SIMULATION OF ENERGY-AWARE BACKBONE NETWORKS

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KEYWORDS

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ABSTRACT

An optimization of the energy consumption in network systems has been recently an important research issue. The main challenge is to design, develop and test novel technologies, integrated control strategies and mechanisms for network equipment enabling energy saving by adapting network capacities and resources to current traffic loads and user requirements, while ensuring end-to-end Quality of Service. In general, the idea is to develop low power devices or nano-processors, concentrate network traffic on a minimal subset of network components, and modulate network devices using dynamic voltage and frequency scaling methods. Various power adapting technologies for network devices are described in literature. We developed a framework for a backbone network management which leads to the minimization of the energy consumption by this network. The concept is based on activity control of the network equipment. The framework is presented in (Niewiadomska-Szynkiewicz et al., 2012b). In this paper we describe the design, performance and potential applications of the software environment for energy efficient backbone network optimization and simulation. This system was used to illustrate the performance of our control framework for energy-aware IP networks.

INTRODUCTION

The problem of reducing power consumption in computer networks, while providing for adequate transmission quality has been a hot topic in the last years. It has been observed that information communication technology sector belongs to the group of the big power consumers. Therefore, enabling the reduction of energy requirements of telecommunication networks is the goal of many research groups, network equipment manufactures and Internet Service Providers (ISPs). New solutions both in hardware and software have been developed to achieve the desired trade-off between total power consumption and the network performance according to the network capacity, actual traffic and requirements of the users (Bianzino et al., 2012; Bolla et al., 2010; Chiaraviglio et al., 2009; Coiro et al., 2011; Goma et al., 2011). Approaches ranging from traffic engineering, to routing protocols, and novel architectures have been developed and investigated.

Computer simulation is a standard tool for understanding and predicting the behavior of network systems under the influence of various realistic and stochastic input scenarios. Although simulation has traditionally been viewed as an approach of last resort, recent advances in computer hardware and software have made it one of the most popular technique to attack many real-life problems. In order to efficiently perform simulation experiments, good software tools are needed hence, in recent years we can observe a rapid growth of network simulators. We have developed a software environment for green (in our research energy-aware) IP networks optimization and simulation. We used it to evaluate the performance of our control scheme for such type of networks.

BACKGROUND AND RELATED WORK

In general, power management methodologies in networks can be classified into static and dynamic technologies (Kołodziej et al., 2012). Recently various activities aimed at developing energy-efficient network devices have been undertaken and described in literature, see (Bianzino et al., 2012; Bolla et al., 2011; Niewiadomska-Szynkiewicz et al., 2012b) for an overview. These devices can operate in different states, which differ in the power usage, and implement dynamic power manage-

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ment techniques. Power scaling and smart standby capabilities are widely used to reduce power consumption. The power scaling capability assumes scaling the performance of the device to reduce the energy requirements. The smart standby is the capability of reducing the energy requirements by switching off the device or its component or putting it in very low energy mode.

In (Niewiadomska-Szynkiewicz et al., 2012b) we described a control framework for an energy-aware backbone network, and possible algorithms to exploit smart standby capabilities of nodes and links in such type of network, developed by the ECONET project (http://www.econet-project.eu). Our framework requires the presence of a central control unit. The decisions about activity and power status of devices in a whole network are calculated by the central operator. In our scheme we tackle the minimization of the power consumption by putting in low energy states selected network devices, such as routers, line cards and ports, (Niewiadomska-Szynkiewicz et al., 2012b; Arabas et al., 2012). Next, the respective routing tables for the MPLS protocol are computed due to suggested optimal states of these devices. The optimal network performance is calculated based on known network topology and expected demands (traffic matrix).

ALGORITHM FOR GREEN IP NETWORKS

It can be observed that the traffic is subject to strong fluctuations, especially when comparing incoming traffic during the day and night. Therefore, many network devices are underutilized when traffic is low (during off-peak hours). Hence, forcing a sleep state for selected network equipment and using the rest to transmit the whole traffic through the network can significantly reduce the power consumption. Thus, to reduce the energy requirements we have to calculate the optimal operational modes for all network devices based on current load, traffic and estimated demands. We consider a network formed by R routers ($r = 1, \ldots, R$), each equipped with C cards ($c = 1, \ldots, C$). Each card contains P ports ($p = 1, \ldots, P$). All pairs of ports from different routers and cards are connected by E direct links ($e = 1, 2, \ldots, E$). Routers, cards and links (both connected ports) can operate in one of K energy-aware states ($k = 1, \ldots, K$). These states are related to the application of power scaling and standby techniques, and are defined as power settings. We assume that both routers and cards can operate in only two states, i.e., active and sleeping, and each link can operate in several (at least two) states with different energy usage and at the same time different capacity. Hence, in our approach the power profile model is defined by a stepwise function describing power consumption due to a given throughput – the throughput of link e in state k is defined as M_{ek}. The power consumption in state k is defined as ξ_{ek}. Moreover, fixed power levels W_c and T_r are associated to cards and routers, respectively. We assume D demands transmitted by means of flows allocated to given MPLS paths under QoS requirements ($d = 1, \ldots, D$). The volume of demand d is equal to V_d, and is estimated by the central network operator. The demand d is associated with a link connecting two ports: the port of the source node (s_d) and the port of the destination node (t_d).

Given the presented notation, we can formulate the complete energy-aware network management problem assuming full routing calculation and energy state assignment to all links in a network, (Niewiadomska-Szynkiewicz et al., 2012a,b). In this formulation the total power used in the network system is assumed to be minimized. The constraints guarantee ensuring end-to-end Quality if Service.

$$\min_{x_c, y_{ek}, z_r, u_{ed}} \{F_{LN} = \sum_{e=1}^{E} \sum_{k=1}^{K} \xi_{ek} y_{ek} + \sum_{c=1}^{C} W_c x_c + \sum_{r=1}^{R} T_r z_r\}, \tag{1}$$

subject to the constraints:

$$\forall_{\substack{d=1,\ldots,D,\\ c=1,\ldots,C}} \quad \sum_{p=1}^{P} l_{cp} \sum_{e=1}^{E} a_{ep} u_{ed} \leq x_c, \tag{2}$$

$$\forall_{\substack{d=1,\ldots,D,\\ c=1,\ldots,C}} \quad \sum_{p=1}^{P} l_{cp} \sum_{e=1}^{E} b_{ep} u_{ed} \leq x_c, \tag{3}$$

$$\forall_{\substack{r=1,\ldots,R,\\ c=1,\ldots,C}} \quad g_{rc} x_c \leq z_r, \tag{4}$$

$$\forall_{e=1,\ldots,E} \quad \sum_{k=1}^{K} y_{ek} \leq 1, \tag{5}$$

$$\forall_{\substack{d=1,\ldots,D,\\ p=s_d}} \quad \sum_{e=1}^{E} a_{ep} u_{ed} - \sum_{e=1}^{E} b_{ep} u_{ed} = 1, \tag{6}$$

$$\forall_{\substack{d=1,\ldots,D,\\ p\neq t_d, p\neq s_d}} \quad \sum_{e=1}^{E} a_{ep} u_{ed} - \sum_{e=1}^{E} b_{ep} u_{ed} = 0, \tag{7}$$

$$\forall_{\substack{d=1,\ldots,D,\\ p=t_d}} \quad \sum_{e=1}^{E} a_{ep} u_{ed} - \sum_{e=1}^{E} b_{ep} u_{ed} = -1, \tag{8}$$

$$\forall_{e=1,\ldots,E} \quad \sum_{d=1}^{D} V_d u_{ed} \leq \sum_{k=1}^{K} M_{ek} y_{ek}, \tag{9}$$

where $g_{rc} = 1$ if the card c belongs to the router r (0 otherwise), $l_{cp} = 1$ if the port p belongs to the card c (0 otherwise), $a_{ep} = 1$ if the link e is outgoing from the port p (0 otherwise), $b_{ep} = 1$ if the link e is incoming to the port p (0 otherwise), $z_r = 1$ if the router r is used for data transmission (0 otherwise), $x_c = 1$ if the card c is used for data transmission (0 otherwise), $u_{ed} = 1$ if the path d belongs to the link e (0 otherwise), $y_{ek} = 1$ if the link e is in the state k (0 otherwise).

The meaning of the above constraints is as follows. The constraints (2)-(4) determine the number of routers and cards that are used for data transmission. The conditions (5) assure that each link can be in one energy-aware state. The constrains (6)-(8) are formulated according to Kirchhoff's law applied for source, transit and destination nodes. The constraint (9) assures that the flow will not exceed the capacity of a given link.

SOFTWARE ENVIRONMENT FOR TESTING GREEN NETWORKS

Modeling and simulation are traditional methods used to evaluate network design. Therefore, we have developed an integrated software environment that can by used to support the design of energy-aware control strategies and algorithms. Our software provides tools for defining and implementing the problem of the optimal management of network devices w.r.t. the power consumption, optimization solver for solving the formulated problem and energy-aware network simulator for evaluating the calculated decision policy and checking the compliance of demands.

Components of the System

The software environment *Optimizer&GNS* to test energy-aware network applications consists of two components: optimizer and energy-aware networks simulator, Fig. 1. The *Optimizer-ASim* consists of an user interface responsible for user-system interaction and calculation results presentation, and an optimization solver. In the current version of the system the mixed integer programming (MIP) algorithm implementing branch-and-bound approach is provided. In our future work we plan to extend the optimizer component, and implement a library of solvers. The optimizer is built based on ASim/Java library – a software tool for discrete event systems simulation, (Sikora and Niewiadomska-Szynkiewicz, 2009; Niewiadomska-Szynkiewicz and Sikora, 2012). We used ASim/Java classes to model a network to be simulated and implement the optimization problem as described in the previous section. The user interface is graphical and built based on ASim/Java classes, too. GUI provides setting and display windows. Setting windows (see Fig. 2) are used to define a network topology and its attributes and

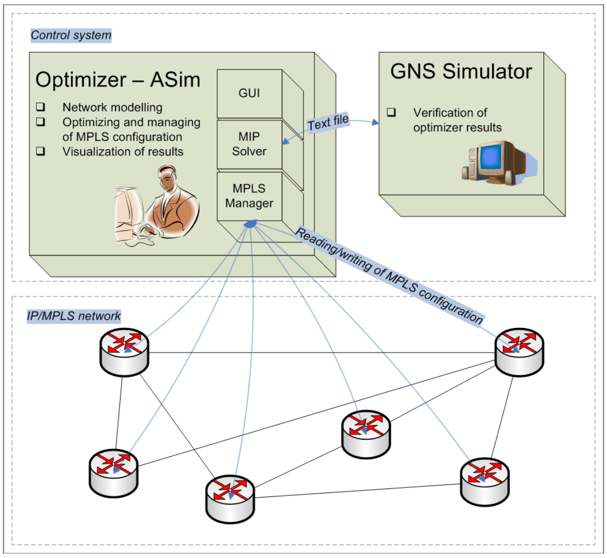

Figure 1: Software environment *Optimizer&GNS*.

introduce all configuration parameters. Display windows are used to present results of the optimization.

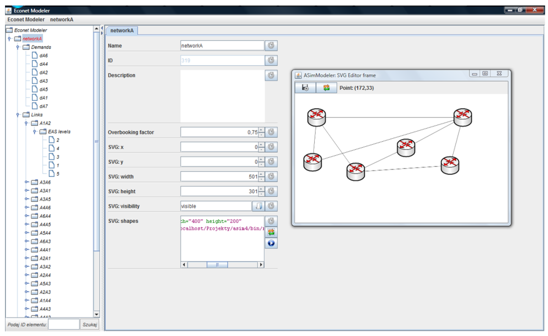

Figure 2: Graphical user interface of *Optimizer-ASim*.

The second component of our software environment named *GNS Simulator* allows to simulate the network systems utilizing energy-aware control strategies and algorithms for reducing of the power consumption. It is packet-level network simulator. *GNS* is completely based on OMNeT++ network simulation framework – free software for academic and non-profit use, and widely used platform in the global scientific and research community. OMNeT++ (http://www.omnetpp.org/) is an extensible, modular, component-based C++ simulation library and framework, primarily for building wired and wireless network simulators. It offers an Eclipse-based IDE, a graphical runtime environment as well as handy results browser. In our system we extensively use the open-source communication networks simulation package for OMNeT++ developed by the INET project. The INET framework (http://inet.omnetpp.org/) provides library of models for networking protocols including UDP, TCP, IP, IPv6, Ethernet, MPLS, OSPF, etc., and models of network hardware, i.e., routers, switches, network cards, etc. *GNS* provides green extensions to the models of devices offered in the INET library. The C++ implementations of routers and line cards were modified to enrich them with basic green abstraction layer functionalities (GAL) developed by the ECONET project and described in details in (Reforgiato et al., 2012). In general, GAL is the standard interface between control algorithms and hardware for exchanging data regarding the power status of the device and its components. The objective is to hide the implementation details of energy saving techniques, as well as to provide standard interfaces between control and monitoring layers and energy-aware technologies. Therefore, the simulators of network components provided in *GNS* introduce methods for setting energy-aware states, and allow for switching the devices to suggested states and measuring energy used by each device.

The *GNS* simulator provides the graphical user interface that was built based on OMNeT++ modules. GUI is organized in a set of nested windows. Setting and display windows can be distinguished. Setting windows are used to define a scenario of the experiment and introduce all configuration parameters. The other way is to load a network to be simulated from the disc file generated by the optimizer module. Display windows are used to present the simulation results, see Fig. 3.

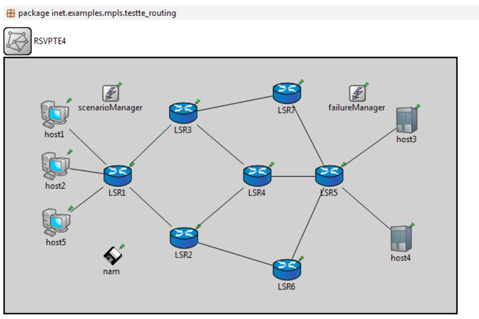

Figure 3: Simulation results presentation.

Both the *Optimizer-ASim* and the *GNS Simulator* can operate as a standalone tools. The optimizer can be used to calculate and compare various control strategies for energy-aware networks, and the simulator can be used to simulate various green networks applications.

User Application and Calculation Stages

Two calculation stages can be distinguish: a preparatory and decision calculation stage, and an experimental stage. At the first stage the model and the properties of the network system to be simulated are investigated and optimal configuration due to power consumption is calculated. The user's task is to define the model of the network. It can be implemented in the XML schema specification and saved in the XML file or created using GUI, Fig. 2. The optimization problem (1)-(9) is formulated and solved for a given network, taking into account its topology and expected demands. The MIP solver is used to solve the optimization task. The result of calculations is optimal power status of all network components (routers, cards and ports). Next, the routing tables for the MPLS protocol are computed for the optimal configuration of the network. Thus, the final outcome of the optimizer is a set of routing tables and optimal states of all devices that are saved to the disc file.

Next, the experimental stage begins. The network topology and the optimal routing tables are loaded from the disc files, the simulation time horizon is defined and the simulation experiment starts. The programs corresponding to all network devices are executed and the results of calculations are displayed in the on-line mode (states of devices, packages transmission, etc.), Fig. 3.

EXPERIMENTAL EVALUATION

Our software environment *Optimizer&GNS* has already proved to be very useful when performing the analysis of green solutions for network systems. We validated our control scheme based on optimization problem formulated in this paper and energy-aware traffic engineering using MPLS and RSVP-TE protocols through simulation. We solved the optimization problem (1)-(9) for several network configurations and evaluated calculated decisions using *GNS* simulator. In this paper we present the results obtained for two synthetic network topologies. The first network system N1 formed by 6 routers connected by 20 links is presented in Fig. 4. The second network system N2 formed by 12 routers connected by 28 links is presented in Fig. 5. The Table 1 reports the power used in different energy-aware states k and corresponding throughput.

We performed experiments both for N1 and N2 networks assuming various numbers of demands D and overbooking factor equal to 0.75. The routers in our tests were equipped with one or more cards. We assumed that each router and card could operate in two states – active and sleeping. Each link could operate in 5 energy-aware states ($k = 1, 2, 3, 4, 5$). $k = 0$ denotes that the link

Router	power = 1 900 W (active state)
Card	power = 90 W (active state)
k=1	throughput = 200 Mb/s, power = 16 W
k=2	throughput = 400 Mb/s, power = 32 W
k=3	throughput = 600 Mb/s, power = 48 W
k=4	throughput = 800 Mb/s, power = 64 W
k=5	throughput = 1000 Mb/s, power = 80 W

Table 1: Power costs and corresponding throughputs.

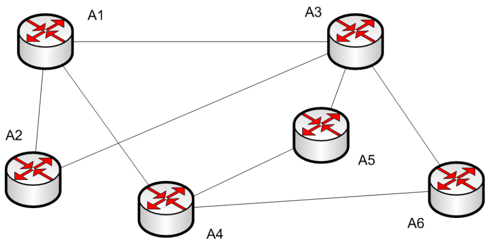

Figure 4: The synthetic network N1.

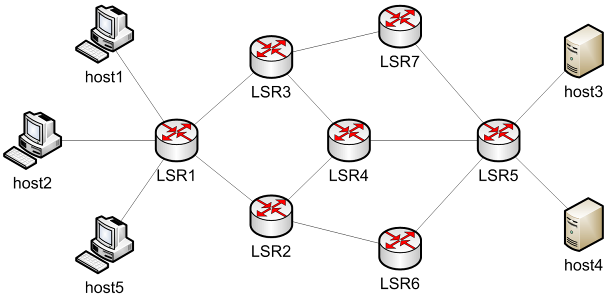

Figure 5: The synthetic network N2.

was not used for data transmission. Selected results of calculations, i.e., the outcome of the *Optimizer-ASim* for both networks – N1: $D = 3$, $D = 7$, $D = 13$ and N2: $D = 3$, $D = 6$, $D = 9$ are presented in tables 2 and 3. The total energy usage without any energy saving mechanisms for both networks are as follows: N1: 13 900 W, N2: 26 120 W. Three last rows in tables 2 and 3 give: numbers of routers, cards and links used for data transmission, total power consumption in a network, reduction in energy consumption relative to the case without any power management.

Next, we validated the results of optimization through simulation. The goal was to test how power saving strategy reduce total energy consumption and affects the end-to-end Quality of Service. We performed several simulation experiments for networks N1 and N2 taking into account routing tables and power status of devices calculated by the optimizer, and presented in tables 2 and 3. In our experiments we assumed energy costs of all devices

Link	Optimal energy state (k)		
(router/card)	$D = 3$	$D = 7$	$D = 13$
A1/2 → A2/2	1	1	1
A1/2 → A3/1	1	2	0
A1/2 → A4/1	0	0	2
A2/2 → A4/1	0	0	2
A2/2 → A3/1	0	1	0
A3/2 → A5/1	0	1	1
A3/2 → A6/1	1	2	0
A4/2 → A5/1	0	0	1
A4/2 → A6/1	0	0	3
A2/2 → A1/2	1	1	1
A3/1 → A1/2	1	2	0
A4/1 → A1/2	0	0	2
A4/1 → A2/2	0	0	2
A3/1 → A2/2	0	1	0
A5/1 → A3/2	0	1	1
A6/1 → A3/2	1	2	0
A5/1 → A4/2	0	0	1
A6/1 → A4/2	0	0	3
Routers/cards/links	4/5/6	5/6/10	6/7/12
Power consumption	8 146 W	10 264 W	12 350 W
Power reduction	5 754 W	3 636 W	1 550 W

Table 2: Routers and cards used for data transmission, and energy states of links (N1 network).

as presented in Table 1. The size of queue of each router was equal 100 packages (default value in OMNet++). We used simple traffic generator TCPSessionApp provided in OMNet++. It is single-connection TCP application (a connection is opened, the given number of bytes is sent, and the connection is closed). Sending may be one-off, or may be controlled by a "script" which is a series of (time, number of bytes) pairs. In tested networks the maximal throughput was equal to 1000 Mb/s.

Three series of experiments for different quality of forecasts of demands were performed: F1-good quality, F2-medium quality and F3-bad quality. The whole simulation horizon was equal to 25 seconds. In the case of F1 we assumed that the volumes of all demands (V_d, $d = 1, \dots, 9$) were equal to those established during optimization. F2 and F3 denote cases in which the real demands V_d^* were greater than forecasted ones, respectively for F2 $V_d^* = 1.5V_d$, and for F3 $V_d^* = 2V_d$. The results of simulation of 40 ms of the network N2 operation are given in tables 4 and 5.

The simulation results indicate that in case of accurate forecasts of expected demands and adequate overbooking factor we can reduce the total power consumption while ensuring QoS (packet loss is very small). It is obvious that a problem appears for bad quality forecast of demands when application of routing tables generated by

Active link (router/card)	Optimal energy state of link (k)		
	$D=3$	$D=6$	$D=9$
host1/1 → LSR1/1	2	2	2
LSR1/1 → host1/1	2	2	2
host2/1 → LSR1/1	2	2	2
LSR1/1 → host2/1	2	2	2
host5/1 → LSR1/1	2	2	2
LSR1/1 → host5/1	2	2	2
LSR2/1 → LSR1/1	0	5	0
LSR1/1 → LSR2/1	0	5	0
LSR3/1 → LSR1/1	5	0	5
LSR1/1 → LSR3/1	5	0	5
LSR3/1 → LSR7/1	5	0	0
LSR7/1 → LSR3/1	5	0	0
LSR3/1 → LSR4/1	0	0	5
LSR4/1 → LSR3/1	0	0	5
LSR2/1 → LSR4/1	0	5	0
LSR4/1 → LSR2/1	0	5	0
LSR5/1 → LSR4/1	0	5	5
LSR4/1 → LSR5/1	0	5	5
LSR5/1 → LSR7/1	5	0	0
LSR7/1 → LSR5/1	5	0	0
host3/1 → LSR5/1	5	5	5
LSR5/1 → host3/1	5	5	5
host4/1 → LSR5/1	0	0	1
LSR5/1 → host4/1	0	0	1
Routers/cards/links	8/8/14	8/8/14	9/9/16
Power consumption	16 752 W	16 752 W	18 774 W
Power reduction	9 368 W	9 368 W	7 346 W

Table 3: Hosts, routers and cards used for data transmission, and energy states of links (N2 network).

the optimizer can result in packets loss (see Table 4). To achieve the trade-off between power consumption and a network performance according to the traffic load a two-level decision scheme consisting of central and local decision mechanisms is proposed. In this approach the goal of the optimizer (the central unit) is to calculate the optimal status for each device, and send it to a local control mechanism of this device. Each device makes decisions about final status for its components based on current load, incoming traffic and expected demands, taking into account decisions from the central unit.

A few local control strategies (LC) have been developed by the ECONET project. In the current version of our simulator a very simple technique is implemented – every assumed time step (1 ms) the local control mechanism checks whether any packets were dropped from the queue. In the case of lost packets it switches the link state to the higher one. The reduction of packets loss due to our local control mechanism is presented in Table 4. The reduction in energy consumption by networks applying energy saving mechanism (1)-(9) relative to the case without any power management (E_{N2}=1 044 800 J) is presented in Table 5.

For. of D	Dem.	Lost pac. (without LC)	Lost pac. (with LC)	Total number of packages
F1	$D=3$	31	4	52120
	$D=6$	52	6	64754
	$D=9$	70	16	67889
F2	$D=3$	90	12	76586
	$D=6$	163	18	91616
	$D=9$	220	39	101545
F3	$D=3$	137	84	100680
	$D=6$	304	124	120011
	$D=9$	437	241	131567

Table 4: Reduction in packets loss due to LC.

Forecast of D	Demand	Energy consumption [J]	Energy reduction [J]
F1	$D=3$	670 080	374 720
	$D=6$	671 462	373 338
	$D=9$	760 358	284 442
F2	$D=3$	673 685	371 115
	$D=6$	676 254	368 546
	$D=9$	776 273	268 527
F3	$D=3$	695 251	349 549
	$D=6$	695 451	349 349
	$D=9$	805 496	239 304

Table 5: Reduction of energy consumption (applied LC).

SUMMARY AND CONCLUSION

This paper presents the software environment *Optimizer&GNS* for designing, developing and testing control frameworks for energy-aware wired networks. We formulated the energy optimization as a mathematical programming problem, and solved it for sample small and medium size networks using our solver from *Optimizer&GNS* package. The designed green network applications were evaluated through simulation. In the nearest future we plan to use *Optimizer&GNS* to test and evaluate other energy-aware control mechanisms developed by the ECONET project and those described in literature. We will compare different solutions due to the energy saving, while providing for adequate transmission quality. Finally, we plan to provide an empirical evaluation of developed control algorithms on a testbed network.

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