User Centric Wireless Testbed*

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Abstract. We propose a user centric wireless testbed that interprets the user as a key component of the network control and operation. The testbed offers programmable entities in both core and access network edges, enabling researchers to implement cognitive and cooperative decision mechanisms for enhancing the end-to-end service experience. Moreover, a basic implementation of the knowledge plane is provided as a distributed repository on individual network elements, where end user devices can also act data providers. The testbed may serve the need for an experimental research environment for developing and testing such semantic and programmable network approaches that covers both wired and wireless domains.

The proposed testbed has already been utilized for research in various scenarios, where we experiment the effect of considering user experience information as an indicator for network condition and taking smart actions accordingly. Ranging from attack and congestion mitigation in wireless local area networks to real-time inter-operator load balancing, we briefly share our experiences and results from those experiments.

Keywords: user centric, wireless testbed, congestion and attack mitigation, resource sharing.

1 Introduction

Consumers in today's telecommunication networks are faced with an end-to-end value proposal, where the network path traverses multiple organizational and technological domains. Wireless access technologies in many different forms started to take an increasing and critical share in this end-to-end path. Therefore it is essential to study the effects of wireless technologies, in conjunction with core networks, from an end-to-end service quality perspective.

Simulation studies have strong dominance as the means for network protocol analysis, particularly in wireless network research. Unfortunately, simulation tools and models largely depend on simplifying assumptions that significantly limit the accuracy of such studies in real-life scenarios, intensified by the physical-layer aspects of wireless communications [15]. Therefore there is an increasing

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need in the research community for performing controlled real world experiments on dynamically programmable testbeds [17].

For service-oriented next generation networks, new networking approaches are suggested where the network is defined as a collection of resources that need to be allocated consciously, for which the intelligence level of network should be increased. This intelligence can be realized by decision entities embodied in the network fabric that collect data from the network and store in semantic repositories [4]. Our aim is to realize an experimental research environment for developing and testing such semantic and programmable network approaches that covers both wired and wireless domains.

Our testbed aims to offer a set of powerful tools for researchers working in this domain: (i) programmable entities in both core and access network edges that enable the implementation of cognitive cooperative decision mechanisms for enhancing the end-to-end service experience, (ii) a basic implementation of the knowledge plane [1] as a distributed peer-to-peer repository on individual network elements, (iii) resource configuration and traffic generation tools for easy creation of realistic test scenarios.

1.1 State of the Art

There exist several substantive definitions of *testbed* in the literature. Erek et al. define testbed as the "perfectly normal instance of the system that is under study in a particular experiment, which is used for meeting various experimental objectives such as collecting data to be interpreted for obtaining indicative results for the system under test (SUT)" [9]. Considering wireless technologies and protocols as the SUT, one encounters numerous studies in recent years.

ORBIT [17] is an indoor radio grid emulator with 400 nodes designed for controlled experimentation, which also gives the opportunity for the researcher to receive feedback from end-user evaluations. This massive indoor testbed is claimed to be a scalable system in terms of the total number of wireless nodes, reproducible in terms of experiments done, open-access and flexible in terms of high-level of control given to the experimenter, capable of extensive measurements and remotely accessible. Unfortunately, ORBIT provides only "expert" users with the ability to perform tests on the MAC layer experiments by giving them full node access, which constrains protocol experimentation.

Emulab [11] is designed for the emulation of not only arbitrary wired network topologies but also wireless sensor networks. This testbed provides a real mobile wireless sensor testbed by which users can remotely control the robots carrying sensor motes. The main purpose of this testbed is to provide researchers with the ability to evaluate WSN applications under mobility with real wireless LAN.

Many aspects of centralized WLAN systems are claimed to be poorly understood in the sense of wired delay and jitter properties, therefore Ahmed et al. describe a large-scale wireless LAN testbed for centralized control, in order to issue centralized control algorithms [3]. This testbed is mainly intended for the researchers who are interested in experimenting centralized control for traffic scheduling and data rate adaptation. Doing experiments on the proposed testbed, Nabeel et al. try to confirm the requirements for a centralized control based on the assertion that central control is necessary to support network optimizations such as centralized packet scheduling [5].

WART (University of Colorado Wide-Area Radio Testbed) is a well known example of outdoor wireless LAN testbeds, which is designed as a facility for studying smart antennas over a significant area [6]. This testbed consists of eight phased array antenna nodes that are mounted to the rooftops of the university and is dedicated for studying the impact of omni-directionality, directionality, null-steering and beam-forming throughout the network stack. In Comparison to WART, Roofnet [2] is a primitive example deployed on Cambridge, which also provides Internet access as a multi-hop mesh network. Roofnet is not a dedicated testbed, which in turn limits the ability of researchers working on this testbed. In addition to these two famous testbeds, RuralNet [16] can also be given as another example of outdoor wireless testbed, which is designed for experimenting on very long range point to point communication.

Some of the wireless LAN testbeds are offered for special purposes. Caltech multi-vehicle wireless testbed [8] is a good example as a platform for testing decentralized control methodologies for multiple vehicle coordination and formation stabilizations. Moreover some testbeds proposed in the literature aim at receiving direct feedback from actual users. For example, Exoticus suggests an IMS (IP Multimedia Subsystem) experimentation testbed experimenting innovative services that will be designed and developed by a composition mechanism with actual users [10]. In another study, Reality Mining, a project at the MIT Media lab, researchers collected data from 100 Nokia Symbian series mobile phones over a period of 9 months in order to understand the social networks (in order to understand human social behavior). It can be inferred from these studies that the new trend in network research is to work with end users and improve mainly Quality of Service (QoS) of the network in cooperation with network users.

1.2 Beyond State of the Art

Several wireless network testbeds provide frameworks for experimenting with specific network technologies and network entities with hardware / software limitations. However, we believe that the end user whom the network must serve should cooperate with the core decision elements inside the network for the realization of reliable end-to-end service quality. In this study, we propose a joint wired and wireless research testbed where clients are proposed to be the core element of the network, and the network entities provide interfaces for programming and storage capabilities. Our intention is to provide a driving force and an experimentation environment for utilizing distributed artificial intelligence (DAI) techniques in the Future Internet research, with a focus on user centricity. Additional tools like traffic generators and malicious client emulators complement the testbed architecture for easy deployment and testing of realistic scenarios.

2 Testbed Architecture

In developing our testbed, our aim was to allow the researches test innovations on wired and wireless nodes jointly over a a variety of realistic topologies. Our guiding assumption has been that end-to-end principle will be gradually replaced by more intelligent nodes on the service delivery path. This is reflected in our choice of using configurable nodes on each level of the network hierarchy.

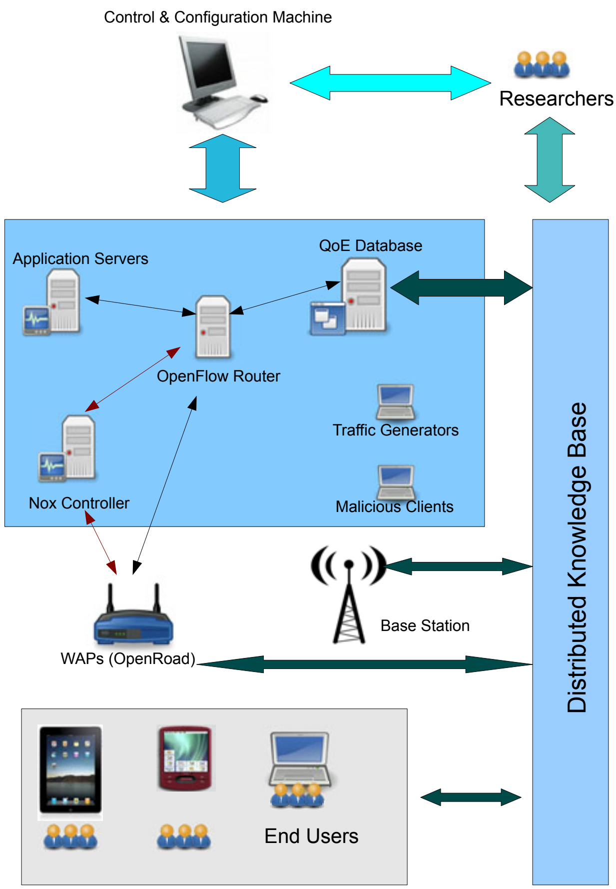

Fig. 1. Testbed Architecture

On the lowest level, we have the various mobile end user devices, e.g. Google Android, Apple iPhone and iPad, on which we run a software that we developed for collecting user Quality of Experience (QoE) reports and submitting to a centralized repository. On the wireless access level, we currently employ 802.11 access points that are based on Voyage Linux operating system. The Linux operating system allows researchers to deploy innovative control algorithms on the access point. Secondly, we have used OpenWRT 802.11 firmware to allow researchers to test innovations on Layer 2.

Different WLAN access points are connected to a set of Linux based routers that run OpenFlow controllers. The connections between the wireless section and the routers are made via a reconfigurable switch, which allows the topology of the experiment to be changed dynamically.

As shown in Figure 1, researchers can program network entities in both core and access network edges that enable the implementation of cognitive cooperative decision mechanisms for enhancing the end-to-end service experience. Innovative concept in this testbed is to provide researchers with the opportunity for a basic implementation of the knowledge plane as a distributed peer-to-peer repository on individual network elements and in any target layer. Moreover, it is possible to generate realistic traffic during normal functioning using traffic generation and malicious client emulation tools, depending on the experiment.

Researchers can monitor distributed knowledge base and fetch semantic data, depicting network QoS from users' perspective. Similarly, distributed intelligent agents running on network elements can revise and improve network service quality according to feedback provided by the end users connecting to the network with their devices. Our testbed architecture, depicted in Figure 1, provides a flexible and easily configurable hardware platform together with configuration tools. Although our configuration tools currently allow us to deploy and perform a variety of different experiments, as will be covered in Section 4, it is ongoing work to implement easy-to-use interfaces for external researchers to access the testbed and apply their innovative ideas related to future network concepts.

3 Testbed Components

Our testbed consists of two components, namely, hardware and software components.

3.1 Hardware Components

Wireless Access Points. Alix boards from PC Engines [20] are configured to be the wireless access points inside the network. This board, which is depicted in Figure 2, consists of 500 MHz AMD Geode LX800 CPU, 256 MB SDRAM and 1 CompactFlash(TM)-Slot for the operating system installation. The board has 2 Fast Ethernet slots for the backbone connection and 2 mini PCI slots for wireless module expansions.

Wireless Module. Compex (miniPCI) wireless modules are used as an extension to the Alix boards. These modules support IEEE 802.11 a, b, g mod operations with 108 Mbps maximum transfer rate. The modules are configurable in 2,4 GHz - 5GHz band and are designed with Atheros chipsets. It is also possible to set frequency selection dynamically.

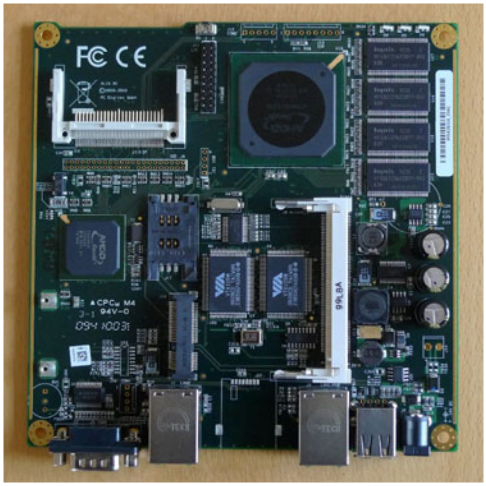

Fig. 2. Alix Board

Clients and Traffic Generators. PCs are used for well-aimed, malicious clients and traffic generators in the proposed WLAN testbed architecture. Traffic generators have 4 wireless LAN interfaces in order to throttle bandwidth when needed.

Control and Configuration Machine. This machine is also a PC connected to the backbone and also used as a traffic generator inside the system when needed.

Miscellaneous Tools. NEO-Industrial PC IPC Embedded computer is used for openflow routers, user experience database and application servers. This computers consist of 1.6 GHz Intel Atom Processors and 2.5" HDD with 1 PCI Card for operating system and additional software installation. Moreover, there exist 4 ethernet port and 2 PCMCIA sockets for networking purposes. Figure 3 shows the top view of this embedded computer.

3.2 Software Components

WAP Operating System. The operating system running on the wireless access points is Voyage linux [23], which is a Debian derived distribution and suitable for running full-feature firewall, wireless access points, Asterisk/VoIP gateway, music player or network storage devices. Although this distribution is a stripped-down version of Debian, it is possible to customize it and expand the capabilities with Debian packets.

Fig. 3. NEO-Industrial PC IPC Embedded Computer

Routing Table Configuration Program. This program is written with Qt cross platform [22] and gives user the ability to select network elements from a given library and connect them through network interfaces. The output of this software is an xml file defining routing tables for each component that will be used during experimentation. Later on, control and configuration machine configures routing table for each selected component accordingly.

Traffic Generator Program. Distributed internet traffic generator (DITG) [7] is used as traffic generation tool. This platform provides researcher with the capability of producing traffic at packet level accurately replicating appropriate stochastic processes for inter departure time and packet size. It is possible to define probability distribution functions for both of the given random variables as exponential, uniform, cauchy, normal and pareto. Packet randomization capability of DITG gives the opportunity for users to create realistic traffic load over WAPs during the experiment.

Protocol Experimenting. Openflow software [13] installed on the routers in this testbed, provides researchers with the ability to perform practical experiments on new ideas proposed for network protocols in sufficiently realistic settings. Openflow is developed in order to encourage new ideas proposed for networking community on protocols to be practically experimented on networks. This software is basically an Ethernet switch of which flow-table can be manipulated by dynamically adding or removing flow entries. A controller program (in our case NOX [21]) communicates with openflow switch through openflow protocol on the secure channel and routes experimental packets to an experimentation node on the network without disturbing normal traffic.

Similarly OpenRoads is an open-source platform as a wireless extension of OpenFlow, enabling researchers to innovate new protocols and products in mobile networks [18]. Architecture of this software is identical with Openflow; Flow, slicing and controller are the three layers in the architecture of OpenRoad which incorporates multiple wireless technologies, specifically WiFi and WiMAX.

Configuration and Control Program. This software runs on the control and configuration machine and is the first interface on the network for the researcher.

An experiment xml script defining experimentation timing, applications running on any node with timing, application load position, resulting data tracker program load position together with timing, experiment results and their position on the network, NOX controller applications for protocol experimentations that will be started with controller, should be written by the researcher. Similarly routing table xml should be created using routing table configuration program by the researcher and these two xml files together with data tracking programs, application programs and NOX controller applications should be provided to this main control and configuration tool. This program interprets both xml files, configures all components inside the network and loads all softwares provided by the researcher to the corresponding node. After finishing experiment, this programs collects experimental results defined on the experiment xml script and deletes all software and reboots any node inside the network for a new experiment.

This program is in construction and will be expanded in functionality if needed.

4 Sample Experiments and Results

We have already conducted some experiments on the proposed testbed, which we briefly present in this section, and cite our earlier work that the reader can refer for further details.

4.1 Attack and Congestion Mitigation Experiments

Firstly, we tested an intelligent attack and congestion mitigation system, which is installed on wireless access points (WAPs) and continuously observing the WAPs in the vicinity to decide on a possible congestion, attack or critical system failure cases. Partially Observable Markov Decision Processes (POMDP) [12] ran on the WAPs in order to optimize decision processes and actions taken accordingly. Three basic scenarios were developed during normal operation of a wireless LAN network and we have obtained delay experience of users during these scenarios. Details of these experiments and proposed intelligent system with theoretical background can be found in [14].

RoQ Attack Experiment. We emulated a reduction of quality (RoQ) attack situation inside the wireless LAN with the sudden appearance of 20 malicious flows that aimed to reduce the QoS in WAPs by initiating numerous service requests. These attacks were initiated at 80^{th} and 120^{th} second and users experienced a bad delay time during service request. We have observed that our intelligent system distinguished these RoQ attacks from congestion case and threw the malicious user from the network rather than forcing normal users to hand off. The delay time experienced by a client is shown in Figure 4.

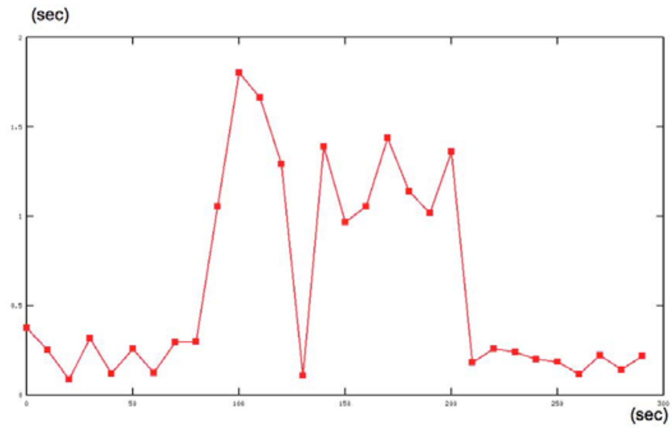

Fig. 4. Attack Scenario User Experience w.r.t Time

Congestion and Load Balancing Experiment. For emulating a congestion scenario, we used a LAN consisting of two access points and associated five users sequentially to one specific access point in the LAN, which was running our own intelligent decision software. Delay times for service requests for each users deteriorated once new comers joined to the network. The agents on WAPs decided on a congestion case at 360^{th} second and took load balancing action. We observed that the WAP running the intelligent decision process shared users fairly in between the two WAPs also at 600^{th}. Figure 5 depicts the delay experienced by three users in this experiment.

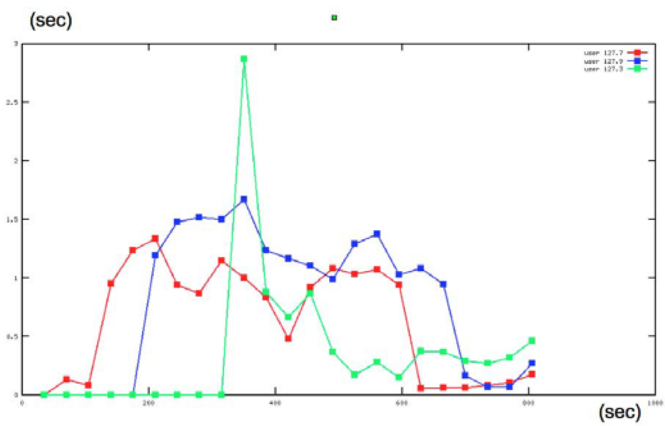

Fig. 5. Congestion Scenario User Experiences w.r.t Time

Critical System Failure Experiment. In this experiment, we emulated a critical system failure case on one of the WAPs. We initiated a simple Linux shell based fork bomb at 100^{th} second on the WAP and observed user experience.

This bomb increased CPU load up to 100% and our intelligent agents complained about critical system failure case after a while at at 230^{th} second and warned the admin for a precaution. Rather than taking an appropriate action, we continued to observe the system and the system failed after at 340^{th} second. Figure 6 depicts user experience for this scenario.

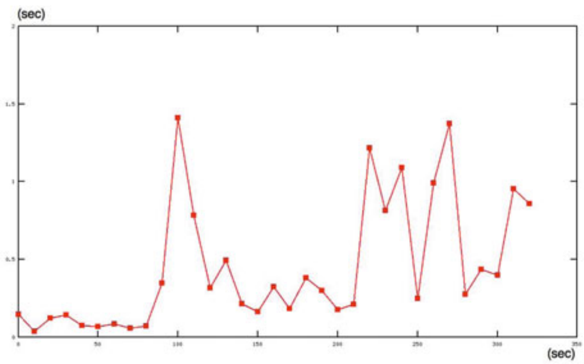

Fig. 6. Critical System Failure Scenario User Experiences w.r.t Time

4.2 Real-Time Inter-operator Load Balancing Experiment

In [19] we propose a POMDP based control algorithm for real-time inter-operator load balancing. This control algorithm runs on the access points belonging to

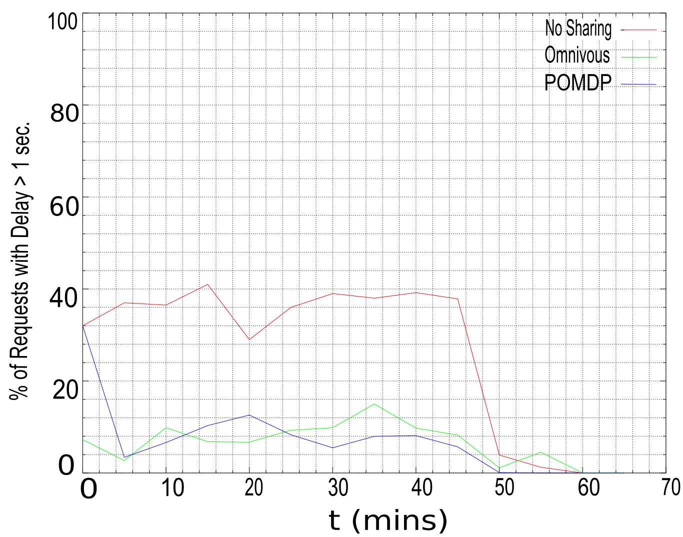

Fig. 7. Borrower User QoE over time

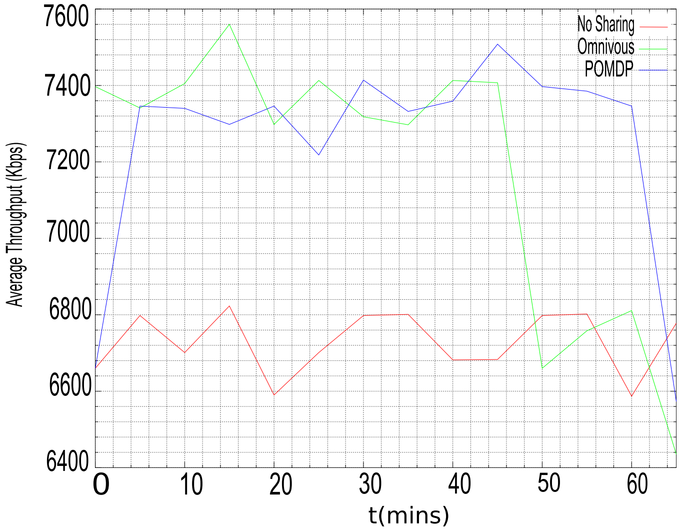

Fig. 8. Donor Throughput over time

different operators. The operators are in an agreement to carry each other's traffic in the case one of them is congested and the other is under-loaded. The main obstacle in front of such a real-time sharing is the fact that operators are not willing to share their operating information such as number of users connected to the AP. A congested operator should make sure that the other operator which would receive additional traffic is under-loaded. Similarly, an under-loaded operator would not help another under-loaded operator. Both operators use the user QoE database to gauge the congestion status of their peer operators. Based on their observations, they take decisions to share or to stop sharing.

We used the developed testbed to evaluate the performance of the POMDP algorithm. We varied the traffic load on two access points by using a realistic stochastic traffic model, and measured jointly the overall throughput and user perceived QoE. We quantified QoE in terms of the probability that the end to end delay exceed a given threshold.

In Figure 7 we plot the ratio of sessions that have a delay larger than one second in the congested access point. It can be seen that the algorithm is able to reduce the ratio from 40% to 12%. Similarly the access point that accepts additional traffic from the congested access point is able to increase its average throughput from 6.6 Gbps to 7.4 Gbps over a period of an hour, as depicted in Figure 8.

5 Conclusion

We presented the design of a user centric wireless network testbed that can easily be reused by new configuration and experimentation scripts. Our aim was to experiment deploying intelligence on network nodes and utilizing the QoE information on end-user devices for enhancing the end-to-end service quality.

We developed some realistic usage scenarios where we monitored user experiences with respect to time and observed how intelligent engines inside the network reacted to the user experience feedbacks dynamically.

Future work includes the incorporation of new access technologies, e.g. femtocells, LTE / WiMAX base stations, with programmable interfaces. Furthermore, although our testbed configuration tools currently allow us to deploy and perform a variety of different experiments, it is ongoing work to implement easy-to-use interfaces for external researchers to access the testbed and apply their innovative ideas related to future network research. Our aim is to encourage researchers to develop and test their intelligent-network concepts and achieve autonomous wireless networks by interpreting the users as a key component of the network.

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