MAC Performance of Conventional and Multihop Cellular Networks

Varsha Sharma
SoIT, RGPV,
Bhopal, India

R.C. Jain
Director, SATI,
Vidisha, India

ABSTRACT
Recently, there has been increasing interest in adding relaying functionalities into cellular networks. When relaying is added to conventional cellular networks (CCNs), the resulting system is known as Multihop Cellular Nework (MCN). MCNs combine the benefits of ad hoc networks and conventional cellular networks. For maximizing the benefit of multihop relaying, a good medium access control (MAC) layer protocol is required. A medium access control (MAC) protocol moderates access to the shared medium by defining rules that allow devices to communicate with each other in an orderly and efficient manner. Different medium access control (MAC) protocols have been devised for different type of architectures, applications and media, but MAC Protocols for conventional cellular networks and ad hoc networks cannot be used directly for MCNs. In this paper, we have presented an overview of multihop cellular technology and propose a MAC protocol for multihop cellular networks. The analysis of MAC layer protocol performance of multihop cellular network is done in time division duplex mode. The results show that multihop cellular networks using the proposed MAC protocol perform better than conventional cellular networks.

Keywords
Conventional cellular network, Multihop cellular network, MAC Protocol, Relays

1. INTRODUCTION
The revolutionary growth in new developments in the market demand and an ever increasing number of new applications led to tremendous demands for additional capacity and for new radio frequency band allocations. Instead of the previously used "broadcast model" of a high-power transmitter, placed at a high elevation, transmitting the signal to a large area, the cellular model called for many lower-power transmitters, each specifically designed to serve only a small area called a cell. Cellular systems use the concept of frequency reuse. The same frequencies (channels) could be reused in different cells with sufficient distance, where the effects of interference between users of the same channel were negligible. The real power of the cellular idea is that interference is not related to the absolute distance between cells but to the ratio of the distance between same frequency cells to the cell radius. The cell radius is determined by the transmitter power and cell-site antenna height.

Conventional cellular networks are unable to satisfy the demand for high data rates because of the following reasons- First, the limited power problem: For a given transmit power level, the higher transmission rates lead to a lower energy per bit. Second, the radio propagation: Above a few GHz the vulnerability to bad non-line-of-site conditions is higher. In effect, the path loss is higher between base stations and mobile. Third, the maximum data rate offered by the base station depends on the distance of the mobile to the base station. Close to the base station a higher SINR value is achieved, which allows the highest modulation and coding scheme and therefore highest data rate. At the cell edge the offered data rate is one order of magnitude lower. A transmission of a certain data rate therefore requires ten times more radio resources at the edge than near the BS.

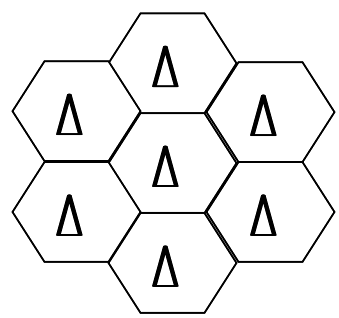

Fig. 1 A Conventional Cellular System

1.1 Multihop Cellular Networks
Multihop cellular networks are designed based on the idea of using mobile and/or fixed terminals to relay signals from source nodes to BSs or destination nodes. In such architecture, the link is broken down into shorter paths requiring less power and hence creates less interference to the neighboring cell. With less interference, more users can be accepted in the system. Relaying enhances coverage, capacity and design flexibility with low cost. It also improves the QoS of the network and reduces the transmission power of the nodes which is crucial due to the limited battery capacity of mobile or portable devices [1]. In the literature two different types of relaying network architectures

have been investigated. One proposed to use other user's terminal (mobile relay terminal) to relay the traffic while others proposed to use fixed relay station. There are two basic methods to construct MCN from CCN. One is MCN-b, where the number of bases is reduced such that the distance between two neighboring bases becomes k_b times of that in CCN. The other one is MCN-p, where the transmission range of both bases and mobile terminals is reduced to $1/k_p$ of that in CCN. In both cases, a base is not always reachable from a mobile terminal in a single hop. Hence multihop routing is necessary [2].

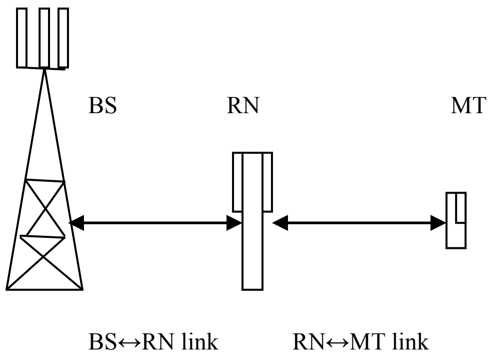

Fig. 2 Cellular Communication using Relays

Since RNs will transmit data to the BSs and receive data from the MTs, it will cause the self-interference at RNs. To avoid the self-interference at RNs, the RNs should not transmit and receive on the same frequency at the same time. MCNs can operate in two modes FDD (Frequency division duplexing) and TDD (Time division duplexing). The advantage of TDD mode over FDD mode is that TDD mode uses a single unpaired frequency channel and offers the flexibility to dynamically allocate bandwidth for uplink and downlink to deal with future unbalanced packet data traffic. MCNs which operate with TDD mode require only one set of interface for each relay to separate the two transmission links, one between the mobile terminal (MT) and relay node (RN) and another between relay node and base station (BS) using different time slots. In this paper we have used TDD mode of multihop communication. The use of multihop relaying requires careful consideration of topology, propagation environment, relay selection routing, and scheduling of user data to maximize the benefit. Relays must be placed at appropriate locations, and routing and scheduling are more complicated than in a one-hop system.

1.2 Medium Access Control

Networks based on radio communication provide examples where a medium is shared. The shared medium is the only means available for the stations to communicate with each other. Typically, several stations share two frequency bands, one for transmitting and one for receiving.

There are two broad categories of schemes for sharing a transmission medium. The first category involves a static and collision-free sharing of the medium. We refer to these as channelization schemes because they involve the partitioning of the medium into separate channels that are then dedicated to particular users. Channelization techniques are suitable when stations generate a steady stream of information that makes efficientuse of the dedicated channel. The examples of channelization schemes are FDMA, TDMA and CDMA. The second category involves a dynamic sharing of the medium on a per frame basis that is better matched to situations in which the user traffic is bursty. We refer to this category as MAC schemes. The primary function of medium access control is to minimize or eliminate the incidence of collisions to achieve a reasonable utilization of the medium. The two basic approaches to medium access control are random access and scheduling. The examples of random access MAC schemes are ALOHA, CSMA, CSMA/CD etc. Random access approaches are relatively simple to implement, and under light traffic they can provide low-delay frame transfer in broadcast networks. However, the randomness in the access can limit the maximum achievable throughput and can result in large variability in frame delays under heavier traffic loads. The scheduling MAC schemes attempt to produce an orderly access to the transmission medium. Reservation systems, Polling, Token-Passing Rings are examples of scheduling MAC schemes.

In reservation MAC schemes a node has to reserve one or more time slots within a frame before the actual packet transmission can take place. Contention occurs during the reservation phase. A certain number of slots form a frame and frames are repeated. Stations compete for empty slots. Once a station reserves a slot successfully, this slot is automatically assigned to this station in all following frames as long as the station has data to send.In polling, stations take turns accessing the medium. At any given time only one of the stations has the right to transmit into the medium. When a station is done transmitting, some mechanism is used to pass the right to transmit to another station.

The role of a MAC protocol is to determine when a node is allowed to transmit its packets. It typically controls all access to the medium [3].

The focus of this paper is on designing a reservation based MAC protocol for a cellular network with relays (MCNs). We have considered two-hop cellular network model, such that all communication between the source and destination nodes is routed through the base station. All the mobile terminals (MTs) communicate with the BS in either single-hop or two hops. In section 2 we have presented the literature review, section 3 presents the system model, section 4 presents the proposed MAC procedure, and in section 5 we have analyzed the performance of multihop cellular network with the proposed MAC protocol. We have also compared the MAC performance of CCNs and MCNs. Finally section 6 concludes our work

2. LITERATURE REVIEW

Most previous researches on wireless networks and medium access control protocols consider either a pure ad hoc or a cellular network. Previous researches on MAC protocols have focused on conventional cellular networks (CCNs). MCNs are more demanding on MAC protocols than CCNs. The MAC procedure for MCNs is different from that of CCNs because in CCNs the MT cancommunicate with the BS directly without the use of relays. This simplifies the MAC protocol design and MAC protocols as simple as slotted ALOHA are adequate. But in case of MCNs a MT is not always connected to the BS directly. Those MTs farther away from the BS may use relay stations to communicate with the BS. Therefore MAC protocols for CCNs cannot be used for MCNs [4]. In paper [5], authors have numerically analyzed the multihop operation in the frequency division duplex mode and discussed the MAC-layer protocol performance for the 3GPP-LTE system. In [6], authors have proposed integrated radio resource allocation to perform resource allocation for throughput maximization for FDD-WCDMA multihop cellular systems. In [7], authors have proposed congestion based routing scheme for TDD-CDMA MCNs. In [8], authors present an overview of existing work in this area, pointing out key research issues and their possible solutions and also presented a resource allocation framework for out-of-band relaying. The throughput enhancement due to the proposed framework is demonstrated through numerical results.

For conventional cellular networks, one important multiple access protocol is joint code-division multiple access/ packet-reservation multiple access (CDMA/PRMA) [9]. In joint CDMA/PRMA the time axis is slotted, with the time slots grouped into frames (as in PRMA). The time slots are divided into fixed number of code slots. Each code slot can be used by a MT regardless of the variation of interference level in the system in that corresponding time slot. The access of packets to the channel is controlled such that the channel load is kept as near as possible to an optimum in terms of maximum throughput. Furthermore, perfect power control is assumed such that all MTs can be connected to the base station with the same received power level. However the interference levels in different time slots will vary and perfect power control is practically difficult because MTs have their respective transmit power limitations and channel conditions.

3. SYSTEM MODEL

A multicellular system, with a BS at the center of each cell, is considered in the network design. There are 19 hexagonal cells. These 19 cells are arranged in two tier fashion. A center cell is surrounded by six cells in the first tier and twelve cells in the second tier. Each cell is divided into two layers, inner layer and outer layer. Fixed relay nodes are placed at the boundary of inner layer and outer layer. Fixed relay nodes have a higher implementation cost but lower management complexity than mobile relay nodes [10].There is no restriction on the number of hops, but routing paths longer than two hops results in only little improvement in system throughput, and may lead to significant implementation complexity as well as communication overhead. Therefore for simplicity we consider a scenario where at most two hops are allowed.

- Inner Layer: This is the area close to the BS; and the MT in this area communicates to the BS directly using a single-hop (without using relays).
- Outer Layer: This area is located around the inner layer and the MTs located in this area communicate to the BS in two hops with the help of relay nodes located at the boundary separating the inner layer and the outer layer. One hop is for the MT-RN and one hop is for the RN-BS communication. We have considered six fixed relay nodes (RNs) placed symmetrically as in figure 3.

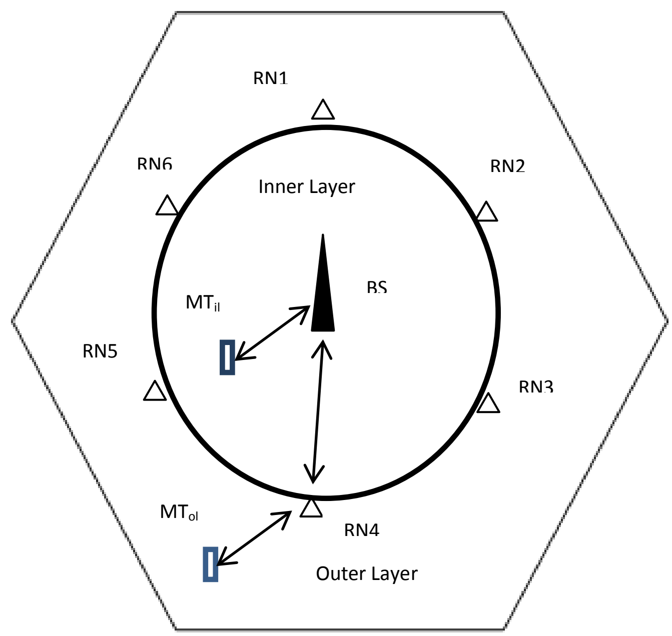

Fig.3 Cell with fixed Relays

4. THE PROPOSED MAC PROTOCOL

This paper proposes a reservation based MAC scheme for MCNs by considering a scenario where at most two hops are allowed. We have considered TDD duplexing mode of multihop operation and CDMA for multiple access. CDMA (Code-Division Multiple Access) allows numerous signals to occupy a single transmission channel by using different codes, optimizing the use of available bandwidth.

Coding is an important consideration in the design of highly reliable communication systems. If error control is to be used, it is important to use codes with good burst-error detection and correction capabilities. Codes are categorized as block and convolutional codes. Of all the linear block codes, the most useful and popular are the cyclic codes. A cyclic code is one for which an end-around shift of a codeword yields another codeword. In other words, if (y_1, y_2, y_3,… y_n) is a codeword, it follows that for a cyclic code, (y_n, y_1, y_2, …, y_{n-1}) is also a codeword. The Bose-Chaudhury-Hocquenghem (BCH) codes are perhaps among the most important codes in the class of cyclic codes. The design of these codes is straightforward, and for a given block length, n, codes can be designed with a wide range of rates and error-correcting ability. BCH code is used to protect packets from being corrupted due to the interference. We have used two types of BCH codes for contention and information packets respectively.

In the proposed MAC scheme each frame has duration of 10ms. Each frame is divided into 15 time slots. The first 7 time slots are for uplink (MT→RN/BS) transmission and last 8 slots are for downlink (BS→RN/MT) transmission. Time slots are further divided into code slots. A code slot can be either free for contention or reserved by some MT for information transmission.

In the proposed MAC, MTs in the inner layer can directly communicate with the BS like CCNs using one hop transmission. MTs in the outer layer will communicate with the BS with the help of a Relay node (RN) using two hop transmission. One hop is for the MT→RN and one hop is for the RN→BS communication. We have considered six fixed relay nodes (RNs) placed symmetrically as in figure 3. Being served by a RN means that the decision has been taken that the MT is better supported by the RN than by the BS. This means that MT receives a higher signal-to-noise ratio at its current position and the total amount of resources needed for first hop (BS→RN) and second hop (RN→MT) is less than what would be required if it was a single hop transmission between BS and MT.

4.1 MAC Procedure for MTs in the Inner Layer

The MAC procedure is divided into contention and reservation phases.In the Contention Process a MT in the inner layer i.e. MT_{il} which can directly communicate with the BS, listens to the broadcast from the BS during the downlink sub frame. The BS will broadcast whether the code slots in the time slot are free to be used for contention or reserved by some other MT for information transmission. The broadcast also includes permission probabilities and acknowledgements for contentions happened in the previous uplink sub frame. The MT_{il} selects the first free code slot in a time slot to transmit its contention packet with permission probability p. If there are multiple free code slots in the time slot then, MT_{il} selects a code slot randomly with equal probability. The required transmit power in dBm, for a MT_{il} to transmit in a given time slot x is determined by

$$P_{reqMT_{il}} = \delta_{cont} + P_{intf} + PL_{MT_{il}}$$

δ_{cont} is the E_b/N_o(ratio of bit energy to noice density) in dB for contention packets, P_{intf} is the interference level at the base station for time slot x, PL_{MTil} is the estimated path loss between MT_{il} and the base station in dB, where,

$$PL_{MT_{il}} = K_{PL} + 10\alpha\log_{10}(d) + X$$

K_{PL} is the constant of path loss in dB because of the background noise, α is path-loss exponent, d is the distance between MT_{il} and the base station in km and X is for shadowing effect.

This process repeats in the current uplink sub frame in other time slots. The MT is allowed to transmit multiple contention packets using code slots in different time slots of the same uplink sub frame. When the base station successfully receives a contention packet then that code slot is converted into a reserved slot for the MT_{il}. The MT_{il} can then transmit its information packets in that reserved slot in the next uplink frame with a received E_b/N_o, δ_{MTil} at the base station. If the transmit power of MT_{il} is above the upper limit, the BS will inform MT_{il} to reduce its transmit power. If the transmit power of MT_{il} is less than the lower limit then BS informs it to increase its transmit power. These instructions of power control are sent by the BS in the downlink broadcast in the downlink subframe. In the next uplink subframe, MT_{il} adjusts its transmit power according to the BS instructions. When MT_{il} completes transmission of information, it will inform the base station to release the corresponding reserved slot.

4.2 MAC Procedure for MTs in the Outer Layer

The MTs in the outer layer will use relay nodes for communicating with the BS. For such MTs the contention process is divided into two phases- the MT→RN phase and the RN→BS phase. Relay nodes have to receive packets from MTs and forward those packets to the BS. Thus, two separate time slots are required for MT→RN transmission and RN→BS transmission in order to avoid self-interference at the relay node. A mobile terminal MT_{ol} in the outer region determines the path loss to all RNs. Then it chooses the RN with minimum path loss to relay its packet to the base station. In the contention phase the MT_{ol} listens to the broadcast by the selected RN in the downlink sub frame. The broadcast contains information about the occupied time slots by the RN to transmit packets to BS in the previous uplink sub frame, the interference level at RN and the acknowledgements to the contentions happened in the previous uplink sub frame. MT_{ol} will not send contention packets in the occupied slots. It will send contention packets in free time slots by the same procedure as MT_{il}. If the MT→RN contention is successful the MT_{ol} starts sending information packets to the RN in the next uplink sub frame. If this contention process is unsuccessful due to unavailability of free time slots, the MT_{ol}

will keep the information packets in the buffer and wait till next uplink sub frame for contention. This contention process is repeated until the MT_{ol} finds a free time slot. After successful MT_{ol}→RN contention, RN will start the RN→BS contention. During the downlink sub frame RN listens to the broadcast of BS which contains the information about the interference level at BS of all time slots, the status of time slots and the acknowledgements to contentions happened in the previous uplink sub frame. RN tries to use free code slots in occupied time slots for RN→BS to leave empty time slots for MTs in the outer region for their MT_{ol}→RN contention. If there are no occupied time slots only then RN sends contention packets in empty time slots. So MT in the outer layer is given first preference to use empty time slots. Thisprovides better efficiency. If RN→BS contention is successful, RN starts sending information packets to the BS in the reserved slots. If the contention process is unsuccessful due to unavailability of free code slotsin any time slot, the RN will buffer the packets received from MT_{ol} and wait till the nextuplink sub frame.The RN will transmit the packets in the buffer in the first-in-first-out manner after success of RN→BS contention.

5. PERFORMANCE EVALUATION

A system level simulation is conducted by applying the proposed scheme to multi-hop cellular network. For simplicity we have assumed stationary MTs in our simulations, i.e. the MTs do not change their position during a simulation run. We have used packet voice data in our experiments. The source of voice has a rate of 8 Kbps. The Markov two-state machine is used to model the voice data. Two states are required because voice is a sequence of talk spurts which are separated by silence gaps. The average duration of talk spurts and silence gaps are set to 1 second and 1.3 seconds respectively. If the number of errors occurring in a received packet is greater due to large interference, that packet is corrupted; otherwise it is decoded and successfully received at the BS (RN). The upper and lower limit of transmit power for power control are set to 2dB and 1 dB respectively. For voice transmission, voice packets remaining in the MS's/RN's buffer longer than T_{max} have to be dropped as they require timely delivery. T_{max} is set to .02 seconds.

For evaluating the performance of MCNs using the proposed MAC protocol, we have considered four performance metrics: Throughput, Capacity, Packet Drop Probability and Power Outage Probability. The cell radius is set to a constant value of 0.75 km and the number of simultaneous users supported per cell is varied from 30 to 70. For evaluating the performance of MCN, six fixed relay nodes are used and for CCN no relay nodes are used.

5.1 Throughput of MCN

The throughput is defined in terms of packets received per time slot. The cell throughput is defined as the sum of each user's throughput within a cell. From Fig. 4, we find that the throughput of MCN is better than CCNs. The throughput is increased when the number of simultaneous users supported per cell is large.

5.2 Capacity of MCN

The capacity of a cellular system is normally defined as the number of simultaneous calls with an acceptable quality of service in a cell. We have considered capacity in terms of average mobile terminals per time slot. From Fig.5, we find that the capacity of MCNs is greater than CCNs.

5.3 Packet Drop Probability of MCN

Packets can be dropped when there is excessive delay or the voice packets have to stay in the buffer of RNs longer than $T_{max.}$ because they require timely transmission. Packet drop probability is defined as the the ratio of number of dropped packets to the total number of generated packets. It is clear from fig.6. that packet drop probability of MCNs is lower than that of CCNs. Varying the number of simultaneous users per cell, does not show much variation in packet drop probability.

5.4 Power Outage Probability of MCN

Power Outage probability, is the probability that a MT reaches its maximum transmit power. High power outage probability leads to higher packet loss due to interference. The power outage probability is defined as the ratio of the number of packets transmitted with power greater than the upper limit to the total number of transmitted packets. From fig.7, it is clear that power outage probability of MCNs is lower than that of CCNs.

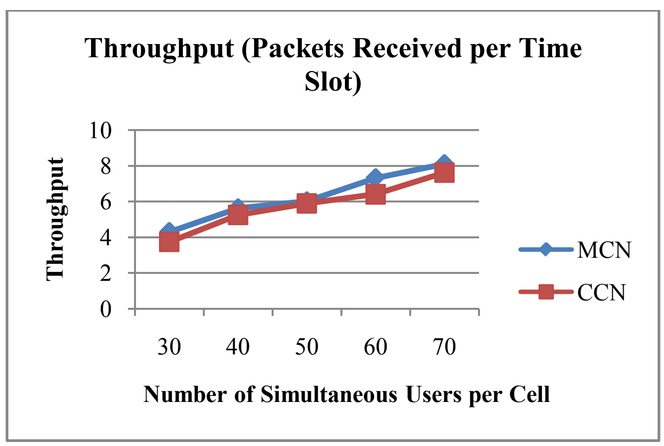

Fig.4 Throughput Comparison

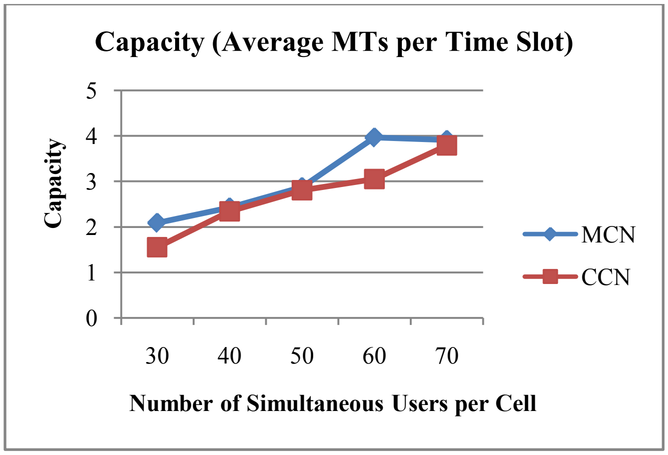

Fig. 5 Capacity Comparison

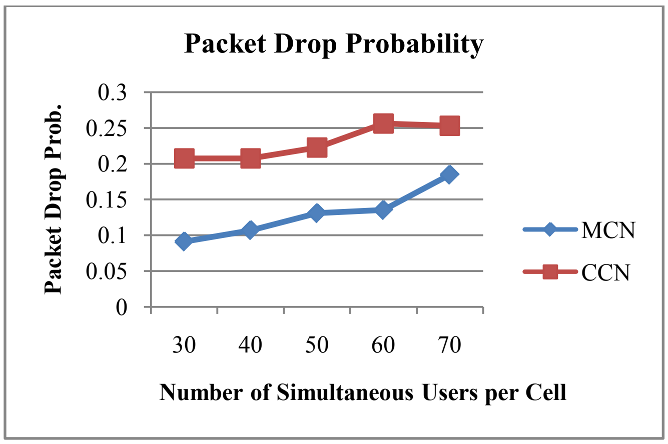

Fig. 6 Packet Drop Probability Comparison

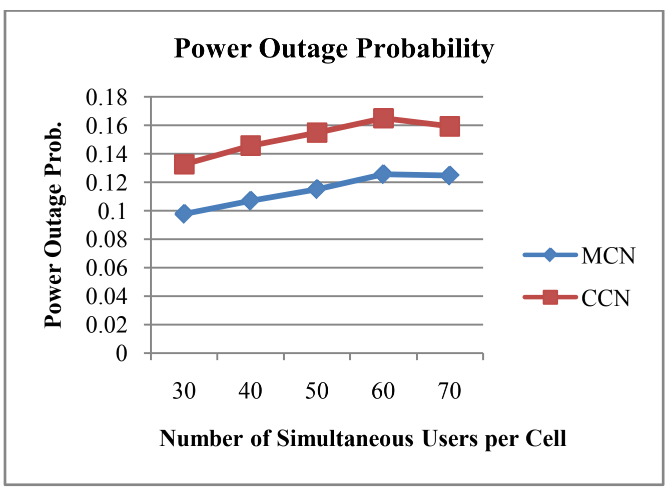

Fig. 7 Power outage probability comparison

6. CONCLUSION

In this paper, we have discussed the importance of multihop cellular networks and propose a reservation based MAC protocol for multihop cellular networks. For evaluating the performance of multihop cellular networks using the proposed MAC protocol we have considered the performance metrics, of throughput, capacity, packet drop probability and power outage probability. From the results of simulation we find that the performance of multihop cellular networks using the proposed MAC protocol is better than conventional cellular networks. In future we will analyze the performance of multihop cellular networks by varying other parameters like the number of relays and cell radius. We will also study the effect of relay positions on the MAC performance of multihop cellular networks.

7. REFERENCES

[1] Zaher Dawy and Sami Arayssi, “ Advanced Fixed Relaying in Multihop Based Cellular Networks”, IEEE ICC proceedings 2006, pp. 4526-4531.

[2] Yu-Ching Hsu and Ying-Dar Lin, “Multihop Cellular: A Novel Architecture for Wireless Data Communications”, Journal of Communications and Networks, Vol.4, No.1, March 2002, pp.30-39.

[3] Ajay Chandra, V. Gummalla and John O. Limb, “ Wireless Medium Access Control Protocols”, IEEE Communications surveys, 2000, pp. 2-15.

[4] Ananthapadmanabha R., B.S. Manoj and Siva ram Murthy, “Multi-hop Cellular Networks: The Architecture and Routing Protocols”, IEEE 2001.

[5] Rainer Schoenen, Ruediger Halfmann and Bernhard H. Walke, “MAC Performance of a 3GPP-LTE Multihop Cellular Network, Proceedings of IEEE ICC proceedings 2008, pp. 4819-4824.

[6] Y. Liu, R. Hoshyar, X. Yang and R. Tafazolli, “Integrated Radio Resource Allocation for Multihop Cellular Networks with Fixed Relay Stations”, IEEE J. Select. Areas Commun., vol.24, Nov 2006, pp. 2137-2146.

[7] T. Rouse, S. McLaughlin, I. Band, “Congestion based routing strategies in multihop TDD-CDMA networks”, IEEE J. Select. Areas Commun., vol. 23, Mar. 2005, pp. 668-681.

[8] Long Le, Ekram Hossain, “Multihop Cellular Networks: PotentialGains, Research Challenges, and a Resource Allocation Framework”, IEEE Communications Magazine, September 2007, pp. 66-73.

[9] Alex E. Brand, A. Hamid Aghvami, “Performance of the JointCDMA/PRMA Protocol for Voice Transmission in a CellularEnvironment”, 1996 IEEE, pp. 621-625.

[10] Baldomero Coll-Perales and Javier Gozalvez, “ Energy Efficient Routing Protocols for Multi-hop Cellular Networks”, IEEE 2009, pp. 1457-1461.