Tradeoffs of a converged wireless-optical access network

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***Abstract*—With the constant increase of traffic volume the energy consumption of telecommunication networks is also increasing. Energy conserving solutions are needed to maintain their sustainability. With access networks being the leading contributor to overall network energy demand, their energy-aware operation is of primary importance.**

Future access networks are expected to be based on a hybrid wireless-optical architecture. This paper examines such a network consisting of a small cell LTE wireless part and a wireline PON backhaul. We investigate the trade-off between serving the user population with a reduced number of active cells and the quality of network services. We explore two directions: selectively switching off currently dispensable cells with the aim of reducing power consumption and loosing some cells due to a failure in the underlying PON network. In case of the PON the effect of the optical topology is also considered. Simulations are used to quantify the impact on network services from the standpoint of network availability and throughput.

I. Introduction

More and more people around the world use mobile devices to access the web. Moreover as the services offered by these devices become more complex, their bandwidth-hunger also grows. To be able to cope with this increasing demand, network infrastructure needs to be expanded/upgraded regularly. But capital costs of this are only one side of the coin. A higher capacity network also incurs higher operating expenses, and in recent years energy consumption became a very significant factor in these.

It is estimated, that access networks are responsible for 70% of the total energy consumption of telecommunication networks [1]. Therefore energy efficient access networks can result in major savings.

In this work we evaluate a hybrid access network architecture which consists of a small cell Long Term Evolution (LTE) network and a Passive Optical Network (PON) which serves as the backhaul connection for the cells.

Small cells are low-powered, close to mid range radio access nodes. Mobile operators can use them to extend service coverage in indoor or rural deployments or increase network capacity at hotspots. They are especially useful in dense urban areas, where the small cells can help to relieve congestion on the macro cells while increasing network performance in critical areas. Moreover they are cheaper and easier to deploy in dense urban areas, than macrocells.

PONs are point-to-multipoint fiber-optic access networks. They employ unpowered optical splitters to serve multiple endpoints. A PON consists of an Optical Line Terminal (OLT), which is at the service provider's premises, and of multiple Optical Network Units (ONUs), which are located at the consumers end. The OLT is connected to the splitter through optical fiber, and then the splitter is connected to the ONUs. Downstream signals are broadcast to all ONUs and encryption is used to prevent access to data that is not intended for a given endpoint. Upstream transmission is handled using multiple access protocols, usually Time Division Multiple Access (TDMA).

It is envisioned that ONUs will be capable of entering a low-power state for idle periods. Proposals to the IEEE 802.3av task force have been made to standardize this [2].

The PON as wireline backhaul is a suitable match for the LTE small cell network since it can meet the bandwidth and QoS needs of it.

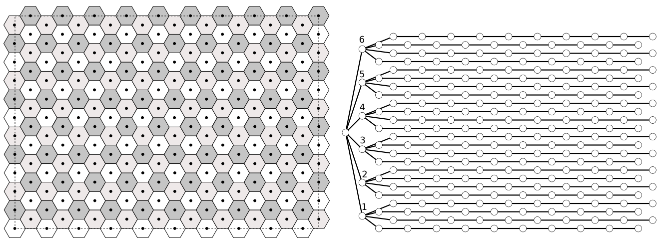
A. Contribution

This work investigates the triple trade-off between power consumption, availability and Quality of Service (QoS) assuming a hybrid access network consisting of a small cell LTE network and a wireline PON backhaul.

Two orthogonal possibilities are investigated: switching off cells voluntarily to save power, and loosing part of the cellular network due to failure of the underlying PON. Both of these lead to a reduced number of active cells, but also both can have a negative effect on the QoS and the availability of network services. In the first case the switch-off algorithms need to consider these effects, while in the second case the PON topology can be adapted to mitigate them.

B. Related Work

Several previously published papers cover partially the topic of this one. [3] and [4] investigate a similar hybrid wireless-optical access network, the main difference being the wireless part is a multi-hop wireless mesh network and backhaul failures are not investigated. [5] also investigates a hybrid access network consisting of a PON and Wireless Fidelity (WiFi). It focuses on the trade-off between throughput and power consumption. [6] analyzes the QoS in an LTE access network combined with different optical backhaul solutions.



(a) Cells (b) PON

Fig. 1. Scenario

[7] considers selective switch-off with a focus on transients between states.

II. System model

A. Network architecture

Figure 1 shows the scenario evaluated in this work. Figure 1a illustrates the wireless part. This consists of 24 rows (henceforth streets) with 10 cells in each. That is 240 cells in a regular hexagonal grid.

Figure 1b illustrates the PON connecting the cells to the core network. The leftmost node represents a 6 port OLT. The 6 direct neighbors of this node represent the 6 splitters. The rest of the nodes are ONUs which connect the cells to the PON. Each OLT port serves 4 streets, that is 40 ONUs/cells. The fibers leading from a splitter to a given ONU are not depicted separately for visual clarity.

B. Selective switch-off

We devised two strategies for switching off unneeded cells, in order to save power.

The first strategy is based on the set covering problem [8]. The elements to be covered are the User Equipments (UEs), while the sets to choose from consist of the UEs covered by a cell. This optimization problem is solved periodically, and the cells corresponding to the minimum covering sets are kept active, the others are switched off.

We defined three variants of this method. The first one (SCP-1) is the set covering problem as is. Here the objective is to select a minimum number of cells so that all UEs are covered by at least one cell.

$$\min \sum_{j \in \mathcal{C}} x_j \tag{1a}$$

subject to:

$$x_j \in \{0,1\} \qquad \forall j \in \mathcal{C} \tag{1b}$$

$$\sum_{j: i \in \mathcal{U}_j} x_j \geq 1 \qquad \forall i \in \mathcal{U} \tag{1c}$$

where $\mathcal{C}$ is the set of cells, $\mathcal{U}$ is the set of UEs, and $\mathcal{U}_j$ is the set of UEs inside the coverage area of cell j. Variable x_j indicates whether cell j should be turned on, or off.

In the second variant (SCP-2) we require that each UE is covered by two cells. This formulation only differs in one constraint from the above. Instead of (1c) one must use (2a).

$$\sum_{j: i \in \mathcal{U}_j} x_j \geq 2 \qquad \forall i \in \mathcal{U} \tag{2a}$$

In the third variant (SCP-3) we require that each UE is covered by two independent cells, that is two cells in different streets.

$$\min \sum_{j \in \mathcal{C}} x_j + K \sum_{i \in \mathcal{U}} s_i \tag{3a}$$

subject to:

$$x_j \in \{0,1\} \qquad \forall j \in \mathcal{C} \tag{3b}$$

$$y_{ik} \in \{0,1\} \qquad \forall i \in \mathcal{U}, \forall k \in \mathcal{S} \tag{3c}$$

$$\sum_{j: i \in \mathcal{U}_j, j \in \mathcal{C}_k} x_j \geq y_{ik} \qquad \forall i \in \mathcal{U}, \forall k \in \mathcal{S} \tag{3d}$$

$$y_{ik} \geq x_j \qquad \forall i \in \mathcal{U}_j, j \in \mathcal{C}_k \tag{3e}$$

$$\sum_{k \in \mathcal{S}} y_{ik} \geq 2 - s_i \qquad \forall i \in \mathcal{U} \tag{3f}$$

$$s_i \geq 0 \qquad \forall i \in \mathcal{U} \tag{3g}$$

where $\mathcal{S}$ is the set of streets, and $\mathcal{C}_k$ is the set of cells in street k, K is a large enough number so that the second term dominates the objective, while the rest of the notation is the same as before. Here variable y_{ik} indicates whether UE i is covered by some cell of street k or not. Variable s_i ensures that the problem has a solution even if not all UEs can be covered by at least two cells in different streets. Its large coefficient in the objective ensures that in an optimal solution $\sum_{i \in \mathcal{U}} s_i$ is minimized.

The second method is based on an assignment problem. It tries to assign each UE to a cell in a way that no cell is overloaded. For each UE-cell pair it calculates how many Resource Blocks (RBs) would it take to satisfy a given throughput demand if the UE would be served by the given cell.

$$\min \sum_{\forall j} y_j + K \sum_{\forall j} s_j \tag{4a}$$

subject to:

$$x_{ij} \in \{0,1\} \; y_j \in \{0,1\} \qquad i \in \mathcal{U} \; j \in \mathcal{C} \tag{4b}$$

$$y_j \geq x_{ij} \qquad \forall i \in \mathcal{U} \; \forall j \in \mathcal{C} \tag{4c}$$

$$\sum_{\forall i} x_{ij} \geq y_j \qquad \forall j \in \mathcal{C} \tag{4d}$$

$$\sum_{\forall j} x_{ij} = 1 \qquad \forall i \in \mathcal{U} \tag{4e}$$

$$\sum_{\forall i} x_{ij} D_{ij} - s_j \leq R \qquad \forall j \in \mathcal{C} \tag{4f}$$

$$s_j \geq 0 \qquad \forall j \in \mathcal{C} \tag{4g}$$

where $\mathcal{U}$ is the set of UEs, $\mathcal{C}$ is the set of cells, R is the number of resource blocks, D_{ij} is the number of resource blocks required by user i if connected to cell j, and K is a large enough number so that the second sum dominates the objective. Variable x_{ij} indicates whether UE i is assigned to cell j, or not. Variable s_j ensures that the problem has a solution even if there are not enough RBs to satisfy all demands.

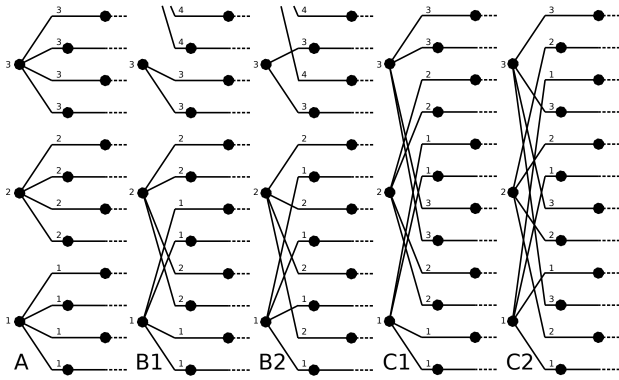


Fig. 2. PON topologies

This method has a parameter, which is the throughput which it tries to allocate for all UEs. The value of this parameter influences the calculation of D_{ij}.

C. PON tree failure

The failure of a tree in the PON network causes the failure of a large number of cells. To mitigate the effects of this the PON trees can be formed in such a way that the cells of a single tree are spatially distributed. That is, even if a given number of cells fail, at least they should be spread out, and not concentrated to the same area.

Besides the simplest solution (named topology "A") depicted in Figure 1b, we evaluated four others. Figure 2 shows the scheme in which the streets are assigned to OLT ports. Note that the figure shows only the first cell of each street, and only the bottom 12 streets.

- In topology "A" 4 neighboring streets are connected to the same OLT port. This will be a worst-case scenario, since in case a tree fails, all the affected cells are in the same rectangular area.
- In topology "B1" the streets are assigned to OLT ports in blocks of two, where a block consists of two neighboring streets. Then every second block is connected to the same OLT port.
- In topology "B2" every second street is connected to the same OLT port.
- In topology "C1" the streets are assigned to OLT ports in blocks of two, where a block consists of two neighboring streets. Then every third block is connected to the same OLT port.
- In topology "C2" every third street is connected to the same OLT port.

III. EVALUATION

This section presents a performance analysis regarding power consumption, throughput and availability of the previously described access network instance.

The scenario used for evaluation is deployed over an area of $1.892\,km^2$. The scenario covers 24 vertical streets with 10 cells in each. The distance between two cells in a street is $173.21\,m$. The distance between neighboring streets is $50\,m$.

TABLE I. SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
#eNodeBs	240	UE Ant. Gain	$0\,dBi$
Sectors per eNodeB	1	UE Ant. Pattern	Omni
Site-to-site distance	$173.21\,m$	UE Ant. Height	$1.5\,m$
Carrier Frequency	$2.0\,GHz$	UE Noise Figure	$9\,dB$
Channel Bandwidth	$10\,MHz$	UE Body Loss	$0\,dB$
Duplexing	FDD	Type of Service	Full buffer
Frame Duration	$1\,ms$	Min Service BR	$2\,Mbps$
RBs	50	Shadowing s.d.	$8\,dB$
OFDM Data Symbols	11	Correl. shadow. dist.	$50m$
BS Tx Power	$30\,dBm$	Intra BS correl.	1.0
BS Ant. Pattern	Omni	Inter BS correl.	0.5
BS Ant. Height	$4\,m$	Path Loss Model	COST Hata
BS Noise Figure	$5\,dB$	User Distribution	Uniform
BS Cable Loss	$3\,dB$	FRS	reuse 3

TABLE II. DEVICE POWER CONSUMPTION [12]

Device	Active	Inactive
eNodeB	$14.7\,W$	$4.3\,W$
ONU	$10\,W$	$1\,W$
OLT (per port)	$12\,W$	-

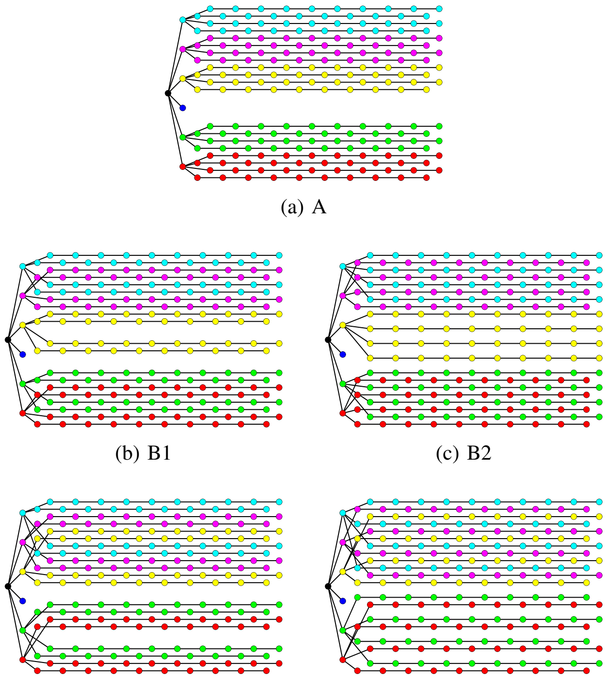
Users are placed uniformly distributed within the scenario area and move along random waypoints according to a pedestrian mobility model based on [9]. The simulations were done with 100 to 500 UEs in the scenario. A full buffer model is used to simulate the traffic of users, i.e. there is always data available to be transmitted for a user. Furthermore, all users have a throughput demand of $2\,Mbps$.

Only downlink transmission is simulated. We applied a Frequency Reuse Scheme (FRS) of 3, that is each eNodeB is restricted to a third of the available frequency resources. Inside this one-third band round-robin scheduling is used to assign RBs to the UEs. More details about the dynamic System-Level Simulation (SLS) tool used for this experimental evaluation can be found in [10]. The simulation parameters and scenario are presented in Table I and Figure 1, respectively. Path loss was modeled according to the COST Hata model. Further details of the simulator can be found in [11]. $30\,min$ of network functioning was simulated. Samples of power consumption, throughput, availability and other indicators were taken every $30\,s$.

When calculating the power consumption we assume that when switching off a cell then the corresponding ONU is set to the inactive state as well. We also assume that when a PON tree fails the affected ONUs and cells enter the inactive state. The power consumption of each network element can be found in Table II. Note that in this paper the terms inactive state, sleep state, and switched off are used as synonyms. They indicate a state of the device, in which it does not perform its usual function, but consumes less energy, and is able to recover from fairly quickly.

When evaluating the effect of a failed PON tree, we assume that the failed three is the one rooted at the 3rd splitter (counting from below; see Figure 1b and Figure 3).

The average solution time of the ILPs was $0.01s$ for the SCP problems, and $47.23s$ for the AP problem (300 UEs, Intel Xeon E5645 CPU).



(a) A

(b) B1

(c) B2

(d) C1

(e) C2

Fig. 3. PON topologies after tree failure

A. Power consumption

Figure 4 shows the average power consumption. These results were obtained using the “C2” topology. The first bar shows the case when there is no selective switch-off. This yields the maximum power consumption, since every device is always turned on.

The next six bars show the power consumption with the three different variants of the SCP selective switch-off method enabled. The last ten bars correspond to the AP selective switch-off method with different UE throughput demands. Both in case of SCP and AP the first half of the bars shows the power consumption with 200 UEs in the scenario, while the second half of the bars shows it for 400.

In all cases the power consumption increases with the number of UEs in the scenario, since having more UEs decreases the chance that a cell can be turned off.

When considering the three variants of SCP one can see that requiring a two covering cells (SCP-2) instead of one (SCP-1) slightly increases the number of required active cells, while requiring two independent covering cells increases it sorely. This can be explained by the distances between streets and the distances between cells in the streets.

When considering the AP selective switch off method with different UE throughput demands one can see that for guaranteeing more throughput increases the number of required active cells, and thus the power consumption too.

The effect of the PON topologies and tree failure was not depicted in the figure, because they are easily explained. A failed tree decreases the power consumption proportionally (40 out of the 240 cells are permanently inactive). Otherwise the trends are the same as in the case without failure.

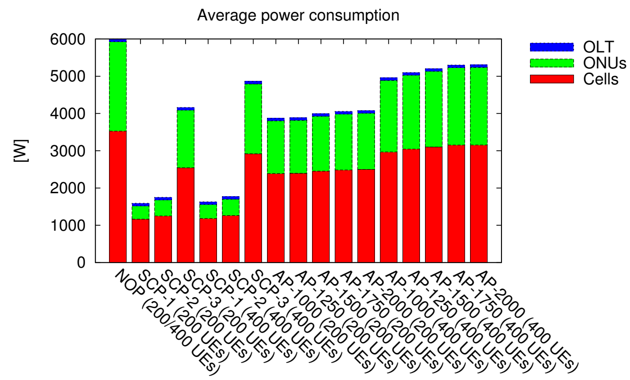


Fig. 4. Average power consumption

TABLE III. NEIGHBORING TREES OF THE FAILED ONE

	1	2	3	4	5	6
norm.	18.77	17.68	16.71	17.42	17.29	12.13
A	17.24	**28.05**	0.00	**24.50**	16.87	13.34
B1	17.18	**23.79**	0.00	**27.87**	17.60	13.56
B2	17.76	**18.86**	0.00	**30.66**	17.97	14.75
C1	**19.11**	**27.10**	0.00	**21.02**	18.76	14.00
C2	**26.96**	**21.76**	0.00	**19.73**	17.38	14.17

B. PON load after tree failure

In case a PON tree fails, the remaining trees need to carry additional traffic. The distribution of this additional load is of interest, since it can overload some trees.

Table III shows the percentage of UEs connected to the 6 trees. The first row corresponds to the case when all trees are functioning, while the rest of the rows show the cases when three no. 3 failed for different PON topologies.

In case there is no failure the load of the 6 trees is approximately the same, as expected. In case of topology “A”, “B1” and “B2” the additional traffic is shared by two trees (2 and 4). The sharing is most imbalanced in case of “B2”, where tree no. 4 handles most of the UEs of the failed tree. While in case of “C1” and “C2” the additional traffic is distributed among three trees (1, 2 and 4).

C. Availability

The availability of a UE reflects the probability that it can connect to the access network and through it reach the core network. The following figures show the distribution of the availability values computed for all UEs and all sampling time points during the simulation. The availability primarily depends on how many cells the UE is close enough to connect to. Moreover it results in a higher availability if these cells are connected to different PON trees.

It is to be noted, that if a UE can only connect to cells of a single tree, then its availability will be around 0.999. In case it can connect to at least two trees, it can achieve an availability of 0.999999.

Figure 5 shows how the availability depends on the PON topology in case the network is in working condition (norm.) and if there is a failed PON tree (ft.). This figure shows the results for 300 UEs, but the results for the other UE counts are very close to these. This is due to that the UE count affects

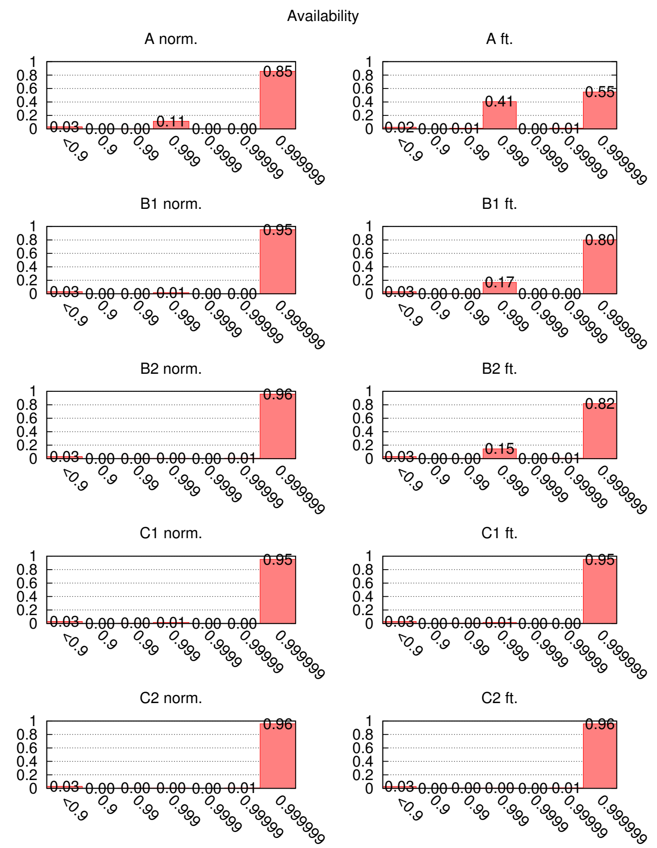


Fig. 5. Availability vs. PON topology (300 UEs)

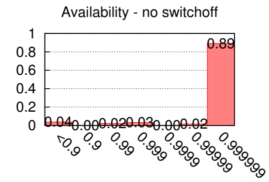


Fig. 6. Availability without switch-off (topology “C2”, 400 UEs)

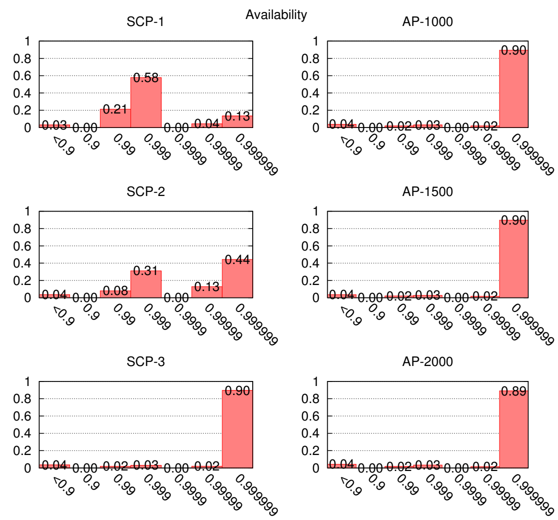


Fig. 7. Availability vs. selective switch-off (topology “C2”, 400 UEs)

only the number of availability samples taken. In case there is no failure, only topology “A” shows lower than 0.999999 availability for a significant percentage of samples. This is due to that large continuous areas are covered by the same PON tree. In case of the rest of the topologies, the UEs are able to connect to at least two trees. This changes when one of the trees fails (ft. cases). The availability for “A” gets worse, and it decreases for both “B1” and “B2” too, while for “C1” and “C2” it is unaffected. This can be explained by the properties of topology “C1” and “C2”. For these the areas of the failed streets are always surrounded by different trees from the south and from the north. This is not always true for “B1” and “B2”. While topology “A” has this favourable property, the area affected by the failure is just too wide.

In case the PON tree failure happens when one of the selective switch-off algorithms is enabled, the availability is affected similarly to the case without the failure. The impact of the tree failure and that of the switch-off on the availability accumulates, but the trends remain the same.

The selective switch-off schemes also influence the availability, since they reduce the number of active cells. Figure 7 shows the availability distribution for the SCP and AP schemes, while Figure 6 shows the same with all cells active all the time. The numbers for the “C2” topology are shown here. This topology was chosen, because it is one with the least impact on the availability due to the distributed nature of its trees.

In case of SCP-1, the availability distribution peeks at, and before 0.999. This is a consequence of SCP-1 trying to thin out coverage as much as possible. That is it covers the set of UEs with a minimum number of cells. This causes that most UEs are covered by one cell or by cells of the same tree. Compared to this the SCP-2 method slightly improves the availability, since it always ensures that each UE is covered by at least two cells. While the SCP-3 method provides the same availability as if all cells are switched on.

In case of the AP method the availability is always high regardless of the reserved UE throughput. This is because this method leaves active most of the cells. This can be seen from the power consumption figures too.

The effect of the number of UEs in the scenario is not depicted separately, but in case of all selective switch-off methods a higher number of UEs slightly improves the availability since the methods turn less cells off.

D. Throughput

These throughput histograms were computed the same way as the ones for the availability. That is a sample was taken for every UE and every sampling time point during the simulation.

Figure 8 shows the effect of a PON tree failure on the throughput for different topologies. While the difference not being substantial, topologies “B2” and “C2” are the least affected. These are the only two topologies, where the failed streets are never neighbors.

Figure 9 shows the impact of the selective switch-off algorithms on the throughput. The SCP-1 and SCP-2 methods severely limits the throughput due to taking into account only

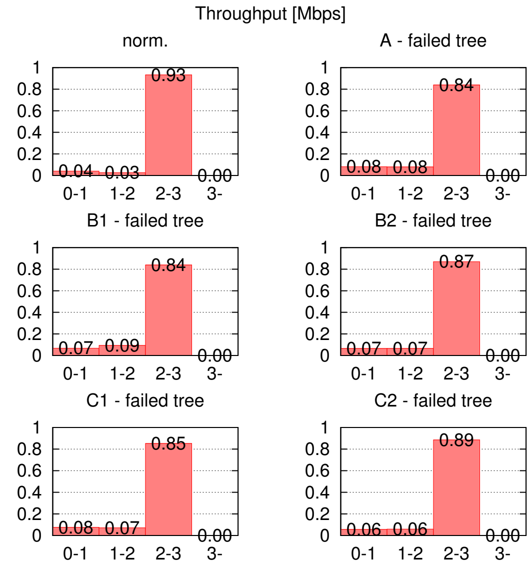


Fig. 8. Throughput vs. PON topology (100 UEs)

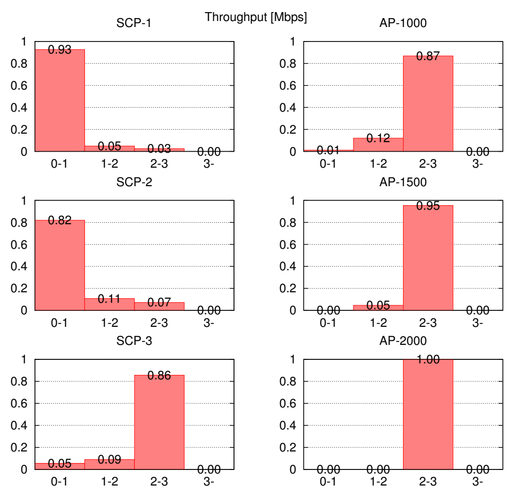


Fig. 9. Throughput vs. selective switch-off (200 UEs, topology "C2")

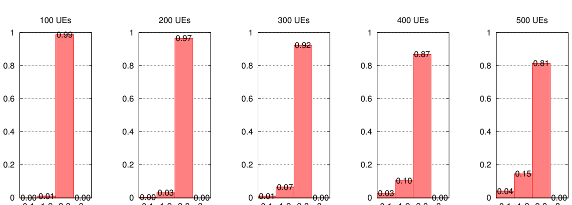


Fig. 10. Throughput vs. number of UEs (topology "C2")

that the UE is in the coverage area of the cell, which can leave many UEs at cell edges. The SCP-3 method affects the throughput to a lesser extent, because it leaves much more cells active. The AP method works as expected. If the allocation target is less than the UEs throughput demand, then it slightly impacts throughput, otherwise it does not affect it. The effect of the selective switch-off methods on the throughput remains the same even if there is a failed tree in the network.

Figure 10 shows how the number of UEs affects the throughput. As expected with the growing number of UEs less and less of them has its $2\,Mbps$ demand satisfied.

IV. Conclusion

The results of the system-level simulations show the following evidence about the implications of selective switch-off techniques and the choice of PON topologies:

PON topologies with spatially distributed and interleaved trees can help achieving higher availability and better excess load distribution for both cells and PON trees. For PONs serving as backhaul for cellular networks possessing such property is especially favourable. The drawback of such topologies might be increased complexity and longer cabling.

When applying selective switch-off algorithms it is not enough to consider UE locations on the level of whether they are within the coverage area of a cell or not. Turning off cells so that many UEs are left on cell edges is detrimental to service quality.

The availability is more susceptible to cells disappearing (either due to failure or switch-off) than the throughput.

Acknowledgment

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