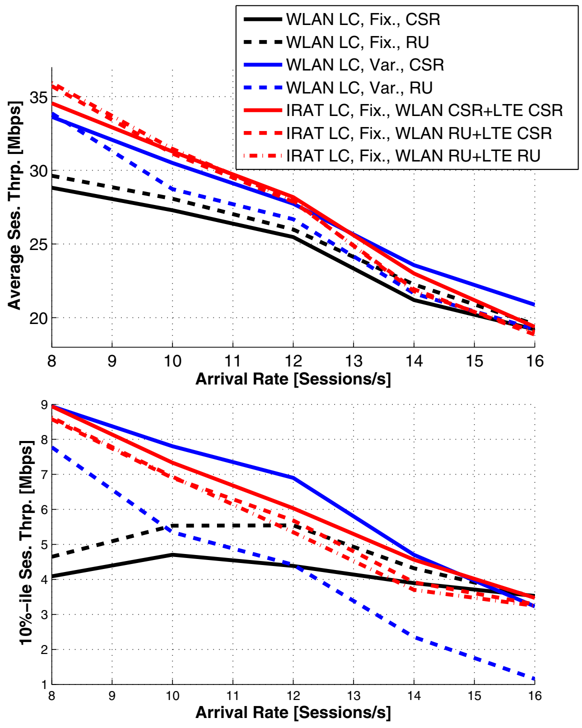

Fig. 10 User session throughputs for different session arrival rates with CSR and RU monitoring KPIs for selected load control SON functions

mechanism is used to protect the WLAN cell from operating in over-load regime, such as the variable step size algorithm.

6.4 LTE load control policy analysis

As described in Section 3.3 and presented in Table 1, there are multiple alternatives to perform LTE macro and LTE micro traffic steering towards WLAN.

In Fig. 11, three SON functions providing three different levels of LTE macro ANS controllability are shown. The "Micro LC, No Macro offloading" policy, which does not allow for the steering of LTE macro users to WLAN, is used as a reference case. The gain in average user session throughput when enabling macro offloading, by deploying Micro LC and relaying the control parameters (threshold values) over the X2 interface ("Micro LC"), increases with increasing load levels and can be as high as 30 %. Nevertheless, the gain in the 10th percentile is negligible; the observed variations with respect to "Micro LC, No Macro offloading" are mainly due to the different layers determining the overall 10th percentile performance: micro LTE cells in low load and WLAN APs in high load conditions.

Alternatively, the introduction of a separate LTE macro and LTE micro ANS controllability, by deploying both Macro LC and Micro LC ("LTE LC"), provides improvement in the 10th percentile session throughput; up to 30 % at high load levels. In terms of average session throughput, performance of the LTE LC SON slightly surpasses the case where there is no separate macro controllability, although only at higher load levels. One can also note that the percentage of user sessions on WLAN is quite similar regardless of the SON LC policy used.

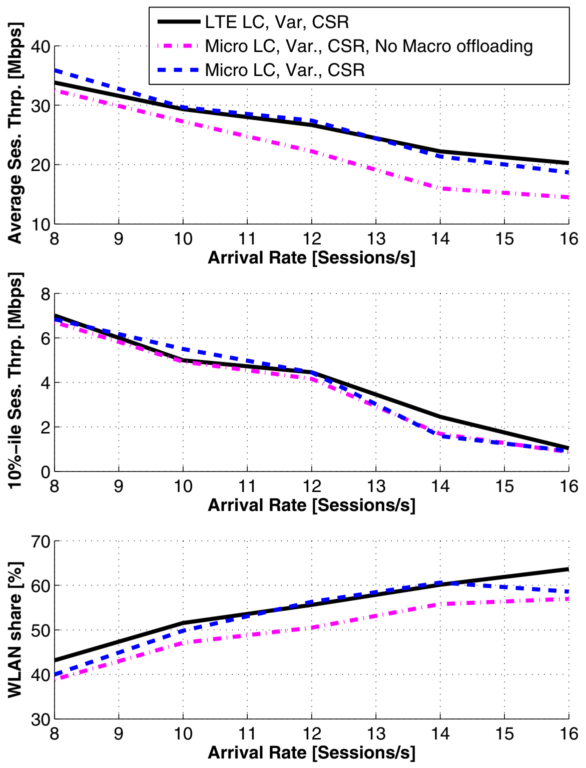

Fig. 11 User session throughputs and fraction of WLAN sessions for different session arrival rates with different alternatives for LTE macro cell offloading

These results indicate that employing a more complex scheme with separate control over micro and macro UE steering to WLAN ('LTE LC') brings slight performance improvements compared to the load control policy where only the micro cell load is used as input KPI ("Micro LC"). This conclusion can be generalized to any dense network deployment scenario where most of the traffic load is in the coverage area of the LTE micro cells.

6.5 Overall load control policy comparison

In order to evaluate the benefit of exchanging WLAN load information between LTE and WLAN systems via a network interface, in this section, we compare the single-RAT LC SON functions' performance, for the schemes identified in previous sections to perform best {LTE LC, WLAN LC} with variable step size design, with the IRAT LC SON function's performance. All these SON functions use the CSR load measure as monitoring KPI. The user session throughput results are summarized in Fig. 12.

The first observation is that significant gains, between 30 % and 200 %, in 10th percentile session throughputs are achieved for IRAT LC compared to the case with LTE LC. A modest performance improvement is also visible

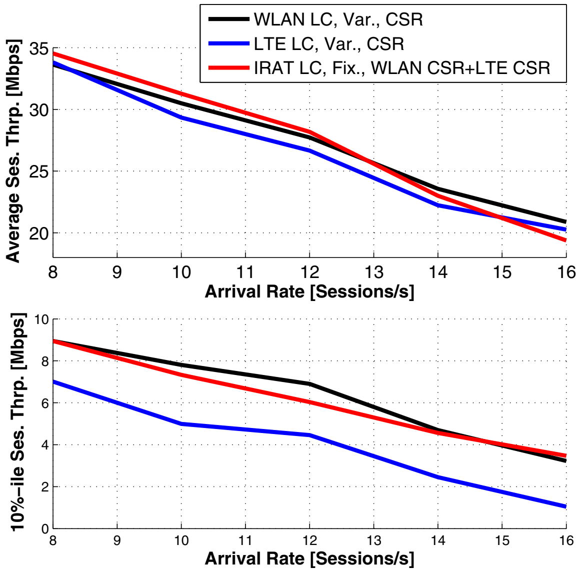

Fig. 12 User session throughputs at different session arrival rates, with and without information exchange between LTE and WLAN

in the average session throughputs, in most of the simulated session arrival rates. Based on the results from the Section 6.4, the conclusion of this comparison remains the same when the Micro LC with Macro offloading SON is used instead of the LTE LC SON. The WLAN LC SON performance is very close to the performance of IRAT LC SON and in certain load conditions it can even improve the average user session throughput by up to 20 %.

The analysis in Section 6.3 has highlighted the benefits of using the CSR load measure as the monitored KPI in the SON algorithms. The Reference Throughput value (Section 3.4) is an important parameter in the CSR calculation. For the results presented in the previous sections the reference throughput was always set to 12 Mbps, as was indicated in Table 2. The sensitivity of the SON algorithms' performance when varying the reference throughput from 1 to 50 Mbps is studied next.

Figure 13 shows the user session throughput results for the same three LC policies and a fixed arrival rate of 14 sessions/s . It can be observed that the WLAN LC SON shows the largest sensitivity to the reference throughput value and experiences large degradation for reference throughput values below 5 Mbps and above 30 Mbps. The LTE LC SON shows a large degradation only when reference throughput values are below 5 Mbps. These settings of the reference throughout value lead to either a too high or too low number of UEs steered to WLAN and therefore a suboptimal usage of the available network capacity.

On the contrary, the IRAT LC SON performance was found to be less sensitive to the setting of the reference throughput parameter and generally outperforms both WLAN LC and LTE LC SON. We have also analyzed the performance of the IRAT LC SON for other load levels between 8 and 16 sessions/s while sweeping the reference throughput parameter value. This is because the cell load levels of both the LTE micro cells and the WLAN APs are affected in similar fashion by the value of the reference throughput parameter; hence, the overall system resources are better utlized without over/under loading the cells.

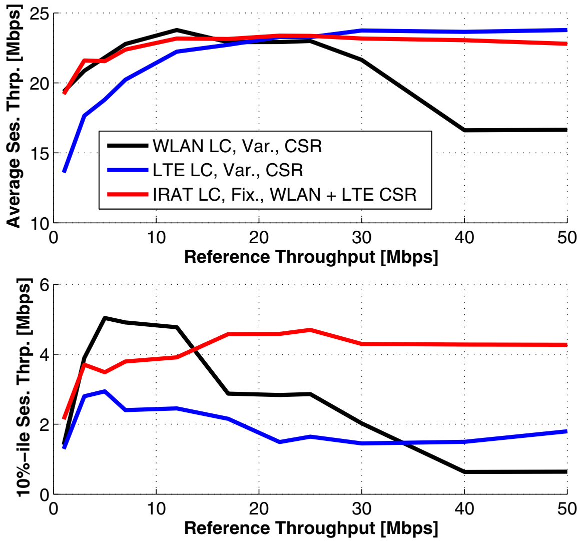

Fig. 13 User session throughputs and WLAN session rate of the three proposed load control policies when varying the CSR Reference Throughput parameter

These results show that, due to the large impact on the overal SON algorithm's performance, the value of the reference throughput has to be chosen carefully when utilizing either LTE LC and WLAN LC SON. Such optimization is rather challenging in practical deployments where the overall cell layout and radio charactersitics have to be factored in and possibly evaluated. On the other hand, the more stable performance property of the IRAT LC SON versus the reference throughput parameter value represents a unique advantage in real scenarios. Nevertheless, even for IRAT LC SON one can observe some perfomance variation and an optimal range of values for the reference throughput parameter. Our results indicate that any value above 20 Mbps would perform close to optimally and in all load scenarios.

7 Conclusions

The optimization of access network selection (ANS) between cellular and WLAN systems is challenging due to the ever increasing complexity of heterogeneous radio networks. In this study, we apply the SON approach to automate and optimize ANS between LTE and WLAN. A user selects the access network based on ANS rules and related RSRP/RSS thresholds that the SON scheme adjusts dynamically per cell, aiming at single-system prioritization and congestion control or inter-system balanced performance. We evaluated the proposed ANS SON schemes with system level simulations in a realistic dense urban scenario, comprising LTE macros and co-located LTE micros/WLAN APs. The results show that the adoption of SON provides remarkable gains compared to the simple baseline of "WLAN if coverage" which results in WLAN congestion. Any proposed SON algorithm yields to a more balanced loading across the layers/systems and thus improves the QoS of end users.

The SON design employing variable step size of the ANS threshold outperforms fixed step size design yielding gains in the 10th percentile user throughput of up to 100 %. Particularly, the WLAN LC SON achieves similar performance as the IRAT LC SON, which relies on and benefits from inter-system load information exchange. However, the WLAN LC SON does not appear as a viable solution in practise due to the limited support from industry standards and the large sensitivity to scenario and configuration parameters that neutralize the SON benefits.

We have demonstrated also that, while both schemes are supported by the recent developments of the 3GPP standard, the IRAT LC SON achieves significant gains compared to the LTE LC SON, particularly in terms of 10th percentile user throughput, yet assuming a reasonable amount of signaling between networks and UEs.

One further observation is that even in the investigated deployment scenario where LTE micro cells and Wi-Fi APs are co-located, the capability to offload the LTE macro layer to WLAN results in performance benefits as compared to limit the offloading to the LTE micro layer only.

At least three aspects are considered beneficial as future work: first, the extension of the promising SON design with variable step size to be applicable to the IRAT LC SON; second, the design of QoS-based triggers for tuning the network selection control parameters; furthermore, automatic traffic steering, which may steer ongoing connections between the LTE and WLAN systems.

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Competing interests
The authors declare that they have no competing interests.

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