COBA: Concurrent Bandwidth Aggregation – A Case Study in Parallel Wireless Communications

Dilip Krishnaswamy, Danlu Zhang, Dirceu Cavendish, Weiyan Ge, Samir Soliman, Bibhu Mohanty, Srinivasa Eravelli
Qualcomm Research Center
5665 Morehouse Drive, San Diego CA 92121
{dilipk, dzhang, dirceuc, wge, ssoliman, bmohanty, eravelli}@qualcomm.com

Abstract— **Parallel Wireless Communications is an emerging area of research that enables mobile clients to access and utilize multiple wireless networks concurrently. This paper explores concurrent bandwidth aggregation techniques to enable parallel wireless communications on mobile devices. Concurrent aggregation can be performed using wireless modems on one device or cooperatively across devices within wireless proximity of each other.. The aggregation can be achieved on the application-layer, transport layer like MultipathTCP, or on layers below IP such as the RLC layer. These schemes are compared. In general, aggregation on the lower layer is closer to the client device and easier to adapt to the varying channel and loading conditions. However, lower layer aggregation needs more changes to wireless access stratum infrastructure. Aggregation above the IP layer is simpler to implement. A feasibility study of MultipathTCP aggregation over multiple WWANs is presented. The aggregation scheme on the RLC layer in evolved HSDPA is also presented, including protocol design and performance evaluation.**

Keywords- Parallel Wireless Communications; Concurrent Bandwidth Aggregation; Application-layer aggregation; MultiLink protocols; MultipathTCP; Multi-link RLC; Wireless Wide Area Networks; Heterogeneous Networks; Tunneling; Cooperation

I. INTRODUCTION

In recent times, mobile platforms have evolved significantly with parallel processing using multiples cores to support high performance computing. Wireless communications technology has also evolved providing higher performance compared to previous generations with the ability to use high bandwidth channels such as 20MHz or 40MHz bands with 802.11n or LTE technologies. Mobile operators may have limited spectrum available to deploy new wireless technologies, so that even though a 40MHz LTE technology may be available for deployment, only a 5MHz LTE may be actually deployed based on the contiguous available bandwidth in a given region. Now, while the available contiguous bandwidth may be limited, there may be multiple non-contiguous bands available for simultaneous usage. For example, an operator who has deployed a 5MHz HSPA network could deploy an additional 5MHz LTE system in a non-contiguous band. In addition, the performance in a wireless communication channel for a specific user is dependent on various factors including the width of the frequency band, the number of users simultanenously sharing the channel, their respective link conditions with access points or base-stations, and the overall load on the channel.

*Manuscript received March 9, 2012; accepted March 27, 2012

It would therefore be desirable to attempt parallel wireless communications over different wireless channels to utilize multiple available wireless channels in either contiguous or non-contiguous bands simultaneously to deliver higher performance to a given user. Different technologies can be used simultaneously such as the ones depicted in Fig 1 to enable parallel wireless communications using multiple wireless modems on one device. Multiple wireless modems across multiple devices that are within proximity of each other can also be used to enable parallel wireless communications. A client device can access any any available direct paths to wireless networks through its own wireless modems. In addition, multiple devices can bond together over p2p links for example, or a proxy device can expose a wireless access point to a client device, to enable an indirect path for the client device.

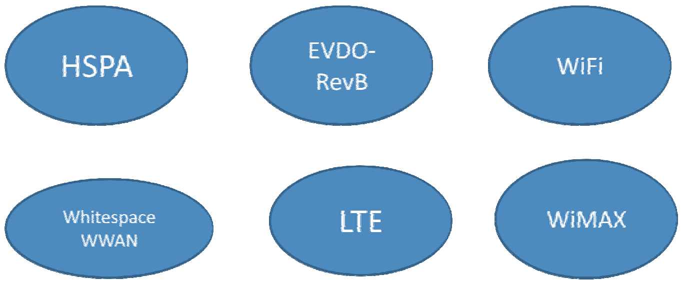

Figure 1: Network options for parallel wireless communications

Mobile devices are getting smarter with better ability to manage multiple wireless network connections simultaneously. In most cases, however, a mobile device utilizes only one preferred wireless data network connection at a time. Such a selection of a preferred wireless data network can be based on which data network has the least cost or has the better performance at a given location and time. This can be termed as *selective parallel wireless communications* so that the best available network is chosen, and if it becomes unaavailable, then the next best network is selected.

In addition to selecting a best network, it would be more desirable to select multiple networks for simultaneous usage. In such modes of operation, different applications on a device could use different network connections so that multiple networks could be used simultaneously. However, a given application or data stream may just use only one network at a time. This can be termed as *multi-stream parallel wireless*

doi:10.4304/jcm.7.7.524-537

communications. For example, some applications may use WiFi whereas other applications that may be mobile operator specific can continue to utilize a WWAN managed by the mobile operator. In this manner, different data streams or applications use different networks delivering higher overall communications performance on the platform. However, a single application or data stream is not able to utilize the multiple wireless network connections simultaneously.

In the most aggressive form of parallel wireless communications, it would be desirable to use multiple wireless network connections simultaneously for a single data stream or application. This can be termed as *single-stream parallel wireless communications.* This mode of operation for concurrent bandwidth aggregation (COBA) over multiple wireless networks using multiple paths across networks simultaneously for a single data stream is the primary focus of this paper.

A. Concurrent Bandwidth Aggregation

As more and more WWAN data technologies [1] become available and deployed around the world, on different frequency bands, it would be desirable to consider aggregation of services across multiple WWANs to improve the peak rate, throughput and latency performance for data applications delivered to a mobile device. Likewise, aggregation is also helpful across multiple carriers of the same WWAN technology, or across multiple cells on the same carrier. Aggregation across multiple WWANs typically necessitates aggregation above the IP layer. The client devices will have separate IP address for each of their network connections. Each of the wireless connections could happen over contiguous or non-contiguous frequency bands. It would be desirable to combine IP streams associated with each of the networks and corresponding IP addresses to aggregate performance across the networks for the same client. This paper addresses concurrent bandwidth aggregation (COBA) over heterogeneous WWANs using wireless modems on a mobile client device. Utilization of indirect paths via WWAN modems on neighboring client platforms over local p2p wireless links is also possible. Client devices can utilize licensed or unlicensed channels, and opportunistic whitespace channels as well. The connections could utilize different technologies [1][2] such as LTE+WLAN or HSPA+WLAN or WLAN + CDMA20001x-EVDO or LTE + WiMAX. Each of the network connections can have its own IP address, and the associated IP streams could be aggregated. For aggregation across carriers of the same WWAN technology, or across cells on the same carreir, aggregation could also be considered below the IP layer in the RAN, with a split and merge of traffic managed at an ENodeB (LTE) or an RNC (WCDMA, HSPA) or a BSC (CDMA2000) or an ASN-GW (WiMAX) or a Node B (HSPA) with the possibility of tunneling data between such nodes, if a multipath communication needs to be established using different technologies.

II. BENEFIT OF WWAN AGGREGATION

Fig. 2 shows the dynamic variation in actual throughput for a given user at a given location as time varied during the day on two different WWAN networks at a given fixed location. It can be observed that the performance varies significantly based on the number of users in the network. In general, a typical WWAN can have a cell spectral efficiency of ρ, where ρ may typically vary from 0.8 to 1.65 bps/Hz. Assuming a channel bandwidth of W, the total available spectral performance is ρW. Congestion on the network due to signaling and low bandwidth background traffic can reduce spectral efficiency dynamically. Various background applications running on these connected mobile devices can cause a reduction by a fraction η ("twitter inefficiency factor"). Then the effective dynamically available spectral efficiency in the system for true data transmissions is given by ηρ. Active users (N) are a subset of the connected users (M). If each connected user utilizes effectively δ bps in the system, then M connected users utilize Mδ bps of resources effectively. Therefore η is given by

$$\eta = (1 - M\delta / \rho W) \tag{1}$$

For a system with $\rho = 1$ bps/Hz, $W = 5$MHz, $\delta = 25$kbps, and $M = 100$, then $\eta = 0.5$. A WWAN S has a state determined by a quintuple (η, ρ, W, N, M), the number of active data users N, the average available performance for an active data user in the network is given by,

$$T_u(S) = \eta\, \rho\, W / N \tag{2}$$

Here ρ is the average spectral efficiency of the WWAN system assuming full resource availability, including codes, time slots, and power management.

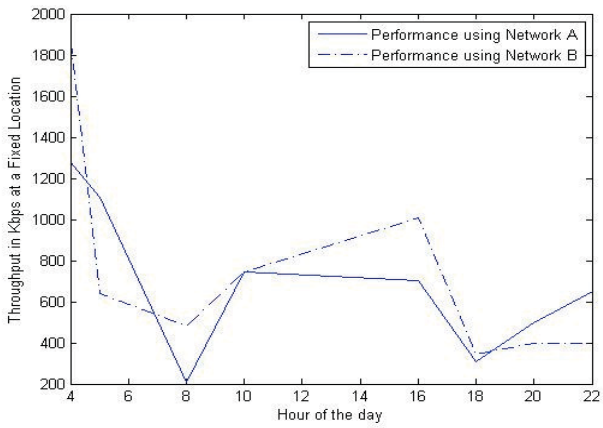

Figure 2: Dynamic Variation in Throughput vs. Time at a Given Location

For K WWANs with states $S_1, S_2, \ldots S_i..S_K$, where $(\eta_i, \rho_i, W_i, N_i, M_i)$ is the state S_i associated with the i^{th} WWAN, then the expected average aggregated bandwidth is given by,

$$T_u(S_1, S_2, \ldots S_K) = \Sigma_i\ \eta_i\, \rho_i\, W_i / N_i \tag{3}$$

It should be noted that equation (3) is just an average estimate of expected performance. The true performance of a specific user will be a refined estimate based on the dynamic link condition for each of the wireless links associated with the user, desired fairness of the schedulers in the networks, traffic patterns, and the network loading on each of the network connections considering an average spectral efficiency and twitter inefficiency associated with each of the networks. Additional performance could be obtained if non-WWAN networks are available (such as WiFi/Whitespace/DSL/Cable networks) for concurrent utilization.

One approach of evaluating the dynamic gain from aggregation is queuing analysis. Since data applications are inherently bursty [3], the user experience can be measured by the burst rate defined as the ratio of the burst size and the total time the burst stays in the system, including the transmission time and queuing time. As shown in [4], aggregation across networks, compared to static load balancing among the constituent networks, provides burst rate gains from statistical multiplexing. For example, when the data sessions arrive according to a Poisson process, as often the case, aggregation across N networks with identical capacity and equal loading results in N-fold burst rate increase. To understand this result, let us start from the simple M/G/1 system with a FIFO scheduler. Assuming the arrival rate in each network is λ, mean service time is T and mean service rate is μ=1/T. If the system employs a FIFO-like scheduler, the total burst delay is given by the classic Pollaczek-Khinchin (P-K) formula[5]:

$$T_{total} = T + \frac{\lambda \overline{t^2}}{2(1-\lambda T)} \qquad (4)$$

where *t* is service time with E[t]=T=1/μ. With aggregation, the system can be seen as another M/G/1 with (Nλ, Nμ), since the aggregation of multiple Poisson processes produces another Poisson process. Meanwhile, the mean service time is reduced to T/N and the second moment of the service time $\overline{t'^2} = \overline{t^2} / N^2$. It is easy to see that the average total burst delay is reduced to 1/N of its baseline value with equal loading λT<1. It is further shown in [5] that the N-fold burst rate gain is generally true for a wide range of scenarios of the channel conditions and scheduling mechanisms. The main argument is the following time-compression. Let the clock for the M/G/1 system with (Nλ,Nμ) run N-times as fast. All the arrival events in the (Nλ,Nμ) system have the same probability as in any one (λ,μ) system. If the same scheduling algorithm in the aggregated system of (Nλ,Nμ) is the same as in the baseline (λ,μ) system and is not dependent on the absolute time, all the scheduling events in the (Nλ,Nμ) system have the same probability as in the (λ,μ) system. Hence the departure events have the same probability. Therefore, the (Nλ,Nμ) system is statistically identical to the (λ,μ) system with the time compression, which implies the average total burst delay in the (Nλ,Nμ) system is 1/N of that in the (λ,μ) system. Moreover, it is common that the loading in the wireless networks are dynamic and uneven in time, across carriers and technologies, and across different cells in the same technology.

In the baseline system without aggregation, when the single network serving the client mobile is heavily loaded while the other networks participating in the aggregation are lightly loaded, more substantial gains can be obtained by aggregation across the multiple networks.

In general, the available bandwidth/performance on each path can be different resulting in differential service times along the paths. This therefore results in an asymmetric queue with an arrival rate λ, and departure rates μ_1 and μ_2 for one faster server and one slower server respectively. The above time compression based queuing analysis can also be applied to the asymmetric aggregation. Under the M/M/1 assumption, a system with combined service of $\mu_1+\mu_2$ will outperform a system based on static partitioning of the arrivals λ into λ_1 and λ_2. For a two-path system, aggregation on asymmetric links can be studied based on asymmetric queue analysis for a two server system suggested in [6]. The differential service times along paths results in an asymmetric queue with an arrival rate λ, and departure rates μ_1 for one faster server and and μ_2 for one slower server. The mean number of jobs, K, in the system can be shown to be

$K = \frac{1}{A(1-c)^2}$ where $= \frac{\mu_1\mu_2(1+2c)}{\lambda(\lambda+\mu_2)} + \frac{1}{(1-c)}$, and $c = \frac{\lambda}{(\mu_1+\mu_2)}$.

As generally true in a queueing system, the closer the arrival rate gets to the service capability in the system the longer is the packet delay. This often leads to larger differential delay across paths. When differential delays increase (such as several 10s of ms), then it would be useful to implement improved packet scheduling techniques across paths (delayed or early packet scheduling or tight flow control), to reduce the reordering delay for packets at the receiving buffer.

III. KEY INGREDIENTS FOR CONCURRENT AGGREGATION

This section discusses the key ingredients needed for heterogeneous bandwidth aggregation, including WWAN modems, carriers, technologies, p2p service discovery, distributed stack processing, and aggregation endpoints.

A. Multiple WWAN modems

The cooperating WWAN modems can be local WWAN modems in a COBA client device, and/or other WWAN modems in any nearby COBA proxy devices that are within wireless proximity of the COBA client device. These modems may each support a different WWAN technology such as HSPA or LTE or EVDO or TVWhitespaceWWAN or other WWAN technologies. They may utilize a common WWAN technology but operate on different carrier frequencies or using different operators to aggregate bandwidth.

B. P2P Connectivity and Service Discovery

The connectivity between the COBA client device and a COBA proxy device can be a wireless p2p link. Bluetooth 3.0 + H.S. protocol can be used for the p2p link for example, where the BT stack can be used for COBA service discovery, and either BT or WLAN can be used for data transport depending on the bandwidth desired on the p2p link. A client access terminal can listen to broadcasts from its peers over p2p wireless channels, or request service over such channels. A proxy access terminal can either broadcast its service capabilities or respond only when it hears a client service broadcast request. Aggregation service may be enabled by a WWAN operator. This could be accomplished, for example, by a certificate stored on the devices for all devices belonging to a user or a family or a corporation. A client may request service after verifying credentials. Likewise, a proxy may approve to provide service after verifying client credentials. At this point, we consider the two devices to be bonded to each other for aggregation.

C. Aggregation end-points

The client node is an aggregation end-point where traffic is merged for the downlink and split for the uplink. A corresponding aggregation end-point exists in the network, which merges the traffic from uplink paths, and splits traffic for the downlink paths. This network aggregation end-point can reside in the access stratum such as the RNC or BSC or ENodeB/NodeB. Alternatively the network aggregation point can be a common tunneling anchor in the network across multiple networks in the non-access stratrum. Finally, the network aggregation point could reside directly at an application server on the internet that delivers or receives traffic to/from the client on different paths. For downlink paths, the network aggregation point becomes the transmitting aggregation endpoint, and the client device becomes the receiving aggregation endpoint. For uplink paths, the client is the transmitting aggregation endpoint, and the network aggregation endpoint is the receiving aggregation endpoint.

D. Dynamic Network Interface Management

Only the lowest cost path (energy/bit, or price * energy/bit) needs to be utilized at times when bandwidth requirements are low, such that the chosen lowest cost path meets bandwidth and delay requirements needed at that time. When higher bandwidths are needed, then additional available wireless paths can be turned on, utilized, and then released.

IV. CONCURRENT BANDWIDTH AGGREGATION (COBA)

Multiple wireless connectivity paths are established by a client using multiple wireless modems that the client device may have. Additionally, if available, the Client device can combine with multiple paths via nearby proxy devices which have their own wireless connectivity to WLANs or WWANs. Thus bandwidth from multiple modems and multiple devices belonging to a user (such as a tablet, a laptop, a smartphone, a car modem, etc.) can be aggregated. The WWAN modems on the Client node and its Proxy nodes can coordinate with each other to best select the networks for usage by the Client. The Client obtains an IP address from each of its wireless network interfaces. Proxy nodes obtain IP addresses from their wireless network interfaces and provide the IP addresses to the Client directly, or serve as access points for connectivity to their respective networks. In addition to WWANs or WLANs, connections through Cable/DSL or other networks are also possible for aggregation. Available paths can by added or deleted dynamically as they become available based on user mobility and availability of proxy aggregating devices.

A. D-COBA (Direct-COBA)

Aggregation can be performed directly between an application server on the internet and a mobile client platform, and such aggregation requires the application server on the internet to be able to directly setup and utilize multiple flows with the client platform. Fig 3 shows concurrent aggregation directly between a client device and a Multipath-capable application server on the internet (Direct-COBA) using available multiple paths. The transmitting aggregation endpoint for the downlink flows and the receiving aggregation endpoint for the uplink flows is directly at the application server on the internet such as a multipath video application server or a web-server. The receiving aggregation end-point for the downlink flows and the transmitting endpoint for the uplink flows remains at the client, with the COBA proxy nodes (if available) providing assistance. Such usage can be termed D-MA-COBA (MA for Multipath Application) where the multipath aggregation is managed at the application layer or say a HTTP networking layer. In some variants, application layer software could create multiple HTTP/TCP flows and manage them independently at the application layer or the HTTP networking layer. An example application would be to deliver multiple description coded streams along multiple paths to enhance the the quality of the video received at the client. A combination of techniques such as distributing different layers of coded video, with increased redundancy techniques such as employing raptor codes or reed-solomon codes as well can be applied, as well. Research in [7] has demonstrated performance improvement using dynamic multipath streaming generally provides satisfactory performance when the aggregate achievable TCP throughput is 1.6 times the video bitrate. In general, for each path, the application server can set up a separate RTP/UDP/IP path or a TCP/IP path to deliver information. Such an application-layer-based aggregation may be useful in special use-cases where the client directly interacts with such a multipath-capable application server, with assistance from its proxy nodes when available to aggregate all available WWAN bandwidth.

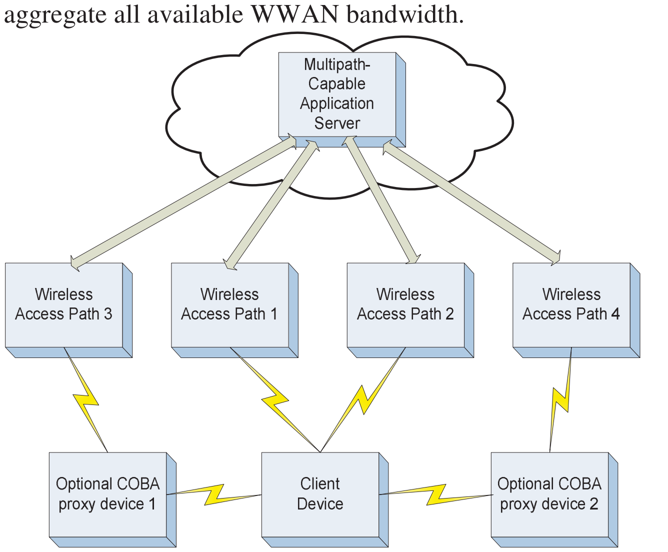

Figure 3: D-COBA (Direct-COBA) using multiple wireless paths from client directly to an application server (optional paths via proxy nodes possible)

MultipathTCP [8][9][10][11] is now an emerging standard for aggregating performance over multiple IP paths over the internet. Therefore, alternatively, the application server could utilize a multipath transport connection such as a MultipathTCP protocol over multiple wireless network paths.

SCTP [12] is an option although traditionally SCTP has been utilized for fault tolerant operation across paths. A typical application could include streaming of a video application such as a movie from a MultipathTCP capable application server on the internet where the streaming application could use HTTP-based dynamic adaptive streaming with emerging standards such as MPEG DASH [13]. The application server does not need to be aware of the multipath capability of the transport layer. It can merely stream the data at a higher data rate, or transfer the data in significantly less time, but utilizing the performance achievable at the multipath transport layer. Such usage can be termed D-MT-COBA (MT for Multipath Transport). A concern with such application-layer aggregation is that it requires custom modifications in the application-server to utilize multipath connectivity to the client device.

B. ML-COBA (MultiLink-COBA)

Aggregation requires a split and merge of traffic across multiple paths. It is possible that instead of the application layer, one could consider a split/merge of traffic at a multilink layer below the IP layer. Access Stratum aggregation can be accomplished with the aggregation endpoint in the Access Stratum layer. A typical aggregation endpoint is in the RLC layer [14] for a UMTS/LTE system for aggregation across multiple cells at different Node Bs[15]. A similar split/merge is possible in the RLP layer for EVDO systems [16] for aggregation across different cells or different carriers. Alternatively, a MAC-layer could support the split/merge of traffic across multiple carriers in multicarrier wireless systems such as Dual-Cell/Carrier-HSDPA in WCDMA Rel. 8 and its extensions in later releases[4]. A similar MAC-layer split/merge is also considered for a UMTS/LTE system for aggregation across multiple cells at the same Node B[15]. This requires awareness in the wireless access strata for the WWANs to enable the split/merge. For example, in EVDO, an BSC can sends different traffic to a BTS which transmits to different modems using different wireless carriers. In an LTE system, an ENodeB can directly communicate with different WWAN modems on different carriers. Alternatively, one RNC/BSC can send traffic to different NodeBs/BTSs which transmit respectively to different WWAN modems. This is achieved by the flow control between the RNC and Node Bs. Further, an LTE ENodeB serving a client WWAN modem, can forward traffic through a tunnel to a different ENodeB or RNC serving another WWAN modem which forwards the traffic to the multi-link aggregation layor on the client. The reverse paths are taken for uplink traffic from the client. Thus the network-aggregation endpoint for ML-COBA can typically be either an RNC or an ENodeB or a BSC. In such implementations, backpressure-based flow control algorithms can be used to guarantee a delay-bound across each link, with aggregate performance management across links, including the possibility of retransmissions on alternate links if needed. Adaptivity is required based on available performance on each wireless link which can change due to changes in network loading or channel conditions. The delay bound per link can be conservatively estimated, to account for dynamic fluctuations in such available performance. A key concern with multilink-based aggregation techniques is the need for upgrading wireless network access stratum infrastructure with support for aggregation across technologies, which can be an expensive proposition.

Currently, the 3GPP is studying the performance and possible standardization of aggregating the services from two cells from either the same NodeB or different NodeBs [19] for HSPA evolution. For the Intra-NodeB aggregation, the protocol architecture is the same as aggregation across multiple carriers in DC-HSDPA in WCDMA Rel. 8 where a single MAC entity handles two HARQ entities, each mapped to a cell. For the Inter-NodeB aggregation, the data split/merge may happen on the RLC layer, or on the PDCP layer which is above RLC but below IP.

The MAC layer throughput of both Intra-NodeB and Inter-NodeB aggregation schemes are presented in [15][21], where the gains in burst rates are particularly significant if the system is partially loaded or unevenly loaded.

The design aspects in the Inter-Node B aggregation with RLC split are studied in more details here. Discussions comparing RLC split with PDCP split can be found at [18]. The RLC protocol for WCDMA and HSPA was originally designed for a single link where the RLC PDUs are received by the UE (User Equipment (client device)) in the same order as they are sent by the RNC and the UE sends NAK for all the RLC sequence number gaps. However, when the RLC packet stream is split and RLC PDUs are sent over multiple cells at different Node Bs, they can be received by the UE in different order from the order sent by the RNC. Thus the UE may detect sequence number gaps due to out-of-order, or skew, rather than genuine packet loss. To avoid unnecessary retransmissions, minor enhancements to the RLC protocol and implementation are needed to handle the skew more efficiently. On the UE side, existing feedback mechanisms, including the format for the feedback messages and the triggering of them, can be re-used. On the RNC side, for each reported sequence number gap, if the packets have never been retransmitted, the RLC sender has to distinguish whether it is due to genuine loss on the physical layer, or out-of-order delivery between the two cells. Since in-order transmission is maintained at each cell among packets which are transmitted for the first time, a sequence number gap is identified as genuine loss if a packet with a higher sequence number in the same cell is ACKed. This requires the RLC sender to associate each sequence number to the cell it is sent to. It also has to remember which packets have been retransmitted. There is no need to associate a retransmission packet to any cell because the retransmissions are given higher priority by the MAC-ehs scheduler at the Node B and the in-order delivery is not guaranteed between packets first transmitted and packets retransmitted. In case a sequence number gap is considered by the RLC sender as caused by skew, the retransmission should be delayed to allow the gap to be filled by the subsequent transmissions. For each sequence number gap first identified as caused by skew, a timer called RetranmissionDelayTimer is started. In the subsequent Status PDU, part of the gap may be ACKed. When the timer expires, any missing data will be retransmitted. The sketch for managing the retransmission is shown in Figure 4 below.

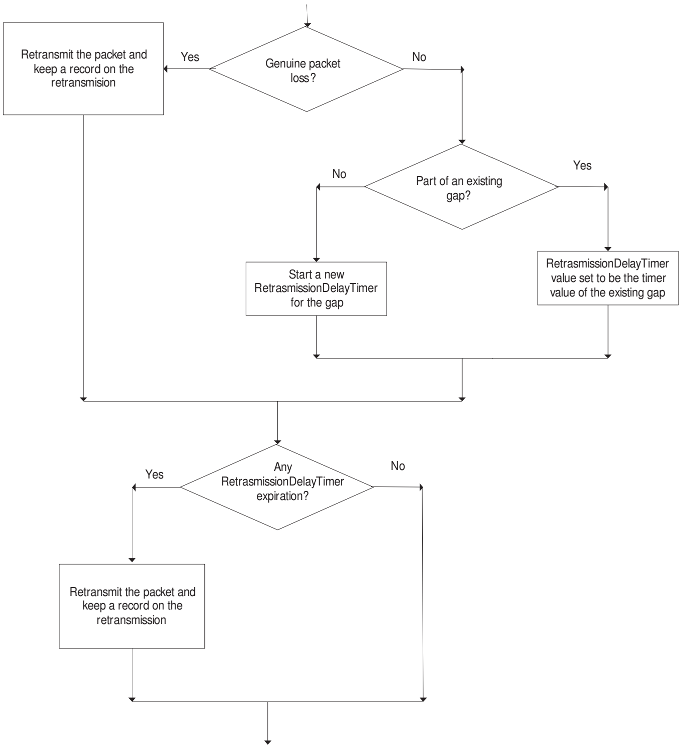

Figure 4: RNC algorithms for RLC retransmissions in ML-RLC in HSPA evolution.

In addition to the enhancements to the RLC protocol and implementation, the amount of skew must be controlled by the flow control on the Iub between the Node B and RNC. To limit the skew, a short queue at each Node B is desirable. However, frequent buffer underruns have to be avoided to fully utilize the physical layer resource. Therefore, the amount of data each Node B requests from RNC in each flow control request has to match the UE throughput. The Iub flow control implementation may need to be enhanced to achieve this. The basic idea is to maintain a tight range of the queuing delay at Node B such that the delay differential between the Node B remains manageable.

C. T-COBA (Tunneled-COBA)

A new alternative to modifying wireless access strata (ML-COBA) or modifying application servers (D-COBA) to support aggregation can be considered. One can consider a multipath transport tunnel (T-COBA) to be established between a client node, and a tunneling anchor node in an operator's network or across operator networks, where the tunnel aggregates bandwidth across all available paths. Figure 5a shows the suggested tunneling architecture (T-COBA) with multiple WWAN paths for a COBA client to a tunneling anchor in the network. Application servers merely communicate via a tunneling server to a client, such that the tunneling server interacts with the multipath-capable client to aggregate bandwidths across paths. This allows the peak rate bandwidth for the application to be increased by concurrently utilizing the bandwidths of available WWAN or WLAN paths in the multipath tunnel. In addition, it provides the ability to aggregate across different wireless technologies. Aggregation based on MultipathTCP [8][9][10][11] can be performed across IP streams and over wireless networks operating in non-contiguous frequency bands or contiguous frequency bands. Allowing TCP subflows to operate on each path, one can distribute the required performance for an application across multiple subflows such that performance degradation on one subflow does not significantly impact the performance of other subflows. In this manner, subflows on paths that are dynamically providing lower performance may be utilized less at any given time and location. Appendix A shows a typical packet from from a client device to the internet and back using MultipathTCP tunneling.

Figure 5b shows tunneled aggregation using WWAN modems in cooperating devices as well. The ClientVPN address that is dynamically assigned to the Client by the network(s) is then used by applications on the Client node to interact with servers on the internet. A tunnel based on an SSL-based tunneling solution such as OpenVPN [20] could be used to setup the MultipathTCP tunnel in T-COBA. Legacy application servers can leverage the aggregated performance without needing to support MultiPathTCP. Paths can be dynamically added or deleted within the multipathTCP tunnel in T-COBA or in D-MT-COBA. The multipath tunnel can persist during transitions between states of single-path-utilization and multipath-utilization in the system.

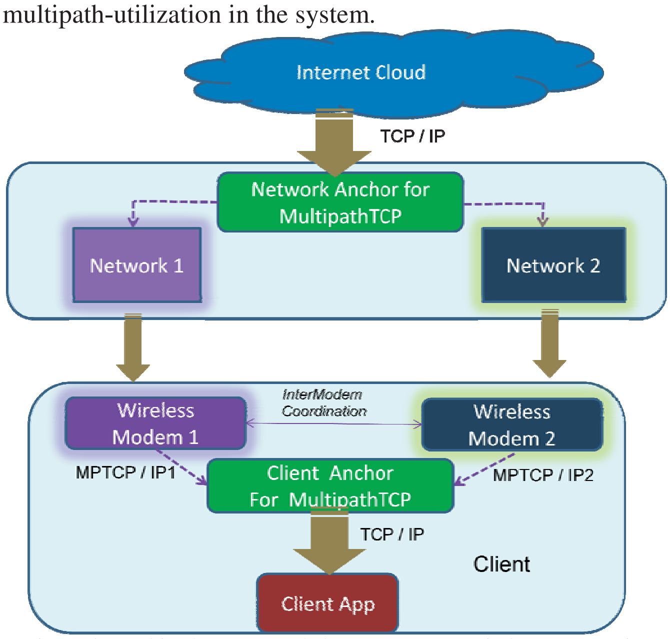

Figure 5a: MultipathTCP Tunneled Heterogeneous Wireless Aggregation

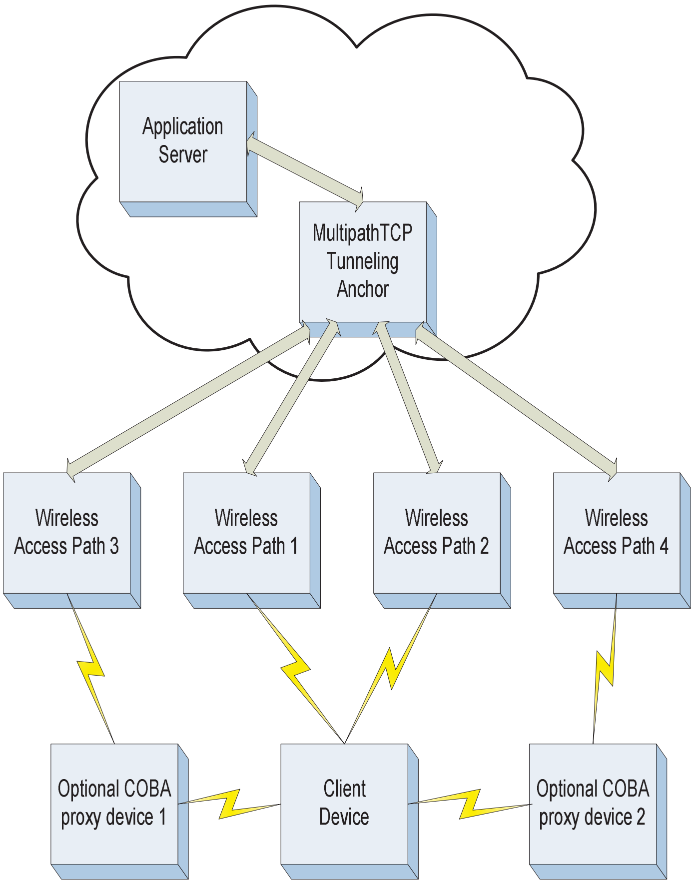

Figure 5b: T-COBA(TunneledCOBA) uses multiple wireless paths from client to internet via a tunneling anchor (optional paths via proxy nodes

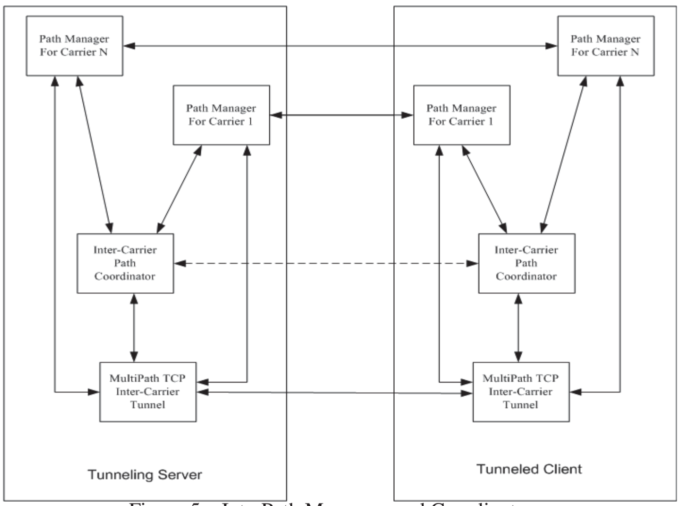

Figure 5c: InterPath Managers and Coordinators

1) Proactive Overlays for Path Mgmt and Coordination

Fig. 5c depicts the possibility of lightweight overlays (over UDP or TCP) that could be used to exchange information end-to-end between a Multipath Client and a Multipath Server. A path manager is created for each path between the client and the server. The path managers are useful to enable discovery and setup for each subflow for each carrier, and to exchange dynamic WWAN performance information. An IntercarrierPath Coordinator is established at both nodes that dynamically analyzes the performance of each Path, to then optimize the distribution of flow across the available paths. These overlays can be used to optimize the simultaneous utilization of both paths using the MultipathTCP tunnel between the mobile client and the tunneling anchor node in the network.

Fig. 5d depicts multipathTCP utilization over multiple WWANs. The IP address for each of the direct WWAN connections can be utilized as the IP address for each subflow on each of the direct paths from a client. Indirect paths can be used via proxy devices. In some variants, the IP address of the proxy device can be directly used the end COBA client device using a peer-to-peer application over WiFi-Direct or LTE-D2D to forward IP packets between a COBA client device and a COBA proxy device. In other variants, the proxy device can serve as an access point (WiFi for example) supporting a local access network that is accessed by the client device. In such cases, network address translation can be used to translate a local IP address for a subflow path on the local network to the IP address of the WWAN connection of the proxy device.

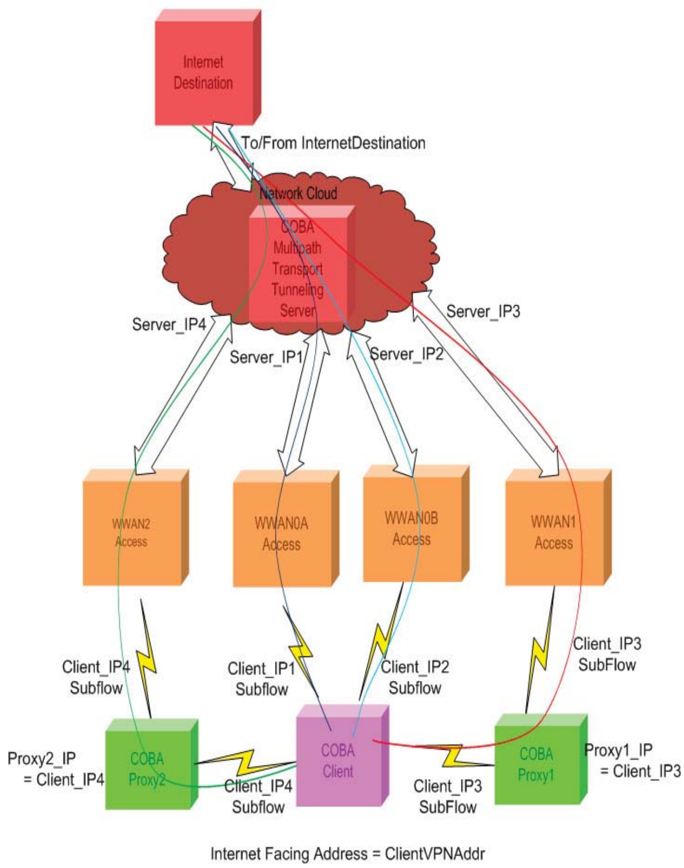

Figure 5d: MultipathTCP over multiple WWANs

Fig. 5e depicts a network setup with a primary path over LTE and secondary path over HSPA with P-GW as anchor. The client device (UE – User Equipment) can request an IP address over its LTE connection (let this be UE_LTE_IP). It can additionally request an IP address over its HSPA connection (let this be UE_HSPA_IP). If the UE decides to operate using multipathTCP, it provides both its IP addresses to the a MPTCP tunneling Anchor (MPTCP_Server_IP node) in the LTE EPC (Evolved Packet Core). The EPC then provides the client tunnel address (UE_Global_IP) for the client and this address is used by applications on the client device to interact with application servers on the internet. Typically each of the stages (such as the GGSN or the SGSN or the RNC or the P-GW or S-GW) in the WWAN can incur a few 10s of ms of latency. When different WWAN paths are used for heterogeneous aggregation, a key concern is the differential delay due to the different stages used for each of the paths. Another key concern for a multipathTCP-based solution is the need for a multipath tunneling anchor in the network that carries the traffic. This would have to reside in the data plane for the data traffic, to be actively participating in the data flow. The P-GW node or a server node connected to the P-GW can be an ideal anchor in future evolutions of the LTE EPC.

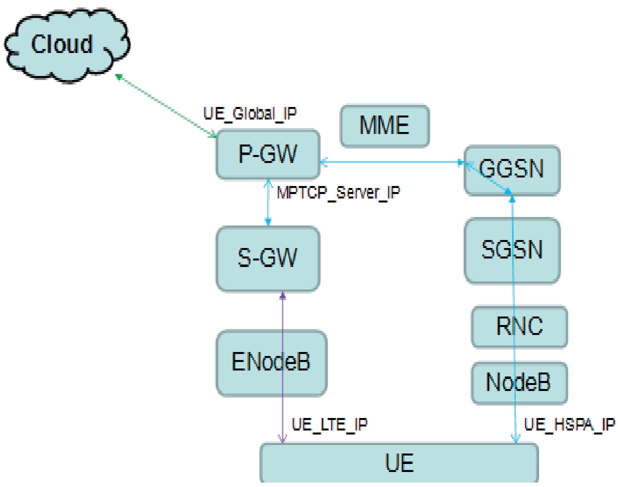

Figure 5e: LTE+HSPA T-COBA Aggregation

3) CoCOBA (Cooperative COBA)

Multiple devices belonging to a user, such as a tablet or a smartphone or a laptop or a car-modem, could bond over local wireless links such as WiFiDirect, and then subsequently utilize their backhaul connectivity to aggregate bandwidth Each of the neighboring devices (COBA-proxy) could obtain an IP address from its network connectivity, and subsequently offer an IP address to the client device, either via an access point capability, or by exposing a virtual network interface to the client device over a p2p link. The client device can provide all available IP addresses to the MultipathTCP Server. On the downlink paths, the MultipathTCP server delivers data utilizing the client IP addresses and the proxy IP addresses. The COBA proxy devices receive packets, and forward the IP packets to the client over their respective P2P links with the client. The aggregating client receives all IP packets over all paths and presents the packets to the MultipathTCP layer on the client, which subsequently delivers a higher data rate to the application layer on the client device. Such an option is possible for the uplink paths as well, to jointly utilize the higher aggregate bandwidth available. Such a mode of usage is termed CoCOBA (Cooperative COBA). When utilized directly with an application server on the internet, the usage is termed D-CoCOBA. When concurrent aggregation is utilized in the multilink-aggregation scenario, the usage is termed ML-CoCOBA. When concurrent aggregation is utilized via a multipath tunneling server, the usage is termed T-CoCOBA. In general, aggregation can be accomplished using multiple wired/wireless modems and network interfaces, utilizing wired/wireless networks, such as WWAN data technologies such as LTE, HSPA, CDMA2000-EVDO, or WiMAX or DSL/Cable/WLANs or opportunistic whitespace networks.

Figures 5b and 5d depicted cooperative COBA for multipath connectivity using multipathTCP. Fig. 6a shows cooperative COBA operating at the access stratum layer. In this case, an ENodeB or an RNC can tunnel data over to another ENodeB or RNC to enable a split across multiple paths in the access stratum. A second path could be provided through the access stratum connection of a COBA proxy device, and the two streams can be merged at a COBA client device using a peer-to-peer link between the two devices. Fig. 6b shows a more detailed diagram of a logical split of RLC-layer traffic between a direct and an indirect path, with a fractional distribution of traffic across the paths. The fractional distribution can dynamically vary in the uplink (UL) and downlink (DL) directions. The traffic is merged at the RLC layer of the COBA client device to accomplish cooperative aggregation at the access stratum layer. Figure 3c depicts a call flow that enables utilization of neighboring client devices for bandwidth aggregation.

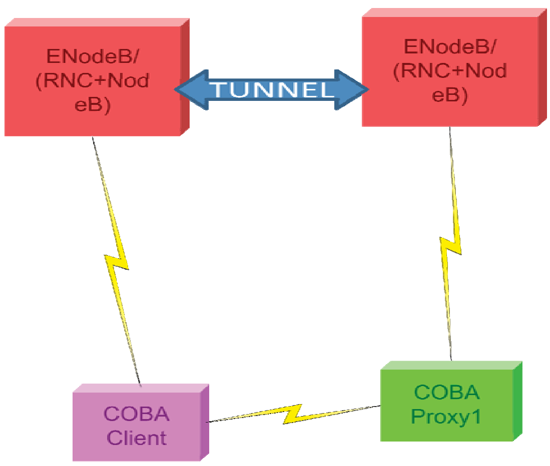

Figure 6a: Access-stratum-based CoCOBA

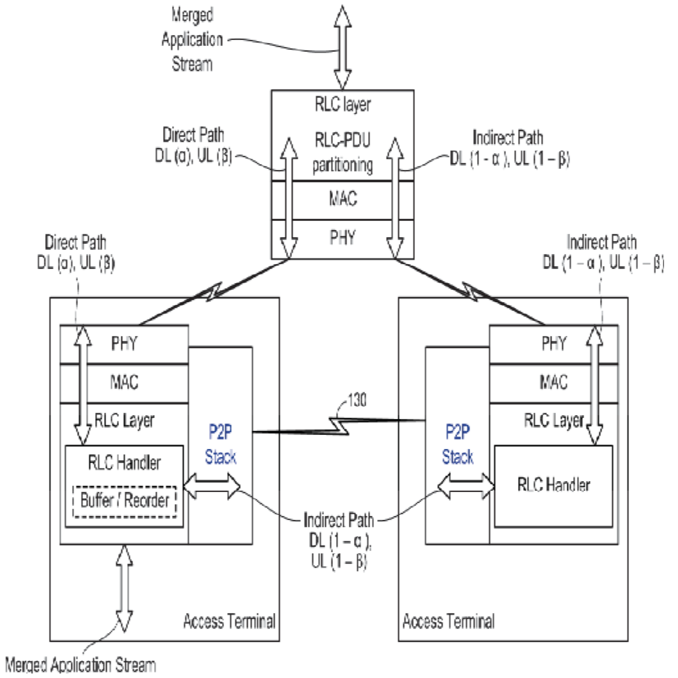

Figure 6b: RLC-layer partitioning of data across direct and indirect paths

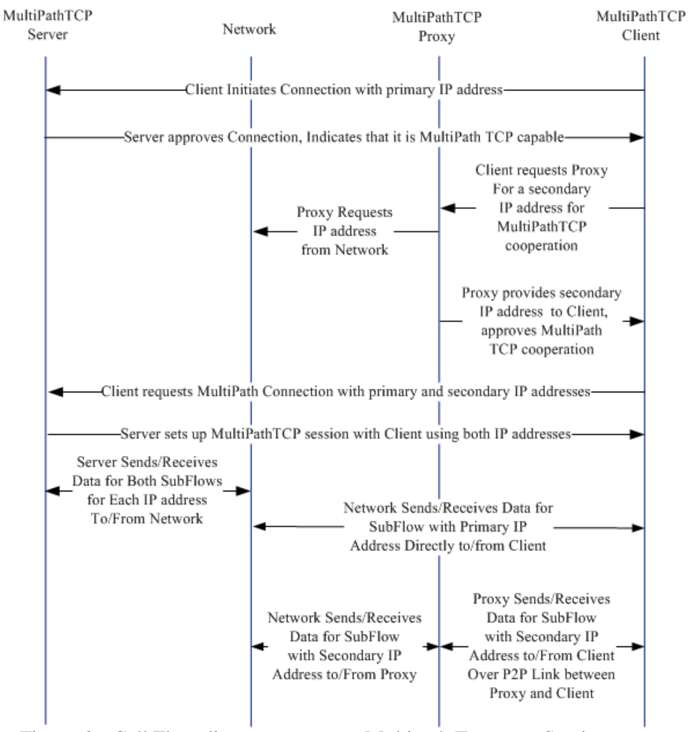

Figure 6c: Call Flow diagram to setup a Multipath Transport Session over multiple WWAN paths including neighboring devices

V. RLC-LAYER AGGREGATION FEASIBILITY STUDY

We have evaluated the TCP layer performance aggregation using RLC split with the above RLC enhancements and flow control. The Node B generates flow control request every T_{fc} and the request is based on the data needed to reach a target queuing delay, which is a decreasing function of the flow throughput at the Node B. In our study T_{fc}=60 ms and target Node B delay is in the range of 60 to 200 ms. The RetransmissionDelayTimer for skew is set to be 300 ms. The RNC sends data to both Node Bs according to their requested amount. If the RNC does not have enough data to fill both requests, it will send data to each Node B in proportion to its requested amount. Here we show an example result. In a 21-cell system, one foreground UE in the soft handover region engages in ftp downloads. The wireless channel between the UE and each cell is modeled as Pedestrian-A 3km/h fading. We compare the ftp throughput with RLC/FlowControl modeling without loading, and with symmetric and asymmtric loading. The TCP layer is modeled by ns2 using NewReno with Delayed ACK.

As seen from Table I, the RLC enhancements combined with the flow control algorithm shows improved performance with aggregation using one carrier in two different cells with and without loading in the cells. The results are discussed in detailed in [17] which show very little degradation due to RLC skew with the RLC enhancements and the tight flow control. The probability of unnecessary RLC retransmissions due to the delay timer expiration is below 10^{-3}. Results in [4] show higher gains when two carriers are used in DC-HSPA due to the increased diversity with multiple carriers. The data split/merge happens on the MAC layer in DC-HSDPA.

TABLE I. TCP THROUGHPUT WITH RLC-BASED AGGREGATION ACROSS TWO CELLS C1 AND C2 ON THE SAME CARRIER

	Throughput w/o loading (Mbps)	Throughput with even loading(Mbps) 50% load – C1 50% load – C2	Throughput with uneven loading (Mbps) 80% load - C1 20% load - C2
UE w/o aggregation	4.4 (C1 or C2)	2.6 (C1 or C2)	0.9 (C1) 3.5 (C2)
UE with aggregation	6.8	4.3	4.2
Gain	54.5%	65.4%	367% wrt C1

It is worth noting that the above RLC enhancement serves as one reference design. Other choices are possible as well. For example, all the RLC enhancements can be implemented at the UE side (UE-based ML_RLC). Particularly,the UE may delay its reporting of the RLC seqeunce nubmer gaps which can't be determined as genuine loss. This scheme is discussed in details in [21]. It can be shown that the UE-based scheme can achieve similar performance as the RNC-based scheme. Another aspect in the Inter-NodeB aggregation is the possible congestion in the backhaul link between Node B and RNC. We have extended our flow control design to manage the backhaul congestion. The design is shown in detail in [22].

Table II shows the TCP throughput and throughput gain with limited backhaul. From the table, we observe that Inter-NodeB aggregation achieves significant throughput gain over legacy operation in all the cases. More interestingly, in the backhaul limited case, the throughput is determined largely by the backhaul capacity, and UE with aggregation shows ~100% gain over the UE without aggregation. This is because Inter-NodeB aggregation offers a new dimension of diversity by utilizing two backhauls to serve one UE. This new diversity can be seen as "backhaul diversity".

TABLE II. TCP THROUGHPUT WITH RLC-BASED AGGREGATION UNDER LIMITED BACKHAUL

		Air-interface limited case	Imbalanced backhaul	backhaul limited case	Imbalanced backhaul
backhaul capacity (Mbps)	C1	6	6	2	2
	C2	6	2	2	6
UE w/o aggregation		4.4 (C1 or C2)	4.4 (C1)	1.9 (C1 or C2)	1.9(C1)
UE with aggregation		6.7	5.3	3.8	
Gain		52.3%	20.5%	100%	179%

VI. MULTIPATHTCP AGGREGATION FEASIBILITY STUDY

Fig. 7 illustrates a downlink aggregation via multipath TCP. Two congestion control mechanisms are active simultaneously: H-ARQ at the RNC, and TCP congestion control, at the end-points. Fig. 7b also shows a TCP packet manager, which distributes packets to different session paths at the server side, and aggregates the packets into a single TCP packet stream, at the device side. Path selection is typically driven by delay estimates on each path. As RNC retransmissions increase, wireless MAC layer delays increase, causing TCP packet manager to redirect packets to a lower delay path. Path selection based on packet loss is not convenient, as random losses from the wireless MAC layer are not good indication of congestion.

Fig. 8 shows a setup for performance analysis using CDMA20001x-EVDORevA emulators on each path, with MultipathTCP running end-to-end between the client and server nodes. The loading on the network (additional users), the link quality experienced by a node (good or poor), and the mobility of the node (pedestrain 3kph or vehicular 120kph), are varied to obtain different single-path performance measures. The emulator provides an option to force a fixed static delay (such as 0ms or 100ms) to mimic possible delays in network paths. Path performance measures are as follows: smooth rtt – average round trip time of a path; cwnd – the congestion window exercised by TCP sender on each path; number of cummulative bytes transmitted on each path.

A. Wireless link quality characterization

Fig. 9 reports results of a pedestrian speed scenario, when path delays are similar. Fig. 9a) reports results for similar light load on each radio link, whereas Fig. 9b) captures results with one of the links has poor quality. One can see that the number of bytes delivered gets decreased, as a result of the packet scheduler selecting the good link as a reaction to the rtt increase of the bad path.

Fig. 10 reports results of the same pedestrian scenario, except that the cellular network load is increased in one of the paths. One can observe that the high wireless network load keeps the corresponding path cwnd small, to prevent packet loss. This helps keep the rtt of the high load path under control, as evidenced by the srtt curves – no path delay dominates, as in the previous scenario. Similar conclusions can be drawn for vehicular speed scenarios.

B. Differential delay characterization

Fig. 11 reports results of pedestrian/vehicular speed scenarios, for comparative purposes. Fig. 11a) reports results of vehicular speed scenario of lightly loaded wireless links, with a differential delay of 100msecs between paths, whereas Fig. 11b) reports the same scenarios, except that one of the wireless links quality is poor. Comparing vehicular and pedestrian scenarios, we first notice that vehicular speeds cause a larger rtt path delay, well above 100msecs. So, a differential delay of 100 msecs can be handled by the packet scheduler, so as to keep both path byte delivery similar. In addition to differential delay, the pedestrian case of Fig. 11b) includes one wireless link heavily loaded, which causes one of the paths to shut off around t=2secs, due to stalling of MAC layer delivery.

Fig. 12 reports results of pedestrian/vehicular speed scenarios, similar to the previous one, except that one of the wireless link has poor performance (capacity). The delay difference of 100msecs has little impact on overall performance of each path, since in this case rtts are way beyond that value. Notice how the congestion window (cwnd) curves cross each other at various points of the experiments. The path with poor wireless link maintains a small cwnd, and hence delivers less cummulative bytes. However, the path with good link conditions increases its cwnd to a point of TCP packet loss, when its cwnd gets reduced drastically.

In summary, differential delays may play a role in path performance, all other things equal. However, different cellular load and fading conditions have a more drastic and significant effect on path performance.

C. Summary of Throughput Results

Table III shows the performance for a single TCP flow over only one path. Using this information, one can estimate the ideal average throughput that one can expect when combining two paths, as computed in the penultimate column in Table III. However, some degradation can be expected between the actual performance obtained when using MultipathTCP over two wireless paths, due to differential delays and differential loading/link qualities along paths. A MultipathTCP efficiency measure is determined as the ratio between the aggregate performance of MultipathTCP to the sum of the expected single path performance in each path. Table IV shows the performance obtained using MultipathTCP over two concurrent paths with differential link quality, mobility, and loading across paths. The MPTCP linux port from [23] was utilized and instrumented to analyze per flow performance. The overall aggregate performance for MultipathTCP is shown for each experiemental setup option. When both paths have similar link conditions, such as both networks not loaded, and/or the link quality is good on both paths, then regardless of pedestrian or vehicular speeds, the performance is quite good with a high MultipathTCP efficiency even if delays increase. However, when the disparity between the network conditions increases on each path, it can be observed that the MultipathTCP efficiency can drop with increasing differential delay across paths such as when one of the network connections is of poorer link quality or if one of the network path is more loaded than the other. As the disparity between paths increases, and the MultipathTCP efficiency decreases, the MultipathTCP layer could choose to utilize only the better path, until the other path recovers. Research work is underway to characterize the performance of MPTCP-based concurrent aggregation over commercial LTE and HSPA/WiFi networks.

VII. Conclusion

Parallel wireless communications is an emerging area of research. In this paper, concurrent bandwidth aggregation techniques were explored to dynamically exploit performance diversity and concurrent utilization over multiple wireless networks at a given location and time. In general, various aggregation techniques including heterogeneous concurrent wireless bandwidth aggregation and aggregation across multiple carriers or multiple cells have been discussed. Application-layer aggregation is possible and this requires custom application servers to be modified for aggregation support. Aggregation below the IP layer, inclduing those using multi-link techniques with flow control requires access strata changes and can offer robust performance against time varying wireless channel and loading conditions. A new alternative using MultipathTCP tunneling is suggested for aggregation across multiple IP paths with results from a feasibility study. Multilink RLC techniques were also described for aggregation below the IP layer. To conclude, COBA or Concurrent Bandwidth Aggregation is possible at multiple levels in wireless networks using Direct-COBA, Tunneled-COBA, MultiLink-COBA techniques. COBA can improve performance for a user depending on application-level needs, and network constraints. Cooperative COBA can be used to enable multiple devices to cooperate to deliver higher performance. In general, COBA can improve performance by combining performance using contiguous/non-contiguous available frequency bands across wireless networks. Depending on the constraints and the needs of a concurrent aggregation end-to-end system, any one of the alternatives could be utilized to achieve concurrent bandwidth aggregation across wireless networks.

References

[1] http://www.3gpp.org, http://www.3gpp.org/lte, http://ww.3gpp2.org, http://www.wimaxforum.com.

[2] IEEE,Wireless LAN MAC and PHY specifications, ANSI/IEEE Standard 802.11 (August 1999).

[3] M. N. Ellanti, S. S. Gorshe, L. G. Raman, W. D. Grover, *"Next Generation Transport Networks: Data, Management, and Control Planes,"* Springer, 2005.

[4] D. Zhang, P. K. Vitthaladevuni, B. Mohanty and J. Hou, "Performance Analysis of Dual-Carrier HSDPA," 71st IEEE VTC 2010-Spring.

[5] Dimitri P. Bertsekas and R. Gallager, *"Data Networks,"* Second edition, Prentice Hall, 2002.

[6] G. Bloch, S. Greiner, H. de Meer, K. S. Trivedi, "Queueing Networks and Markov Chains," John Wiley and Sons.

[7] B. Wang, W. Wei, Z. Guo, D. Towsley, "Multipath Live Streaming via TCP: Scheme, Performance, and Benefits," ACM Transactions on Multimedia Comp Comms and Apps, Vol. 5, No. 3, pp. 1-23, Aug '09.

[8] H. Han, S. Shakkottai, C. V. Hollot, R. Srikant, D. Towsley, "Multi-path TCP: a joint congestion control and routing scheme to exploit path diversity in the internet," IEEE/ACM Transactions on Networking, Volume 14 , Issue 6, Dec 2006.

[9] Kelly, F.P., Voice, T., "Stability of end-to-end algorithsm for joint routing and rate control," ACM/SIGCOMM CCR 35(2) (2005).

[10] A. Ford et al, "TCP Extensions for Multipath Operation with Multiple Addresses," IETF MPTCP proposal - http://tools.ietf.org/id/draft-ford-mptcp-multiaddressed-03.txt .

[11] P. Key, L. Massoulie, D. Towsley, "Multipath routing, congestion control and Dynamic Load Balancing," Proc. of Acoustics, Speech, and Signal Processing, ICASSP07, pp.IV-1341-IV-1344., 2007.

[12] Stream Control Transmission protocol, http://tools.ietf.org/html/rfc4960

[13] http://mpeg.chiariglione.org/working_documents.htm#MPEG-B

[14] 3GPP specifications TS 25.322, "Radio Link Control (RLC) protocol specification," v 10.1.0, May, 2010.

[15] D. Zhang, P. K. Vitthaladevuni, B. Mohanty, J. Hou, "'Performance Gains of Single-Frequency Dual-Cell HSDPA," IEEE Globecom 2011.

[16] R. Attar, D. Ghosh, C. Lott, M. Fan, P. Black, R. Rezaiifar, P. Agashe, "Evolution of CDMA2000 networks: Multicarrier EVDO," IEEE Communications Magazine, June 2006.

[17] Qualcomm 3GPP contribution, "System Performance Evaluation of SF-DC Inter NodeB Aggregation in Uniform Loading Scenario Assuming Realistic RLC and Flow Control," 3GPP doc R1-111538, May 2011.

[18] Qualcomm 3GPP contribution, "Impact to RAN protocol architecture and UTRAN implementation due to Multiflow HSDPA MP-TX schemes," 3GPP doc R2-112849, May 2011.

[19] 3GPP technical report TR 25.872, "HSDPA Multipoint Transmission," v1.0.0, June, 2011.

[20] M. Feilner, "OpenVPN – Building and Integrating Virtual Private Networks," Packt Publishing, April 2006.

[21] W. Ge, R. Kapoor, D. Zhang, S. Sambhwani, and M. Scipione, "System Performance of Inter-NodeB MF-HSDPA with RLC and MAC Enhancements", to appear in ICC, 2012.

[22] W. Ge, R. Kapoor, D. Zhang, S. Sambhwani, and M. Scipione, "System Performance of Inter-NodeB MF-HSDPA with Enhancements to Backhaul Flow/Congestion Control", submitted to VTC, fall, 2012.

[23] MPTCP Linux Kernel Implementation, http://mptcp.info.ucl.ac.be/.

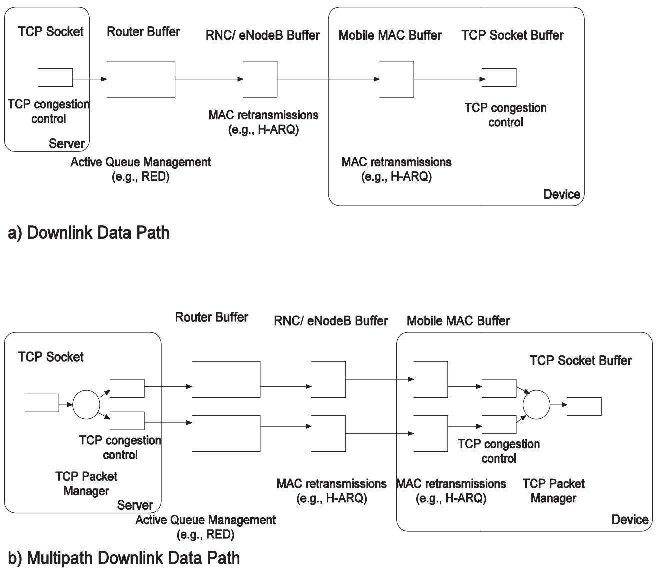

Figure 7: MulipathTCP Downlink Aggregation

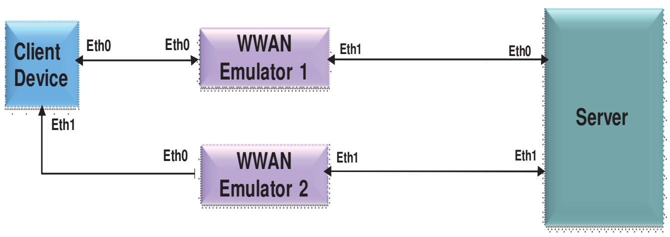

Figure 8: Emulator-based Setup for MultipathTCP Performance Analysis

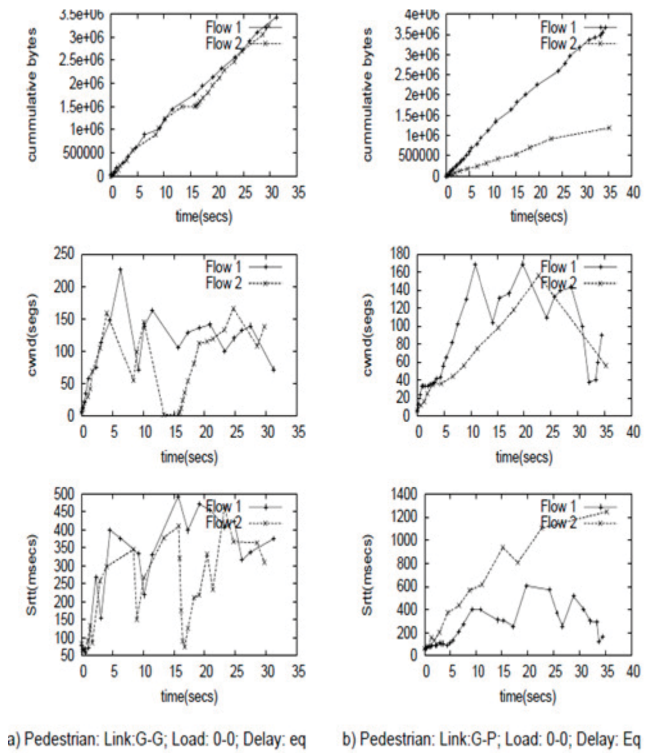

Figure 9: Pedestrian speed - good/poor WWAN links

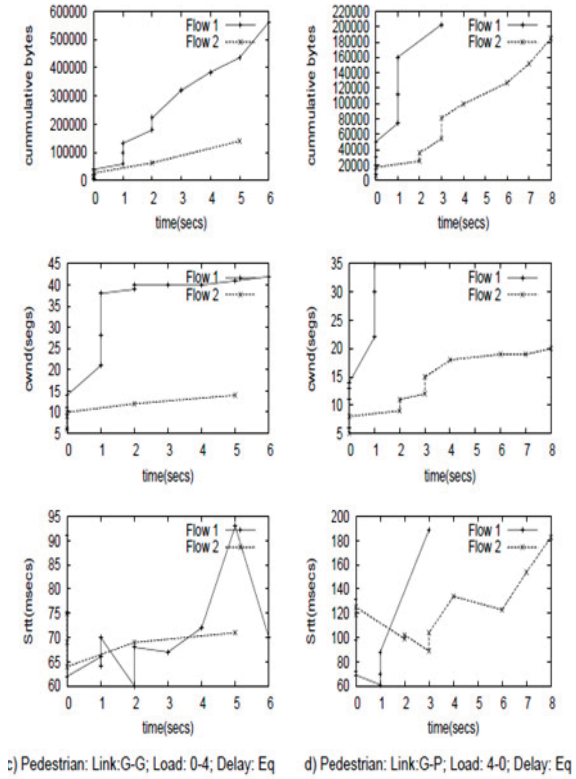

Figure 10: Pedestrian speed; good/poor WWAN links; High wireless load

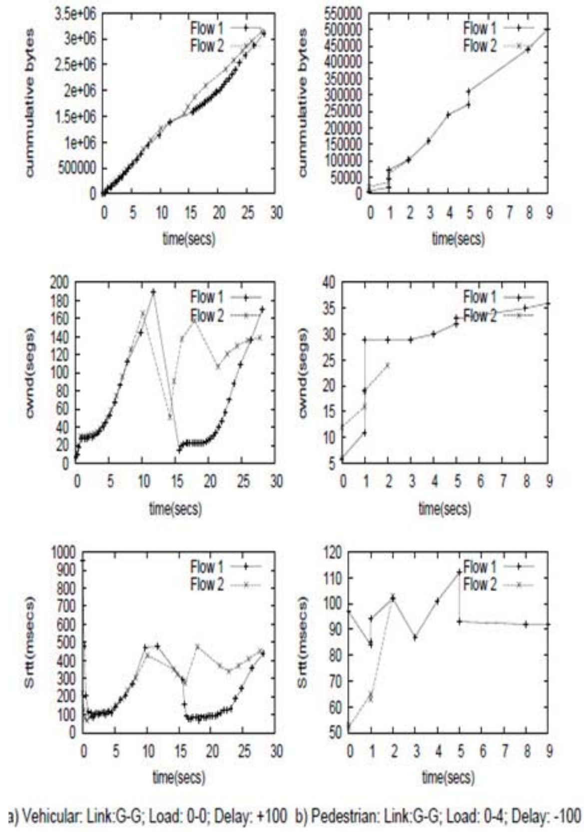

Figure 11: Pedestrian/Vehicular speeds; differential delay

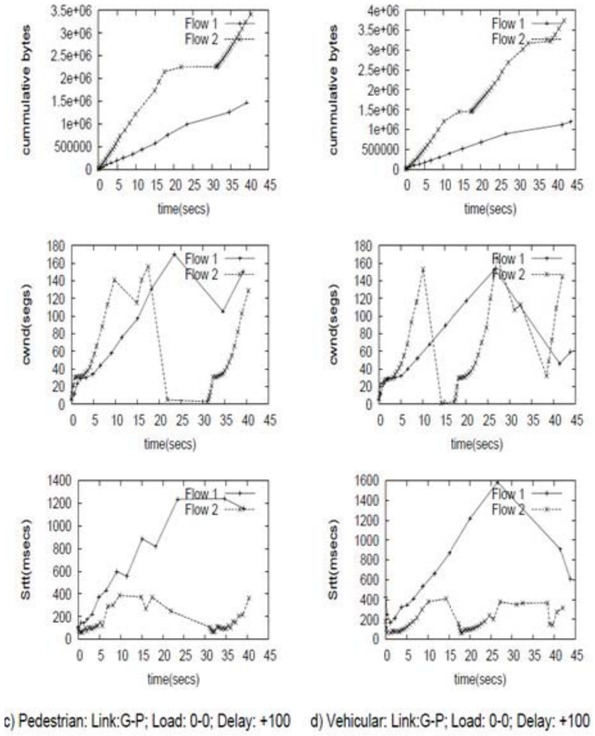

Figure 12: Pedestrian/Vehicular speeds; differential delay; high wireless load

TABLE III. AVERAGE THROUGHPUT FOR SINGLEPATH EXPERIMENTS WITH MULTIPATHTCP

Speed	*LinkQuality (G : Good Vs P: Poor)*	*Network Load (Additional users)*	*SinglePath Avg Thpt (kbps)*
Pedestrian (3kph)	G	0	864.20
Pedestrian (3kph)	G	4	317.72
Pedestrian (3kph)	P	0	263.93
Pedestrian (3kph)	P	4	91.17
Vehicular (120kph)	G	0	854.47
Vehicular (120kph)	G	4	340.13
Vehicular (120kph)	P	0	206.0
Vehicular (120kph)	P	4	61.7

TABLE IV. AVERAGE THROUGHPUT FOR MULTIPATH EXPERIMENTS WITH MULTIPATHTCP

Experimental Setup	*Explicit Additional Path Delay Introduced*	*Subflow1 Throughput (Kbps)*	*Subflow2 Throughput (Kbps)*	*MultipathTCP Aggregate Throughput (Kbps)*	*Expected Max Avg Throughput (based on singlepath data)*	*MultipathTCP Efficiency*
Pedestrian Path1: No Load, Good Link Path2: No Load, Good Link	None	867.35	830.77	1698.12	1728.4	0.98
	100ms	828.99	823.19	1652.18	1728.4	0.95
Pedestrian Path1: No Load, Good Link Path2: No Load, Poor Link	None	729.42	253.76	983.18	1128.13	0.87
	100ms	717.57	168.32	885.89	1128.13	0.78
Vehicular Path1: No Load, Good Link Path2: No Load, Good Link	None	842.56	841.91	1684.47	1708.94	0.98
	100ms	824.66	812.02	1636.68	1708.94	0.95
Vehicular Path1: No Load, Good Link Path2: No Load, Poor Link	None	743.95	204.96	948.91	1114.47	0.85
	100ms	725.05	145.66	870.71	1114.47	0.78
Pedestrian, Path1: No Load, Good link Path2: Load 4 Additional users, Good Link	None	814.65	322.21	1136.86	1181.92	0.96
	100ms	455.38	227.28	682.66	1181.92	0.57

APPENDIX A

An example packet flow with MultipathTCP Tunneling is depicted in Fig. 13 for data flowing from the Client to the Internet and back.

- At the Client - IP packet for application data at client to an Internet Destination (InternetDest)

Source IPAddress (Client VPN adddress)	Destination IPAddress (InternetDest)	TCP Source Port (Application Port #)	TCP Dest Port (Application Port #)	Application Data

Tunneling Payload

- Tunneling Wrapper at Client (using one of the MPTCP sub-flows)

Source IPAddress (ClientIPAddr 1)	Destination IPAddress (Tunneling ServerIPAddr 1)	MPTCP Source Port (Client VPN port#)	MPTCP Dest Port (Server VPN port#)	Encrypted (Optional) Tunneling Payload

- At MPTCP Tunneling Server -- Extract Tunneling Payload & Forward to Internet Destination

Source IPAddress (Client VPN adddress)	Destination IPAddress (InternetDest)	TCP Source Port (Application Port#)	TCP Dest Port (Application Port#)	Application Data

Data Flow – Internet to Client return path

- *At the Internet Destination*

Source IPAddress (InternetDest)	Destination IPAddress (Client VPN address)	TCP Source Port (Application Port#)	TCP Dest Port (Application Port#)	Application Data

- *At the Tunneling Server (using one of the MPTCP subflows)*

Source IPAddress (Tunneling ServerIPAddr 1)	Destination IPAddress (ClientIPAddr 1)	MPTCP Source Port (Server VPN port #)	MPTCP Dest Port Client VPN port#)	Encrypted (Optional) Tunneling Payload

- *At the Client - Extract MPTCP tunneling payload, Extract application data*

Source IPAddress (InternetDest)	Destination IPAddress (Client VPN address)	TCP Source Port (Application Port #)	TCP Dest Port (Application Port #)	Application Data

Figure 13: Example Packet flow with MultipathTCP tunneling