# Multi-hop Cellular Networks: Integrated IEEE 802.11 Ad hoc and Universal Mobile Telecommunications System (UMTS) Networks

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**Abstract.** Multi-hop cellular network is a new emerging wireless communications system, which leverages the advantages of ad hoc networking and those of cellular networks. This paper presents an architecture for a multi-hop cellular network, which is composed of two popular and complementary technologies, namely the Universal Mobile Telecommunications System (UMTS) and the IEEE 802.11. The two networks are seamlessly connected via a gateway. The gateway composition including self-configuration protocols for addressing, gateway discovery and routing in the multi-hop cellular network were proposed. Finally, we have examined the end-to-end performance of the Transmission Control Protocol (TCP) over the multi-hop cellular network.

**Keywords:** Multi-hop cellular, Ad hoc networks, IEEE 802.11, UMTS

## 1 Introduction

Multi-hop cellular network [1] is a new emerging wireless communications system, which incorporates the ad hoc characteristics into cellular networks. In ad hoc networks, nodes communicate with each other on a peer-to-peer basis without the need of infrastructure support. If direct communication is not feasible between a source node and a destination node, then intermediate nodes are used as routers, which results in multi-hop communication. Cellular networks, on the other hand, rely on the support of fixed infrastructure and require network planning. Since multi-hop ad hoc and cellular networks have different but complementary features, the co-operation between these two networks would leverage the advantage of each other.

In this paper, we discuss a multi-hop cellular network architecture based on the Universal Mobile Telecommunications System (UMTS) and the IEEE 802.11 ad hoc mode. UMTS [2] is a Third-Generation (3G) cellular network which is currently being deployed world-wide. UMTS enables ubiquitous mobile Internet connectivity in a seamless fashion at data rates up to 2 Mb/s. IEEE 802.11 [3] has recently emerged as an important technology for ad hoc networking. IEEE 802.11 operates in the unlicensed frequency band of 2.4 GHz and offers data rates up to 54 Mb/s for the enhanced version, i.e., IEEE 802.11g. The co-operation between UMTS and IEEE 802.11 ad hoc networks poses a new set of problems. Currently cellular networks including UMTS only allow connectivity of single terminals. If a notebook PC accesses the Internet via UMTS, then the single terminal functions merely as a modem. In multi-hop cellular networks, we no longer have single terminals but a mobile ad hoc network wanting to establish co-operation with UMTS for Internet connectivity. Hence, the functionality of UMTS terminal should be enhanced to play the role of a gateway between the UMTS and IEEE 802.11 ad hoc networks.

The contribution of the paper is twofold. Firstly, it presents an architecture for the multi-hop cellular networks, which includes the design of the UMTS-802.11 ad hoc network gateway and self-configuration protocols for addressing, gateway discovery and routing. Secondly, it evaluates the end-to-end performance of Transmission Control Protocol (TCP) [4]. TCP is a transport protocol employed in the Internet to provide reliable end-to-end data transfer and congestion control. It is used by a large number of Internet applications such as Email, File Transfer Protocol (FTP) and web browsing. TCP is very likely to continue to be the dominant transport protocol in the multi-hop cellular network. To date, the performance of TCP over multi-hop cellular networks has not been investigated yet although the performance of TCP over each individual technology has been extensively studied. Hence, our work advances the knowledge and results published in prior research work by providing an insight into TCP performance in such a network. We have developed simulation modules that model the multi-hop cellular network in the widely used network simulator, *ns-2* [5].

## 2 Related Work

In this section, we review prior related work in the integration of ad hoc and cellular networks.

The authors of [6] described the main issues in the realization of an integrated ad hoc and cellular architecture. Specifically, their work focused on gateway discovery mechanism, mobility and routing. The ad hoc GSM cellular system [7] proposes a relay mechanism that enhances the coverage of GSM networks over dead spots where direct communication with the base station is not possible. Lin and Hsu [8] proposed a multi-hop cellular network where every mobile station participates in relaying traffic. Their work aimed at reducing the number of base stations and used relays to improve coverage. The work of Lin and Hsu was further extended by the authors in [9] to include an explicit control channel, neighbor discovery mechanisms, routing protocol and channel allocation scheme for both best-effort and real-time data.

In [10], the authors proposed a hybrid cellular and IEEE 802.11 ad hoc network architecture. In stead of multi-hop, their work focused on one-hop relay in the ad hoc network. The rationale behind their design was to reduce system complexity, avoid inefficient ad hoc routing, and the impact of inefficient medium access mechanism. The authors in [11] also proposed a hybrid cellular and ad hoc network architecture namely, UCAN, to increase cell throughput without sacrificing fairness. The proposed architecture required every mobile station to have both cellular and IEEE 802.11 ad hoc links. In [12], a similar integrated cellular and ad hoc network architecture as UCAN was proposed. However, the authors primarily focused on reducing connection blocking probability by diverting traffic from congested cells to neighboring lightly-loaded cells. They used specialized stationary relays which were strategically placed between cells for this purpose. In [13], the channel pool is divided into a set of fixed channels and a set of forwarding channels so that traffic can be redirected to non-congested cells using the forwarding channels.

SOPRANO [14] advocated self-organization at the physical, data link and network layers for the purpose of optimizing the capacity of multi-hop cellular network. The authors of [15] described an integrated ad hoc and cellular network architecture whereby base stations were involved in coordinating peer-to-peer communications in order to increase cell throughput and coverage. The opportunity Driven Multiple Access (ODMA) [16] provides a relaying protocol to enhance cellular coverage and reduces radio transmission power and co-channel interference.

## 3 Application Scenarios

In this section, we present two scenarios to illustrate the practical application of the multi-hop cellular networks. The first scenario extends the reach of UMTS connectivity to mobile users on offshore oil and gas production fields. In the second scenario, we show how the multi-hop cellular network can provide communications in times of calamity – earthquakes, hurricanes, tsunami, terrorist attacks, etc.

### 3.1 Offshore Communications

The coverage of terrestrial infrastructure cellular networks (e.g., UMTS) is limited by the radio transmission range of the basestations. In many remote areas (e.g., sea), terrestrial cellular networks are simply not available. Consequently, satellite technologies are usually used for communications, which are expensive. Figure 1 shows the multi-hop cellular network as an enabling technology for offshore communications, which is cheaper than satellite systems. The multi-hop ad hoc network is used to extend the reach of terrestrial cellular network to mobile users on an oil rig. In the figure, the ad hoc network can be realized using the IEEE 802.11 technology. The ad hoc network is connected to the terrestrial cellular such as UMTS via a gateway.

### 3.2 Disaster Recovery Operations

When a natural disaster or terrorist attack strikes, search and rescue operations are usually hampered by communication failure as the incumbent communications infrastructure is damaged or destroyed in the incident area. An ad hoc network, with the support of Voice over IP and video streaming, can be spontaneously set up to restore communication. In addition, the ad hoc network can provide global connectivity if it is connected to the nearest undamaged basestations of the cellular networks. One or more ad hoc nodes function as a gateway for interworking with the infrastructure basestation.

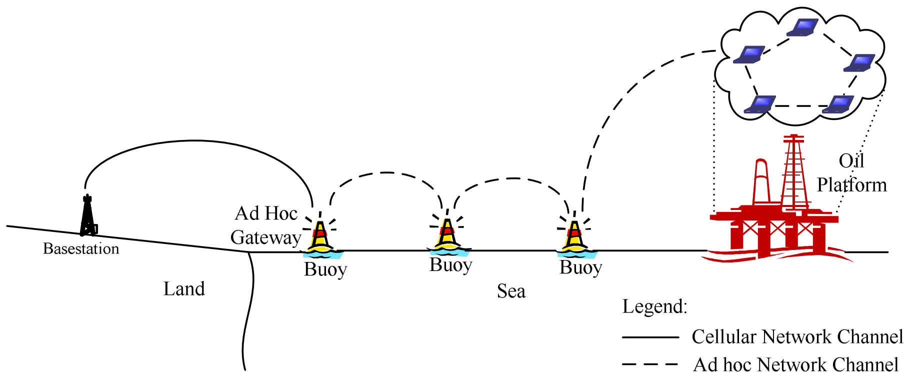


**Fig. 1.** Offshore Communications

## 3 Multi-hop Cellular Network Architecture

The multi-hop cellular network shown in Figure 2 is engineered using two complementary technologies, namely UMTS and the IEEE 802.11 technologies. The architecture of the multi-hop cellular network comprises three tiers: *tier 1* − the UMTS network, *tier 2* − the UMTS-802.11 gateway, *tier 3* − the IEEE 802.11 ad hoc network, which comprises a group of IEEE 802.11 mobile nodes. The protocol architecture for the multi-hop cellular network is shown in Figure 3.

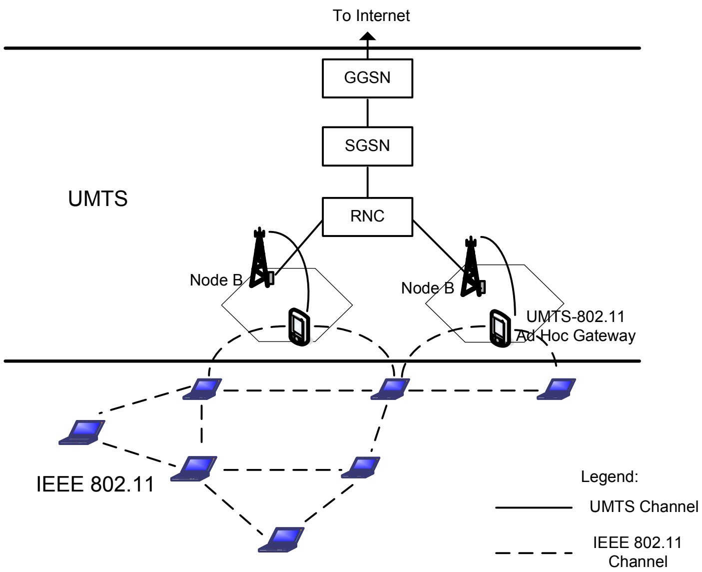


**Fig 2.** Multi-hop Cellular Network Architecture

*Tier 1* – the UMTS network provides connectivity to the Internet. The main components of the UMTS network are Node B, Radio Network Controller (RNC), Serving GPRS Support Node (SGSN), and Gateway GPRS Support Node (GGSN). The Node B sees each UMTS-802.11 ad hoc gateway as a UMTS mobile station. In other words, the IEEE 802.11 mobile nodes are transparent to the UMTS network. The Node B is connected to the RNC which is in turn connected to the SGSN. The SGSN is responsible for routing data packets to the correct RNC from GGSN and vice-versa.

*Tier 2* – the UMTS-802.11 ad hoc gateway is a hybrid device which has two different network interfaces located between the UMTS network and the IEEE 802.11 ad hoc network. On the UMTS side, it contains the UMTS radio access protocol stack, and on the other side, it is the IEEE 802.11 ad hoc mode protocol stack.

*Tier 3* – the IEEE 802.11 mobile nodes are end-user devices. They can either stationary or mobile, and can form a wireless ad hoc network among themselves.

For simplicity, we will refer to the UMTS-80211 ad hoc gateway and the IEEE 802.11 mobile node as ad hoc gateway and Mobile Node (MN), respectively.

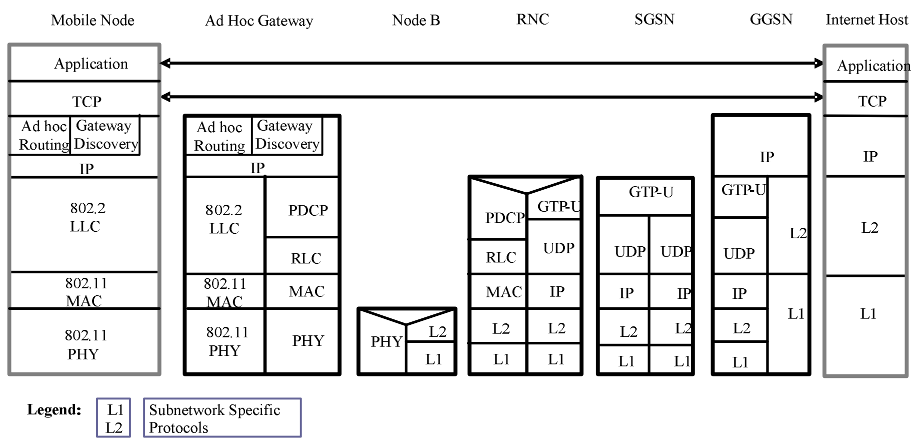


**Fig. 3.** Multi-hop Cellular Network - Protocol Architecture

### 3.1 UMTS-802.11 Ad Hoc Gateway Discovery

For Internet access, an MN must search for an ad hoc gateway that provides Internet connectivity. The ad hoc gateway can be more than one hop away from the MN. The ad hoc gateway discovery is a process by which an MN finds the ad hoc gateways. The ad hoc gateway discovery can be realized proactively or reactively. In the latter approach, the ad hoc gateway discovery is triggered by an MN, while the former is initiated by the ad hoc gateway. To leverage the advantages of both approaches, a hybrid approach is appropriate for the ad hoc gateway discovery.

Instead of defining a new ad hoc gateway discovery protocol, we chose to overlay the ad hoc gateway discovery mechanism on an existing ad hoc network routing protocol. We selected AODV [17] as the ad hoc network routing protocol and defined two new ad hoc gateway discovery messages: Gateway Advertisement and Gateway Solicitation. Gateway Advertisements are periodically broadcast into the ad hoc network by the ad hoc gateway through its IEEE 802.11 radio interface. Note that, the Gateway Advertisements are not broadcast to the UMTS network. If an MN in an ad hoc network wants to learn about the ad hoc gateway immediately, it can broadcast a Gateway Solicitation which triggers immediate Gateway Advertisements. For instance, an MN will send a Gateway Solicitation message if the frequency of the Gateway Advertisement is low. The advantage of overlaying ad hoc gateway discovery protocol on an existing ad hoc network routing protocol is that routes between the ad hoc gateway and an MN are concurrently constructed during the ad hoc gateway discovery phase using the AODV mechanism rather than separating the gateway discovery from route construction, which leads to shorter route discovery time and lower overhead. The Gateway Advertisement message format includes the ad hoc gateway identification (i.e., IP address), sequence number, Time to Live (TTL), hop count and subnet prefix. Intermediate MNs may only forward the Gateway Advertisement if the number of hops has not been reached, which is defined by TTL.

### 3.2 IP Address Auto-configuration

For Internet connectivity, each MN is assigned a unique and globally routable IP address. We will assume IPv6 since it has much larger address space than IPv4. IPv6 defines two dynamic address allocation schemes, namely, stateful auto-configuration and stateless auto-configuration techniques. The former auto-configuration scheme relies on a Dynamic Host Configuration Protocol (DHCP) [18] server to allocate IPv6 addresses. The server maintains a database containing the necessary information and keeps tight control over the address assignment. In the stateless auto-configuration [19], the MN is more involved in the allocation of the address. The MN generates its own address by combining a subnet prefix with an interface identifier (i.e., the IEEE 802.11 MAC address). Both auto-configuration techniques cannot be used unchanged since they are not designed for multi-hop networks. The stateless auto-configuration is preferred over stateful because it does not rely on a dedicated server, which is natural in an ad hoc environment.

The signaling involved in the IPv6 address allocation is shown in Figure 4. When an MN joins the multi-hop cellular network, it generates a link-local address by adding the interface identifier (IEEE 802.11 MAC address) to the link-local unicast prefix (FE80::/64). The MN uses this link-local address to send a Gateway Solicitation message (step 1). If the ad hoc gateway does not have a subnet prefix and no Packet Data Protocol (PDP) context exists, it must establish a PDP context using the PDP context activation (steps 2-5). The PDP context is a logical connection between the ad hoc gateway and the GGSN. Once a PDP connection is established, the ad hoc gateway is visible to the UMTS network and it can send and receive data packets. Furthermore, the ad hoc gateway issues a Router Solicitation message to the GGSN (step 6), which in turn triggers a Router Advertisement message (step 7). After the ad hoc gateway receives the Router Advertisement message, it constructs a Gateway Advertisement message which includes the subnet prefix contained in the

Router Advertisement. The ad hoc gateway broadcasts the Gateway Advertisement message to the MN (step 8). The MN generates a globally routable IPv6 address by concatenating its interface identifier and the subnet prefix.

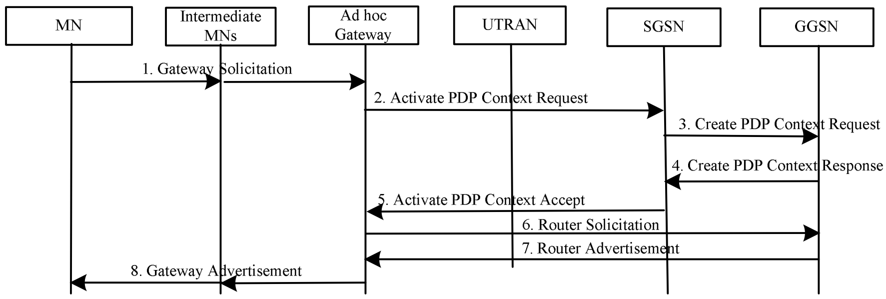


**Fig. 4.** Modified IPv6 Stateless Address Allocation

## 4 Performance Evaluation

In this section, we evaluate the performance of end-to-end TCP over the multi-hop cellular network.

### 4.1 Simulation Set-up

The end-to-end performance of TCP was evaluated using an event-driven simulator, *ns-2* [5]. *ns-2* supports the TCP/IP protocol suite, several ad hoc routing protocols and the basic IEEE 802.11 ad hoc and infrastructure functionality. The UMTS modules, which were developed in our previous work [20], were used since *ns-2* did not support UMTS. However, the UMTS modules lacked an ad hoc gateway component. Hence, extensions were made to the UMTS modules for modeling the ad hoc gateway. The AODV implementation of *ns-2* was extended to support the gateway discovery protocol. With the extensions in placed, instances of the ad hoc gateway together with the IEEE 802.11 MNs, and the UMTS components can be instantiated and formed the simulation topology shown in Figure 5. For the ad hoc network, a chain topology was configured from 1 hop to a maximum of 4 hops. A chain topology was chosen because it is a good example of multi-hop scenario. Each MN was stationary and equally spaced with a distance of 130 m from its adjacent MNs. All the MNs were single-mode 802.11 nodes. The chain topology was connected to the UMTS network via a single ad hoc gateway. A full-duplex UMTS Dedicated radio CHannel (DCH) was allocated to the ad hoc gateway. The downlink and uplink bit rate of DCH were set to 2 Mb/s and 384 kb/s, respectively. An independent and uniformly distributed error model was used to model the DCH channel characteristics. The transport block error rate in the range of 0% to 30% was considered. A transport block corresponds to a UMTS MAC data frame. The TCP version employed was New Reno. For ad hoc network, the IEEE 802.11b was used since *ns-2* only supports this version. The gross bit rate offered by the IEEE 802.11b is 11 Mb/s.

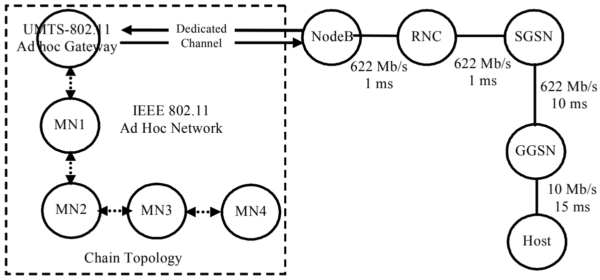


**Fig. 5.** Simulation Topology

## 4.2 Simulation Results

In the performance evaluation, we consider a single data flow and multiple data flows.

### 4.2.1 Single Data Flow

The performance metrics of primary interest is *throughput*. The throughput at the RLC and TCP layers was obtained using a single file transfer flow between an MN and a fixed host. Data were flowing in the downlink direction from the host to the MN. That means, the only data going in the reverse or uplink direction were the TCP acknowledgements. RLC throughput is defined as the amount of correctly received data (both RLC blocks and control messages) at the RLC layer in bits per second (b/s), excluding the RLC header. TCP throughput (b/s) is defined as the amount of successfully received TCP segments (including header) at the TCP layer. The TCP segment and RLC payload size was set to 512 bytes and 40 bytes, respectively.

In order to simulate long-lived TCP connection, the file transfer session was set to run for 1000 s, which is equivalent to 100,000 UMTS radio frames. Firstly, the simulation was run using the IEEE 802.11 basic CSMA/CA mechanism, and then, the same set of simulation was repeated for the CSMA/CA with Request to Send (RTS)/Clear to Send (CTS). Figures 6 and 7 depict the normalized throughput of RLC and TCP as a function of transport block error rate. Both the obtained RLC and TCP throughputs were normalized with respect to the UMTS downlink channel bit rate of 2 Mb/s. The throughput was evaluated from 1 to 4 hops in the IEEE 802.11b ad hoc network. The throughput for UMTS without the ad hoc part was also evaluated as a performance reference. In the figures, the throughput when the receiver is just the UMTS mobile station without the ad hoc part is denoted as *0-hop* while the other throughputs are labeled with the number of hops in the ad hoc part. For example, *1-hop* refers to an MN when it is directly reachable by the ad hoc gateway. With reference to Figure 5, MN1, MN2, MN3 and MN4 are *1*-, *2*-, *3*-, *4-hop* away from the ad hoc gateway, respectively. The normalized RLC and TCP throughput plots with and without the RTS/CTS mechanism are shown in Figures 6 and 7, respectively.

The attained throughput for RTS/CTS is lower, which is due to the overhead incurred by transmitting the RTS/CTS frames. The normalized TCP throughput plot is non-linear. The non-linear behavior is due to the underutilization of the UMTS radio channel as a result of the large TCP bandwidth-delay product. [4]. In the simulation, the TCP window size was set to 256 segments (or 131,072 bytes), which was bigger than the maximum allowable TCP window advertisement (65,535 bytes) [4]. Since the delay in the Internet and the UMTS network is fixed, the large bandwidth-delay product is attributed to the large transmission delay over the UMTS radio interface which is the result of RLC retransmission and in-sequence delivery. In the case of 30% transport block error rate, the mean TCP round-trip delay was 1.74 s, which gave a bandwidth-delay product of 435,000 bytes. This would require a TCP window size of approximately 850 segments. The underutilization problem can be overcome by increasing the TCP window size using the TCP Window Scale option, but this option can cause TCP timeouts due to excessive queuing delays at RLC and requires larger buffer size.

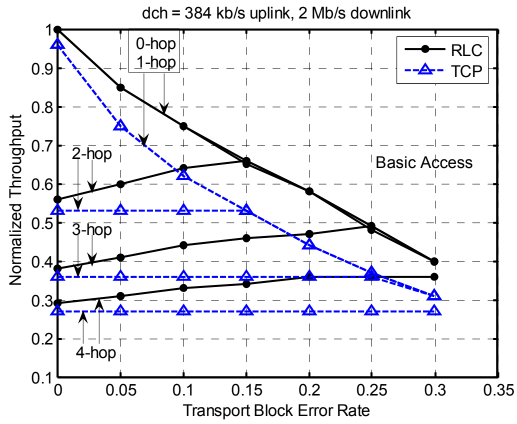


**Fig. 6.** Throughput versus Transport Block Error Rate for Basic Access

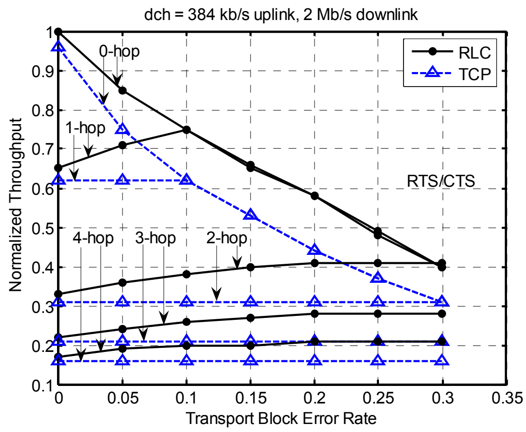


**Fig. 7.** Throughput versus Transport Block Error Rate for RTS/CTS

An interesting phenomenon was observed in Figures 6 and 7. The TCP throughputs obtained for 2- (only RTS/CTS), 3- and 4-hop scenarios saturated at a fixed level for all the different transport block error rates. For the 2-hop scenario of the basic access case, the TCP throughput saturated at transport block error less than 15%. The simulation traces were examined and did not reveal any timeout or abnormality in

TCP. However, the RLC plot in Figures 6 and 7 indicate that the UMTS radio channel was underutilized. This led us to study the performance of the IEEE 802.11b chain topology alone without the UMTS network. The relevant simulation parameters (e.g., TCP segment size, window size, etc.) for the chain topology were the same as those used in the integrated UMTS-802.11 network simulation. The saturation throughput of TCP obtained from the chain topology alone corresponds to the achievable TCP throughput in Figures 6 and 7. For instance, the TCP throughput for the basic access case for 4-hop scenario was 0.56 Mb/s, which was approximately 28% of the UMTS channel capacity of 2 Mb/s as indicated in Figure 6. For more than 1-hop, the RLC throughput initially increased with the transport block error rate because of redundant retransmissions of RLC data. The retransmission is controlled by a fixed value timer, which is non-optimal for higher transport block error rate.

### 4.2.2 Multiple Data Flows

We now consider multiple competing data flows in the downlink direction with the same network topology as in the previous subsection. In this case, each MN was allocated an FTP flow. Therefore, we have a total of four FTP flows that are active concurrently. All of the FTP flows are originating from the same fixed host. The first to the fourth FTP flows were assigned to MN1 to MN4, respectively. The FTP flows were sequentially started with a 10 s delay between two successive FTP flows. The fourth FTP flow was set to commence the earliest at 0 s then followed by the third FTP flow which started 10 s later, and the first FTP flow begins at 30 s. All of the FTP flows ended at the same time 600 s. It is important to note that all the flows share a single DCH channel. Even though, the FTP flows commenced at different times, the throughput was only computed over the period at which all the FTP flows were concurrently active. We computed the TCP throughput attained for each FTP flow and also the aggregate throughput. In addition to computing the throughput, we also determined the *fairness index* ($f$), which is defined as [21]

$$f = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n\sum_{i=1}^{n} x_i^2}$$

where $n$ is the number of concurrent FTP flows and $x_i$ denotes the throughput achieved by the $i$th flow. In our case, $n$ is equal to 4 and flows 1, 2, 3 and 4 correspond to the FTP flow at MN1, MN2, MN3 and MN4, respectively. The fairness index is used to investigate if the UMTS and the IEEE 802.11b radio channels are equally shared among all the FTP flows. When $f$ equals to 1, it indicates that both the UMTS and the IEEE 802.11b radio channels are equally shared by all the competing flows. The TCP throughput plots and fairness indices with and without RTS/CTS are shown in Figures 8 and 9, respectively. The aggregate TCP throughput for the basic access mechanism is higher than the RTS/CTS, which is consistent with the throughput results obtained for the single flow case. The fairness indices were less than 1 for all the different transport block error rates. As observed in Figures 8 and 9, the TCP throughput of flow 1 was approximately two times larger than other flows, which leads to unfairness. Flow 1 gained a larger share of the radio channel because it had the shortest round-trip time, which encouraged the TCP window size to increase faster.

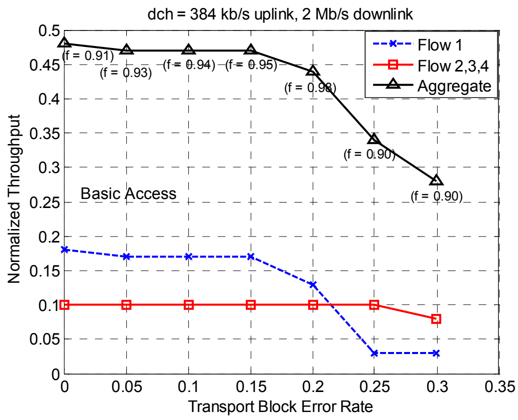


**Fig. 8.** TCP Throughput versus Transport Block Error Rate for Basic Access

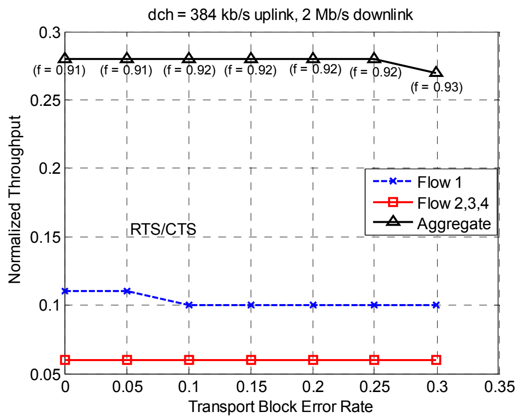


**Fig. 9.** TCP Throughput versus Transport Block Error Rate for RTC/CTS

## 5 Conclusion

The paper has proposed a multi-hop cellular network which is composed of the UMTS and IEEE 802.11 ad hoc networks. In such a network, the IEEE 802.11-enabled nodes can get ubiquitous Internet connectivity via UMTS. A UMTS-802.11 gateway is used to seamlessly interwork the UMTS and IEEE 802.11 ad hoc networks. The gateway composition and self-configuring protocols for addressing, gateway discovery and routing were discussed. We have evaluated the end-to-end performance of TCP over the multi-hop cellular network. Simulation results show that multi-hop cellular network using the IEEE 802.11 basic access mechanism outperforms the access mechanism with RTS/CTS. The IEEE 802.11 ad hoc network can be the performance bottleneck if the number of hops is more than one. When there are multiple data flows, the UMTS radio channel resource can be unfairly shared. The data flows, which span the least number of hops in the 802.11 ad hoc network, will gain a larger share of the UMTS radio resource.

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