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Modeling of Bandwidth Aggregation over Heterogeneous Wireless Access Networks

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Abstract

Motivated by the multihomming capability of the mobile devices and the fact that the heterogeneous wireless access networks overlap in coverage, mobile operators are looking for solutions that will benefit by simultaneous use of the available multiple access interfaces. Multipath or multilink transfer deals with the problem on how to effectively aggregate the bandwidth by simultaneous usage of heterogeneous networks that a host is attached to in order to improve the throughput.

This paper deals with a simulation based analysis of bandwidth aggregation techniques and their impact on higher layer applications. The analysis is performed on a multipath model developed with OPNET Modeler, which is an advanced research tool that supports modeling and integration of various kinds of built-in networks.

Introduction

Recently developed reach multimedia applications and real time services for mobile users require a large traffic throughput and consequently much higher bandwidth utilization[1][2]. On the other hand, the existing wireless technologies and providers differ widely comparing their capabilities to offer wider coverage, sufficient bandwidth, consistent QoS, corresponding billing etc. Furthermore, most of the wireless mobile interfaces today are able to support the multihomming concept. This means that the mobile stations have an ability to simultaneously connect to different overlapping access networks in the heterogeneous environment while maintaining separate IP addresses for each network they are connected to. In order to fully satisfy the needs of mobile users, these three facts inevitably lead toward a need of a heterogeneous platform where advantages and disadvantages of each network, device, or application will compensate from each other and the user will get the most/best of the available resources offered by the actual momentum of the heterogeneous environment. For example, the ability to establish a new connection to a stronger network, while keeping the connection with the fading network, allows for a seamless vertical transition through the heterogeneous environment.

Thus, the multiple network coexistence within a single user multihomming interface opens a wide area of research possibilities in the field of performance aggregation across heterogeneous networks. Topics like the above mentioned mobility handoff support, bandwidth aggregation support for demanding applications, load balancing, strict reliability support, resource sharing etc. are of high importance. One appropriate approach of investigating the performance aggregation in a given network constellation is to model and simulate such a constellation under various relevant conditions and then to analyze the obtained results.

OPNET modeler, as an advanced research tool, enables modeling of various kinds of networks and currently provides models supporting LTE, WLAN and WiMAX standards. For the purpose of this paper we have developed an OPNET model suitable to provide the means for simulation based analysis of bandwidth aggregation techniques at the network layer over two heterogeneous wireless links. As for simulation, an UDP based application has been considered while the impact on higher layer applications is analyzed through packet reordering metrics.

This paper is organized as follows. Section II defines the bandwidth aggregation problem. The required process models are described in the following three sections. Section VI and VII present the node and the network models. Section VIII presents the simulation parameters. A discussion of the simulation results is provided in Section IX. Concluding remarks and future work directions are offered in the last section.

Bandwidth Aggregation-Problem Statement

Bandwidth aggregation deals with the problem on how to successfully aggregate the throughput over two or more heterogeneous links. Heterogeneity and the dynamics of access networks over which the multilink transfer is achieved present the main challenge in achieving bandwidth aggregation. The following characteristics can be summarized as main issues:

- Asymmetric link characteristics (uplink and downlink) of each wireless channel,
- Fluctuation of wireless channels due to interference, mobility,
- End-to-end delay variation,
- Inconsistent QoS provisioning,
- Different billing systems, etc..

When packets are sent over different wireless access networks, they experience different delays due to the above mentioned issues. Thus, packet reordering is higher than in the case when single access network is used. For TCP application, packet reordering can be misinterpreted as lost packets, which will invoke the congestion control at the TCP sender and impact the calculations for the round-trip time (RTT). As a result the sending rate will be decreased [4]. Therefore, the packet reordering needs to be reduced in order to ensure improved application throughput. This paper considers a sender side solution where the sender is responsible for scheduling packets over the multiple links so that the packet reordering is reduced. The basic architecture for multilink transfer for this solution consists of the following three modules:

- Path monitoring tool,

- Packet scheduler, and
- Buffer management module.

The following three sections describe these three modules and their process models.

Path Monitoring Tool

The path monitoring tool is required in order to obtain an estimation of the throughput and the latency of the individual links. This is used as an input to the packet scheduler. Deciding on the path monitoring tool is of importance as it has impact on the accuracy of the estimation, as well as on the amount of overhead that is introduced to the system.

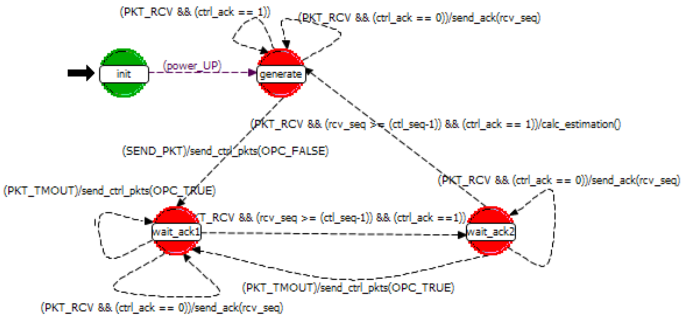

Figure 1. Path Monitoring Process Model

Figure 1 shows the process model of the path monitoring tool. It is based on the packet pair technique [5]. The basis of the algorithm is the following. Two packets of the same size are sent immediately one after another (state generate). The receiver sends acknowledgements for each received packet. The difference between the sending time and the first received acknowledgement presents the RTT delay for the link (state wait_ack1). The time difference between the two acknowledgements indicates the data rate (state wait_ack2) which can be estimated by dividing the packet size with the time that elapses between the receptions of the two acknowledgements. In order to make more precise estimation, 10 last values for the RTT and bandwidth estimations are kept and then an average is calculated (the transition from wait_ack2 and generate state). For this process model two events can happen: a generation of control packets (user defined packet size and sending rate of packet pairs) as well as a timeout that defines the time interval for lost packets and/or corresponding acknowledgements.

Buffer Management

As the data rates and the packet delay are estimated with a certain error, packet reordering will still exist but in lower order. The buffer management is required at the receiver side in order to hide the possible packet reordering from the higher layer.

Figure 2 shows the process model for calculation of reorder metrics. In particular, RFC 5236 [6] metrics was used to show the magnitude of disorder in the received sequence for different types of bandwidth aggregation algorithms. Two metrics have been implemented, namely *reorder entropy* and *reorder buffer occupancy density*. Reorder entropy (RE) is based on the reorder density (RD), and it is calculated according the following formula $RE = -\sum_{i\in D}(RD_i * \ln(RD_i))$ [7]. Reorder entropy expresses the total disorder of a sequence as well as the degree of the displacement. The displacement is expressed through the reorder density which actually shows how many packets have a certain displacement. For example in the sequence {2, 1, 5, 4, 3} packet with sequence number 2 has displacement -1 as it was received earlier, while packet with sequence number 3 has displacement 2 as it was received 2 places later. A certain threshold is defined in order to deal with lost packets. This threshold governs the max and min displacement, thus reducing the memory requirements and computation complexity. Reorder buffer occupancy density expresses the distribution or the frequency of the size of the buffer that is required in order to reduce the disorder at the receiver side.

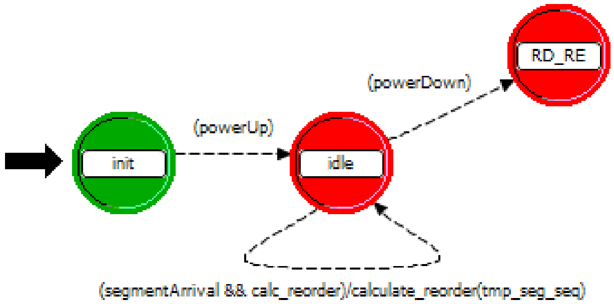

Figure 2. Reorder Metrics Process Model

Packet Scheduler

The packet scheduler needs to dynamically adapt to the network conditions. The packet scheduler schedules packets on each path based on the throughput and the delay estimations from the path monitoring tool. At this stage of the project, the Round Robin (RR), the Weighted Round Robin (WRR) and the WRR with a buffer at the sender side (Buff_WRR) algorithms have been implemented. The purpose of this project is to show that bandwidth based scheduling improves the packet reordering. Additionally we show that the estimation of the RTT is also important and can cause lower aggregated bandwidth and higher packet reorder. Algorithms like Earliest Delivery Path First (EDPF) [2], which consider the propagation delay, will be considered and implemented later as this model is further improved.

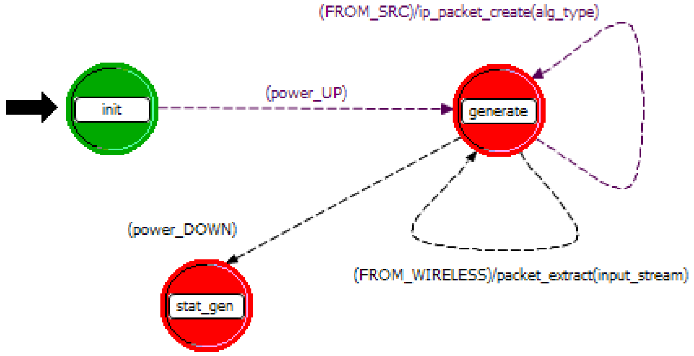

Figure 3. Bandwidth Aggregation Process Model

The process model is shown in Figure 3. Beside that it deals with the packet scheduling, this process dynamically creates the processes described above: path monitoring processes for each link at the sender node, and reorder metrics process at the receiver node.

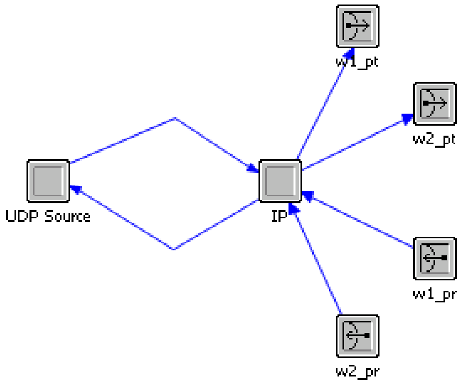

Figure 4. UE Node Model

Node Models

The node model of the UE is depicted in Figure 4. The node model of the element in the core networks that can accept packets from two separate streams is symmetrical, and, instead of UDP Source element, it has a UDP Sink element that collects statistics such as throughput and packet delay.

Networks and Wireless Link Models

The network model is simple and consists of two nodes: UE and core element, connected with four simplex point-to-point links.

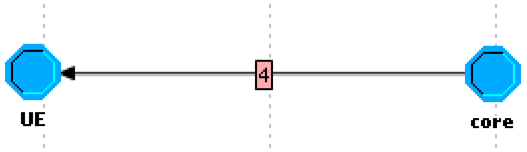

Figure 5. Network Model

At this stage of the project the wireless links have been abstracted with point-to-point transceivers. Namely four links have been defined: wireless1 uplink and downlink, and wireless2 uplink and downlink paths. The reason for separating the downlink and uplink is to introduce difference in the uplink and downlink delay for each link separately. Two pipeline stages have been identified as crucial to this project: the transmission delay and propagation delay.

Simulation Parameters

The data rate at the UDP Source is set to 6 Mbits/s, while at the path monitoring tool it is set to 12.5 Kbytes/s for all conducted simulations. Several scenarios have been considered, and their settings are presented in Table 1.

		wireless link 1	**wireless link 2**
Simulation run 1	**Scenario 1**	*data rate*	
		const. 1 Mbits/s	const. 5 Mbits/s
		propagation delay	
		0	0
	Scenario 2	*data rate:*	
		const. 2 Mbits/s	const. 4 Mbits/s
		propagation delay	
		0	0
Simulation run 2	**Scenario 3**	*data rate*	
		const. 1 Mbits/s	const. 5 Mbits/s
		propagation delay	
		normal dist. (90ms, dev 5ms)	normal dist. (10ms, dev 5ms)
	Scenario 4	*data rate*	
		const. 2 Mbits/sec	const. 4 Mbits/sec
		propagation delay	
		normal dist. (90ms, dev 5ms)	normal dist. (10ms, dev 5ms)

Table 1. Simulation Parameters

Simulation Results

Figure 6 shows the average throughput achieved with the multilink transfer, while Figure 7 and Figure 9 show the average end-to-end delay. In the first simulation run, the two algorithms "WRR" and "Buff_WRR" achieve the maximum possible aggregated throughput. The RR algorithm achieves relatively high aggregated throughput, but the average end-to-end delay for this algorithm is very high.

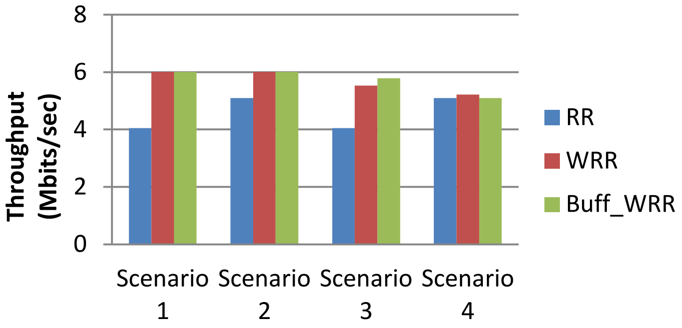

Figure 6. Average End-to-End Throughput

In the first two scenarios, the "RR" algorithm utilizes link1 to the maximum, while link 2 is under-utilized and therefore, the aggregated throughput is 4 and 5 Mbits/s. The average end-to-end delay on link2 is low, but because link1 is loaded with higher data rates that it can support, the total average end-to-end delay is high. Figure 7 shows that both "WRR" and "Buff_WRR" have low end-to-end delay. The delay is higher at the "Buff_WRR" algorithm due to the fact that some of the packets are additionally delayed at the sender.

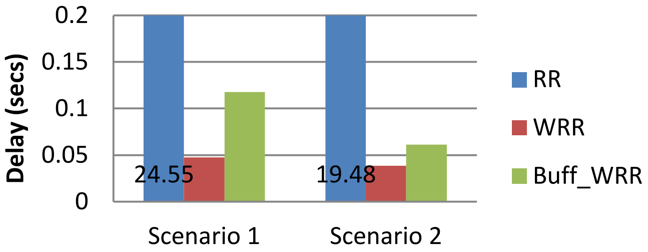

Figure 7. Average End-to-End Delay

Figure 8 shows the buffer occupancy at the receiver side for Scenario1. Similar results were achieved for Scenario 2. This figure shows that for the "RR" algorithm a larger buffer is required in order to hide the packet reordering from the higher layers. If the buffer size is reduced, the packet loss will be higher compared to the other two algorithms. The buffer is least occupied with the "Buff_WRR" algorithm, but this algorithm requires a buffer at the sender side as well. "Buff_WRR" algorithm reduces the requirement for the buffer size at the sender, which on the other hand can prevent scalability issues. Additionally, this algorithm reduces the packet reordering as it can be seen through the reorder entropy shown in Figure 8.

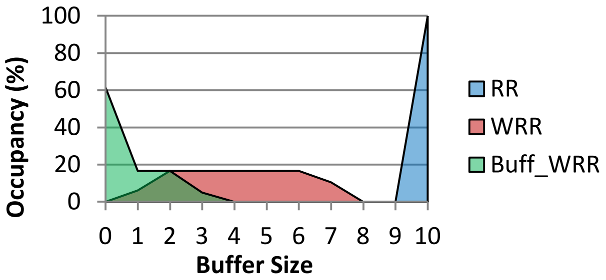

Figure 8. Buffer Occupancy Density (Bandw. Ratio 1:5)

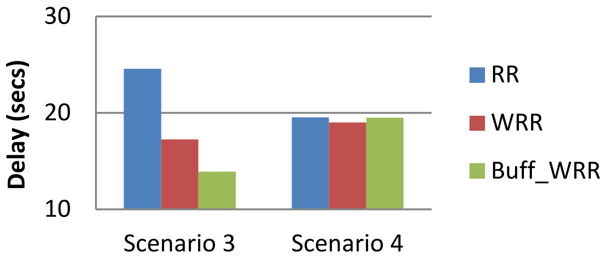

Figure 9. Average End-to-End Delay

In the second simulation run, propagation delay was included as normally distributed delay for each link. The obtained results show that the propagation delay has high impact on the aggregated performances. As it can be seen from Figure 6 and Figure 9, the averaged throughput and delay are still better with the "WRR" and "Buff_WRR" algorithms compared to the "RR" algorithm. But, the average delay is very high and it should be in the order of 200 ms or lower. Therefore, the scheduling algorithm needs to not only consider the bandwidth ratio, but also the propagation delay. Algorithms like EPDF that consider the propagation delay can be used in order to improve the delay performance.

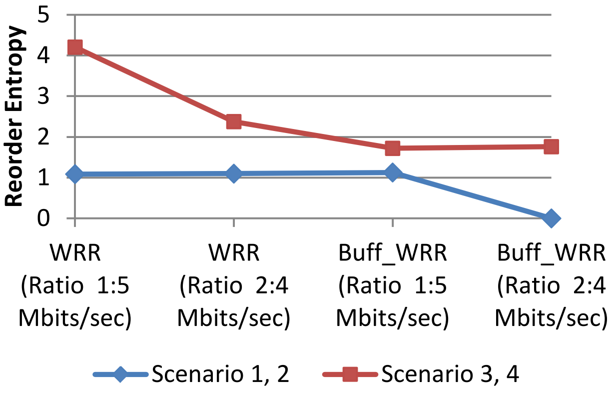

Figure 10. Reorder Entropy Comparison

The purpose of this simulation run is to show that the packet reordering can be increased when the propagation delay is not considered in the bandwidth aggregation algorithm. This can be depicted in Figure 10, where the increased out of order packet delivery is expressed through the reorder entropy metrics. The figure shows that when the propagation delay is not accounted, the overall degree of displacement is increased (red line). This means that the packets experience increased displacement in the sequence, and therefore larger buffers will be required at the received side in order to hide the packet reordering from the higher layers.

Conclusion and Future Work

This paper elaborates the design and implementation of a model for bandwidth aggregation over multiple links. Packed scheduling algorithms based on bandwidth estimations have been developed and estimated. The model includes reorder metrics that are used to analyze the impact on the higher layers. The reorder entropy metrics illustrates the degree of the disorder in a sequence, while the buffer occupancy shows the required buffer size at the receiver required to hide the reordering.

The results show that not only the bandwidth, but also the propagation delay characteristics of the individual links need to be considered by the scheduler. The comparison of the three algorithms indicates that, when packets are buffered by the scheduler, the packet reordering and consequently buffer requirements at the receiver are reduced.

The model should be further improved such that the wireless links abstraction is aligned with the existing wireless standards (LTE, WiFi) and various network conditions are to be considered. The scheduling algorithms that improve the QoS and include other requirements (for ex. load balancing) should be evaluated as well. Furthermore, the analysis can be enhanced by including the impact on specific service types, like video streaming or ftp service.

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