Network Coding with Association Policies in Heterogeneous Networks

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Abstract. *We focus on implementing a modified TCP/IP protocol stack by positioning network coding functionalities in the form of a new layer in between the transport and the network layer, thereby allowing incremental deployment. We implement this proposed modification for the TCP/IP stack in the OPNET Modeler and analyze implemented functionalities for heterogeneous wireless environments where a mobile user can connect to both LTE (Long Term Evolution) and WLAN (wireless LAN). In this context, we simulate various user-network association policies in such heterogeneous wireless environments with the goal of usage cost optimization under a Quality of Service (QoS) constraints. To this end we implement off-line and online decision policies in the OPNET Modeler and compare them in terms of throughput and usage cost. The results show that the network usage cost can be improved significantly by using a threshold-based online policy while remaining within the user's QoS requirements.*

Keywords: *TCP/IP protocol stack, network coding, incremental deployment, heterogeneous wireless environments, OPNET Modeler, user-network association, cost optimization*

1 Introduction

Network coding is a promising technique that provides benefits such as throughput improvement and loss resiliency [6], [7]. It has proven its merits over traditional routing approaches by mixing the information at packet level [6], [7], [8], [10]. It is a useful technique for reducing latency and retransmission overhead of lost packets for reliable delivery of packets in wireless networks [9]. We use the solution proposed in [1], [2] for realistic network coding and implement it in the OPNET modeler [11], a network simulator software with a complete protocol suite which is used widely in leading industries. The proposed solution introduces a network coding layer between the transport layer and the network layer of the protocol stack. This solution provides a clean interface of network coding layer with transport layer since addition of the new network coding layer does not require any change in the basic features of Transmission Control Protocol (TCP) [2].

On the other hand, a large variety of wireless technologies such as second-generation (2G), third-generation (3G) and pre-4G also known as Long Term Evolution (LTE) cellular, Wi-Fi/WLAN, and WiMAX are being widely deployed with the success of wireless and mobile communications. These heterogeneous wireless networks with multihome clients provide worldwide internet access by combining various wireless technologies [3]. Mobile devices with multiple wireless interfaces such as cellular and Wi-Fi are widely available in the markets. Therefore, when such a user equipment having access to such multiple networks (e.g. from a base station/an access point or a peer device), it must take decisions on associating with one or more such access networks. However, the usage costs for accessing these different networks might be different. For example, accessing the base station of a cellular network can result in additional charges per unit information, while it might be possible to receive the same information from the access point of a local Wi-Fi with a lower cost or possibly for free. However, the cellular network usually provides better reliability for the charges applied to the end user for the connection, whereas the Wi-Fi network does not guarantee the reliability. A user who requests for service would like to use free or less costly Wi-Fi connection as much as possible and to use costly network intermittently only to satisfy quality-of-service (QoS) demands. In [4] individually optimal user-network association in WLAN-UMTS networks has been studied under non-cooperative game framework. The mobile user decides only at the start to which network to connect depending on the estimate of expected service time required. In [3] authors propose data broadcast mechanism for network association and adaptive network coding problem based on Lagrangean relaxation and proves that these problems are NP-hard. These user-network association decisions can be optimal when decision process becomes stationary Markov with respect to the user's state [5].

The heterogeneous networks resemble multicast networks with a multicast receiver group considered as a receiver with heterogeneous connections. Random linear network coding asymptotically achieves capacity in multicast networks [10]. Also intuitively, a distributed random linear network coding will remove the need of coordination between these heterogeneous networks and will eliminate the intelligence required in routing methods to avoid reception of duplicate packets from these networks.

2 Simulation Scenario

Fig. 1 shows the simulation scenario created in the OPNET modeler. This simplified network model depicts the real network wherein a mobile user can connect to the cellular/LTE network and WLAN hotspots whenever available. These two networks are independent since the transmission activity in one network does

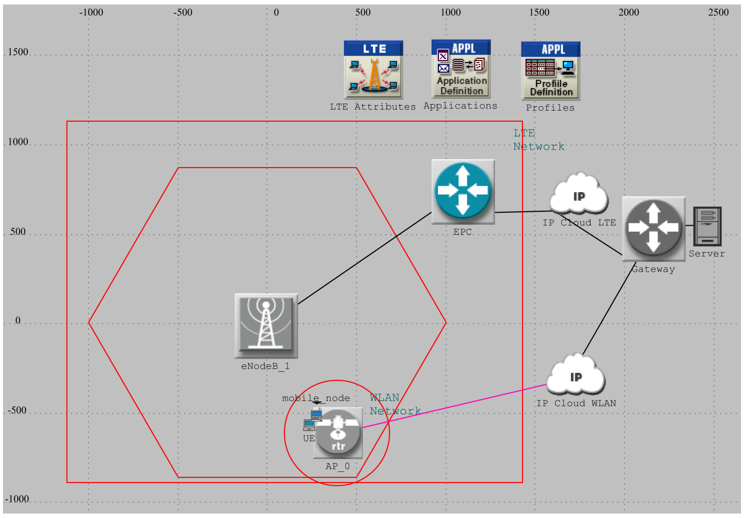


Fig. 1: Simulation Scenario created in OPNET Modeler.

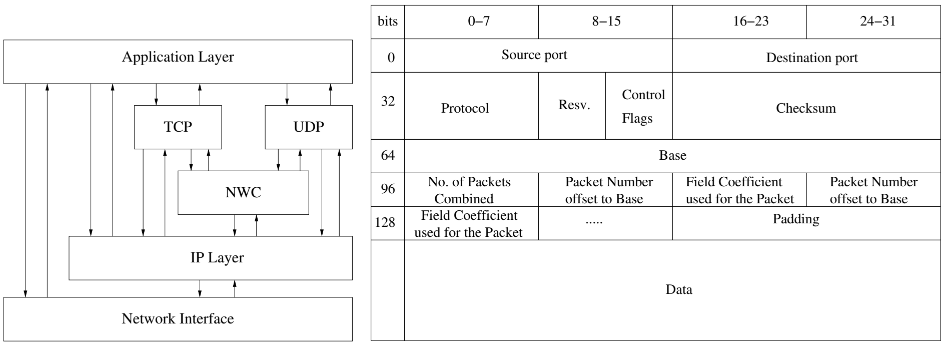
not create interference with the other [4]. The LTE network comprises of the Evolved Packet Core (EPC) and the Base station (eNodeB) connected to the EPC by wired link, whereas the WLAN network consists of the Access Point (AP) at the hotspot location and is connected to the internet service provider (ISP) via a router node. Out of the two mobile nodes shown, the UE can connect to the LTE network whereas the mobile node can connect to the WLAN network. They together in group are considered as one heterogeneous client which can connect to both the LTE & the WLAN network.

In such a heterogeneous environment, consider a user requesting a multimedia application from the server, for instance, a specific video file from YouTube. Such applications typically run as progressive downloads over Hypertext Transfer Protocol (HTTP) that run over TCP. The server divides a media file into chunks, which are then further divided into packets for transmission. Network coding is employed to mix these packets and combined packets are sent over these networks. The use of network coding eliminates inter-dependence between the two networks at the receiver side and packet re-ordering related issues. The user can demix the received randomly combined packets to construct original packets. After each complete chunk is received by receiver, it is given to the application for playout purpose. The absence of a chunk at the time of its playout would cause an interruption, which is to be avoided if possible. Thus, our goal is to investigate the performances of various user-network association policies in such a WLAN-LTE hybrid network based on a cost for download of the media file from server, aiming at a minimal use of the LTE network while remaining within certain required quality of user experience (QoE) constraints.

3 Implementation of Network Coding Layer in OPNET Modeler

3.1 Modified TCP/IP Protocol Stack Architecture

To bring network coding into practice, we need a protocol that can bring the results of network coding with very little changes to current protocol stack. To this end we rely on the architecture proposed in [1], [2] as shown in Fig. 2a and integrate in the OPNET Modeler. This newly introduced NWC layer masks the packet losses in the network from the TCP. We leverage the fact that the packets between the two peer NWC layers are delivered in a rate-less fashion, independent of the specific network interface.



(a) Modified Stack Architecture (b) Packet Format used by NWC Module

Fig. 2: Modified TCP/IP Protocol Stack.

3.2 Packet Format

Fig. 2b shows the packet format used by the network coding (NWC) module. This packet format is a modified version of the packet format used in [2]. The current packet format is packet-based as opposed to byte-based in [2] which helps in reducing header overhead. For a more detailed description, refer to [12].

There is a fixed part of the NWC header consisting of first 8 bytes shown in Fig. 2b which will be prepended to every incoming TCP packet. This will add 4 bytes of overhead (Note that the port information is not counted in this overhead, since it has been removed from TCP header). Whereas for TCP data packets which will be coded by the NWC layer, coding vector information has to be added as an extended part of header. This will add $(5 + 2n)$ bytes of overhead, where n is the number of source packets involved in the random linear combination. Typically, TCP segments have a length of around 1500 bytes and with maximum value of n taken as $n = 12$, the NWC header overhead per TCP segment will be 2.2% in contrast to 4.467% for the packet format proposed in [2] which adds $(7 + 5n)$ bytes of overhead for the network coding header.

Process Model The new process model is implemented for network coding protocol as described in [1], [2] without any significant changes in it. The sender NWC module generates and sends R random linear combinations of the packets in the coding window, where R is the redundancy parameter used. The coding window is the subset of the packets chosen from within the coding buffer where TCP packets are stored until they are ACKed by the receiver module. W is the fixed parameter used by NWC module for the maximum coding window size. The receiver NWC module retrieves original TCP packets by performing Gaussian elimination on received randomly combined packets. For more details about implementation in the OPNET Modeler, refer to [12].

4 Achieving Heterogeneity in OPNET Modeler

In the OPNET modeler, we can create multihome clients with multiple interfaces using the device creator utility. However, the OPNET Modeler does not support a construction of a heterogeneous client that can support LTE & WLAN technologies together. Hence, we use two separate node models that are already available in the OPNET Modeler, namely LTE workstation & WLAN workstation and group these two separate client nodes into one client forming a heterogeneous client. Here the WLAN client will behave as virtual client and deliver received packets over WLAN interface to the LTE client directly using OPNET kernel procedures. Similarly, for sending packets out, the LTE client can use the LTE interface as well as the WLAN interface by virtually delivering packets to the NWC module of the WLAN client and then the WLAN client will send these packets out. For this, another process model is defined in the OPNET modeler which will perform virtual delivery functions for heterogeneity and is assigned to the NWC module of the WLAN client. The LTE client will use the usual NWC process model. This solution can be considered as a virtual 'NWC' multicast where the LTE client and the WLAN client form the virtual multicast group.

Association Policies An association policy is a decision policy for user-network association in such a WLAN-LTE hybrid network based on an individual decision cost criteria, aiming at a minimal use of the LTE network while remaining within a quality-of-service (QoS) constraints.

A deterministic association policy [5] denoted by π is a Boolean function defined as

$$\pi(t) = \begin{cases} 0 \text{ if only WLAN network is used,} \\ 1 \text{ if both LTE \& WLAN networks are used,} \end{cases} \tag{1}$$

and the total cost associated with this policy is given by

$$C^{\pi} = C_{WLAN}.\tau + C_{LTE}. \int_0^{\tau} \pi(t)\mathrm{d}t, \tag{2}$$

where τ is the time required to download a file from the server and C_{WLAN} & C_{LTE} are the costs per unit time for using the WLAN and the LTE networks respectively. The optimization problem is to minimize the cost required to download a media file subject to QoS constraints. The metric for QoS can be defined in different ways such as: 1. time required to complete file download: $\tau \leq \tau^*$, 2. the probability of interruption in media playback: $p^\pi(t_{initial}) \leq \epsilon$, where $t_{initial}$ is the initial playout delay at the receiver.

Such several association policies are proposed in [5].All these policies discussed in [5] are implemented in the OPNET modeler. These implemented user-network association policies can be grouped as follows:

- Off-line Policies : The decision for association is made at the start of service use and is not changed during the use of service. User with this policy uses both the LTE and WLAN networks for the time period t_s from the start of the service use and after that it uses only the WLAN network.
- Online Policies : The decision for association is made online during the use of service depending on policy parameters. User with the threshold-based online policy uses the LTE network along with the WLAN network only when the receiver buffer size drops below the threshold value T, else it uses only the WLAN network.

In contrast to that work, here the time is assumed discrete as the OPNET Modeler is a discrete event simulator [11] and also the decision for association made at the user end is conveyed to the server node using remote interrupt method in the OPNET Modeler[11].

5 Simulation Results

We tested the performance of the proposed NWC protocol on a TCP flow running from a server to user that can connect to both the LTE and the WLAN network. The WLAN channel uses DSSS as modulation scheme and supports a bit-rate of 2Mbps. Link losses are modeled using IP cloud and are introduced before the wireless link (see Fig. 1). Hence, they will not be recovered by the link layer retransmissions, and have to be corrected by the layer above IP. The OPNET LTE Specialized Model supports Release 8 of the 3GPP standard. The LTE channel PHY parameters are set as default during simulations. (No packet losses are experienced in the LTE channel.) We assigned the application profile to the UE (the LTE client which is used as a real client) and mobile node (the WLAN client) is used as a virtual client for the UE to achieve heterogeneity. The assigned user profile uses FTP application traffic model from the OPNET standard model library which resembles YouTube traffic. We have chosen the NWC parameters as 1. redundancy factor, $R = 1.25$, and 2. maximum coding window size, $W = 4$. Note that TCP connection control procedures happen only through the LTE network for all the policies simulated.

We compared the off-line policies and the online policies with the limiting case of the off-line policy, where user is only using the WLAN network for all the time. We model the QoS parameters for the online policy as 1. Initial Playout Delay, $t_{initial} = 5$ seconds, and 2. Playout Rate = 240kbps.

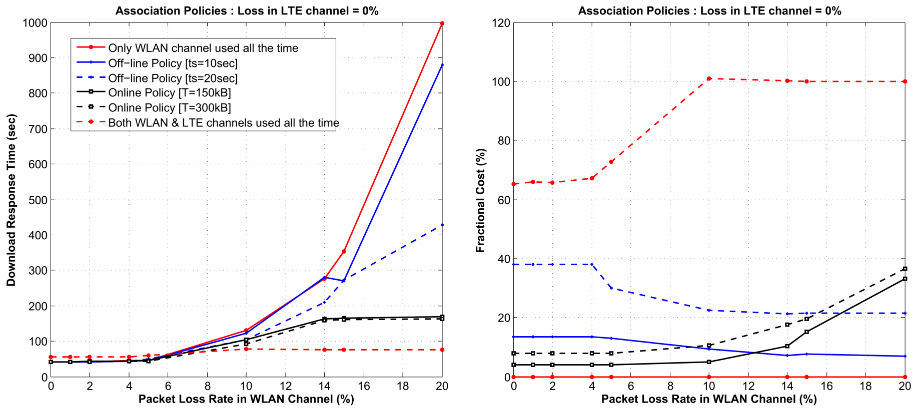


Fig. 3: Performance evaluation for various association policies.

The plot in Fig. 3 shows the performance comparison between various simulated association policies in terms of the download response time and the usage of the LTE network. The usage of the LTE network is shown as a fractional cost in percentage calculated as below:

$$\text{Fractional cost in } \% = \frac{\text{Total Cost associated with the policy used}}{\text{Total Cost if only the LTE network is used}} \times 100. \quad (3)$$

For above cost analysis, unit cost per received byte is assigned for the LTE network and the WLAN network is considered to be free.

From these plots we can see that the policy of using only the WLAN network for all the time is the upper bound for all other association policies in terms of the download response time and lower bound in terms of the cost for downloading a media file (here it is zero). In case of the association policies where the LTE network is used during a file-download process, the coded packets coming from the LTE network may help in the decoding process at the user side reducing the download response time. With very few losses in the WLAN network, less than 5%, as shown in the plot, network coding operations below TCP suffice for masking packet drops from the TCP and to achieve required rate and delay constraints at the user side. Hence the user will only use the WLAN network for usage cost optimization. (The receiver buffer dynamics for this situation is not included due to space limitation.) With increased losses in the WLAN network, to maintain the required rate and delay constraints at user side, the LTE network is used. With the off-line policy the LTE network helps only for the losses in the WLAN link during the time period of t_s at the start of application and the usage cost is incurred only for that time duration. The usage cost shows gradual decrease as the download response time goes up with increasing packet losses in the WLAN network.

With the online policy intermittent use of the LTE network helps to maintain the receiver buffer size at the threshold level guaranteeing QoS. With packet losses in the WLAN network, the receiver buffer size starts dropping and when it reaches the threshold value selected by the online policy, the decision is made by the user to use the LTE network. Then the combined use of the LTE network and the WLAN network helps the user to be within QoS constraints required. But the user has to pay for using the services from the LTE network. When the buffer size goes above the threshold value, the user decides to switch to the WLAN network only for which it does not have to pay. With increased losses in the WLAN network, the receiver buffer drops below the threshold size more often and hence the user will use the LTE network more and more increasing the usage cost. Look at Fig. 4 showing the receiver buffer dynamics for different losses in the WLAN channel and with the lossless LTE channel using the online policy with the threshold size = 300kB. But with online policy the download response time for a media file is still within the maximum download response time, τ_{max} = 5MB/240kbps = 166.67 seconds as per QoS parameters used as seen from the plot.

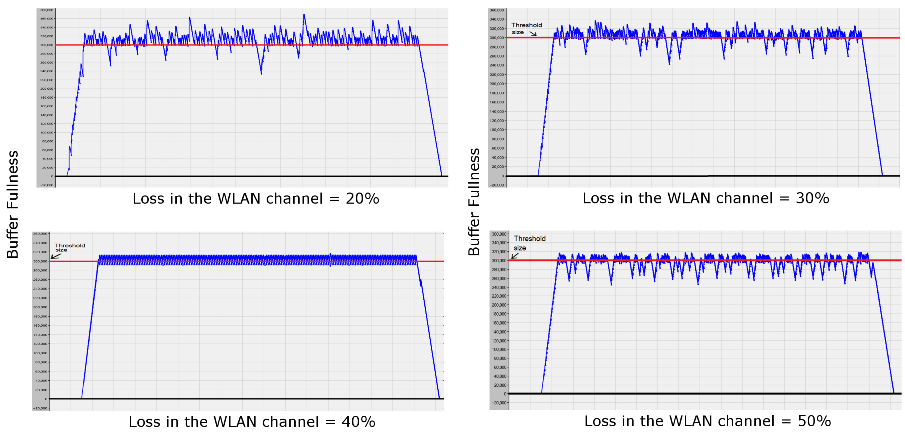


Fig. 4: Receiver Buffer Dynamics for a file download application with the lossless LTE channel using the online policy with the threshold size = 300kB.

The policy where the user use the LTE network and the WLAN network together for all the time, the usage cost incurred will be the maximum as shown in Fig. 3. Thus we can say that the usage cost is significantly improved by the online policy with a guaranteed QoS. Even with 20% losses in the WLAN network, the LTE network is only merely used, to maintain QoS, reducing the cost by around 65%.

6 Conclusion and Future Work

We simulated a media streaming application in the presence of LTE & WLAN networks and evaluated the performance in terms of the time required to download a media file and usage cost for using the services from these networks. User-network association policies such as off-line policies and online policies have been implemented for the purpose. The threshold-based online policy turns out to be an improved (possibly an optimal?) policy for which the network usage cost is significantly improved while remaining within the user's QoS requirements parameterized by initial waiting time and playout rate. The mere availability of costly LTE network as a backup network improves the experience of media streaming without incurring a significant usage cost. Even by just using the unreliable but free WLAN network (with unreliability modeled as packet losses up to 20%), the usage cost is reduced approximately by 65% with a guaranteed QoS.

Currently we have only simulated network operations with network coding performed on end hosts. We suggest to simulate network coding operations on intermediate network nodes for future work. Also we have simulated one TCP flow from server-to-client. Multiple TCP flows between server to same client node or server to multiple client nodes should be simulated to see the scalability of the system with and without re-encoding operations enabled on network nodes. The benefit of network coding of masking the losses in the network to achieve fast transmission of data and to avoid retransmissions of lost data gives us another choice for implementing network coding at the link layer. With this approach of implementation, a base station (eNodeB) in the LTE network and an access point (AP) in the WLAN network can also take part in network coding.

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