The Interoperability of Wi-Fi Hotspots and Packet Cellular Networks and the Impact of User Behaviour

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Abstract

The rapid emergence of Wi-Fi hotspots that are aimed at providing broadband wireless access to users in and around places of commercial interest presents the unique problem of integrating the existing cellular networks with these. The traditional cellular networks have in-built mechanisms for billing, authentication, and resource allocation. However, the Wi-Fi hotspots provide the user with instant, inexpensive, and faster connectivity, and the user may prefer to connect to a locally installed Wi-Fi Access Point instead of the packet cellular network. In this paper, we present an architecture that explores the interoperability issues between the hotspots and the traditional cellular network. In the presence of multiple wireless networks with different access costs, different areas of coverage and bandwidth, the user's choice to select a particular network can significantly impact the user benefits and resource usages. We identify three major user profiles – cost conscious, bandwidth conscious and glitch conscious user profiles - and study their impact on resource utilization.

I. INTRODUCTION

Wireless Fidelity (Wi-Fi) systems refer to high speed wireless LANs that were originally intended to extend the wired Ethernet in offices to wireless clients. The coverage area and ability to support high bit rates are the two major reasons behind the name Wi-Fi. Though the popular wireless LAN standards IEEE 802.11b and 802.11a are considered as the standard wireless LAN protocols for deployment of Wi-Fi networks, any high speed wireless LAN protocol such as ETSI HiperLAN can be used.

Wi-Fi networks operate in the unlicensed 2.4 and 5 GHz radio bands, with an 802.11b or 802.11a or with products that contain both bands (dual band), so that they can provide enriched network experience. Wi-Fi systems are potential candidates for provisioning high speed multimedia content delivery at areas such as indoor offices, airport lounges, and shopping malls. The advantages of Wi-Fi systems are ease-of-use, ubiquitous high speed computing, and low setup/deployment cost. The integration of Wi-Fi hotspots (wireless LANs) with wide area wireless networking technologies such as Global System for Mobile Communications (GSM) and General Packet Radio Service (GPRS) provides an added advantage for the mobile stations (MSs). Such an integrated system provides secure, reliable, and high speed wireless connectivity. A Wi-Fi network can be used to connect computers to each other, to the Internet, and to wired networks.

The major issues for seamless roaming across Wi-Fi systems require technological solutions for routing, authentication, billing, and QoS provisioning. In this paper we essentially consider the Wi-Fi system to be a realistic and efficient implementation of a Multihop Wireless LAN, which has the advantages of enhanced throughput due to multihop relaying.

The rest of the paper is organized as follows. In Section II we present some of the work that has been undertaken in the areas of Wi-Fi systems and in systems with multihop relaying. Section III gives a description of the system architecture. The different types of user profiles which influence how a mobile station behaves in the system are described in Section IV. In Section V we analyze the key issues involved in the routing mechanism and also describe the proposed routing protocol. The simulation results, which study the impact of the different classes of MSs on the network are given in Section VI. Section VII concludes the paper.

II. RELATED WORK

In this section, we present some of the possible service provider models for Wi-Fi systems, and also some of the existing work in the area of multihop relaying in cellular networks.

A. Wi-Fi Service Models

The service provider model in a Wi-Fi-WAN framework assumes significance due to the presence of multiple peer and hierarchical service providers. Some of the possible service provider models for Wi-Fi systems are as follows.

- **The Wi-Fi Micro Carrier Model**

  In this model, small business operators can setup their own access points and maintain customer relations and billing with subscribers. An example of this category is a restaurant operating a small Wi-Fi system with a set of APs in its premises.

- **The Franchiser-Franchisee Model**

  This model for Wi-Fi systems is that a Franchiser company making an agreement with a Franchisee (e.g., a restaurant which has an inbuilt Wi-Fi system for its internal purposes) for providing Wi-Fi connectivity on a revenue sharing basis. The external communication, access network costs, and back office softwares may be supplied and maintained by the Franchiser. Hence the Franchiser company can extend its services to the public.
- **The Wi-Fi Carrier Model**

  In this model, a particular company referred to as Wi-Fi Carrier can own, deploy, and operate a number of Wi-Fi system enabled APs at public places. The subscribers can utilize the designated carrier's network services in their coverage area based on acceptable billing models.
- **The Aggregator Model**

  This model refers to an abstract service provider which strikes wholesale partnerships with Wi-Fi operators. Such Aggregators mainly focus on two major things: (i) reselling of the services provided by the Wi-Fi operators and (ii) giving its subscribers access to large number of networks.
- **The Extended Service Provider Model**

  The synergy with existing cellular systems especially Third Generation (3G) systems can increase profits for cellular operators. This can even lead to reduction in the deployment cost of 3G systems. The widespread deployment of Wi-Fi systems can be considered as complementing the 3G systems. Also the availability of wireless devices equipped with Wi-Fi and cellular interfaces encourages the possibility of switching to the Wi-Fi systems whenever an AP is detected. Vertical handoff schemes can be used to switch back to the wide area cellular networks as and when necessary in such cases. Thus Extended Service Provider model envisions the provisioning of Wi-Fi services as an extension to the existing service provided by the cellular network operators.

B. Multihop Wireless Networks

In the recent past multihop relaying has been proposed as a throughput enhancement alternative to the traditional cellular model. Lin and Hsu have studied by analytical methods the throughput enhancement of Multihop Cellular Networks (MCNs) in [2]. The MCN model helps to reduce either the number of BSs required or the power expenditure of the mobile sta-

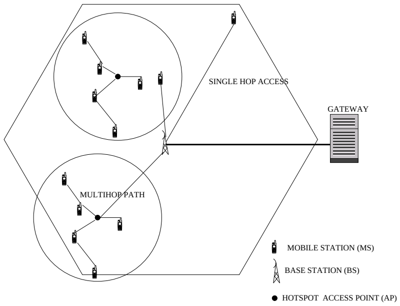

Fig. 1. The Interoperability Framework

tions (MSs) (the new transmission range is a fraction of the cell radius). Ananthapadmanabha et. al. proposed in [3] a feasible architecture for MCNs and an efficient routing mechanism for MCNs. This proposal assumes an approximate knowledge of the network topology by the Base Station (BS). All MSs in a cell take part in the topology discovery wherein each MS regularly sends to the BS, information about the beacon power received from its neighbors. This information is used by the BS to estimate distances between MSs. A best-effort routing protocol and real-time extensions to the above architecture were also suggested in [3]. Lin and Hsu have also proposed in [4], a protocol for multihop relaying in a Multihop Wireless LAN (MWLAN) environment called Base Driven Multihop Bridging Protocol, that achieved routing by building up bridging tables at each MS with the help of the BS. [5] proposes an architecture that uses a multi-powered architecture using multiple radio interfaces, operating at varying transmission powers. Even though the average power consumption per packet is lower, the total power consumption is higher than in [3].

III. SYSTEM ARCHITECTURE

The system under consideration essentially consists of a set of Base Stations (BSs) that belong to a Packet Cellular Network that can provide wide area coverage to the Mobile Stations (MSs), and a set of Wi-Fi Access Points (APs) that act as Wi-Fi hotspots that provide high speed connectivity to the MSs. Each MS is assumed to support only one wireless interface, that can switch between the packet cellular and Wi-Fi mode of operation. The Wi-Fi APs are assumed to be interconnected with one another, and with the BSs by means of either a wired backbone network, or by high bandwidth point-to-point wireless links. The BSs are connected by means of a high speed wired network.

Figure 1 shows a schematic representation of the system under consideration. The BSs are placed in such a manner that the entire terrain is covered, while the Wi-Fi hotspots are assumed to be randomly distributed throughout the metropolitan area. The packet cellular network in our system is represented by a Single hop Cellular Network (SCN), in which the MSs are in communication with the BS on the control as well as data channels, with a transmission range equal to that of the cell radius. As considered in [6] and [7], in MCNs partitions may arise when an MS does not have a multihop path to the BS. The Wi-Fi hotspots are considered as a multihop relaying environment that is similar to an MCN. The Wi-Fi AP acts as the coordinator for enabling routing and reserving bandwidth for MSs in the hotspot. The MCN architecture as described in [3] assumes a control interface of transmission range equal to that of the cell radius, and a data channel with a transmission range equal to half the cell-radius. In our system, the Wi-Fi AP has a transmission range of R/2, and the transmission range for the data channel at the Wi-Fi AP is R/4. Wi-Fi APs with multihop relaying is an attractive option in WLANs as it can extend the coverage of a high bandwidth AP to a much larger area. As is evident, each MS has the option of operating either under the control of the BS or under the control of the Wi-Fi AP. In the following section, we identify three different classes of user behaviour, which determine how the MS chooses between the various available networks.

IV. USER PROFILES

The different MSs in the system can choose to connect to any of the available networks at any place. The behaviour of the MS is driven by its resource requirements and user interests. For example, an MS engaged in a multimedia transmission will have different requirements from one which is just downloading email from a server. We associate each MS with a user profile that reflects its requirements. This user profile in turn determines how the MS chooses the BS or Wi-Fi AP it connects to. In this section, we describe the following three different classes of user profiles that an MS may possess.

1) **CLASS 1 – Bandwidth Conscious User Profile**: The MSs with a bandwidth conscious user profile will choose to connect to the BS or Wi-Fi AP which offers the maximum bandwidth. An estimate of the free bandwidth available (Estimation of the free bandwidth available is described in Section V) is sent along with each beacon packet periodically originated by the APs or the BSs. A CLASS 1 MS on receiving such a beacon determines to switch to the new BS or Wi-Fi AP if the bandwidth advertised is greater than the free bandwidth estimate at its currently registered BS or Wi-Fi AP. MSs with high bandwidth requirements (like those engaged in a multimedia download) possess this

type of user profile.

2) **CLASS 2 – Cost Conscious User Profile**: An MS with a Cost Conscious user profile always chooses to connect to the network with the lowest transmission cost per byte. Each BS or Wi-Fi AP advertises its associated transmission cost in the beacons sent by it. A CLASS 2 MS will switch to a new network only if the cost of the new network is less than that of its currently registered network by a threshold value. An MS engaged in non-real time file downloads is an example of a CLASS 2 MS.
3) **CLASS 3 – Glitch Conscious User Profile**: A Glitch Conscious MS has glitch free connectivity as its priority. We define a glitch as an interruption in the transmission or connectivity which occurs when an MS moves from one network to another. Thus an MS with this user profile tries to minimize the number of handoffs it undergoes between different networks to achieve the smoothest possible transmission. This is done by remaining connected with the cellular network, which has a larger coverage area, at all possible times. An MS engaged in a voice call may be classified under this profile.

In all the three different user profile classes, we assume that maintaining connectivity is of utmost importance to the MS. In order to maintain connectivity, an MS may connect to a network whose parameters go against its user profile. For example, a Cost Conscious MS may connect to a higher cost network when it falls outside the coverage area of the low cost network to which it is currently connected. We analyze the impact of the different classes of MSs on the system under different network conditions through extensive simulation studies in Section VI.

The user profile of an MS affects MS's behaviour, the resource consumption of the network and the traffic patterns, as it moves across the terrain. This behaviour is illustrated in Figure 2, in which an MS moves from point A to point E along the dotted line shown. The total bandwidth available at the base station BS1 is 5 Mbps while that of the two access points AP1 and AP2, are 11 Mbps each. In the scenario depicted here, we assume that that the free bandwidth available at AP1 is much less than that available at either BS1 or AP2 due to a large number of mobile stations registered to AP1. The free bandwidth available at AP2 is greater than that at BS1 due to lighter load. Also, the transmission cost per byte associated with BS1 is considered to be four times that of either AP1 or AP2. We now describe the behaviour of the MS for each of the three different user profile classes it may posses.

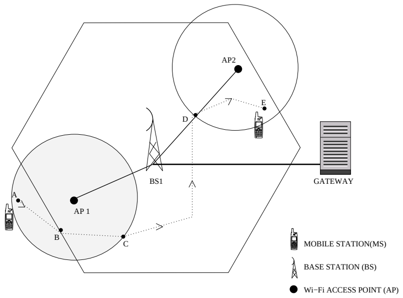

Fig. 2. Behaviour of the mobile stations with different user profiles as they move across the terrain

- **CLASS 1 MS:** The bandwidth conscious CLASS 1 MS always tries to be registered to the network offering the maximum free bandwidth. It can be seen from Figure 2 that the MS registers with the sole AP accessible to it at the beginning of its journey (Point A). At point B, the MS comes under the transmission range of BS1 also. Since BS1 has more free bandwidth than AP1, the MS will switch over to BS1 and will remain registered with it till the point D. On entering the range of AP2 at D, the MS switches over to AP2, although it is still in the range of the BS. This is because AP2 offers a higher amount of free bandwidth than BS1. The MS remains with AP2 till the end of its journey.
- **CLASS 2 MS:** The cost conscious CLASS 2 MS tries to register with the least cost network at all times. After starting its journey from point A, the MS remains registered to AP1 till the point C. It must be noted here that the MS does not switch over to BS1 after it enters BS1's transmission range at point B. This is because the transmission cost associated with BS1 is higher than that associated with AP1. At point C, the MS goes out of the range of AP1 and is thus forced to register with the higher cost BS1 in order to maintain connectivity. On reaching the point D, the MS registers with the lower cost AP2 and remains with it till the end of its journey.
- **CLASS 3 MS:** The glitch conscious CLASS 3 MS tries to minimize the number of glitches in its connection by registering with the larger range cellular network at all possible times. The MS remains registered with AP1 between points A and B. However, once it enters the range of BS1 at point B, it switches over to the BS and remains with it till the end of the journey at point E.

V. ROUTING MECHANISM

The protocol proposed in [3] works essentially as an infrastructure-aided source routing mechanism [8], that uses the topology information available at the BSs. We now present a brief description of the protocol in [3], and also describe some of the required modifications needed to support the new architecture. Each BS periodically generates *Beacon* messages that can be received by all mobile stations within a distance R from it. An MS chooses to register with a particular BS depending on the received signal strength. It then sends the *RegReq* packet, to which the BS replies with a *RegAck* packet.

Once the registration is complete (i.e., after the MS receives the *RegAck* packet), the MS will periodically generate *Beacon* messages, and it updates the BS on the set of neighbors that are within its transmission range. The *NeighUpdt* packets are sent whenever the received signal strength for an MS differs from the previously recorded value by a certain threshold. Whenever there is a packet to be sent to a destination MS, the source MS originates a *RouteReq* packet to its BS. The BS responds with a *RouteReply* packet with the shortest path, and the MS can send the packet along this path using the source routing mechanism. One obvious way to reduce the control overhead is the use of a route cache, with an appropriate timeout, which can be used to store the route information either from the *RouteReply* packets or from packets that the MS forwards for other sources. There is also a recovery mechanism to adapt to mobility, wherein an MS on the source route from the source to the destination on realizing that its next hop is out of its transmission range, sends a *RouteError* packet to the source of the packet. The source MS has to then acquire a new route for the destination after receiving the *RouteError* packet, by sending another *RouteReq* packet.

There are certain important issues to be handled, which necessitate changes to the registration and routing mechanism described above when we have to deal with mobile stations with different user profiles. Both the BSs and the Wi-Fi APs will periodically generate *Beacons* with transmission ranges R and r, where R is the cell-radius of the cellular network, and r= R/2 is the transmission range of the control channel of the Wi-Fi hotspot (modeled as a MCN). Each such beacon advertises the transmission cost per byte offered by the network as well as an estimate of the free bandwidth that will be available to a new node registering with it. The crucial difference between the MSs with different user profiles occurs in the registration mechanism. A bandwidth conscious MS (CLASS 1) will register with the BS or Wi-Fi AP which advertises the maximum free bandwidth among all the beacons received by it during a registration interval. An estimate of the free bandwidth at a BS or an AP is obtained by dividing the total bandwidth available at the BS or the AP by the total number of MSs currently registered with it. This approach requires an assumption by which the AP or the BS has a fair packet scheduling scheme running. A cost conscious MS (CLASS 2) will register with the BS or Wi-Fi AP which advertises the lowest transmission cost per byte among all the beacons received by the MS within a specific period. A glitch conscious MS (CLASS 3) will try to register with the network with the largest coverage area(in this case, the BSs) in order to reduce the handoff probability and thus minimize the number of glitches in transmission.

The network usage that we consider in this paper is essentially one of gateway access, with one of the BSs acting as a gateway to the Internet or as a content server. This means that each MS needs to only find a route to its nearest infrastructure node (either a BS or an AP), which can then connect to the gateway by means of the backbone network. For MSs registered to the Wi-Fi AP, the routing mechanism proceeds in a similar fashion to the MCN routing protocol discussed above. However in the case of multihop wireless LANs, the problem of network partitions can arise, especially if the node density in and around the hotspot is low. This essentially means that the MS cannot find a multihop path over the data channel (of transmission range r/2) to its AP. In such a case the AP generates a *PartitionMsg*, to indicate to the MS that it is in a partition, and thus cannot utilize the network. On receiving the *PartitionMsg*, the MS deregisters from the AP and tries to use the nearest BS, so that connectivity is not lost.

The mechanism discussed for the new architecture can be easily extended to any form of network access. In the general case a source MS tries to find a route to a destination MS. It is assumed that all the BSs have the complete topology information and also information about where each MS in the system is currently registered. The MS sends a *RouteReq* to its BS/AP, which then computes the shortest path as follows. In case the destination MS belongs to the same cell as the source the BS/AP employs the shortest path algorithm. Note that it is possible for the path to bypass the BS/AP if the node density is sufficiently high. There are two types of *PartitionMsg*s that are generated in a multihop wireless LAN – one where the source is in a partition and the other when the destination is in a partition. In each case the respective BS/AP will notify the MS of the fact that it is in a partition so that the MS can take a remedial measure. It is to be noted that MSs registered to BSs can never be in a partition.

TABLE I

SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
Terrain X range	2010m	Beacon period	1s
Terrain Y range	2610m	Bandwidth BS (Control)	1 Mbps
Number of cells	11	Bandwidth BS (Data)	5 Mbps
Cell radius	500m	Bandwidth AP (Control)	1 Mbps
Transmission range BS	500m	Bandwidth AP (Data)	5 or 11 Mbps
Transmission range AP (Control)	250m	Transmission range AP (Data)	125m
Transmission cost per byte (BS)	4 units	Number of MSs	300
Transmission cost per byte (AP)	1 unit	Mobility of the MSs	10 m/s
Mean inter-packet arrival time	2000	Number of APs	20

VI. SIMULATION RESULTS

We have simulated the system using GloMoSim [9]. The free space propagation model and no-capture model were used in the radio layer. The effect of the different user profiles was analyzed under different conditions of MS mobility, system load, number of APs and number of MSs. In the first set of results described below, the simulations were individually carried out for each of the three different classes of MSs. Later, we analyze systems in which the three different classes of MSs were present in equal proportions. The parameters used in the various simulation runs are given in Table I. The values of the parameters *Number of MSs, Mobility of the MSs, Mean inter-packet arrival time* and *Number of APs* given in the table are respectively used only in those simulations in which they are not the target of variation. For example, in the simulation where the mobility of the MSs is varied from 2 m/s to 20 m/s, the value for mobility given in the table is ignored.

A. Simulations with all mobile stations of a single class

In the first set of simulations, all the MSs in an individual simulation run belong to the same user profile class. Separate simulations were carried out for each of the three classes of MSs. The variations in network performance with varying network parameters for the three classes of MSs are discussed in this section.

1) Mobility: We first analyze the effect of the mobility of the MS on the packet delivery ratio (PDR). The mobility was varied from 2 m/s to 20 m/s in steps of 2 m/s. It can be observed from Figure 3 that CLASS 3 users achieved the highest average PDR. It can also be seen that the PDR dropped off significantly for the CLASS 2 MSs with increase in mobility. However for CLASS 1 MSs, there was a slight increase in the PDR with increasing mobility. This is because at high mobility, the BS moves out of the range of all APs very often and thus registers with a BS, where a lot of free bandwidth is available. These MSs remain with the BS till they encounter a network with a higher amount of free bandwidth. As we can see in Figure 4, this will also lead to an increase in the average cost per byte for CLASS 1 MSs. CLASS 2 MSs also switch to the BSs when they go out of the range of the APs. However, they switch back immediately to the low cost AP whenever possible, even if the BS with which it is currently registered has higher free bandwidth. The lower average cost incurred by these MSs, as we can see in Figure 4, also suggests that these MSs dominantly remain registered to the APs. With increasing mobility, the possibility of partitions arising in the multihop Wi-Fi hotspots increases. This again is a cause for a lower PDR for MSs registered with the APs.

The variation in the average number of glitches experienced by the different classes of MSs is shown in Figure 5. As expected the CLASS 3 MSs experience very few glitches. A CLASS 1 MS switches networks whenever it comes into the range of a new network advertising a higher free bandwidth. This results in the CLASS 1 MS experiencing a much larger number of glitches than a CLASS 2 MS, which switches only on encountering a cheaper network.

We observe here that the glitch conscious CLASS 3 MSs achieve a higher PDR than the bandwidth conscious CLASS 1 users. This can be explained by the fact that both CLASS 1 and CLASS 2 users encounter a large number of glitches and network partitions (refer Section III) whenever they switch from one network to another. This leads to the loss of a large number of packets during the time these MSs remain in an unregistered state. The CLASS 3 users experience very few glitches and the 5 Mbps bandwidth available at each BS is sufficient to efficiently service the UDP loads generated in this set of simulations. We study the behaviour of the network in a different scenario where the Wi-Fi hotspots are implemented as a single hop LAN and the bandwidth available at each BS is only 1 Mbps. The results of this study, discussed in Section VI-C vary from those discussed above.

2) Varying Offered Load: In this section, we describe the effect of varying the load on the system. The traffic consisted of UDP packets with a payload of 1900 bytes. The load was varied by adjusting the value of the mean inter-packet arrival time. Figure 6 shows that the packet delivery ratio (PDR) does not follow any particular trend with varying load. The highest PDR was achieved by the CLASS 3 MSs while the CLASS 2 MSs had the least. The high PDR achieved by the CLASS 3 MSs also resulted in these MSs incurring the largest average cost per byte. The cost conscious CLASS 2 MSs incurred the lowest average cost per byte. As shown by Figure 7, the average cost incurred by none of the three classes of MSs showed any marked trend with increasing load. CLASS 1 MSs suffered the maximum number of glitches while CLASS 3 MSs the least. The reasons for this behaviour has been previously discussed in Section VI-A.1. Again, the number of glitches for any particular class of MSs did not change significantly with varying load.

3) Number of APs: We now study the effect of increasing the number of APs on the various network performance measures. It can be observed from Figure 9 that the packet delivery ratio (PDR) shows a steady decrease as the number of APs increases from 0 to 100. When there are 0 APs, all the three classes of MSs operate under the BSs and thus incur a cost per byte of 4 units. As the number of APs increases, many CLASS 1 and CLASS 2 MSs register with the APs. However, they fail to achieve a high PDR due to a large number of collisions at the AP as the number of APs in the terrain increases. This is because we have assumed that all the hotspots operate in the same transmission band. The larger number of network partitions encountered by these two classes of MSs also play a role in reducing the PDR. The small degradation in performance of the CLASS 3 MSs, which try to remain with the BS at all times, is due to the radio interference from the large number of nearby APs.

As the number of APs is increased, the probability of a CLASS 1 or CLASS 2 MS registering with the cheaper Wi-Fi AP also increases. Figure 10 shows the steep decrease in the average cost per byte incurred by these MSs. The average cost incurred by the CLASS 3 MSs remains close to 4 irrespective of the number of APs. Figure 11 indicates that the average number of glitches experienced by a CLASS 1 or a CLASS 2 MS also increases with an increasing number of APs. This can be attributed to the increased availability of cheaper or higher bandwidth networks to switch to. Once again, this has very little effect on the CLASS 3 MSs.

4) Number of MSs: Figure 12 shows the variation in the packet delivery ratio (PDR) for the three classes of MSs as the number of MSs in the system is increased from 50 to 500 in steps of 50. The CLASS 3 MSs were observed to attain the highest PDR. It can be observed from the figure that the PDR achieved by CLASS 1 MSs increases slightly as the number of MSs

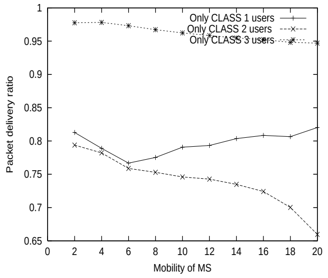

Fig. 3. Packet delivery ratio vs Mobility of the MSs

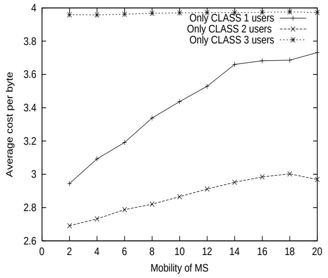

Fig. 4. Average cost per byte incurred by an MS vs Mobility of the MSs

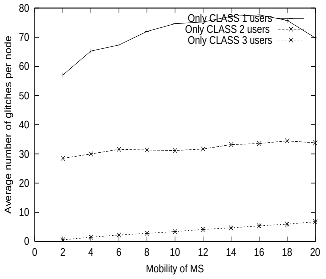

Fig. 5. Average number of glitches experienced by an MS vs Mobility of the MSs

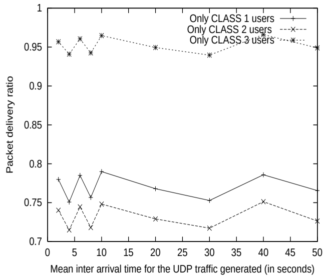

Fig. 6. Packet delivery ratio vs Mean inter-packet arrival time

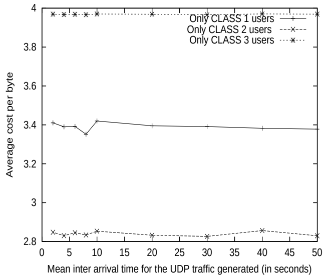

Fig. 7. Average cost per byte vs Mean inter-packet arrival time

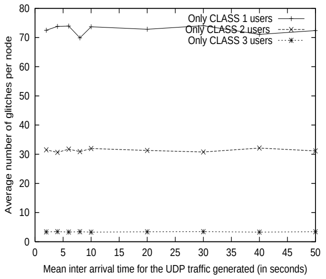

Fig. 8. Average number of glitches experienced by an MS vs Mean inter-packet arrival time

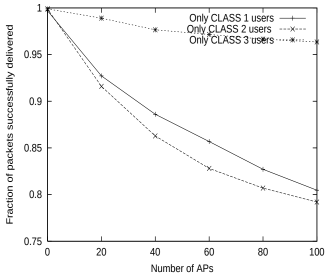

Fig. 9. Packet delivery ratio vs number of APs

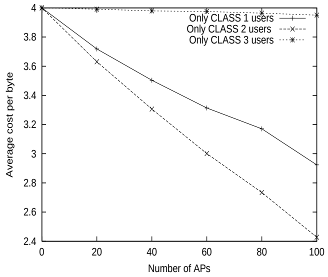

Fig. 10. Average cost per byte incurred by an MS vs number of APs

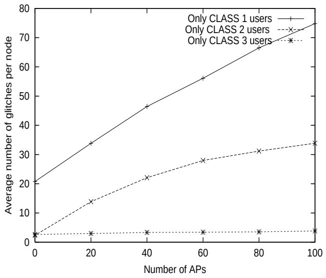

Fig. 11. Average number of glitches experienced by an MS vs number of APs

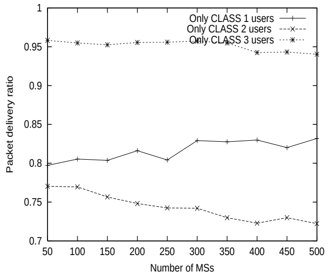

Fig. 12. Packet delivery ratio vs number of MSs

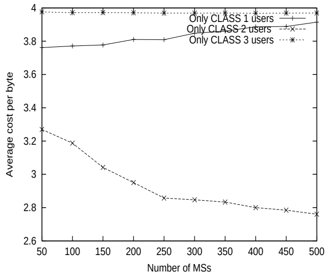

Fig. 13. Average cost per byte incurred by an MS vs number of MSs

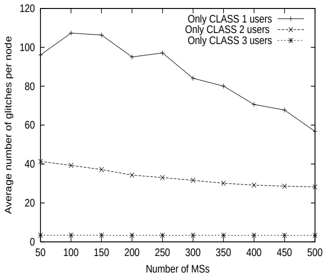

Fig. 14. Average number of glitches experienced by an MS vs number of MSs

increases. As the number of MSs increases, the free bandwidth available at the APs decreases and some of the MSs register with the BS, which are less congested. This factor leads to the achievement of a higher PDR. The PDR obtained by CLASS 2 MSs however declines steadily with increasing number of MSs. The CLASS 2 MSs always go for the cheaper network and thus remain registered to the more and more congested APs, but cheaper APs.

The variation in the average cost incurred by the different classes of MSs is captured in Figure 13. The average cost per byte incurred by the CLASS 3 MSs does not vary as the number of MSs in the system is increased. The average cost for these MSs remains very close to 4, the cost per byte of transmission using the BSs. The average cost per byte incurred by the CLASS 1 MSs increases as the number of MSs increases. As in the case of the increased PDR explained previously, this can be attributed to the MSs registering with the costlier BSs due to high congestion and lower free bandwidth at the APs. It can also be observed from the figure that there is a sharp decrease in the average cost incurred by the cost conscious CLASS 2 MSs. As the number of MSs in the system increases, there is a larger opportunity for the MSs to remain connected to the cheaper APs through multihop paths, i.e. they are less like to switch to a costlier BS to maintain connectivity.

The decrease in the number of glitches suffered by CLASS 1 MSs, as shown in Figure 14 also supports the view that more and more CLASS 1 MSs register with the BSs due to increased congestion at the APs when the number of MSs increases. There is not much further opportunity to switch to a higher bandwidth AP as most APs are congested. CLASS 2 MSs also exhibit a very slight decline in the average number of glitches suffered. This can again be accounted for by the increased possibility of remaining registered with the APs through multihop paths. As expected, the number of glitches suffered by the CLASS 3 MSs remains very low throughout.

B. Simulations with equal proportions of CLASS 1, CLASS 2 and CLASS 3 MSs

In the second set of simulations carried out, equal proportions of MSs of the three different classes - CLASS 1, CLASS 2 and CLASS 3 - constituted the system in each run. In this section, we discuss the behaviour of the network under this scenario.

Figures 15, 16 and 17 show the effect of varying the mobility of the MSs on the packet delivery ratio (PDR), average cost per byte and the average number of glitches experienced by an MS. We can see that the same trends are followed here as in Figures 3, 4 and 5, where only a single class of MSs is considered in each simulation run. This suggests that the presence of MSs of the other classes do not impact the MSs of a particular class to a great extent. As we can see from the figures, the CLASS 3 MSs have the highest PDR and CLASS 2 the lowest value irrespective of the presence of other MSs. Similarly the CLASS 2 MSs experience the lowest average cost per byte while the CLASS 3 MSs experience the lowest number of glitches.

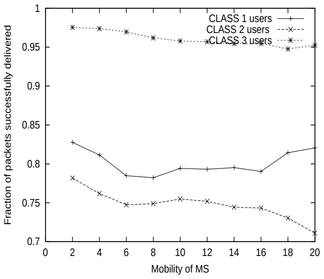

Fig. 15. Packet delivery ratio vs Mobility of the MSs (33% CLASS 1 MSs, 33% CLASS 2 MSs, 33% CLASS 3 MSs)

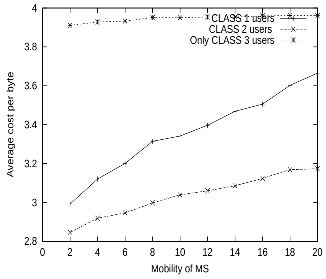

Fig. 16. Average cost per byte incurred by an MS vs Mobility of the MSs (33% CLASS 1 MSs, 33% CLASS 2 MSs, 33% CLASS 3 MSs)

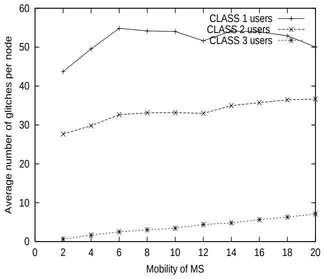

Fig. 17. Average number of glitches experienced by an MS vs Mobility of the MSs (33% CLASS 1 MSs, 33% CLASS 2 MSs, 33% CLASS 3 MSs)

The same trends as in Section VI-A.2 were observed when the UDP load on the system was varied. The results obtained with varying the number of APs again follow trends similar to those observed in Figures 9, 10 and 11 of Section VI-A.3. The graphs obtained by varying the number of MSs in this scenario also closely resemble those obtained in Section VI-A.4 in which each class of MSs was individually studied.

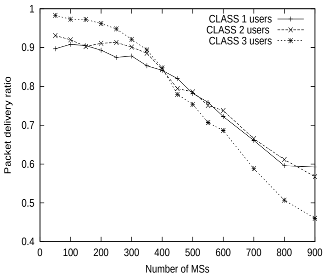

Fig. 18. Packet Delivery Ratio vs Number of MSs (SCN, BS with 1Mbps)

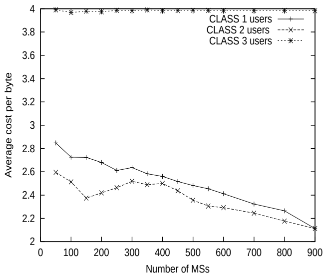

Fig. 19. Average cost per byte incurred by an MS vs Number of MSs (SCN, BS with 1Mbps)

C. Single hop LAN and bandwidth of 1 Mbps at the BS

In all the previous simulations it was observed that the glitch conscious CLASS 3 users obtained the highest Packet Delivery Ratio (PDR) – higher than the PDR of even the bandwidth conscious CLASS 1 MSs. This behaviour can be explained as follows. The CLASS 1 MSs suffer a very large number of glitches. The switching over to a new BS or AP is not instantaneous – there is a time lag involved in the registration as well as the topology discovery processes. This delay causes the node to find itself in a partition immediately after a network switch. Any packets generated by the MS or those sent to it during this handoff period are lost. Another factor which contributes to the high PDR for CLASS 3 MSs in the Sections VI-A and VI-B, is the relatively light load at the BS. In this section, we study the network when the BSs are congested. We do this by increasing the number of MSs to 500 and by lowering the total amount of bandwidth at each BS from 5 Mbps to 1 Mbps. We also change the implementation of the Wi-Fi hotspots from multihop to single hop networks, so that the CLASS 1 and CLASS 2 MSs do not suffer a large number of partitions as in the earlier simulations.

We first look at how the system behaves as the number of MSs is increased from 50 to 900. Figure 18 shows that the CLASS 3 MSs have a higher PDR than the other two classes till the number of MSs reaches around 400. After this point, congestion sets in at the BS and the PDR falls below that of both the CLASS 1 and CLASS 2 users. The CLASS 1 and CLASS 2 MSs achieve approximately the same PDR after this point. This is because there is no advantage for the CLASS 1 MSs to switch over to the already congested BSs (as against the case discussed in Sections VI-A and VI-B). Both the CLASS 1 and CLASS 2 MSs remain mostly registered with the APs and thus behave similarly. This fact is supported by the decreasing average cost per byte of transmission for the CLASS 1 and CLASS 2 MSs shown in Figure 19. A lower cost indicates that a larger amount of time is spent registered with the APs.

In Figure 20, we can see the effect of increasing the number of APs when the number of MSs in the system is fixed at 500. We see that, as we increase the number of APs, the performance of all three classes of MSs goes up. When the number of APs is 0, MSs of all three classes are forced to use the BSs for connection. As the number of APs increases, more and more CLASS 1 and CLASS 2 nodes register with the APs. This decreases the congestion at the BSs and there is a significant increase in the PDR achieved by the CLASS 3 nodes, as shown in Figure 20. The CLASS 1 and CLASS 2 MSs achieve a higher PDR as long as the number of APs in the system is less than approximately 30. After this point, the PDR of the CLASS 1 and CLASS 2 MSs start to decrease. This can be attributed to the increased interference between the the large number of randomly placed APs which operate in the same frequency bands and to which a large number of CLASS 1 MSs and almost all the CLASS 2 MSs are registered.

We can also observe that the CLASS 2 MSs achieve a higher PDR than CLASS 1. This is because the CLASS 1 MSs suffer a very large number of glitches (see Figure 21). The large number of switches between the APs and BSs do not result in an increase in the PDR for the CLASS 1 MSs. This is because the already congested BSs can offer only a small increase in free bandwidth while the the transmission at the APs is adversely affected by the large number of collisions. Figure 22 shows how the cost varies as we increase the number of APs. When there are 0 APs, the average cost incurred by all three classes of MSs is 4, the cost associated with the BSs. As the number of APs increases, the average cost incurred by the CLASS 1 and CLASS 2 nodes decreases while that of the CLASS 3 nodes remain unchanged.

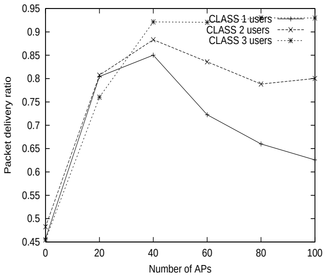

Fig. 20. Packet Delivery Ratio vs Number of APs (SCN, BS data with 1Mbps)

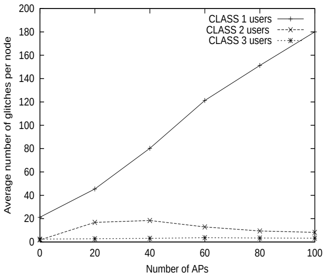

Fig. 21. Average number of glitches suffered by an MS vs Number of APs (SCN, BS with 1Mbps)

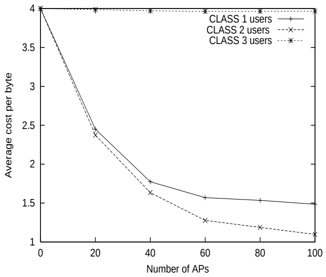

Fig. 22. Average cost per byte incurred by an MS vs Number of APs (SCN, BS with 1Mbps)

VII. CONCLUSION

In this paper we proposed a novel system architecture for studying the interoperability of Wi-Fi hotspots and wide area packet cellular networks. We identified three distinct user profiles associated with the MSs in the network and studied their impact on the resource utilization in the network. It was observed that the CLASS 3 MSs, which try to minimize the number of glitches suffered, achieved the highest packet delivery ratio when the Wi-Fi hotspots were modeled as a multihop LAN and the bandwidth alloted to each BS was 5 Mbps. However, in the scenario of single hop Wi-Fi LANs and 1 Mbps bandwidth at each BS, the CLASS 1 and CLASS 2 MSs were observed to give better performance than the CLASS 3 MSs. The CLASS 3 MSs incurred the highest average cost per byte while the CLASS 2 MSs incurred the lowest. The sharp decrease in the packet delivery ratio with increasing number of APs also suggests that APs (possibly belonging to different service providers) in a region must be operated in different frequency bands and must be adequately separated from each other. It was also observed that the CLASS 1 MSs suffered a very large number of glitches as they kept switching to APs or BSs advertising higher free bandwidths. Such a large number of glitches is often unacceptable to any type of user. Hence we must fix a threshold bandwidth difference for switching to a new network for CLASS 1 MSs, i.e. the CLASS 1 MS will switch to the new network only if the bandwidth offered is greater than that of its currently registered AP or BS by at least T.

REFERENCES

[1] IEEE Standards Board, “Part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications,” *The Institute of Electrical and Electronics Engineers Inc.*, 1997.

[2] Y. D. Lin and Y. C. Hsu, “Multihop Cellular: A New Architecture for Wireless Communications,” in *Proc. IEEE INFOCOM 2000*, Tel-Aviv, Israel, March 2000.

[3] R Ananthapadmanabha, B. S. Manoj, and C. Siva Ram Murthy, “Multihop Cellular Networks: The Architecture and Routing Protocols”, in *Proc. IEEE PIMRC 2001*, San Diego, USA, October 2001.

[4] Y. D. Lin, Y. C. Hsu, K. W. Oyang, T. C. Tsai, and D. S. Yang, “Multihop Wireless IEEE 802.11 LANs: A Prototype Implementation ” in *Journal of Communications and Networks, vol.2, no.4, December 2000*.

[5] K. Jayanth Kumar, B. S. Manoj, and C. Siva Ram Murthy, “MuPAC: MultiPower Architecture for Wireless Packet Data Network” , in *Proc. IEEE PIMRC 2002, September 2002* .

[6] Christo Frank. D, B. S. Manoj, and C. Siva Ram Murthy, “Throughput Enhanced Wireless in Local Loop (TWiLL) –The architecture, protocols and pricing schemes”. in *Proc. of IEEE LCN 2002*, November 2002 .

[7] Vyas Sekar, B. S. Manoj, and C. Siva Ram Murthy, “Routing for a Single Interface MCN Architecture and Pricing Schemes for Data Traffic in Multihop Cellular Networks” in *Proc. of IEEE ICC 2003*, May 2003.

[8] D. B. Johnson and D. A. Maltz, “Dynamic Source Routing in Ad hoc Wireless Networks”, *Mobile Computing, Kluwer Academic Publishers*, vol. 353, pp. 153-181, 1996.

[9] “GloMoSim: A Library for Parallel Simulation of Large-scale Wireless Networks,” in *Proc. PADS-98*, Banff, Canada, May 1998.

[10] S. Zhong, J. Chen, and Y. R. Yang, “ Sprite: A Simple, Cheat-Proof, Credit-Based System for Mobile Ad-Hoc Networks.” to in *Proc. of IEEE INFOCOM 2003*, April 2003.

[11] M. Jakobsson, J. P. Hubaux, and L. Buttyan “A Micro-Payment Scheme Encouraging Collaboration in Multi-Hop Cellular Networks” in *Financial Cryptography 2003*, January 2003.