Wireless Controller Placement Problem

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***Abstract*—Software Defined Networking decouples the control and data planes. The response time and quality of service of the controllers is a key aspect in implementing the Software Defined Networking paradigm. A wireless Software Defined Networking control plane is even more challenging. Many radio communication problems arise in modeling the wireless east west bound and southbound interfaces. Wireless networks feature many unique components and metrics that often do not exist in wired networks: separate control transport may intensify on the latency within the wireless data plain with additional interference. Obviously, Wi-Fi based control plane has its implications, e.g., higher packet loss and hidden or exposed terminals. Moreover, wireless links can be operated in a number of different wireless characteristics, e.g., transmission rates and power settings. In this paper we define and solve the known Controllers Placement Problem, but for a Wi-Fi based control plane: the Wireless Control Placement Problem. We define the metrics for an effective wireless controllers placement and propose a multi-objective optimization for the Wireless Controller Placement Problem. Then we evaluate the influence of the variant metrics on the number of controllers and their locations.**

***Index Terms*—Software Defined Networking, Controllers Placement, Wireless Networks**

I. INTRODUCTION

Software Defined Networking (SDN) paradigm decouples the network's control logic(the control plane) from the underlying routers and switches (the data plane), promoting centralization of network control. In SDN, the complexity of generating forwarding rules is offloaded to the controllers. The wide view of the network gives the control plane the ability to manage also the network resources of the entire network. The rapidly growing networks require a flexible architecture. However the wireless medium gives the required flexibility in installing the network infrastructure and adjusting it to changes of loads. The shared wireless medium is vulnerable for radio interference, noise, fading signals and other RF phenomenon. In modeling network metrics such as propagation latency and throughput we have to take into consideration the Rayleigh or Rician fading. Additionally the performance of the network is measured by factors that do not exist in a wired network, such as transparency and link failure (outage) probability that is negligible in wired networks. The advantage of SDN is mostly significant in managing the wireless complexities and this is why the performance e.g. response time of the control plane is important. We can point out a few research issues that may influence the performance of Wireless SDN(WSDN): 1) the proximity of the controllers to the data plane access point(AP) lowers the outage probability but intensify interference. 2) increasing the transmission power of the controllers improves the received signal for the receiver access point but increase the interference for others. 3) adding controllers enable shorter distances to the data plane thus improving outage probability but the SINR lowers. We propose a new metric which is significant in evaluating the efficiency of the wireless control plane, that is the transparency - the marginal latency on the data plane caused by the interference that is added by the control plane. Our simulations show the relation between the transparency and the controllers placement. The Controller Placement Problem that was first proposed by Heller *et al.* [1] is a major factor in the performance evaluation of SDN. The placement of the controllers defines the number of controllers that are used, their location and the assignment function of data plane switches to the controllers. In this paper we investigate the Wireless Controllers Placement Problem (WCPP), taking into consideration the complexities of the wireless medium. We model the average propagation latency and link failure probability on the southbound interface(SBi), and propose a multi-objective optimization function for the placement. For the constraints we model the transparency and average throughput on the southbound interface. Therefore, our main contributions are the following:

1) A model for the metrics for the WCPP that are exclusive for the wireless SDN, e.g. propagation latency, throughput and link failure probability on the SBi.
2) We propose a new metric for the WCPP, namely the transparency defined as the marginal data plane average latency caused by the additional interference the controllers add to the data plane
3) A multi-objective function for the WCPP
4) A brute-force algorithm for solving the objective function
5) Simulations that evaluate our solution for the WCPP

The remainder of this paper is organized as follows. In section II we list the existing solutions for the placement problem. In section III we introduce the Wireless Controller Placement Problem and propose a detailed model description. In section IV we present the algorithm for solving the objective function and the simulations that we have conducted and discuss the outcomes. We conclude with a few remarks and suggestions for further research in Section V.

II. RELATED WORK

The CPP for wired SDN was first introduced by Heller *et al.* [1]. They defined the CPP and the metrics for evaluating a solution. The average propagation latency based on an euclidean distance, was the main objective. Since then, this problem has been investigated and a variety of solutions were proposed. We mention those solutions that are specifically related to this research. Yao *et al.* [2] added the controller's capacity constraint to the objective of lowering the latency. Sallahi and St-Hilaire [3] calculated the financial cost of expanding the control plane for the objective of minimizing the cost of expanding the control plane. Vizarreta *et al.* [4] improved the resiliency by adding a backup path for each link on the SBi. Hu *et al.* [5] proposed the objective of minimizing the energy consumption of the network that serves for the control traffic. All the aforementioned propositions are based on wired networks. The wireless network raises many research questions with regard to SDN and specifically the WCPP as mentioned in section I. The Wireless Controller Placement Problem was introduced by Abdel-Rahman *et al.* [6]. They proposed 2 different deterministic solutions for the wired CPP with the objective of minimizing the number of SDN controllers under response time constraints. Then they introduced the WCPP and proposed an objective function that minimizes the number of SDN wireless controllers. The model is based on a TDMA mechanism where both the control plane and the SBi is wireless. Their objective is to minimize the number of SDN wireless controllers constrained to the response time of the controllers. The proposed response time model is stochastic. However they did not model other wireless metrics for an optimal placement. In this paper we add modeling of other metrics for the placement such as the probability of a wireless link outage on the SBi, throughput and transparency. Recently Johnston and Modiano [7] proposed a dynamic controller placement for wireless networks in which the controller is relocated using delayed queue length information at each node, and transmissions are scheduled based on channel and queue length information.

III. WCPP

A. Problem Statement

SDN decouples the control management from data forwarding. The structure and size of the control plane has a major influence on the performance of the network e.g. response time. In wireless networks the response time is higher, link failures are common, retransmissions reduce throughput. The communication between the controllers and the AP and within the control plane is wireless. Our proposal for solving the WCPP consists of 3 elements:

1) the number of controllers k
2) the location of the controllers
3) the assignment of all data plane APs to k clusters. Each cluster is assigned with exactly one controller.

B. The Model

The WCPP is a variation of the K-Means problem. The weights of the edges follow the objective function definition, that is the sum of the latency and the outage probability on the corresponding wireless links. Denote the network by G(V,E), where V is the set of controllers and access points and E is the set of wireless links between the controllers and the access points. The set of K controllers is denoted by $C = \{\Delta_1, .., \Delta_k\}$. Each controller Δ_i is placed at an access point's location denoted by $\psi(\Delta_i)$. A placement of controllers is denoted by:

$$P = \{(\Delta_1, \Psi(\Delta_1)), (\Delta_2, \Psi(\Delta_2)), ..., (\Delta_k, \Psi(\Delta_k))\} \quad (1)$$

Denote the controller assigned to access point v by $\xi(v)$. Denote by $S_\xi(\Delta_i)$ the set of access points that are assigned to controller Δ_i. An assignment of access points to a controller is denoted by:

$$S = \{(\Delta_1, S_\xi(\Delta_1)), (\Delta_2, S_\xi(\Delta_2)), ..., (\Delta_k, S_\xi(\Delta_k))\} \quad (2)$$

The data plane APs are placed randomly within an area of $1000m^2$. The data plane links may be wireless and all the network paths are 1-hop.

C. Preliminaries

An efficient controllers placement depends on the following factors:

1) Latency: Round-trip time between two network nodes
2) Interference: The radio interference caused by wireless nodes in the network, in this case a CSMA based network.
3) Probability for a link failure(outage): The average probability for an outage on a specific link on the SBi. An outage happens when the SINR goes below a threshold Θ. We assume that when $SINR < \Theta$ the interference imposed by this signal is not considered.
4) Retransmission rate: The rate of packets being retransmitted due to communication failure
5) Transparency: The marginal average latency in the data plane caused by the additional interference from the controllers.
6) Overall throughput: The sum of the data rates that are delivered to all terminals in the network per time unit.

D. Placement metrics

There is a number of metrics that need to be considered for the WCPP. We now introduce the model for these metrics.

1) Average Latency: We assume a Rayleigh fading channel with no line of sight. A transmission from node i to node j is successful if the SINR γ_{ij} is above a certain threshold Θ. Otherwise the interference that this signal create is not considered. The SINR γ is given by

$$\gamma = \frac{Q}{N_0 + I} \quad (3)$$

Q is the received power and N_0 denotes the noise power, and I is the interference power, namely, the sum of the received power from all the undesired transmitters.

Theorem 1: [8]
In a Rayleigh fading network with slotted ALOHA, where nodes transmit at equal power levels with probability p, the success probability of a transmission given a desired

transmitter-receiver distance d_0 *and n other nodes at distances* $d_i\ (i = 1, ..., n)$ *is*

$$P_{s|d_0 \dots d_n} = exp\left(-\frac{\Theta N_0}{P_0 d_0^{-\alpha}}\right) \cdot \prod_{i=1}^{n} \left(1 - \frac{\Theta p}{\left(\frac{d_i}{d_0}\right)^{\alpha} + \Theta}\right) \tag{4}$$

where P_0 *is the transmit power,* N_0 *the noise power, and* Θ *the SINR threshold.*

Remark: We assume a CSMA architecture. In the proposed architecture a collision may happen by a transmission attempt of only 2 network nodes. Therefore in this case theorem 1 implies also for the proposed architecture. We also assume that APs that are farther than a certain reception radius R=50m create negligible interference. Controllers use higher transmission power therefore the interferense they create is considered even if they are farther than the reception radius. The total interference received at AP_i from all interfering nodes in the set of all interferes A^I is [9]:

$$\zeta^{ji} = \sum_{z \in A^I, i,j \in A | j \neq z, A^I \subset A} P_{zi} \tag{5}$$

where P_{zi} is the received signal power at AP_i from the z_{th} interfering node at distance d_{zi}. A is the set of all network nodes. As a result of interfering signal power received at AP_i from interferes A^I , the SINR on the link between network node j and AP_i is:

$$\gamma_{ji} = \frac{P_{ji}^r}{(\zeta^{ji} + N_0)}, \quad 1 \leq i, j \leq N \tag{6}$$

N is the number of network nodes. where p_{ji}^r is the received signal power from node j at AP_i over a distance d_{ji}. The received power at AP_i from node j is measured as follows:

$$P_{ji}^r = P^t(mW) G_{ji} d_{ji}^{-\alpha} (dBm) \tag{7}$$

where G_{ji} is the channel gain characterized by an exponential distribution i.e $G_{ji} \sim exp(P_t)$ to account for fading and shadowing effects, and $\alpha = 3.5$ is used as the path loss exponent. The total end to end delay (latency) for a packet at the current station can now be calculated using 5 and 6:

$$t_{ji} = \frac{F(bits)}{R_{ji}} \tag{8}$$

where R_{ji} is the transmission rate, which is determined by SINR γ_{ji} experienced by AP_i when associated with controller j. The mapping between R_{ji} and SINR γ_{ji} in the context of 802.11 is provided by [9]

When a frame from AP_j to AP_i experiences collision, the transmission time is extended as thus:

$$\tilde{t}_{ji} = DIFS + t_{bf} + t_{ji} + SIFS + t_{ack} \tag{9}$$

where $t_{bf} = \frac{CW_{max}}{2}$ x Slot-time is the backoff time, $t_{ack} = \frac{1}{r}$ is the time it takes to transmit ACK frame given basic data rate r (e.g. 1Mbps in an 802.11b network) while SIFS and DIFS are time intervals defined in the 802.11 standard. Finally the average latency on the network is:

$$L_{average} = \frac{1}{N_{links}} \sum_{l \in links} t(l) \tag{10}$$

where t(l) is the latency on the link l as in (9)

2) Transparency: The transparency metric is the marginal average latency in the data plane caused by the interference from the controllers. The average latency on the data plane is:

$$L_{average} = \frac{1}{n} \sum_{u,v} l(u, v), \quad u, v \in Vap, u \neq v \tag{11}$$

Where l(u,v) denote the latency on the shortest path between nodes u and v. The transparency T (percentage) when taking into account the controllers:

$$T = \frac{L_{dp1} - L_{dp0}}{L_{dp0}} \cdot 100\% \tag{12}$$

L_{dp0} denote the average latency on the data plane without taking into account the controllers and L_{dp1} is the new average latency when taking into account the controllers.

3) Throughput: The throughput of a slotted p-Persistent unsaturated CSMA with Heterogeneous Traffic (1-hop paths) is:

$$Th_{ji} = \frac{1}{\tilde{t}_{ji}} \tag{13}$$

$$Th_{average} = \frac{1}{N_{links}} \sum_{i \in C, j \in A} Th_{ij} \tag{14}$$

4) Link failure probability: The scenario assume a star topology structure where each AP has a single route to its exclusive assigned controller. The channel experiences a Rayleigh fading (no line of sight) and we assume that the link failure probability denoted $Pr_{i,j}$ is the probability that the SINR would go below a threshold Θ

$$Pr_{i,j} = 1 - P_{j|d_0 \dots d_n} \tag{15}$$

where $P_{j|d_0 \dots d_n}$ is defined at 4, and i,j are source and destination nodes. The average probability for a link failure is:

$$Pr_{avg} = \frac{1}{N} \sum_{s \in C_t} \sum_{d \in AP^s} Pr_{s,d} \tag{16}$$

Where N is the number of links between APs and controllers which equals to the number of APs, C_t is the set of all controllers, AP_s is the set of APs assigned to controller s.

E. Objective Function and Constraints

The WCPP is formulated as follows:

$$\underset{S \in \hat{S}}{Minimize} \quad \lambda_1 \cdot C_1(S) + \lambda_2 \cdot C_2(S) \tag{17}$$

subject to:

$$\sum_{a \in A_{set}, c \in C_{set}} x_{ac} = 1 \tag{18}$$

$$T < T_{threshold} \tag{19}$$

$$Th_{avg} > Th_{threshold} \tag{20}$$

where:

$\hat{S}$ is the set of all assignments. C_1 is the average outage probability (16), C_2 is the average latency (10), λ_1 and λ_2 are coefficient parameters. Constraint(18) guarantees that each AP

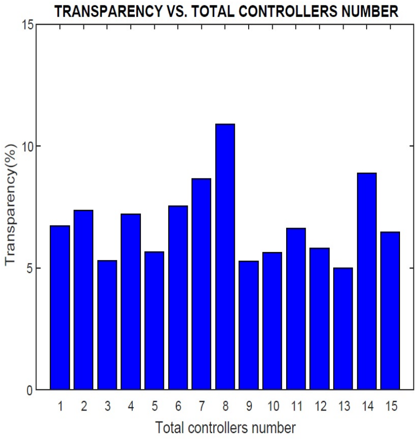

Fig. 1: The network consists of 50 access points and variant number of controllers. changing the number of the controllers change the transparency of the data plane

is assigned to exactly one controller c therefore x_{ac} equals 1 to show that AP a is assigned to controller c and 0 otherwise. Constraint(19) guarantees that the transparency of the control plane is less than $T_{threshold}$. constraint (20) guarantees that the throughput is more than $Th_{threshold}$.

IV. SIMULATIONS

The solution for the objective function (17) is based on the K-Median algorithm. The K-Median clustering algorithm is already proved to be NP-Hard .As mentioned before, the input is a set A of APs located randomly in the plane. The set A is divided into k clusters. All APs in a cluster are assigned with a controller which is located at one of the AP locations in the cluster. The K-median algorithm chooses the clustering and the locations of the controllers such that the sum of weights of all links is minimized. For the weight of each graph edge we use the objective function in (17), namely the sum of the latency and outage probability on the link. The proposed algorithm finds K such that the sum of weights is minimized. For the simulation we use Intel Core i5-2400 CPU @ 3.10GHz, 3101MHz, 4 Cores, running Matlab RS2015a. The solution algorithm uses the Matlab K-Medoid function to find K clusters with controllers for each cluster. A brute force algorithm searches for the K number of controllers that would make the best performance according to the objective function. The results are average results of 10 iterations for each test. Figure 1 shows the relation between the number of controllers and the transparency : adding controllers changes the entire placement therefor the transparency may increase or decrease. in figure 2, λ_2 is constant and λ_1 is variant hence the optimal controllers number changes. The network configuration for the simulation is as follows : the network area is $1000m^2$, an AP transmits in 12dBm and a controller transmits in 20 dBm, SIFS=$10\mu s$.

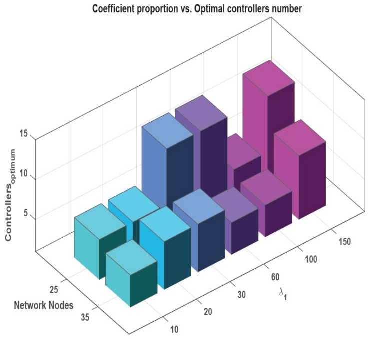

Fig. 2: The influence of λ_1 on the optimal number of controllers. λ_2 equals 10^4

V. CONCLUSIONS

This research shows the complexity of implementing SDN for the wireless. Many more issues are still open, some of which are a natural continuation: the behavior of the network is dynamic - the characteristics of wireless links change and the loads on the network change - the amount of data and control signaling, the number of users and their locations, etc. The controllers placement changes dynamically according to the network loads. The next step may be upgrading the solution to a flexible one. Currently the control plane is a proprietary of a single Internet Service Provider(ISP). We may enable interfacing with multiple ISPs by sharing the control plane. This can also be done using a Life-cycle Service Orchestration (LSO).

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