SWN: An SDN Based Framework for Carrier Grade Wi-Fi Networks

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Abstract: With the rapid growth of mobile data traffic and vast traffic offloaded from cellular network, Wi-Fi has been considered as an essential component to cope with the tremendous growth of mobile data traffic. Although operators have deployed a lot of carrier grade Wi-Fi networks, but there are still a multitude of arrears for nowadays Wi-Fi networks, such as supporting seamless handover between APs, automatic network access and unified authentication, etc. In this paper, we propose an SDN based carrier grade Wi-Fi network framework, namely SWN. The key conceptual contribution of SWN is a principled refactoring of Wi-Fi networks into control and data planes. The control plane has a centralized global view of the whole network, can perceive the underlying network state by network situation awareness (NAS) technique, and bundles the perceived information and network management operations into northbound Application Programming Interface (API) for upper applications. In the data plane, we construct software access point (SAP) to abstract the connection between user equipment (UE) and access point (AP). Network operators can design network applications by utilizing these APIs and the SAP abstraction to configure and manage the whole network, which makes carrier grade Wi-Fi networks more flexible, user-friendly, and scalable.

Keywords: SWN; carrier grade Wi-Fi networks; SDN; seamless handover; load balancing; Hotspot 2.0; traffic offloading

I. INTRODUCTION

In recent years, the rising number of mobile devices lead to an explosive growth of mobile data traffic. The Cisco Visual Networking Index (VNI) reports that global mobile devices in 2014 grew to 7.4 billion, up from 6.9 billion in 2013 and global mobile data traffic reached 2.5 exabytes per month at the end of 2014, up from 1.5 exabytes per month at the end of 2013 [1]. What's more, with the growth of the mobile data traffic, more and more traffic are offloaded from cellular networks. According to the Cisco VNI, in 2014, 2.2 exabytes of mobile data traffic were offloaded onto the fixed network each month, and there will be more traffic offloaded on to Wi-Fi than remains on cellular networks by 2016 [1]. In order to accommodate the explosive growth of mobile data, operators have deployed large-scale network infrastructures to provide users with a variety of network services, among which Wi-Fi networks play an important role [2].

As more and more mobile devices are Wi-Fi enabled, the number of public hotspots expands, and user acceptance grows, Wi-Fi has been considered the most economical and promising technic that helps operators cope with the tremendous growth of mobile data traffic, especially in high-density areas. Mobile operators have viewed the prospect of taking Wi-Fi networks as an extension of their mobile business rather than just as an extension of their fixed broadband business. Therefore, they have begun to deploy carrier grade Wi-Fi networks in some highly concentrated areas where large numbers of people congregate, coexisting with their other networks. However, the current carrier grade Wi-Fi networks have a number of usability problems that can frustrate users. First, in an area where mobile devices are within the radio range of multiple Wi-Fi networks, users must launch the device's connection manager, go through a long list of SSID and select the corresponding SSID to connect. Second, after association to a hotspot, users should launch a browser to enter their user ID and password as credentials which are time-limited, network connection will be lost when the time runs out. Third, those Wi-Fi networks are small autonomous systems which are different from operators' other networks such as 3G and LTE (Long Term Evolution), users can not roaming between different Wi-Fi networks which belong to a same operator. These issues have blocked full use of Wi-Fi and have made its use as an adjunct to cellular less than appealing [3]. Functionality must be added to allow automatic network discovery, selection and unified authentication.

On the other hand, in order to provide users with Internet access services, many venues like enterprise, sports stadium, retail shopping mall and other public places have deployed Wi-Fi networks themselves. These Wi-Fi networks don't fall under the common understanding of hotspot, such as coffee shops, homes, and hotels. Their scale is close to the carrier grade Wi-Fi network. And they always consist of large numbers of access points (APs), wireless local access network (WLAN) controllers, management systems, and a set of network services such as authentication, authorization and accounting (AAA), mobility management, load balancing, interference management, quality of service (QoS) guarantee and so on. There are many solutions proposed by different vendors for this kind of large-scale Wi-Fi networks. But most of those solutions are proprietary and closed-source, which greatly limit the flexibility and scalability of network. Once the network construction is completed, the function and performance of the network would be fixed. It is hard for venue owners to add new network services and management applications according to users' increasingly trenchant requirements.

The emergence of SDN proposes a possible solution for carrier grade Wi-Fi networks. SDN allows network administrators to manage network services through abstraction of lower level functionality. This is done by decoupling the system that makes decisions about network management (the control plane) from the underlying systems that forward traffic to the selected destination (the data plane) [4]. By decoupling these two planes, the controller takes a global view of network resource, which leads to possibility of more flexible network management and more effective network awareness. Meanwhile, the 802.11u [5] ratified by IEEE and Hotspot 2.0 [6] specification proposed by the Wi-Fi Alliance (WFA) make it possible for Wi-Fi networks to overcome the existing defects and live up to the next wave of business requirement being asked of it [7]. The 802.11u protocol focuses on enhancing network discovery by adding new information elements to IEEE 802.11 beacon and probe response frames. And the goal of Hotspot 2.0 is to make mobile devices access to WLAN securely and automatically. Hotspot 2.0 leveraged by 802.11u provides mobile devices the ability of automatic Wi-Fi network discover, streamlined network access and secure authentication. This could help end users roam across Wi-Fi networks seamlessly with a consistent credential, which means Wi-Fi networks are as easy and as secure as cellular networks. Therefore, through the combination of SDN and Hotspot 2.0, an ideal carrier grade Wi-Fi network framework could be achieved. To be specific, SDN could help simplify unified management and ensure consistently high performance of critical business application in WLAN. Automatic network selection and access, roaming and secure authentication could be achieved by introducing Hotspot 2.0.

In order to better describe how to construct an ideal carrier grade Wi-Fi network using SDN and Hotspot 2.0. In this paper, we propose an innovative carrier grade Wi-Fi network framework named SWN. In this framework, we use the idea of separating the data plane and control plane to refactor the Wi-Fi networks [8]. The control plane has a global view of the whole network and could provide northbound APIs for upper network applications. Considering there will be large amount of control requests sent to the controller, which would put tremendous pressure on controller, in the data plane, we construct agents on the APs to release the management pressure of controller. Each AP runs an agent, and the agent can handle some control tasks which are just related with local network. We construct SAP to abstract the connection between AP and UE, which makes the connection between them controllable. With the SAP abstraction, we design seamless handover and load balancing as two network management applications on the controller. Besides, to support automatic access, unified authentication, and traffic offloading with cellular networks, we connect the control plane and data plane of SAWN with LTE EPC (Evolved Package Core) respectively. We also propose an adaptive traffic offloading application based on a biologically inspired attractor selection model.

The remainder of this paper is organized as follows. Section II presents some related research about SDN based WLAN and integration of WLAN with cellular networks. Section III outlines the proposed SWN framework in detail, including SAP abstraction, the control plane, the data plane and the network situation awareness scheme. Section IV gives the example network management applications and use cases that can be developed by leveraging the advantages of SWN. Implementation issues and challenges are discussed in Section V. Section VI shows the evaluation results of the seamless handover application and analyzes its benefit. Finally, Section VII concludes the paper.

II. Related Work

Many researchers have worked on introducing SDN into WLAN. OpenRoads [9] is an early attempt to develop an SDN based wireless platform with OpenFlow by Stanford University. By separating the control plane from the data plane, it can create multiple network slices by the wireless network' SSID. Currently, their platform is used as a testbed for network experiments, different experiments can be assigned to different slices. Vestin J *et al.* proposes CloudMAC [10], an architecture for enterprise or carrier grade WLAN system, which partially offload the MAC layer processing to cloud services, to reduce the complexity of management and configuration. ZHAO Dong *et al*. [11] takes advantages of SDN and OpenFlow to mitigate interference in enterprise WLAN. These two schemes just use SDN to address a particular aspect problem. Ref. [12] presents a system called Chandelle that shows the benefits of having WLAN networks on top of SDN/OpenFlow infrastructure: fast and smooth migration procedure and cost reduction of wireless APs. In Ref. [13], Suresh L *et al*. presents Odin which adopts the SDN concept to redesign the traditional enterprise WLAN architecture in layer 2 and layer 3. These two architectures can realize mobility management in WLAN, but lack of support for roaming and can't interworking with cellular networks.

As for the integration of WLAN and cellular network, [14] explores the advances of the WLAN as an integrated solution using a network-based mobility protocol. This architecture option, also known as *S2a* by its 3rd Generation Partnership Project (3GPP) reference point name, is gaining more interest due to its low impact on UEs. But it lacks the management of WLAN. In Ref. [15][16], the authors

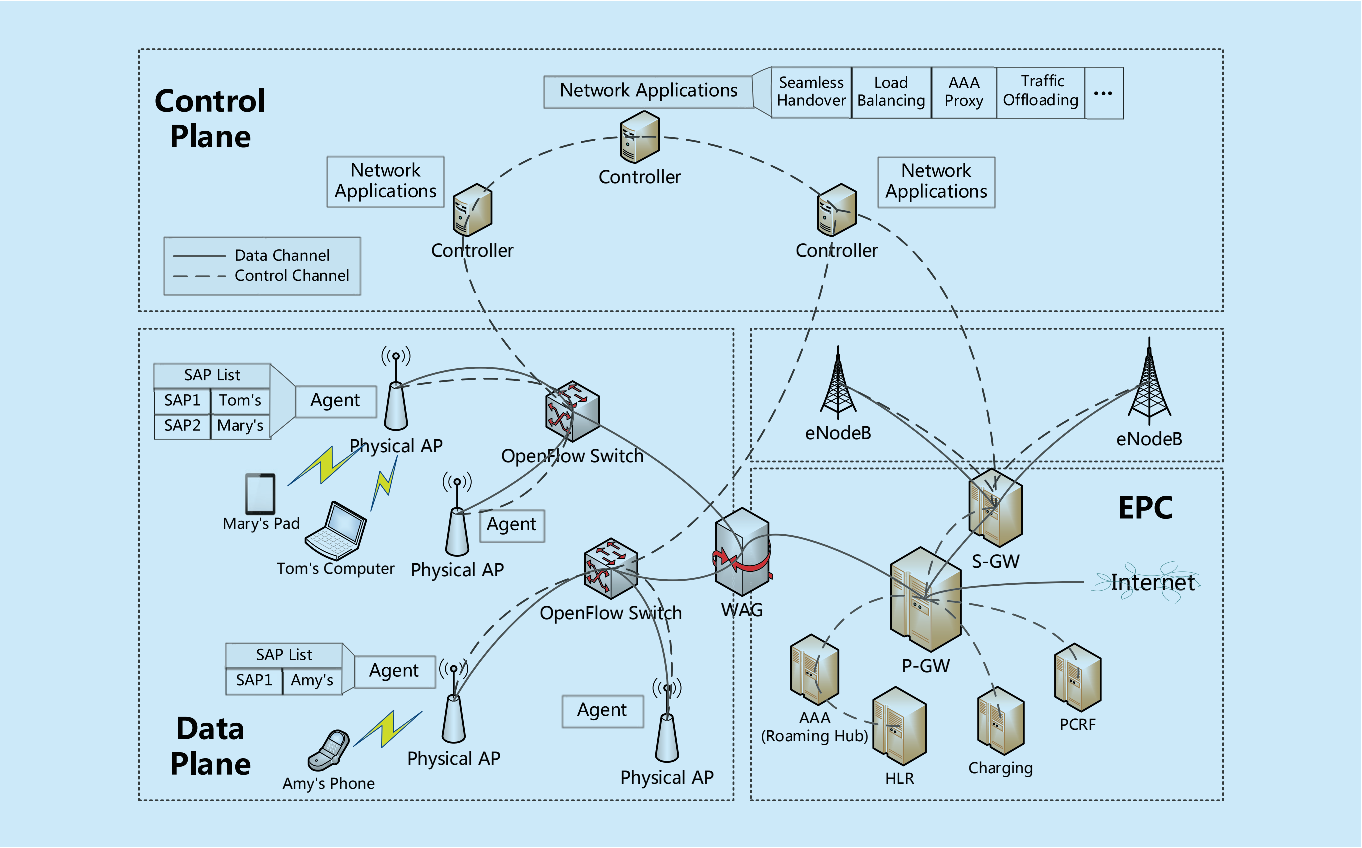

Fig.1 *The framework of SWN*

introduce a network architecture where small cells use the same unlicensed spectrum that Wi-Fi systems operate in without affecting the performance of Wi-Fi systems. They focus on increasing the capacity of cellular networks and interference avoidance other than actual network convergence.

In Ref. [17], Manu Bansal *et al*. presents OpenRadio, a programmable wireless data-plane that provides modular and declarative programming interfaces across the entire wireless stack. By OpenRadio, an operator can expresses decision plane rules and corresponding processing plane action graphs to assemble a protocol. This method can be applied to develop flexible and scalable programmable dataplane of SDN based wireless network, but does not consider the management scheme of the whole network.

III. The Framework of SWN

In this section, we introduce the proposed SWN framework. As Figure 1 shows, SWN framework mainly consists of the control plane, Wi-Fi access networks which also known as the data plane. Since the SAP abstraction is the key technology in SWN, we first introduce it, then present the network situation awareness technology introduced into the proposed framework at the end of this section.

3.1 SAP abstraction

In the traditional IEEE 802.11 standard [18], UE makes the AP association decisions according to user's operation. WLAN infrastructure has no control over these decisions. Users establishes a connection between UE and an AP involving a series of handshakes which are related to layer 2 and layer 3 processes. In this case, if a UE moves from one basic service area (BSA) to another, there is no mechanism to ensure continuity of service [13]. The UE is expected to send a disassociation frame to the previous AP and repeat the association handshakes with a new AP. The interruption of service caused by multi-layer handoff would harm the quality of experience (QoE) severely.

Considering the fact that a UE's association state is defined by the mac address of the UE's wireless card and the mac address of the AP, both of which are physical devices, and only one is mobile. The physical AP which the UE is connecting to can't follow the UE's movement to provide continuous services. Thus, we construct SAP to abstract the connection between UE and AP. The SAP contains the status information of layer 2 and layer 3 which is needed to establish a connection between UE and AP. More specifically, an SAP is consist of UE's MAC address, UE's IP address, SAP BSSID, SAP SSID and a set of OpenFlow flow tables. Each UE has a unique SAP to connect to. From the UE's perspective, an SAP is a general 802.11 AP that handles the regular 802.11 association handshakes with the UE. Each physical AP can host multiple SAPs, so each physical AP can support multiple users to access. In order to distinguish different SAP, each SAP has a unique BSSID. The concept of SAP abstract the connection status between UE and AP, thus giving controller the ability to control their connection status according to corresponding network management demands. Just like virtual machines in data center can be migrated between different physical servers, SAPs can migrate between different physical APs. Migrating a UE's SAP from a physical AP to its adjacent physical AP according to the UE's moving direction achieves the effect of handing off without the UE performing re-association procedure, generating additional layer 2 and layer 3 messages. If this migration is fast enough, the UE can always see the same consistent SAP regardless of the range of physical AP the UE is connecting to. This is because once a UE is associated with an AP, the only protocol level requirement to maintain the wireless link is that the UE receives ACK frames from the AP for the data frames that it sends, and the UE receives beacons periodically from the AP. The migration of SAP can be leveraged by upper layer network applications to implement a variety of network management policies.

3.2 The control plane

The control plane is comprised of SWN controller and network management applications. The SWN controller has a global view of the whole network, and bind operations into northbound APIs for upper applications. Applications running on the top of SWN controller could call these APIs to realize varieties of network management functions.

SWN controller is a SDN controller which has additional function modules for supporting 802.11 MAC layer processing. It uses the southbound protocol to acquire network status and statistics information and binds those information with operations into northbound APIs for upper layer applications. Network applications execute as a thread on the SWN controller, which are easy to design and modify. Especially, controller is expected to receive heartbeat messages from agents in a fixed interval, which is used as a keep-live mechanism. The SWN controller holds a configuration database with two tables. One records all the agents in the network. When the controller receives a heartbeat message, it will check the agent table to see if there is an existing record corresponding to the agent that sends the heartbeat message. If it is, this indicates that the agents physical AP is in the normal

Table I *Required information for sufficient NSA*

Perception	Comprehension	Projection
-Agent table	-Physical AP state	-Network capabilities
-UE table	-Operation status of underlying physical devices	-Future network performance
-SAP identification	-Connected users (Tom, Mary, Amy, etc.)	-Load condition
-RSSI	-Mobility of UEs	-Direction of movement
-Bit-rate and noise	-Link state	-Future link state
-Location	-Available actions	-Handover, Load balancing, etc.
-Network parameters (Delay, delay jitter, packet loss rate, etc.)	-Network overall performance	-Future network state
-Network topology	-Routing information	-Traffic conditions
-Others...	-Others...	-Others...

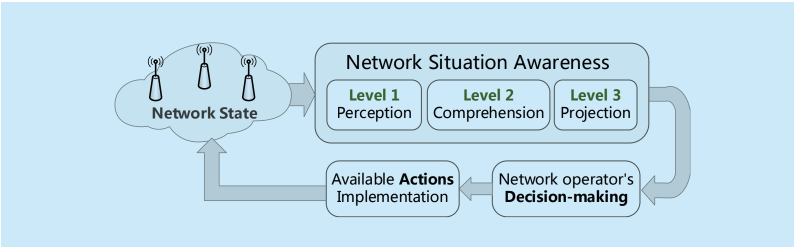

Fig.2 *The process of network situation awareness*

state. If not, the physical AP may be a newly added AP, and the controller will register this physical AP's agent into the agent table. The controller will delete the agent from the agent table when the controller does not receive its heartbeat message in the certain interval.

The other table is UE table. This table contains UEs' SAP and some related information such as the agent which is hosting the SAP. If a UE accesses to the network for the first time and has been authenticated from the remote AAA server, the controller would create an SAP for this UE and write it into the UE table. This table will periodically update UEs' information according to the network status. When an UE accesses to the network for the second time, the controller will find this UE's SAP in the UE table. If it exist, the controller will deliver it to the corresponding physical AP according the strategy of upper network application. If it doesn't exist, the UE is supposed to conduct authentication process again.

Network applications can realize a user-level management by modifying the state of the UE table or by deciding whether to create an SAP for a UE according to a specific control logic. And network-level management can be achieved by dynamically adjusting parameters in the agent table. Network applications can be proactive mode or reactive mode. Proactive applications can use publish-subscribe mechanism to acquire needed information and handle events. The latter mode means the applications periodically react based on inputs from different measurement sources, which is also important due to the dynamic nature of the channel.

3.3 The data plane

The data plane is composed of physical APs with agents running on it, OpenFlow switches, and Wireless Access Gateway (WAG).

The physical APs in the SWN framework are fit APs. They can send and receive 802.11 MAC frames but do not generate all these frames themselves. Only the lower MAC control frames which have real-time constraints are generated by the physical APs. Management frames are generated by the SWN agents.

The purpose of constructing SWN agent is to reduce the controller's processing pressure. SWN agents run on the top of physical APs and can handle some local control logical. Each agent carries the corresponding SAPs of UEs that are connecting with this physical AP. As shown in Figure 5, the agents together with SWN controller implement a Wi-Fi split-MAC logic [19], where the Wi-Fi MAC layer logic is divided into controller and agents. If an agent receives an 802.11 management frame, it will check whether an SAP is already hosted for the UE which sent the management frame. If it is, the agent will reply the UE with corresponding 802.11 frame. Otherwise, the agent will forward this management frame to the controller and the controller checks the UE table to determine the following operations. The agents can obtain all frames that the physical APs receive including both management and data frames. Thus, the agents can collect radio specific information of each frame such as per-frame received signal strength (RSSI), bit-rate and the noise and submit those statistics information to the controller actively. Then the controller issue control commands to the agents to implement corresponding network management function.

OpenFlow switch in the data plane is a switch supporting OpenFlow protocol. It contains flow tables which specific the routing policy. Applications running on the top of controller could configure the flow tables using the OpenFlow protocol.

WAG is a gateway between Wi-Fi networks and LTE EPC. It is connected directly with the Packet Gateway (P-GW) through a secure tunnel, which forwards data packets from the Wi-Fi networks. Wi-Fi authentication frames are sent to AAA server for unified authentication. It can also acts as a dynamic host configuration protocol (DHCP) sever to assign IPs automatically to devices which are trying to connect to the network.

3.4 Network situation awareness

In order to achieve flexible and unified control logic, the SDN controller needs a precise perception of the global network states including underlying physical devices information, network behaviors, and user behaviors, etc. Therefore, we introduce network situation awareness (NSA) into SWN to guarantee the SDN controller's global awareness of the whole underlying network.

NSA is about the perception of network state and to quantify the network situation by using appropriate assessment algorithms, then make projection of the future network state based on the perceived information, and finally present the results to network operators in a friendly way. As shown in Figure 2, NSA can be divided into three levels: (1) perception, (2) comprehension, and (3) projection [20]. When it comes to do NSA in SWN, the meanings of each level can be summarized as below.

- **Level 1 Perception**

The goal of this level is to acquire the information related to the operation of SWN network. Those information mainly consist of three kinds: (1) Underlying physical devices information, including each physical AP's MAC address, hosted SAPs of each physical AP and radio specific information received by physical APs such as RSSI, bit-rate and the noise, etc. (2) User behaviors, such as access request, UE's association status and real-time location information, etc. (3) Network behaviors, such as handoff managements (e.g., handoff decision, handoff initiate and handoff execution), the SAP allocation policy, the configured various control decisions and so on. This level can be implemented through the southbound protocol.

- **Level 2 Comprehension**

This step is to understand what the perceived data means to network operator's goals and objectives, which is based on the synthesis of disjointed Level 1 elements [21]. And researches on this layer mainly consist of knowledge representation and network situation assessment method. Knowledge representation focuses on the representation of uncertain information and every network component. Network situation assessment refers to use some mathematical models to make reasonable explanations of network's current state based on the information perceived in Level 1.

As mentioned before, network operators can implement kinds of network managements through programming in SWN, such as load balancing, flow scheduling, etc. The basic premise of those managements are the comprehension of network state. For example, controller can comprehend the change of one UE's RSSI which follows some kind of trend as the movement of user's location, then make the corresponding operations according to the predicted movement direction executed in the level 3.

- **Level 3 Projection**

As the highest level of NSA [20], this level is to predict the future behavior (or state) of SWN components based on their current state derived in Level 2 and historical data collected in Level 1. For example, the controller should be able to predict the load condition of near future based on that of current state and perceived historical information such as the number of connected users, etc.

Table I shows the information required in each NSA level to achieve a sufficient NSA in SWN. The comprehension and projection results are supposed to be provided to upper network applications through the northbound APIs. Network operators can develop a variety of control strategies to make decisions on some important network management issues according to these information, which contributes to the optimization of network performance and prevention of abnormal undesirable conditions. At last, the upper applications can

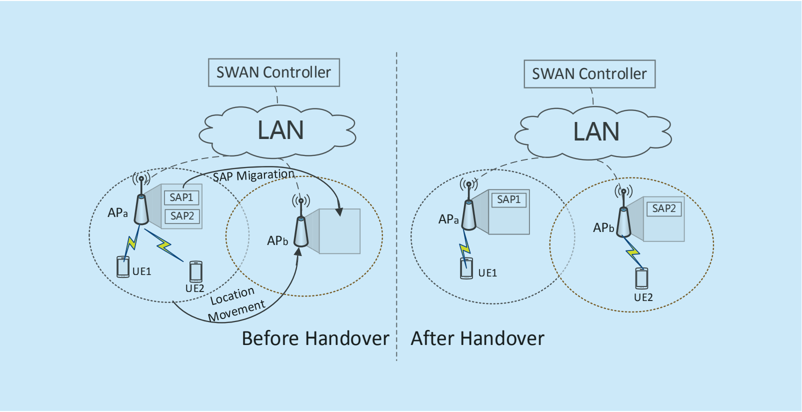

Fig.3 *The seamless handover process*

issue those control commands to the agents through southbound protocol, which makes the available actions eventually implemented on the network and finally forms a control loop.

IV. SWN Applications and Use Cases

In this section, we present four network management applications to demonstrate the advantages of having a logical centralized controller plane and using the SAP abstraction.

4.1 Seamless handover

As mentioned above, SAP abstraction makes the connection status between UEs and AP controllable. An SAP's migration does not affect the 802.11 state machine at the UE. This is because the UE only cares the responses and acknowledge frames sent out from an AP which is identified by BSSID in SWN. If the SAP migrates as fast as the corresponding UE's movement, then the UE can always see the same consistent SAP regardless of the range of physical AP the UE is connecting to. Therefore, the connection between them will not break off. This property can be utilized to implement seamless handover by designing appropriate application. The key issue to achieve this goal is how the controller perceives the mobility of UEs. In SWN, we compare the UE's Received Signal Strength Indicators (RSSIs) received at all agents, which can hear it, with a threshold to detect the UE's mobility. The application can use publish-subscribe mechanism to acquire each RSSI value that agents receive from the same UE and compare those RSSIs with a configured threshold. If there is a RSSI greater than the threshold and the corresponding agent is not the one which the UE is connecting to, this means the UE has moved and the application will inform the controller to invoke a handler. The controller will move the UE's SAP from the source physical AP to which the UE is connecting to the destination physical AP that receives the strongest RSSI. The threshold value should depends on the actual deployment situation of physical APs in order to prevent ping-pong effect [22].

Figure 3 shows a seamless handover process. In this scenario, there are two physical APs, where AP_a initially serves two UEs while AP_b initially serves none. If UE2 moves from AP_a's BSA to AP_b's, the controller will obtain stronger RSSI compared with the configured threshold from AP_b which means that it has detected its movement. Then the controller will move UE2's SAP from AP_a to AP_b, which makes UE2 seamless handover from AP_a to AP_b. The actual effect is that UE2's SAP follows UE2's movement to provide UE2 with continuous services.

4.2 Load balancing

Load balancing in carrier grade Wi-Fi networks can increase the overall throughput of the network and improve the airtime fairness. The SAP abstraction can not only contribute to seamless handover, but also have potential for load balancing. The controller can balance the network's load by dynamically re-assigning UEs to different physical APs. In order to achieve load balancing, both RSSI of each UE and load condition of each physical AP should be taken into account. The load balancing application should request the controller to inspect the real-time traffic load status of per agent and submit this information to the application periodically, it uses this information to build a map of UEs to lists of agents that are candidates for hosting their respective SAPs. The application uses a load balancing algorithm which considers RSSIs each agent collects and traffic load status statistics of each physical AP to make a load redistribution scheme and inform the controller to execute the redistribution scheme.

Figure 4 depicts a scenario in which physical AP AP_a is overload while physical AP AP_b is not serving any UEs. And there are two UEs in the overlapping area of the two APs. In this case, the load balancing application will inform the controller to move these two UEs' SAP from AP_a to AP_b to optimize network load conditions.

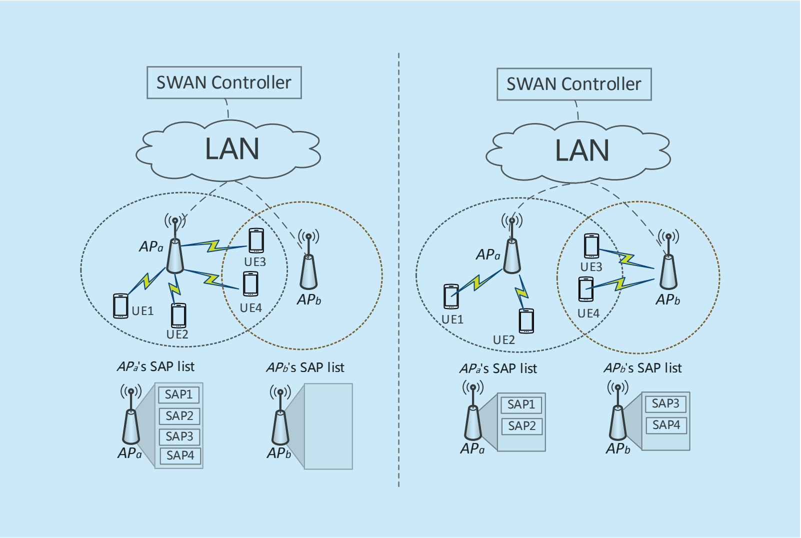

Fig.4 *The load balancing process*

4.3 Automatic access and unified authentication

In SWN, the centralized control architecture of SWN contribute to realize automatic network access and unified authentication. The controller together with agents implements Hotspot 2.0 supported AP. Figure 4 presents the automatic network access procedure which includes automatic Wi-Fi network discovery and selection, unified authentication, and association. The automatic network discovery and selection are leveraged by 802.11u. In traditional 802.11, UEs learn about AP information via beacons and probe response frames. Each beacon or probe response carries information about the AP's capabilities in a component of the frame called an information "element". Naturally, the 802.11u protocol focuses on enhancing network discovery by adding new information elements to these frames. What's more, 802.11u introduces new Public Action frame subtypes, namely Access Network Query Protocol (ANQP), for Generic Advertisement Service (GAS) requests and responses, enabling the mobile device to prompt the AP into action before an association is formed. This is critical for advanced network discovery and automatic network selection capabilities.

For unified authentication, we design an AAA proxy on the controller as the AAA server of the local network that connects to the AAA server in core network of operator. The mobile device acquires the operator domains, roaming consortiums, authentication realms, and EAP type supported by a Wi-Fi network prior to joining. If the network services match the mobile device's security requirement and connectivity policies, it will send 802.1X/EAP authentication requests. These authentication request and response frames are all available to AAA proxy running on the controller, which could be added to the UE table of the configuration database for supporting roaming.

4.4 Traffic offloading

In SWN, Both the control plane and the data plane have connections with the LTE EPC, which could be leveraged to traffic offloading with cellular networks. Based on the SWN framework, we propose a novel traffic offloading application on the controller to offload traffic adaptively in accordance with the dynamic network status by taking advantage of a biologically inspired attractor selection model [23].

We consider an overlay network system model with LTE and WLAN. A LTE eNodeB is located in the center of a cell and several WLAN APs randomly distribute in the overlay area. An UE that enters the overlapping area can choose to access to either the LTE eNodeB or WLAN APs in this area. The traffic offloading application periodically requests the con-

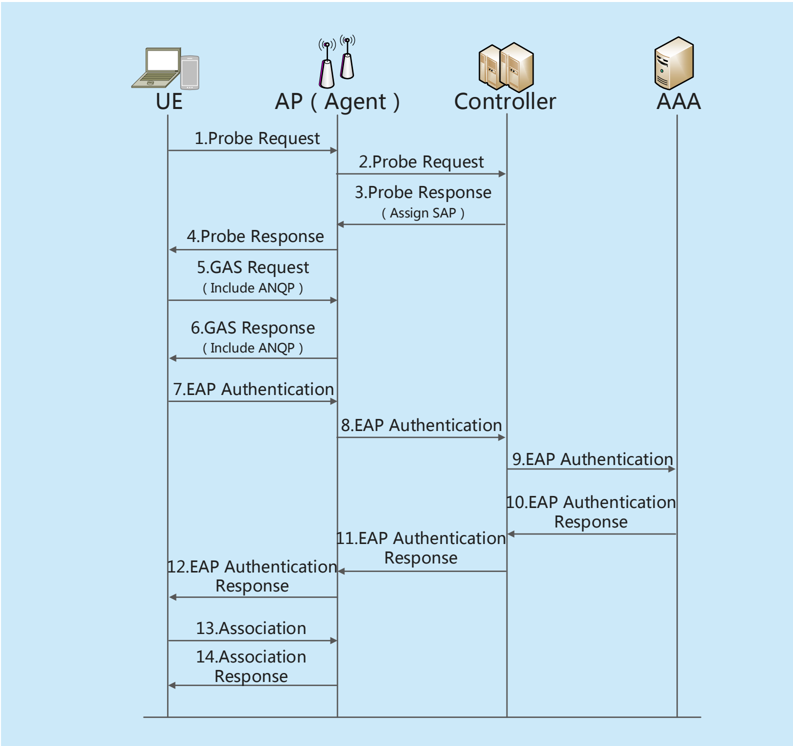

Fig.5 *The automatic network access procedure in SWN framework*

troller to obtain the situation information of all the APs and eNodeBs, such as traffic load status, service type and so on. When a UE requests to access to the LTE network, the traffic offloading application would make use of the attractor selection algorithm to make an appropriate decision based on the real-time status information of the LTE network and WLAN. If the LTE network is able to satisfy the current traffic load, the UE would be allowed to access the LTE network to reduce unnecessary consumption. If not, the traffic offloading application would select a candidate WLAN network for the UE to acquire a better QoS.

Based on the aforementioned scenario, we modify the attractor selection algorithm, redefine the mapping of all the variables as follows:

$$\frac{dm_1}{dt} = \frac{S(\alpha)}{1+m_2^2} - D(\alpha)\times m_1 + \eta_1$$
$$\frac{dm_2}{dt} = \frac{S(\alpha)}{1+m_1^2} - D(\alpha)\times m_2 + \eta_2 \quad (1)$$

and

$$S(\alpha) = \alpha\times(\beta\times\alpha^{\gamma} + \varphi^{*})$$
$$D(\alpha) = \alpha \quad (2)$$

Where $\boldsymbol{m_1}$ stands for the improvement degree of LTE network status, and $\boldsymbol{m_2}$ stands for the degree of improvement of WLAN network status. Parameter α is mapped to the activity of user accessing to the network, which also means the state of user experience. Function $\boldsymbol{S}(\alpha)$ represents the activity promotion rate coefficient, and function $\boldsymbol{D}(\alpha)$ indicates the activity loss rate coefficient, both of which are increasing function of α. Parameters β and γ are factors which influence the stability of attractor and the speed of convergence. In addition, η_i (i = 1 or i = 2) is the Gaussian noise inherent in the whole system, which is independent of the activity α, and φ^* is a constant for the dynamic system to have stable attractors [24].

For convenience, we set

$$\phi(\alpha) = S(\alpha)/D(\alpha) \quad (3)$$

By setting (1) without noise, i.e. $\boldsymbol{dm_i / dt}$ = 0 ($\boldsymbol{i}$ = 1 or $\boldsymbol{i}$ = 2), as **if** $\phi(\alpha) > 2$, one can get the equilibrium $\boldsymbol{m_1} = 1/\boldsymbol{m}^*$ and $\boldsymbol{m_2} = \boldsymbol{m}^*$ or $\boldsymbol{m_2} = 1/\boldsymbol{m}^*$ and $\boldsymbol{m_1} = \boldsymbol{m}^*$, i.e. the model has two attractors, $\boldsymbol{m_1} >> \boldsymbol{m_2}$ and $\boldsymbol{m_1} << \boldsymbol{m_2}$. However, if $\phi(\alpha) \le 2$, the system will get a unstable steady state $\boldsymbol{m_1} = \boldsymbol{m_2}$. In order to make a selection after the system settle out, we set the φ^* as 2.

We now explain how this traffic offloading application accommodates the fluctuating network situation according to the above proposed model. First, if the value of α is large, it means the current access network (CAN) can satisfy the traffic demand. It is unnecessary for UEs to perform handover to the other candidate network, and we keep the CAN to be the suitable selection. In attractor selection model, it represents the system converges to an attractor and the basin becomes deeper so that the force of maintenance of the attractor is strong. If the value of α is small, it means the condition of CAN is poor. Thus, the stochastic noise dominates the system to leave the current basin easily and began random fluctuations. Until fluctuating to a new appropriate attractor, the system becomes stable and the determinant mode controls the system again.

V. Implementation Issues and Challenges

The key characteristics of SWN are the SDN based architecture and the SAP abstraction. Fully realization of the carrier grade WLAN functional components according to the characteristics of SDN framework is the core problem. In this section, we discuss the implementation issues of SWN and the existing challenges.

Northbound API - The foundation of realizing flexible network management by programming and loading multifarious network management applications is the design of northbound API. Just like the REST API of floodlight controller, in SWN, northbound APIs are divided into two types. The first is state-based API which informs network applications of the underlying network state information. As described in section II, controller uses network situation awareness technology to obtain the underlying network state information, comprehend and project future network state based on the perceived information, and encapsulate these information into uniform data format. Network applications can acquire needed information by calling the corresponding APIs. The other type is handler-based API which includes different network management operations. The controller has the network management ability, it encapsulates all kinds of network operations into handler-based APIs. Network management applications can realize different network operation by calling appropriate handler-based APIs. For example, the controller encapsulates the migration of SAP into API. Therefore, seamless handover application can move a UE's SAP to a new physical AP by specifying the corresponding parameters.

Southbound protocol - Southbound protocol is the key functional component of realizing NSA and network management. Controller links with the underlying devices via southbound protocol to obtain information about underlying physical devices, network behaviors and user behaviors, which is the first procedure of NSA. On the other hand, controller use the southbound protocol to execute network management operations. Traditional southbound protocol in SDN is based on OpenFlow which enables remote controllers to determine the path of packets through the switch network. However, OpenFlow does not address the complexities of Wi-Fi protocols and Wi-Fi networks which include mobility management, load balancing and so on. Therefore, in SWN, we adopt two southbound protocols, one of which is OpenFlow, and the other one is our custom protocol. Controller communicates with OpenFlow switches via the OpenFlow protocol to acquire the underlying network information (such as network topology, network devices status) and manage flow tables (such as adding, updating and deleting flow tables) reactively or proactively. The custom protocol is mainly used to manage the SAP and acquire radio specific information. General 802.11 wireless statistics information is submitted to the controller by southbound protocol periodically which is called proactive mode. Particular information is committed to the controller by southbound protocol when a received wireless frame matches a subscription that is set by controller, which is called reactive mode. The controller further process the obtained information, then provide to upper network applications through northbound APIs. Once a network application calls a handler-based northbound API, the controller will use corresponding southbound protocol to issue control instruction.

SWN agent - SWN agent runs on the physical AP, it uses modularization programming method to achieve 802.11 upper MAC layer functions, which include beacon, probe, authentication, and association requests and their corresponding responses. This software-based approach has a high degree of flexibility. The evolution of protocol could be achieved by modifying the software. Besides, agent acts as software proxy of controller, it handles some processing logic such as broadcasting beacon frames, collecting frame statistics information, etc. In our present implementation, the controller uses a TCP-based control channel to invoke commands on the agents and acquire wireless statistics information, which is the realization method of the custom southbound protocol. The agent checks the wireless information on a per-frame basis, comparing it with the subscriptions that have been issued by the controller. If there are some matching frames, the agent then notify the controller, indicating the source address of the frame that triggered the notification and the identifiers of the subscriptions that matches the frame. For instance, a network application can ask the agents to notice whenever a frame is received at an RSSI greater than -60dBm. If an agent receives a frame whose RSSI greater than -60dBm, the agent will notify the controller that a frame was received from a UE which matched the subscription in the subscription list with corresponding information.

After introducing SDN into carrier grade WLAN, the problem of the scale of the network and overhead costs that might be brought by SDN, such as signaling overhead and control delay, are also investigated in this framework.

Scale of the network - The scale that the network can support is related to the type of SDN controller the network employed. For example, the Floodlight controller can support 1023 APs at the same time. To expand the scale of the network, hierarchical control plane is introduced in this framework. The hierarchical control plane is composed of many domain controllers and a global controller. Each domain controller controls the maximum number of APs that it can support. And the global controller controls the information interaction among the domain controllers, which connects these independent domain controllers as a whole control plane.

Signaling and processing overhead - With a global network awareness and management, the controller should perform dynamic network status awareness and network management, which will generate amount of signaling and processing overhead in controller. The hierarchical control plane can also be leveraged to solve this defect, in the hierarchical control architecture, domain controllers and global controller are divided to take charge of handling various tasks respectively. Besides, efficient signaling compression and aggregation schemes could be introduced into the centralized management architecture to reduce the signaling and processing pressure.

Control delay - SDN makes a separation between the control plane and data plane in SWN. The SAP abstraction is accomplished on the data plane while the management and control of SAP is implemented on the control plane. Since the wireless networks are highly time sensitive, the control signaling interaction between control plane and data plane may cause delays. In this framework, we argue that the controller should have a strong processing capacity and the data plane could be realized by X86 based general purpose processor (GPP) devices, which considerably have higher processing capacity.

VI. Evaluation and Results

In this section, we present evaluations to verify the seamless handover application of SWN.

6.1 Experiment environment

We deployed an experimental network of SWN framework. The experimental network consists of 10 Netgear WNDR3800 APs. The operating system of these APs is the OpenWrt "Backfire 10.03.1" release. These APs can be used as an ordinary AP or an SWN based AP according to different configurations. The controller runs on a Lenovo server (ThinkServer RD640), and the seamless handover application runs atop the controller. A laptop running Ubuntu 12.04 system is used as UE.

In order to compare the effect of common 802.11 handoff and our SAP-based handoff on a UE's throughput, we first configure our experimental network as ordinary WLAN. All the APs are set to the same SSID and connected to the same infrastructure. In the evaluation, the UE first connects to an AP and begins an

HTTP download of a large file using the *wget* command. Then, we move the UE from the coverage of its connecting AP to another. We use *tcpdump* to trace the HTTP flow throughout the process, and extract its throughput over one second intervals using *tshark*. The experiment is repeated 10 times to avoid abnormal results. We then set the experimental network to SWN framework based WLAN, and repeat the previous experiment steps. All these experiments are conducted on the 5GHz band which is not as noisy as the 2.4GHz band.

6.2 Experiment results and discussion

Figure 6 shows the throughput over time of a UE in the proposed framework and ordinary WLAN. For the ordinary WLAN, the throughput declines sharply due to the UE's mobility, which indicates that the HTTP download service has a short interruption. For the proposed framework, the throughout cure remains uninterrupted.

The results coincide with the previous analysis. In the ordinary WLAN handover process, a UE is expected to send a disassociation frame to its present AP and execute association handshakes with a new AP, which will lead to interruption of communication. In the proposed framework, SAP-based handoff is performed instead. The UE need not performing a re-association procedure with the new AP generating any additional layer 2 and layer 3 processing messages. Therefore, it can ensure the continuity of network services.

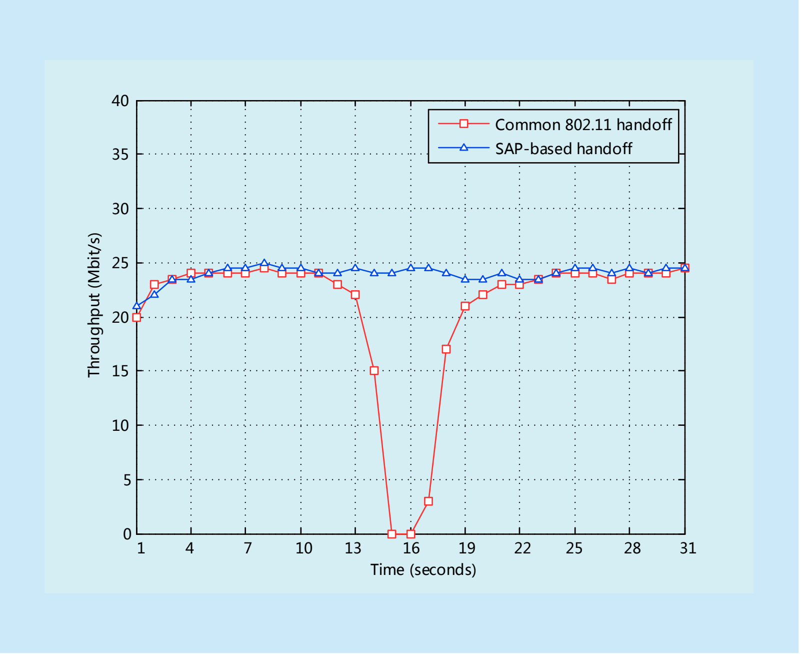

Fig.6 *Effect of common 802.11 handoff and SAP-based handoff on the throughput of HTTP download service*

VII. CONCLUSIONS

We first analyze the importance of carrier grade Wi-Fi networks in the mobile communication networks and the arrears of the current carrier grade Wi-Fi networks. Then we present an SDN based carrier grade Wi-Fi network framework SWN. The architecture of SWN is decoupled into control plane and data plane. We construct SAP to abstract the connection between UE and AP for achieving the connection between them controllable. Operators can configure and manage their Wi-Fi networks by designing network management applications. We present two example network applications that realize seamless handover and load balancing respectively and two use cases that could help achieve the network convergence of Wi-Fi and LTE via automatic network access and unified authentication. Furthermore, we focus on efficient traffic offloading scheme, and proposed a biological attractor selection model based traffic offloading application on our controller.

It remains future work to optimize our seamless handover and load balancing algorithms and design more network management applications.

ACKNOWLEDGEMENTS

This work is supported by the WLAN achievement transformation based on SDN project of Beijing Municipal Commission of Education, the grant number is 201501001.

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