Evaluation of Network Assisted Handoffs in Heterogeneous Networks

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***Abstract*—This paper describes a novel distributed mobility management (DMM) scheme for the "named-object" information centric network (ICN) architecture in which the routers forward data based on unique identifiers which are dynamically mapped to the current network addresses of a device. The work proposes and evaluates two specific handover schemes namely, *hard handoff with rebinding* and *soft handoff with multihoming* intended to provide seamless data transfer with improved throughput during handovers. The evaluation of the proposed handover schemes using system simulation along with proof-of-concept implementation in ORBIT testbed is described. The proposed handoff and scheduling throughput gains are 12.5% and 44% respectively over multiple interfaces when compared to traditional IP network with equal share split scheme. The handover performance with respect to RTT and throughput demonstrate the benefits of clean slate network architecture for beyond 5G networks.**

***Index Terms*—5G, Handover, DMM, Multihoming, Rebinding, LTE, WiFi**

I. Introduction

The 5G heterogeneous network (HetNet) currently [1], [2] under consideration aims to provide high bandwidth and low latency support for IoT devices, mobile vehicular networks and emergency networks. With the expected rise in mobile user traffic by seven folds between 2017 to 2021 [3], a network infrastructure supporting this surge in traffic is required. Thus, telecom operators are focusing on the dense deployment of cells to increase the system capacity and overall throughput [4]. These deployments are expected to involve heterogeneous radio access technologies (RAT) including LTE, WiFi, 5G (sub-6GHz) and 5G mmWave [5], [6].

The HetNet creates newer possibilities to enhance user quality of service (QoS) using access techniques such as multihoming and offloading [7]. Multihoming or dual-connectivity have the potential to alleviate the growing traffic demands by providing multi-RAT access, enabling higher user-level throughput [8]. However, multihoming must address various challenges associated with frequent handovers, seamless access, traffic load balancing and signal interference. As an example, the bands operating at mmWave frequencies have limited coverage and are susceptible to blockage [9]. Moreover the beams have to be highly directional causing frequent inter-beam and inter-base stations (BS) handoff potentially impacting QoS. Providing seamless mobility support between various cells for real-time applications like VoIP, streaming services, live Augmented Reality (AR), etc., is challenging as

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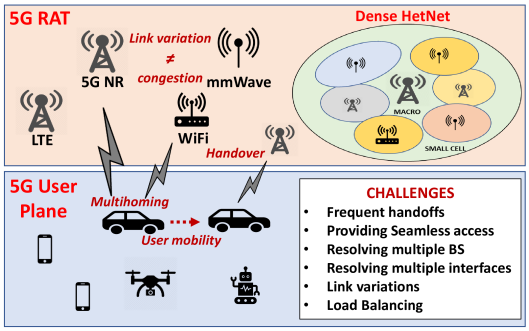

Fig. 1. 5G Heterogeneous Network Challenges

the network entities such as intermediate routers and BS do not collectively participate in the handover decision process. Furthermore, to provide seamless connectivity, multihoming introduces the additional challenge of resolving multiple network addresses associated with a UE or device equipped with multiple radio interfaces.

Existing solutions for multihoming include using the variants of transport layer to enable Multipath TCP (MPTCP) by allowing the end hosts to split the flows across available paths [10]. TCP/IP based networks are primarily designed to support static users and thus, perform poorly for mobile users due to variation in wireless link quality (multipath propagation, fading, etc.). TCP interprets the wireless link errors as congestion, triggering a mechanism to slow down the rate and react aggressively to any packet loss events. MPTCP built on top of TCP faces similar issues by invoking congestion control mechanism for these multiple subflow paths and performs poorly in a highly mobile environment [11]. In addition, extensions to the TCP/IP architecture such as Mobile IP [12] suffer from a number of unresolved issues relating to triangular routing and dual connectivity [13]. Hence, mobility management for dense HetNet becomes a key network design issue to be addressed in next generation 5G mobile core networks (see Fig. 1).

Future internet architectures (FIAs) [14], [15] based on named-object techniques have the potential to enable seamless mobility by dynamically mapping device/object names to their respective network addresses (NAs). The capabilities of these architectures to handle network service interruptions using multihoming and in-network dynamic packet rebinding are still unexplored. This work proposes two handoff schemes as an initial attempt at solving challenges arising from multiplicity of networks in a single geographical domain, specifically tar-

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geted towards seamless handover in heterogeneous networks as proposed by beyond 5G architecture. The major contributions of this work are as follows:

- We demonstrate a tunnel-less set-up to achieve heterogeneous handover using a clean slate flat network architecture having name and address separation.
- We propose two new handover schemes, *hard handoff with rebinding* and *soft handoff with multihoming* in named-object based network architecture.
- We evaluate the handoff schemes with proof-of-concept implementation in the ORBIT testbed as well as simulation by considering real user mobility traces and observe the impact of packet loss and handoff latency on performance metrics such as round trip time (RTT) and throughput.

The rest of this paper is organized as follows. Section II provides related work considering seamless handoff and distributed mobility management. Section III presents an overview of name-object based architecture to support mobility. Section IV discusses about enhancing name based abstraction for seamless handover. Section V discusses the simulation settings for large scale dense HetNet environment. Evaluation of proposed handover schemes with the current IP based network is given in section VI. Section VII concludes the paper with our future work.

II. Related Work

Seamless handover (or handoff) between various radio access networks has been a widely discussed topic in recent years. It is increasingly relevant in the current 5G era as the operators are rapidly upgrading their network infrastructure to support latency-critical applications and enhance the user experience. The increased network density and higher user mobility is expected to cause frequent handovers between various access networks, and therefore will make UE (User Equipment) attachment and packet forwarding complex due to the hierarchical gateway based architecture of existing mobile core networks based on the 3GPP specifications. The prime contributor of handoff latency in current implementations is L2 switching, motivating the authors of [16], [17] to propose mechanisms using single and dual 802.11 radio cards on UEs. These schemes attempt to reduce the channel probing latency with multiple radio cards but involve changes to the kernel and limited support for heterogeneous networks. Various other schemes have also been proposed to optimize WiFi L2 handoff [18]–[21]. However, they face similar issues in deployment, channel selection/grouping and Min/MaxChannelTimes threshold settings. Efforts have also been made for seamless heterogeneous handover and scheduling between WiFi and LTE. Architectures pertaining to core assisted (S2a/S2b interfaces) and RAN assisted (LWA/LWIP) LTE-WiFi integration have been widely discussed in 3GPP standards meetings [22].

The rise in network heterogeneity requires additional solutions such as distributed mobility management (DMM) and centralized software defined network (SDN). In [23], the author's emphasised on elimination of single mobility anchor and categorized IP level DMM schemes into 3 categories – Proxy Mobile IPv6 (PMIPv6), SDN and routing considering BGP. In PMIPv6 based DMM [23], [24], the centralized core architecture of PMIPv6 having LMA (local mobility anchor) and MAGs (mobility access gateways) are eliminated using DMM-GW to provide direct connectivity to the Internet. This approach introduces multiple distributed gateways which in turn increases switching latency and tunneling overhead during UE mobility. Several SDN based DMM schemes have also been proposed with and without IP tunnels [25], [26]. For a large scale network deployment, these solutions face scalability and controller management issues. Further, services such as multicast, multihoming for the current TCP/IP based architecture work as overlays incurring additional overhead and limited network visibility [27]. The architectures described above face challenges in: (a) configuring gateways, (b) setting-up tunnels between various RATs either on per UE basis or operator specific policies, and (c) lack of network support for efficient handover decisions. Table I provides a qualitative comparison between different mobility management schemes currently under consideration with the named-object based solution considered here. The architecture proposed in this work aligns well with routing based DMM for seamless handover considering a flat network having name and address separation, and allowing network components to assist in seamless handoff through rebinding and multihoming.

TABLE I
Comparison of different Mobility Management Schemes

	Mobile IP	Proxy MIP	SDN	Name Based
Architecture	Partially Distributed	Partially Distributed	Centralized	Fully Distributed
Management	Host	Network	Network/ Controller	Network
Addressing	HA and CoA [1]	HA and CoA	Fixed IPs/IDs	Fixed IDs
Mobility Anchor	Multiple	Multiple	Single/ Multiple	None
Data Transport	IP Tunnel	IP Tunnel	No Tunnels	No Tunnels
Route Optimization	No	No	Yes	Yes
Signalling Overhead	High	High	Med	Low

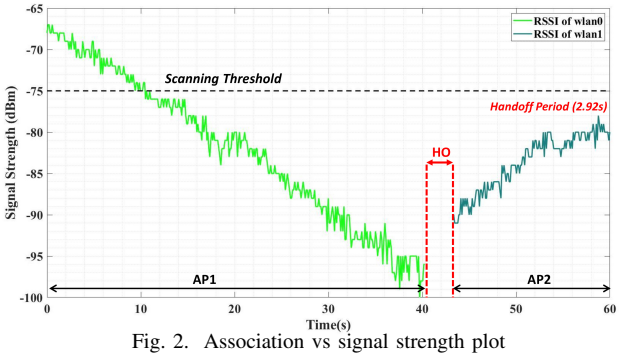

Fig. 2. Association vs signal strength plot

III. Name Based Approach for Mobility Support

Supporting seamless mobility services in telecom networks is achieved via mobility management protocols including authentication, roaming and handover [28], [29]. A UE switches from one AP/eNB (Access Point/eNodeB) to another if the

[1]Home Address and Care of Address

neighboring cell has better channel quality as reported through signal quality measurements (RSSI, RSRP, RSRQ, SINR, SNR, CIR) and UE specific parameters (location, velocity, and direction of movement) [30]. With conventional roaming in WLAN, the UE continuously monitors the signal strength (RSSI – Received Signal Strength Indicator) at the currently associated AP. If the RSSI drops below a certain threshold, the UE scans for available APs on all the channels. The association takes several seconds due to the large number of channels to be scanned as shown in the example in Fig. 2, obtained using emulation on the ORBIT [31] testbed and *wpa_supplicant* [32] roaming package. The handoff disconnection period is 2.92s. Once the best AP is found, the UE disconnects from the previous AP, and attaches with the newly discovered AP post-authentication [17] by acquiring a new IP address. The old IP address can be reused during handoff if the APs are managed by a centralized entity like the SDN controller [33], which introduces additional control plane overhead and decision time. The break-before-make approach therefore, typically interrupts an on-going session. A similar approach is followed in LTE during X2 handover (IP address of the UE is maintained), but a tunnel is set up between the source eNB and the target eNB to forward packets before using the new bearer connecting S-Gw (Service-Gateway) to target eNB for the downlink (DL) traffic.

The problems arising due to constant monitoring as well as allocation of IP addresses due to UE mobility can be addressed in clean-slate network designs by utilizing the concepts of globally unique identifiers (GUID) which are dynamically mapped to network addresses (NAs). This concept of name-based networking has been extensively studied in [34], [35] wherein the name service layer acts like a narrow waist of protocol stack. Each end host or content object is identified with the help of a GUID which remains unchanged during the entire lifetime of a UE session. GUIDs are anchored to the network with the help of NA. The name to address mappings are resolved dynamically by the GNRS (global name resolution service) which is a globally distributed but logically centralized mapping database, periodically updated and queried by the NEs (network entities). This separation of name and address space handles mobility related events, and thus is best suited for handover, specifically when dealing with multiple NEs and RATs in a heterogeneous network. In such a named-object based architecture, packets are directly addressed using GUIDs and SIDs (service IDs). The SID allows the NEs to take an action on a packet, e.g., storage or scheduling. The routers are storage capable and implement store or forward logic on a per hop basis to achieve reliability [36]. This work builds on an implementation of name-based FIA (MF – MobilityFirst [15]) to overcome limitations of the TCP/IP architecture concerning mobility (handover), and particularly focuses on rebinding and multihoming as the key enablers for seamless mobility services.

IV. Seamless Handover Techniques

In this section, we propose two handover schemes supporting seamless handoff using the MF architecture – hard handoff with rebinding and soft handoff with multihoming. The AP/eNBs (Base Stations - BS) run a fully decentralized version of the MF protocol thereby eliminating the need of setting gateways and tunnels. The flat network routing is supported by GNRS which provides current GUID→NA bindings. It is based on the DMap [37] design which maintains K copies of the bindings in the network, ensuring single overlay hop-path with good storage distribution while providing lower lookup latencies as low as 86ms for $K = 5$.

This flat architecture facilitates easy plug-and-play deployment of heterogeneous network avoiding the need of additional authentication mechanism while supporting seamless handovers. The system implementation details of key MF components involving GNRS, MF routers and Hoststack can be found in [7]. We use the LTE (OpenAirInterface no-S1 with L2TP tunnel) [38] and Wi-Fi (802.11g) stack for experimental evaluation using MF.

The following features are enhanced to achieve seamless handover in a heterogeneous network, (a) **In-network rebinding :** the intermediate routers are capable of resolving packets to a new UE address using name resolution server. (b) **Multihoming :** enables UE devices to receive packets on multiple interfaces if available without notifying end hosts as the intermediate routers are capable of handling packet replication and scheduling between these multiple interfaces.

Integrating with IP network: The handoff schemes discussed above can be integrated with the current IP based network using an overlay, by having a naming layer over IP or UDP for incremental deployment [39]. Overlays are useful for clean slate deployment as the approach allows use of the existing network infrastructure.

A. Hard handoff with rebinding

In the hard handoff (break-before-make) scenario, mobility related events are handled by the UE and it always attaches to the best BS based on channel quality measurements. In such traditional schemes, the undelivered packets due to poor connectivity are either lost or buffered at the edge router. Thus, these packets must be forwarded to the new BS through IP tunnels, or the end host can request retransmission using a transport layer solution (TCP). These mechanisms induce additional network overhead particularly when the number of devices attached to the network is large.

The rebinding feature (given sufficiently large router buffer size) makes it possible to design a zero-packet loss system by querying the updated NA for a given GUID, thus allowing a router to dynamically reroute packets. The UE is not aware of packet rerouting except for listening to the new BS channel. Fig. 3 gives an overview of handover procedure using rebinding support. Considering a Wi-Fi AP as an example, the supporting timing diagram involving handover is shown in Fig. 4. Initially the UE is attached to the AP1 using the default 802.11 attach procedure. AP1 inserts a new binding $(GUID_{UEx} \rightarrow NA_{AP1})$ into the GNRS which is periodically queried and updated by itself as well as other NEs. On successful attachment, a data flow path is created between the UE and AP1. The data flow continues using AP1 until

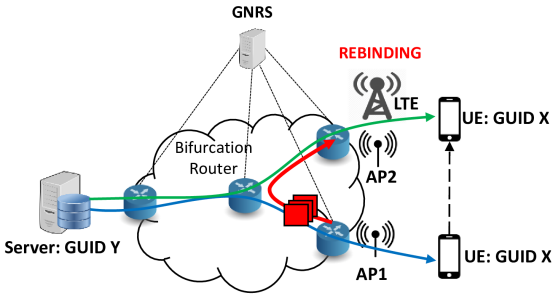

Fig. 3. Hard handoff with rebinding

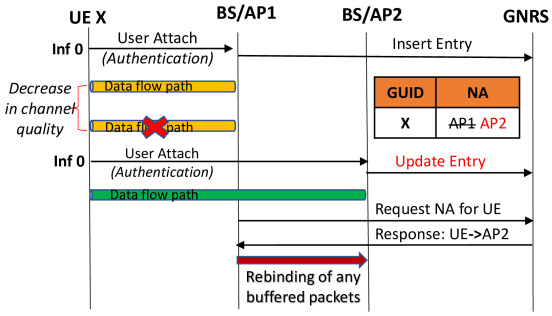

Fig. 4. Timing diagram for hard handoff

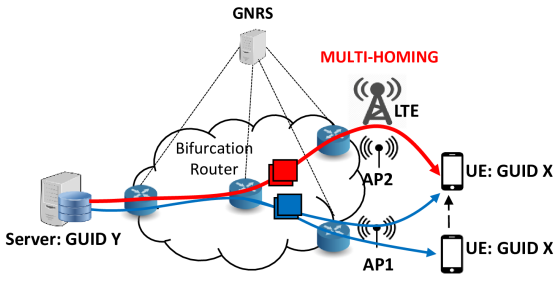

Fig. 5. Soft handoff with multihoming

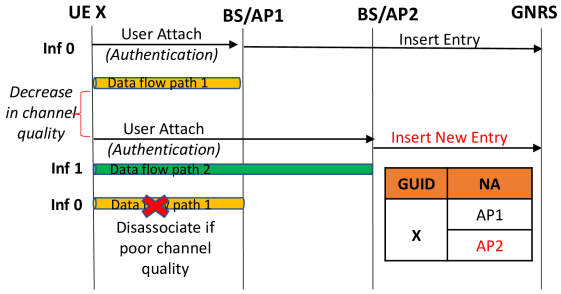

Fig. 6. Timing diagram for soft handoff

the RSSI is less than a specified threshold (-75 dBm) when the handover procedure is initiated. As soon as the UE finds a better AP (in this case, AP2), the UE disconnects from the current AP (AP1) and gets attached to the new target AP (AP2) which will update the GNRS with the new network address, $(GUID_{UEx} \rightarrow NA_{AP2})$. A new data flow path is created.

During this handoff process, the in-network packets are stored at the access router. The absence of periodic link probe packets due to disconnection caused by UE mobility between host (UE) and router (AP1) will force the access router to query the GNRS for the current NA of the UE. The stored packets are then forwarded to the new NA and all the in-flight packets reroute as the intermediate routers update their routing table based on the link state advertisements (LSA). This scheme has no packet loss during handover and does not involve the use of tunnels or bearers. Finally, it can support heterogeneous handover between multiple networks (e.g., WiFi and LTE) without any additional configuration.

Push vs Pull GNRS Service: The above specified rebinding scheme uses a PULL based approach to query the GNRS for the updated NA if there are no periodic link probes between router and a host. This introduces additional latency, which in turn depends on the frequency of link probe packets. In contrast, a PUSH based scheme can also be introduced where the GNRS will send out updates to the previous NA about the current attachment of GUID, and this can be achieved by comparing current vs previous NA logs.

B. Soft handoff with multihoming

During soft handoff (make-before-break) as shown in Fig. 5, we use the multihoming feature to provide seamless mobility support without packet loss. As an example, a timing diagram for Wi-Fi is shown in Fig. 6 where the UE is initially attached to AP1 and a new entry is inserted into the GNRS with $(GUID_{UEx} \rightarrow \text{NA}_{AP1})$ binding as discussed earlier. The Wi-Fi interface at the UE continuously monitors the RSSI every 100ms and reports averaged RSSI values to the L3 layer every 1s. This averaged RSSI computation enables appropriate handover decisions. If the reported RSSI is less than a certain threshold (-80 dBm in our implementation), the second interface, either LTE or WiFi if available, is activated and gets attached to the network. Once the attachment process is complete a new entry with $(GUID_{UEx} \rightarrow \text{NA}_{AP2})$ is added to the GNRS. Thus, the UE is multihomed with two available data paths as shown in Fig. 6 and is capable of receiving packets on both the interfaces, simultaneously. We have incorporated algorithm I in our host software design which allows the UE to access any of the available networks.

Algorithm 1 Soft handoff for 2 Interfaces

```
Interface 1: Inf 1,  Interface 2: Inf 2
Parameters: RSSI, Throughput
Periodically monitor parameters on available interfaces
if parameter < Threshold then
    Begin scanning on Inf 2 for new AP/BS
    if AP/BS exists then
        Associate Inf 2 with the best AP/BS
        Disassociate Inf 1 (if poor channel quality)
    else
        Continue probing on Inf 2
    end if
end if
```

The multihoming feature is achieved using a variable length header specifying multiple network addresses for packets destined to a UE from the server, thereby allowing intermediate routers to select a suitable bifurcation point [7] for traffic split-

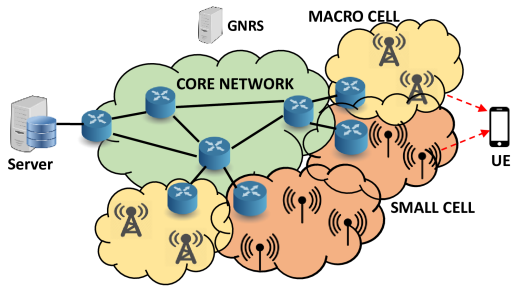

Fig. 7. HetNet flat core architecture

ting. Therefore, packets can traverse different paths towards LTE/WiFi interfaces based on metrics such as ETT (expected transmission time) and achievable data rate. Uplink traffic uses the best available interfaces. Use of multiple interfaces along with the in-network rerouting support eliminates the scenarios with ping-pong effects and thus provides a robust connection to at least one of the available interfaces.

V. City Scale Simulation

To evaluate the performance of multihoming based handover in a realistic deployment scenario comprising of macro and small cells, we developed a discrete event based simulator consisting of dense HetNet deployment with real user mobility traces obtained from CRAWDAD [40]. The user mobility trace consists of X-Y coordinates sampled every 30s obtained through a measurement campaign (duration of about 2hrs), we inserted location updates of 1s to the original dataset for more accurate handover performance evaluation. The system simulation parameters are listed in Table II. The macro cell has a coverage of 500m as against the small cell having 50m coverage, providing maximum throughput of 75Mbps and 18Mbps with 20MHz and 5MHz bandwidth respectively. The macro cell is comprised of 3 sectors with small cells randomly deployed within macro radius with inter-cell distance of 75m.

Network Deployment: A flat core architecture as shown in Fig. 7 with no hierarchy to reach the Internet for macro and small cells is considered. The routers are capable of providing both radio as well as backhaul support, and have sufficient memory for packet storage and rebinding. An average latency of 65ms [41] for the handover between macro cell and small cell, and 300 ms [42] for inter-small cell is considered. Owing to the MF architecture, the routers have in-network packet storage and per-interface scheduling capabilities to inherently support multihoming. The name-based multihoming capability is simulated and the performance with respect to throughput and RTT over user mobility pattern is evaluated against various schemes.

Access Schemes: (user association)

- *Macro only*: UE always uses macro cell during entire mobility path.
- *Best available interface*: UE selects the best interface based on throughput between macro and small cells.
- *Multihoming with rebinding*: UE uses both the interfaces if available; packets lost during the handover are rebound to a new NA.

Scheduling Schemes: (between UE and intermediate router)

TABLE II
System Simulation Parameters

Simulation Parameter	Value
Deployment scenario	Single Macro cell with uniformly deployed small cells inside it
Macro cell radius	500m
Small cell radius	50m
Path Loss Model	LogDistancePropagationLossModel
Inter-cell Distance (small)	75m
Bandwidth	Macro : 5MHz, Small: 20 MHz
Tx Power	Macro: 46 dBm, Small: 30 dBm
Carrier Frequency	2 GHz
Modulation	64 QAM, No MIMO
Number of Small Cells	60 per Macro
Backhaul link BW	10Gpbs

- *Macro only*: only macro cells are used.
- *Round robin for both UL and DL*: the intermediate router and UE device uses the available interfaces alternatively for downlink and uplink transmission respectively.
- *Round robin for DL (UL) & best interface for UL (DL)*: UE uses best available interface based on throughput for UL transmission and for DL, the intermediate router schedules packet alternatively on available interfaces (vice versa).
- *Best available interface always*: UE/router selects the best available interface based on achievable throughput for both DL and UL paths.

VI. Results

We evaluated the following scenarios for seamless handover using *MobilityFirst* name based network architecture: (a) hard handoff with rebinding for a homogeneous Wi-Fi network, (b) soft handoff with multihoming for homogeneous as well as heterogeneous interoperable WiFi and LTE networks, (c) impact of router memory on handover schemes, (d) comparison with IP based handover schemes and (e) Large scale dense HetNet simulation. The evaluation topology for (a)-(d) consists of two BSes and a UE with mobility induced by changing the attenuation between the pair of BS. The BS can be either Wi-Fi APs or a Wi-Fi AP with an LTE eNB.

A. Rebinding for Hard Handoff

Fig. 8 shows RTT and throughput plots during hard handoff considering a homogeneous Wi-Fi network obtained using mfping and mfperf (modified versions of ping and iperf for MF respectively). As observed in the RTT plot, the handover happens at time $t = 20s$ (packet sequence number 20 as the ping inter-packet interval is set to 1s). A disconnection period of 3s is observed because the L2 handoff itself takes around 2.92s as shown in Fig. 2 leading to 3 packets being stored at the access routers which need rebinding. After obtaining the updated network address of UE from GNRS, the stored packets are rebound with the new address, and are delivered to UE after a period of 3.21s for pull based GNRS service as against 3s for push based service. The 200ms additional delay for pull based GNRS is mainly due to routing and timers as all the routers are not synchronized at the start of the experiment. For throughput evaluation mfperf is run over an interval of 80s and the handover happens at time, $t = 20s$. A throughput value of 0 is observed for 2s right after handover and the

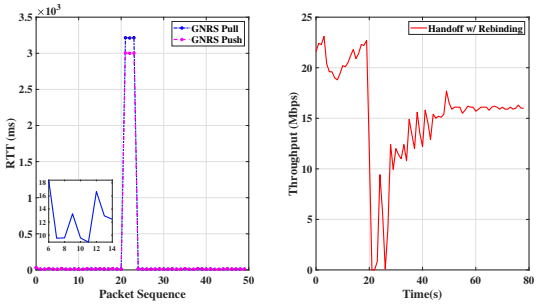

Fig. 8. Homogeneous hard handoff with rebinding in WiFi

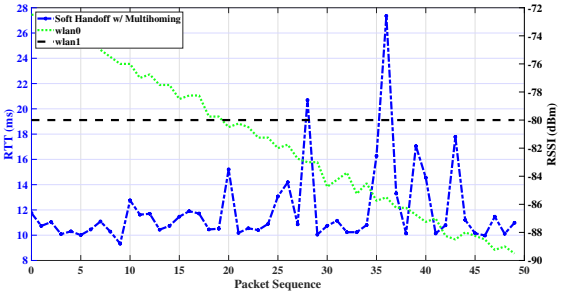

Fig. 9. Homogeneous soft handoff with multiHoming in WiFi

peak obtained after the handover is mainly due to the packet rebinding. The average throughput before and after handover is observed to be 17.28 Mbps and 14.23 Mbps respectively.

B. Multihoming for Soft Handoff

Homogeneous WiFi Network - Considering multihoming based handover with 2 Wi-Fi interfaces, Fig. 9 shows the RTT during handover. The decrease in channel quality with the initially attached AP triggers handover with the next best available AP obtained from the scan using multiple interfaces present at the UE. In our controlled experimental setup, this handover happens at packet sequence number 20 where RSSI of *wlan0* is less than RSSI of *wlan1*, and we observe a drop in the RTT after handover as the packets are rerouted to the new interface. The peaks observed after 20s are mainly due to the multihoming as the packets are delivered via the old interface with lower channel quality leading to a rise in the RTT. The intermediate router is capable of deciding which path to select based on the data rate and hence we observe fewer peaks with high RTT values.

Heterogeneous WiFi and LTE Network - In this experiment we evaluated RTT for handover between heterogeneous Wi-Fi and LTE network. Initially, the UE is attached to only the Wi-Fi network and when the RSSI of Wi-Fi is less than the set threshold (-80dBm), the LTE interface switches from idle to active mode. The UE then attaches to the LTE network's eNB. We ran two different scenarios during this experiment. In the first scenario, upon switching to the LTE network, the UE is disconnected from the Wi-Fi AP. In the second scenario, upon attaching to the LTE network, the Wi-Fi AP is remained in the attached state to the UE, enabling it to receive and send from both the interfaces. Fig. 10 compares the RTT performance for both the scenarios. It is observed that after handover (at packet sequence number 20), the RTT of the second scenario

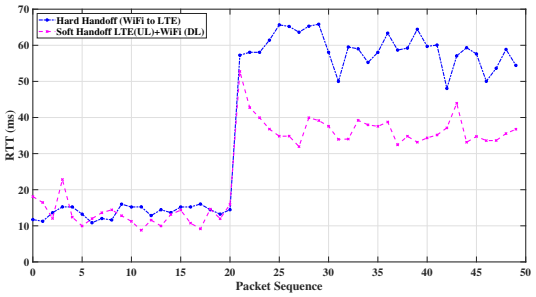

Fig. 10. Heterogeneous soft handoff between WiFi and LTE

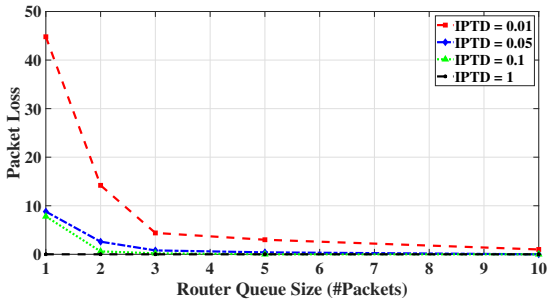

Fig. 11. Packet loss due to queue size during handover

is significantly lower than the first case of single interface use. Therefore, harnessing multiple interfaces during handover can provide seamless connectivity without packet loss.

C. Impact of Router Memory on Handover

The packet loss performance during the handover is evaluated with respect to router queue size and inter-packet transmission delay (IPTD) as shown in Fig. 11. For an IPTD of 1s, there is no packet loss irrespective of the available router memory. As the packet transmission rate is increased by lowering the IPTD to 0.01s, 45 packets are lost. The loss is because there is a handover delay which needs to accumulate packets for store-and-forward feature used in this work which fails if there is an insufficient router queue size. Moreover, the network congestion introduced due to higher arrival rate than the packet processing capability of the router causes packet loss. Therefore, it is essential that for a lossless handover, routers should have sufficiently large memory considering the number of users attached to the network.

D. Comparison with Existing Handover Schemes

We also evaluated packet drops in the IP based handover by using ping with different inter-arrival rate as shown in Table III. For a lower ping interval of 0.1s, 41 packets are lost as compared to 4 packets for 1s inter arrival which aligns with our hard handoff experiment. In addition to the packet loss, applications also have to reset their TCP connection every time a handoff is performed, caused either due to timeout or allocation of new IP address. Further, it is noted that using storage aware routing with sufficient router memory, there are no packet losses using our proposed handover techniques.

E. Large Scale Dense Heterogeneous Network Scenario

The key network parameters such as throughput, RTT and impact of load at the intermediate router on handover performance for a dense heterogeneous network are evaluated

TABLE III
PACKET DROP IN IP BASED HANDOVER

Packet Inter-Arrival (s)	0.1	0.3	0.5	1
Packet drop	41	13	7	4

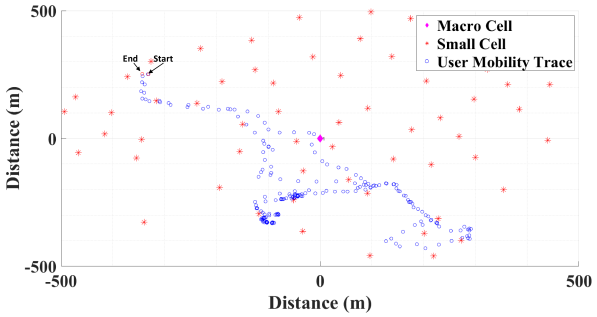

Fig. 12. HetNet deployment with real user mobility traces

with the simulation setup given in Sec. V. Cells are assumed to occupy non over lapping channel and the cell deployment layout is shown in Fig. 12 along with user mobility trace.

The maximum achievable throughput is computed against various UE access schemes. Fig. 13 shows the plot of throughput against various UE access schemes with respect to time sampled every 60s for 10 random trials (7200s x 10). The multihoming scheme provides higher throughput (e.g., at 10-20 time ticks) when the user is at the optimal location to receive the multiplexing gain of both macro as well as small cells. At other locations, the gain varies but still outperforms the best interface scheme. The throughput is mainly limited by the small cell availability due to random deployment within macro cell. The large macro cell always provide better connectivity and seamless mobility to UE and significantly help in throughput performance in the absence of small cells.

Throughput Evaluation: In this section, we evaluate throughput for various approaches.

Throughput Gain and Packet Loss: The use of best interface and multihoming with rebinding provide an average throughput of 20.9Mbps and 23.5Mbps respectively (Fig. 14 right). Multihoming provides a gain of 12.5% with respect to best interface during the entire simulation run. For a single experimental run (7200s), considering stationary UE (10-20 time ticks), multihoming has a gain of 16% against best interface scheme. Hence, use of multiple interfaces for stationary and mobile UE cases improves user perceived QoS, but the current IP architecture lacks this support as it's achieved mainly through MPTCP [10] without in-network support needed for seamless handoff. For a full buffer simulation, we also observed around 12.4k packets (size 1000 Bytes) being buffered at the respective base stations during entire UE trajectory which includes multiple handoff between small and macro cells. With the help of storage capable routers and GNRS, these packets are rebound to the updated UE location avoiding end to end retransmission as in the case of TCP. Use of multiple interfaces with in-network support provides seamless mobility with increased user throughput.

Proportional vs Equal split of flows: Flows at intermediate router can be split proportionally based on achievable throughput across individual interfaces. The bifurcation router will request for the channel quality from each of the access routers and based on the obtainable data rate an optimization problem as given in Eq. 1 can be formulated where the objective is to maximize allocation on individual interfaces (f_i) subject to flow rate (F_r) and the bottled-necked throughput (R_j). N is the total number of interfaces available on a UE device, w_i represents weight for interface i and j represents links present along path (interface) P_i.

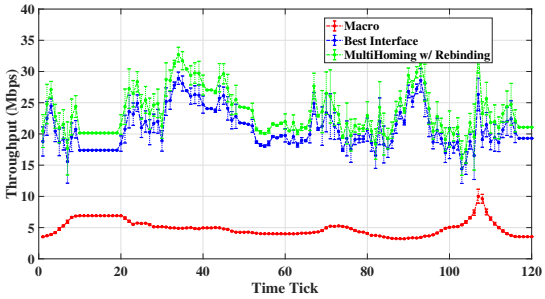

Fig. 13. Throughput for various UE access schemes

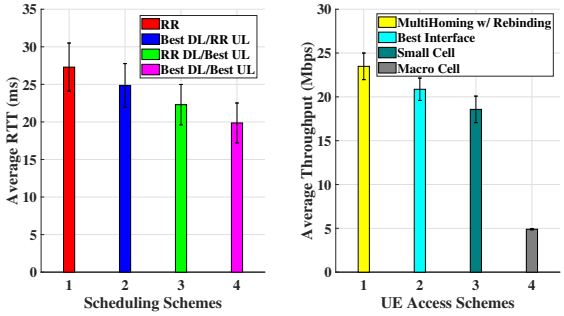

Fig. 14. Average RTT and throughput performance

$$\max_{f} \quad \sum_{i=1}^{N} w_i * f_i \quad \text{s.t.} \quad \sum_{i=1}^{N} f_i \leq F_r$$
$$0 \leq f_i \leq min(R_j) \qquad \forall i \in N, \forall j \in P_i \tag{1}$$

The above optimization problem solves for the optimum rate allocation along individual interfaces. As can be seen from Fig. 15, the proportional scheme always outperforms equal share for a flow (sending) rate of 30 Mbps. An average gain of 44% is observed with $w_i = 1$ considering 10 experimental runs sampled every 60s. The gain is especially higher when user is very close to a small cell and obtains higher throughput than with a macro cell (90-95 time ticks). Equal-share does not prioritize between the interfaces and allocates same rate between them, under utilizing the available bandwidth. Fig. 16,

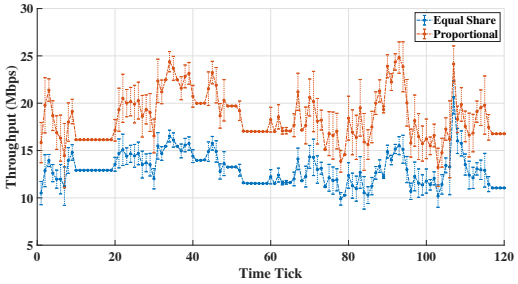

Fig. 15. Throughput performance for flowrate 30 Mbps

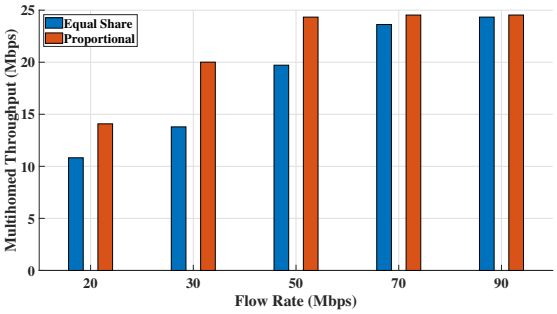

Fig. 16. Multihomed throughput performance

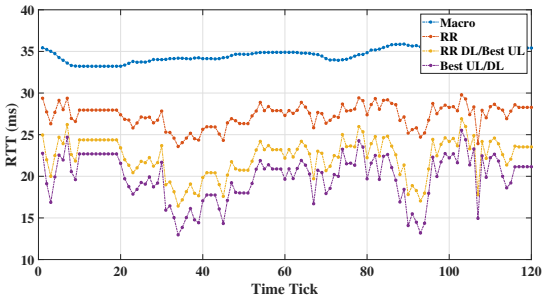

Fig. 17. RTT for various scheduling schemes

plots the multihomed user throughput for various flowrates. A higher throughput gain is observed in the case of lower rate application in proportional scheme as compared to equal share scheme. The gain is not that significant for higher rate applications and the proportional fair scheme converges to the equal share scheme. This is mainly because for higher flow rate, we have access being bottlenecked limiting higher user throughput (the core backhual links have 10Gbps capacity).

RTT Evaluation: To evaluate per packet round trip time from a UE to a remote server, we simulated the scheduling feature at UE and also at the intermediate router to account for multiple interfaces. Fig. 17 shows the plot of average RTT per packet (size 1000 bytes) along the entire UE trajectory sampled every 60s as before. Macro cell provides an average end to end RTT of 34.4ms, the majority of which is contributed by UL channel grant access (17ms) [43]. Use of the best interface for both UL and DL improves the performance of packet reception and also allows for seamless handoff between various RATs. Fig. 14 (left) shows the average RTT for different scheduling schemes. We observe that round robin for DL and best interface for UL provides comparable performance with respect to best interface for both UL/DL which has an additional overhead of periodically querying the access router for the best interfaces.

Load at Intermediate Router: The bifurcation router helps in scheduling of packets between multiple available interfaces. Any load present at the router affects the overall performance as the router has to perform scheduling decisions for multiple users. We evaluated the impact of load on intermediate router with respect to RTT considering various scheduling schemes as described earlier. We considered ∼200 users under macro/small cell representing the highly loaded case (load 1) and no load is represented as load 0 serving a single user. We observed that the round robin scheduling performs poorly under heavily

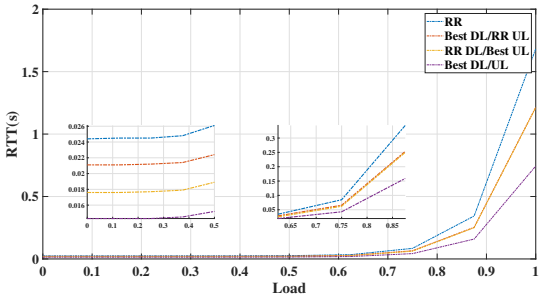

Fig. 18. Impact of load at intermediate router on RTT

loaded scenario as the total end to end latency can be as high as 1.6s (shown in Fig. 18), which impacts live real-time application. Best DL/RR UL and RR DL/best UL performs fairly the same under all load conditions. Best DL/best UL scheme has a better performance as compared with the above schemes having RTT of around 700ms for heavily loaded scenario (roughly half of RR scheme). Therefore, based on the load at intermediate router appropriate scheduling schemes should be selected as for the lightly loaded (load 0 to load 0.4) case all the schemes perform similarly.

VII. Conclusions

This paper evaluated two handover schemes based on an implementation of a named-object based flat mobile core network on the ORBIT radio grid testbed. The results show that rebinding and multihoming capabilities in the architecture can be used to provide seamless mobility. Handover performance was evaluated with respect to RTT (round trip time), throughput and packet loss. We demonstrate that using multiple interfaces during handover can realize seamless connectivity with low RTT as compared with a single interface where the RTT is bounded by L2 handoff latency. Furthermore, dynamic network rebinding for an in-transit packet during handover lowers the average RTT of the system as it avoids end-to-end retransmissions. The proposed approach thus solves the mobility problem in dense HetNets without resetting of end-to-end sessions and tunnels during the handover. Also, unlike IP based handovers, our schemes can achieve seamless connectivity with zero packet loss given sufficient router memory. Soft handoff with multihoming schemes were also evaluated in a dense HetNet scenario with macro and small cells along with real mobility traces.

The results show that the above schemes provide an average throughput gain of 12.5% for mobile users and 16% for static users with zero packet loss when compared with a best interface policy. The proportional flow splitting between multiple interfaces achieves a gain of around 44% relative to equal share for lower bitrate applications. Future work includes large scale evaluation using COSMOS [44] with multiple UEs, emerging access technologies (mmWave, 5G), and more sophisticated handover algorithms using different parameters.

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