Evaluation and Comparison of Capacities and Costs of Multihop Cellular Networks

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Abstract: Multihop Cellular Networks (MCN) have emerged as promising solution to cope with the time persistent problem of poor cell edge and indoor coverage offered by Conventional Cellular Networks (CCN). Furthermore, having potential to increase system throughput and performance while decreasing deployment cost, MCN are being envisioned as essential part of future broadband networks. In prospective of these futuristic trends, this paper addresses the dire need to assess different MCN architecture options and quantify the gains they offer in terms of capacity, performance and system cost compared to CCN. As the first standard for MCN i.e. 802.16j is on the way yet, this paper relies on the most well known example of CCN i.e. GSM to demonstrate the concepts in this study and evaluates the realistic capacity and performance of three different architectural options for MCN. These are : 1) MCN without spectrum sharing between Base Station (BS) to Relay stations (RS) and RS to Mobile Station (MS) links. 2) MCN with spectrum sharing between BS-RS and RS-MS links, and 3) MCN without out spectrum sharing while BS's acting as umbrella cells on top of RS's. Results show the MCN, depending on the their configuration, in addition to improved Grade of Service (GoS) can yield 34% to 170% higher system capacity for a 50 to 67% more system cost compared to an optimised CCN.

I. INTRODUCTION

The consistently increasing demand for higher data rates and better QoS and the fact that radio resources are getting more and more stretched is currently the major unquenched quest behind research in wireless communication regime. New broadband standards have emerged to cope with demands of newly born bandwidth hungry applications for large data rates and better QoS like WiFi, UWB and WiMAX. But initial field trials have shown that conventional cellular infrastructure are not turning out to be very efficient [1] for deployment of these new standards due to power limitations on mobile user's end. As the bandwidth of signal increases the transmission power required also increases nonlinearly. Mobile users can not provide the high Tx powers required to sustain the link over the span of a large cell due to battery limitations. On the other hand spectrum scarceness on operator's end is an issue because when broadband radio channels are deployed in cells, it is highly desirable to keep cells small to enhance the spectrum reuse. Multihop Cellular Networks (MCN) are being considered as potential solution to these problems. There are many other advantages claimed by MCN which include low system cost for a ubiquitous coverage, better QoS, improved capacity and more balanced load sharing among the cells. But there is a dire need for quantification of these advantages by system level capacity, performance and cost assessment of such solutions for the various possible configurations of MCN before such a solution is made commercially and technically viable. This provides motivation for this work.

Since the first standard for MCN i.e. 802.16j is in process of standardisation yet, so the most well know example of cellular system i.e. GSM is considered in this work as case study to demonstrate the concepts. The reason GSM is chosen for this study is that it is the most widely deployed digital cellular standard having over 2 billion users in about 210 countries while adding 1000 every minute and thus constituting a largest share of today's telecom market[2][3].

This paper presents the study performed to evaluate the capacity, performance and cost of MCN for their three different architectural configurations. These are 1) MCN without spectrum sharing between Relay Stations (RS) to Base station (BS) and RS to MS links. 2) MCN with spectrum sharing between RS-BS and RS -MS links 3) MCN without spectrum sharing between RS-BS and RS -MS links while BS acting as Umbrella Cells(U-cells) on top of RS cells.

The work is carried out by developing realistic large scale system level simulations which model two tiers of co-channel cells and other real features of cellular systems which are usually neglected in simulation models due to complexity of modelling but have significant impact on the over all system performance. Most important of these features are macro diversity, non linearity of antenna gain pattern, antenna tilting, imperfection of power control algorithm, soft blocking i.e. blocking because of high interference, hard blocking i.e. blocking due to unavailability of any free physical channel, curtailment of on going calls due to decrease in signal quality with increase in system loading, sectorization, auto-correlated and cross correlated shadowing. For comparison of performance of MCN with a bench mark first optimum capacity of Conventional Cellular Network (CCN) is assessed based on GSM standard. An optimization routine for four major cellular system design parameters namely frequency reuse, cell radius, tower height and fade margin is run to find the optimum system design parameter values which yield maximum capacity in CCN for given Grade of Service (GoS). The optimum capacity (users/MHz/Km2) and performance (GoS i.e. blocking probability) of CCN thus evaluated is used as basis for comparison for the subsequently evaluated performances of MCN for its three variants. Finally conclusion is drawn by quantifying the gain in capacity for given GoS Vs estimated system cost for the three MCN configurations relative to CCN.

Remainder of this paper is organised as follows. Section II gives brief description of simulation model developed and used in this study. Section III describes the optimisation of CCN and assessment of its optimum capacity and performance. Section IV gives brief description of MCN architecture considered in this study and it's modelling for simulation. Section V presents results for evaluation of all three variant of MCN. Section VI describes cost estimation and finally section VII presents a comparison of all systems evaluated and section VIII presents the conclusions of study.

II. MULTI CELLULAR SYSTEM MODEL

System model developed in this study for realistic simulation of a CCN is based on GSM standard and consists of three major parts. Propagation aspects, system dynamics, traffic aspects.

A. *The Propagation Aspects*

Propagation model used in simulator mainly consists of path loss model suitable for microcellular urban environment, antenna radiation pattern model including its nonlinearity

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effect. Log normal shadowing model is used with cross correlation properties modelled according to [4] and auto correlation properties modelled as described in [5, 6].

B. System Dynamics

Power control algorithm described in the GSM standard [7] has been implemented as it is to make results more realistic. System dynamics for new call handling are modelled according to real multi cellular system such that interference effect from two tiers of co channels is considered on instantaneous basis on rest of the network just as in real network and power control algorithms for each MS in the system responds accordingly. Soft blocking on uplink and downlink based on the standard Protection Ratio (PR) threshold i.e. 9dB is included in determining the GoS and hence assessment of realistic system performance and capacity is realised

C. Teletraffic Model

Uniform traffic density is assumed in simulation models. Call arrival is modelled by poison distribution with each user generating on average one call per hour. Holding time is exponential with mean 120s. Thus average traffic per user is 0.0333 E. Table I gives simulation parameters of CCN model developed for this study.

TABLE I.
SIMULATION PARAMETERS FOR CONVENTIONAL CELLULAR NETWORK

	Parameter Name	Value
1	Cell Radius	600m
2	BTS(tower) location Variation	60m
3	No. of Tiers modelled	3
4	BTS Receiver Sensitivity	107dBm
5	MS Receiver Sensitivity	102dBm
6	Mean Call Duration	120sec
7	Maximum BS Transmit Power	39dBm
8	Maximum MS Transmit Power	30 dB m
9	Power control step size	2dB
10	No of power Control Steps	15
11	Power control window	10dB
12	Minimum Protection Ratio	9dB
13	C/Ic threshold	15dB
14	Base Station Antenna Gain	18dBi
15	Mobile station Antenna Gain	0dB
16	BS Antenna Height	30m
17	BS Antenna Height Variation	+/- 20%
18	Mobile Station Antenna Height	1.5m
19	Propagation Model	Cost 231 Hata
20	Propagation Type	Urban
21	Standard Deviation of shadowing	8dB
22	RF Frequency	1800Mhz
23	Sectorization	120°

III. ASSESSMENT OF OPTIMIMUM PERFROMANCE AND CAPACITY OF CCN

Result of the system level simulation done for CCN based on parameters given in Table I with frequency reuse 3*3 are shown in Figure1.

A mobile that finds SINR below PR=9dB is denied service and is said to be softly blocked. Whereas hard blocking or Erlang blocking means that the mobile attempting to make a call is denied service by network because of unavailability of a free channel. It is observed from Figure1 that for PR=9dB total blocking is 5 % most of which is soft blocking on the uplink. We see when power control is ON blocking is reduced slightly but it is still higher than acceptable GoS i.e. above 2%. It means that for this particular system design frequency reuse 3*3 is not acceptable.

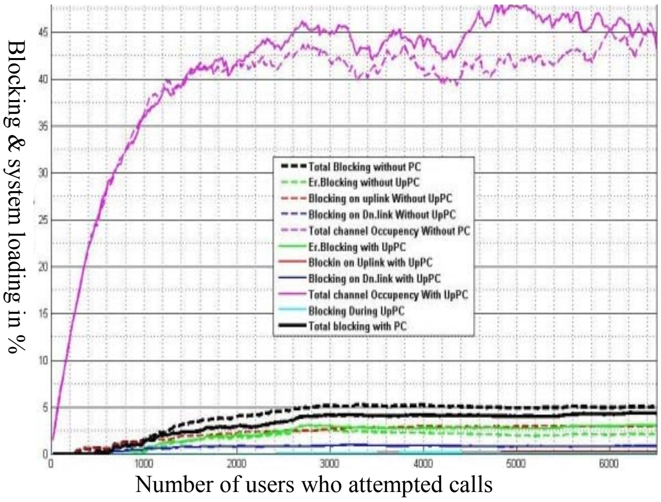


Figure1. Performance with F=3*3(PR=9dB)

Further Simulations with higher frequency reuse for the same system design show that an acceptable GoS is achievable for F=3*7=21. The results of CCN performance with F=3*7are shown in Figure 2

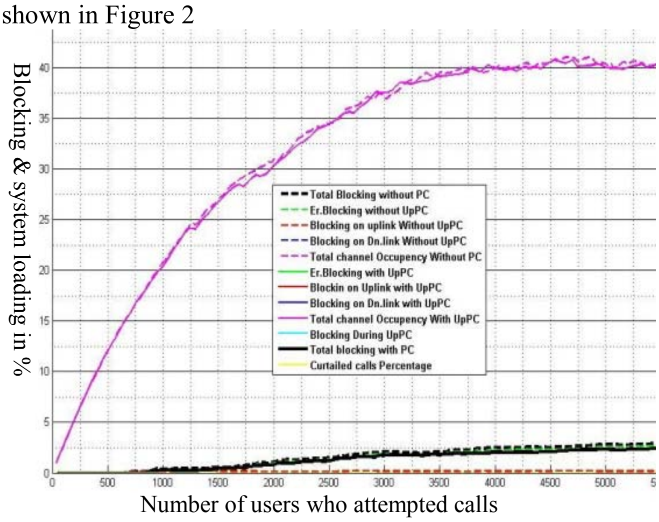
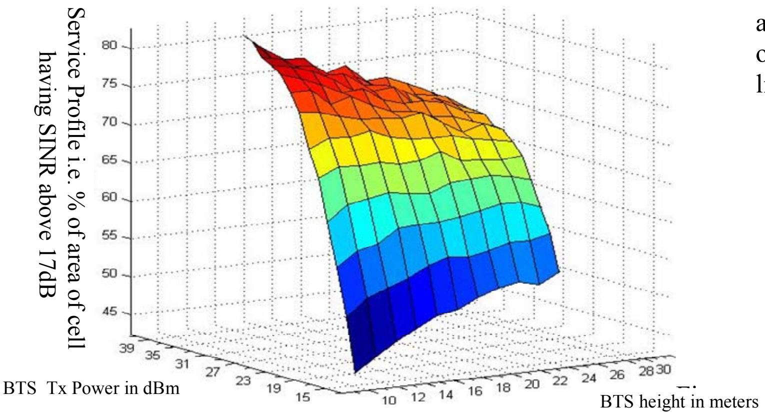


Figure2. Performance with F=7*3(PR=9dB)

Since the system design parameters namely cell radius, tower height and fade margin (in terms of Base Station Transmission Power i.e. BTP) play an important role in the over all system performance so an optimization routine for these parameters is run to get the best SINR profile in the coverage area. This optimisation is done to ensure that evaluated capacity and performance of the CCN that is to be used as base line for comparison with that of MCN is the optimum capacity a CCN can offer. For cell radius of 600m, 500m, 400m and 300m respectively the service profile is measured for a range of tower heights from 10m to 30m and BTP from 39dBm to 15dBm. It is found that the best performance and capacity for CCN under consideration is achievable for BTS antenna height 20m, Base Station Tx Power 39dBm and cell radius 300m (Figure 3).



re3. For optimum cell radius of 300m, service profile Vs BTS Tx Power & BTS height

Results of system performance evaluated with these optimized parameter values Vs that with values in Table 1 are shown in Figure 4.

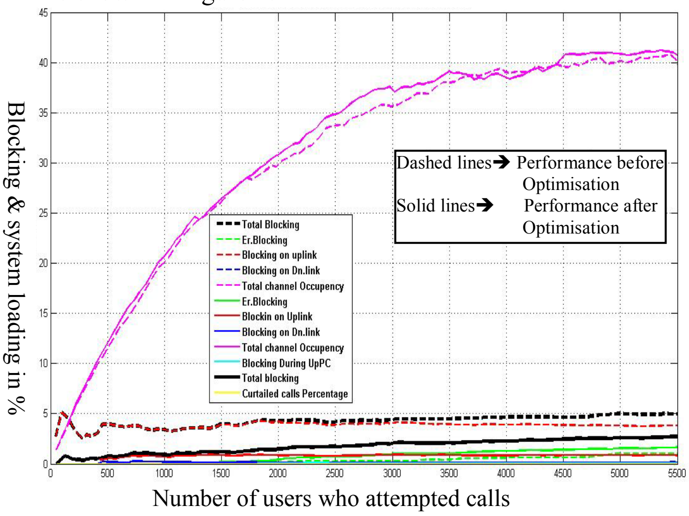


Figure4. Performance of optimized Vs un-optimized conventional cellular system (PR=17dB)

It is worth noting here that results in Figure 4 are based on PR=17dB not PR=9dB as in Figure2. This means that optimization has actually improved the average SINR available to users thus improving the QoS. (This extra 17-9= 8dB margin is enough to support the mobile users with same system model, thus making the results useable for a dynamic user scenario as well.) Having optimized the network design, in terms of cell radius, frequency reuse, tower height and fade margin, capacity offered by such network can be safely assumed to be the maximum capacity of a CCN network. Based on this simulation of CCN with 149 BTS the capacity is found to be 236 users/MHz/Km^2 .

IV. MULTIHOP CELLULAR NETWORK AND ITS MODELLING

Basic idea of the MCN is explained in Figure 5. The semi transparent hexagon in Figure 5 shows a conventional cell where as the small circles represent coverage cells resulted from relay stations (RS). The idea of multihop is to exploit the spectrum reuse more tightly to increase capacity with help of RS's there by extending and improving the coverage and capacity as well. The black triangular spot in the centre of Figure 5 shows the large central BS which provide access link to all the RS's associated with it.

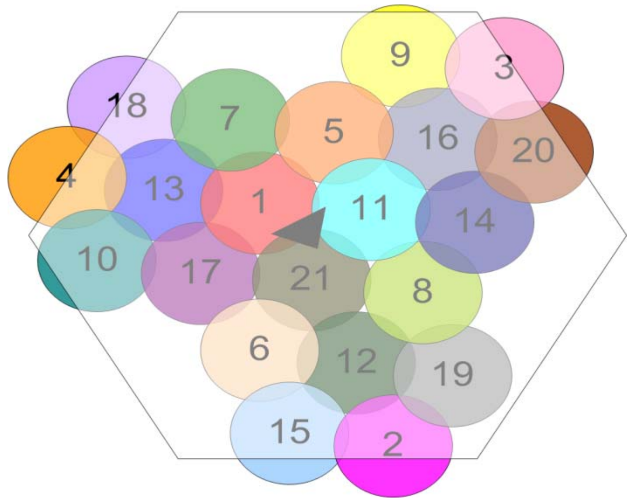


Figure5. Multihop cellular Network layout

These small RS can be actually monopoles with omni directional antennas mounted on them for coverage and directional antennas for access link i.e. RS-BS to corresponding BS in whose coverage area they lie. All RS's in a big cell need to be within good quality coverage by BS to which they are associated. In a MCN, this link between the BS and RS can be provided either by sharing spectrum with links between RS and MS or by some out of band spectrum or optical fibre etc. Further, the BS can only provide access links to RS or they can also provide coverage to MS's directly thus making umbrella cells on top of RS's coverage units. These possibilities constitute different options for the MCN architecture and will be evaluated in next sections. Table 2 shows the system parameters used in this study for simulation of a MCN. First two parameters are calculated by working out the geometry and link budget to provide homogeneous coverage in the area under consideration

TABLE II
SIMULATION PARAMETERS FOR MULTIHOP CELLULAR NETWORK

	Parameter Name	Value
1	RS Cell Radius	450m
2	BS cell Radius	100m
3	BTS location Variation	30m
4	Tiers modelled	3
5	BTS Receiver Sensitivity	104dBm
6	MS Receiver Sensitivity	102dBm
7	Mean Call Duration	120sec
8	Max. BS Tx Power	23dBm
9	Max. MS Tx Power	30 dB m
10	Power control step size	2dB
11	No of power Control Steps	15
12	Protection Margin	15dB
13	Power control window	10dB
14	Min. Protection Ratio	9dB
15	C/Ic threshold	15dB
16	RS antenna Gain	5dBi
17	MS Antenna Gain	0dB
18	RS Mean Antenna Ht	10m
19	MS Antenna Height	1.5m
20	Propagation Model	Cost 231Hata
21	Propagation Type	Urban
22	Standard Deviation of shadowing	8dB
23	RF Frequency	1800 MHz

V. ASSESSMENT OF PEFORMANCE AND CAPACITY OF MCN

This section presents simulation results for the performance and capacity assessment of the three variants of MCN.

A. Assessment of MCN with Out-of-Band Spectrum(or optical fibre/cable etc) used for RS-BS links

For this case we make following assumptions. Spectrum used to provide link between the BS and RS is out of band i.e. BS and corresponding RS are connected using spectrum other than that used for RS-MS links or via optical fibre or some other media. Hence BS-RS links does not cause interference to RS-MS links. Further it is assumed that the RS's are regenerative repeaters and hence noise on BS-RS link is isolated form noise on RS-MS links.

Simulations for this case of MCN, with system design parameters given in Table II are done and tightest possible frequency reuse for RS's that yields an acceptable GoS is found to be 21. The results of simulation of this scenario with frequency reuse 21 are presented in Figure 6. Capacity analysis made for the MCN modelled in the simulation consisting of 19 RS and 19*21=399 RS's shows the capacity of such a network to be ~633 users/MHz/km^2. This capacity analysis of course does not include spectrum used on the BS-RS links if any.

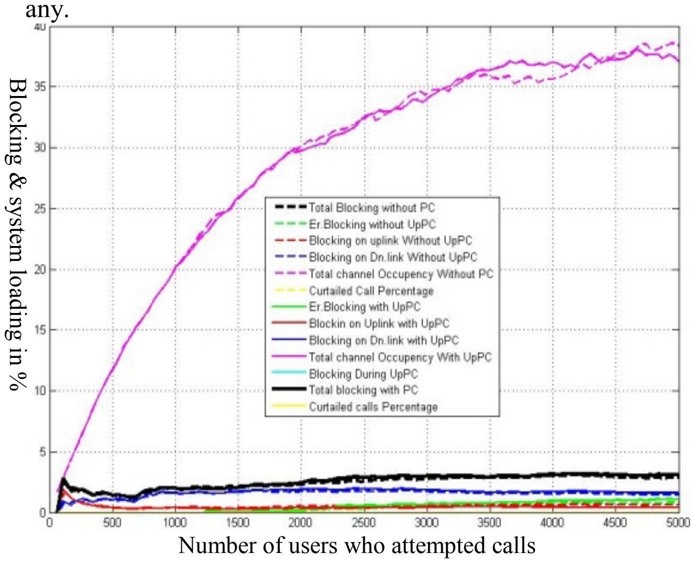


Figure 6. Performance of MCN with out-of -band spectrum.

B. Assessment of MCN with In-Band Spectrum used for BS-RS links

In this case of MCN, rest of the assumptions are same as in section 5A, but now the spectrum used for BS-RS links is same as used for RS-MS links. Obviously a radio frequency channel which links a particular RS to BS can not be used to link the same RS to a MS's because of self interference between the two links so there are two possible options

1. Spectrum is split and reused such that not only the co-channel interference and adjacent channel interference is avoided among the same type of links (i.e. within RS-MS links and within BS-RS links) but also across the two different links i.e. between RS-MS and BS-RS links.

2. Second option is that within a cell different set of channels are used for the BS-RS links and RS-MS links. And this pattern is reused for both links again and again.

First option requires a complex frequency allocation scheme because it not only need to minimize cross interference between BS-RS and RS-MS links but also within different RS-MS and MS-RS links operating at the same frequency. A simulation for performance assessment of such scenario demands a separate rigorous study on spectrum allocation schemes and will be subject of future work. For now we limit our self to 2nd option. Assessment of capacity for 2nd scenario described above can be made by building on the simulation results in section III and section VA. In section III it was observed that, in order to provide good quality link for average cell radius R=300m and design of Table 1, frequency reuse need to be to be at least 7*3.Compared to that scenario, in the case of MCN the Tx. and Rx. antenna on the RS have better gains then MS in the conventional network. Further RS's height is much larger than that of MS so we can safely use the same topology for BS as established in section III after optimization of CCN because this has been verified to provide the required GoS to mobile users of smaller height and weaker antenna gains. Based on this observation and results of section VA, capacity analysis of MCN using in-band spectrum for BS-RS links yields a capacity of ~316 users/MHz/Km^2

C. Assessment of MCN with Umbrella Cells

In this case of MCN, instead of just providing the access link to RS's only, BS can also provide coverage to MS's in the deployment area. Thus in this architecture of MCN, BS effectively makes U-cells overlying the Pico cells made by RS's. The advantage of U-cells is not only that they should enhance the capacity; they should also provide better QoS by improving the degree of macro diversity. Further U-cells can be exploited to reduce the number of hand offs occurring in the system which otherwise would be a great problem in multihop network due to very small cell size.

In order to maximize capacity of while deploying U-cells on top of Pico cells in MCN, optimum frequency reuse for U-cells to achieve an overall acceptable GoS is to be determined first. One may consider trying tighter frequency reuse on BS umbrella cells than that used for RS cells to get higher capacity. Result for such scenario with frequency reuse 1*3 on U-cells and frequency reuse=21 on RS's Pico cells are shown in Figure 7. The results are unexpectedly drastic .The reason for such high blocking rate on U-cells compared to RS cells is two folded. One reason is high interference on U-cell channels because of tight frequency. Second reason is very interesting i.e. Since in CCN, MS selects a suitable serving node around it based on received signal strength and not based on signal quality i.e. SINR. So in presence of U-cells most of mobiles in centre of U-cell register to the BS directly as signal strength is better from them due to large tower height and antenna gains compared to that of RS. Thus relatively fewer MS are registered to RS and most of them are those who are at the edge of umbrella cell. This fact creates an unbalanced load sharing between BS and RS instead of uniform traffic distribution. As can be seen from Figure7, the channel occupancy on BS (dashed pink line) is much higher than that on RS (solid pink line).

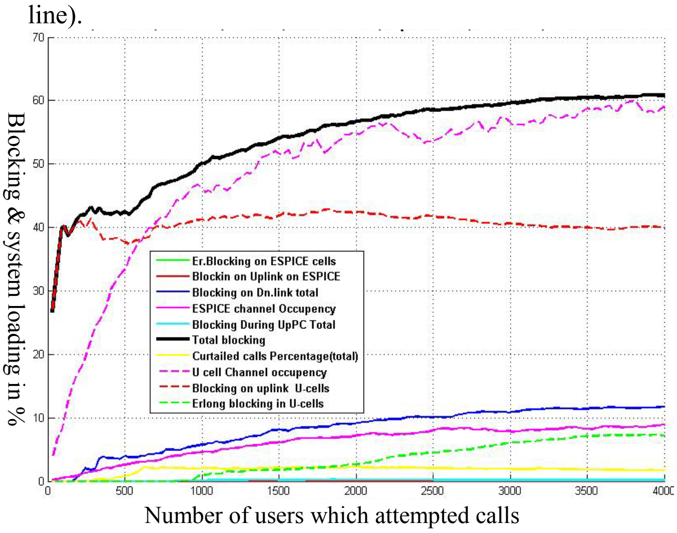


Figure7. Performance of MCN with unequal frequency reuse on BS's and RS's.

In order to make the most of spectrum resources and keep the blocking rate low, the channel occupancy on both BS and RS should stay equal. To solve this issue an insight into system can be achieved by observing the interference noise floor in presence of umbrella cell shown in Figure 8. There are two different mean values of interference floor in the coverage area if two different frequency reuse are used for BS's i.e. 1*3 and for RS's i.e. 21

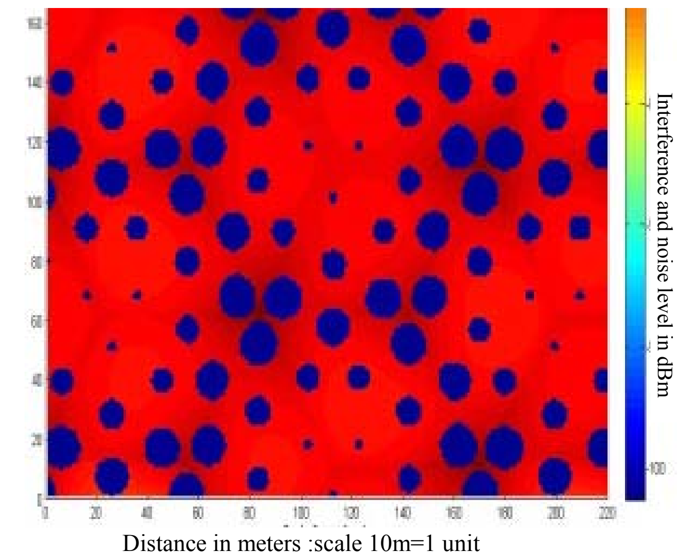


Figure8. Interference and noise floor (dBm) in the coverage area for MCN with umbrella cells, With frequency reuse 1*3 on U-cells and frequency reuse 21 on RS's.

So keeping in view the above observations further simulations are done and the optimum frequency reuse for U-cells in order to achieve optimum channel utilization and balanced load sharing for maximum capacity and acceptable GoS is found to be 3*7=21 i.e. the same as found for RS cells for this system design. An SINR profile of this network is shown in Figure 9 which shows that 99% of the points in coverage area have SINR above 15db threshold

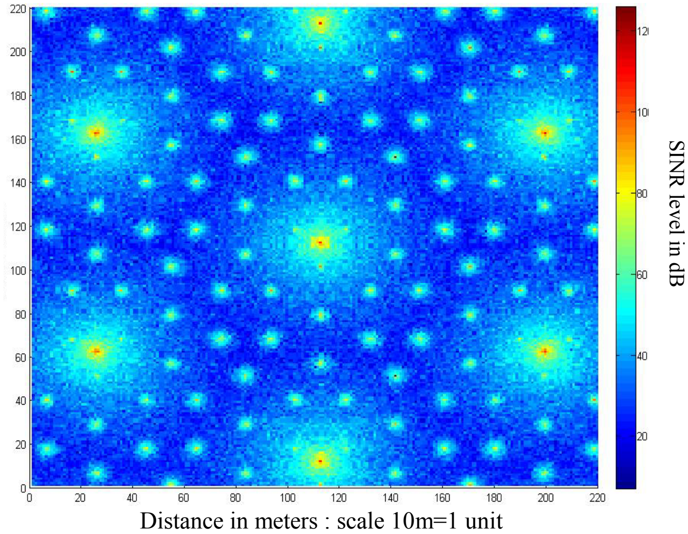


Figure9. SINR (dB) in optimised MCN with umbrella Cells

Capacity analysis for this network with tightest frequency reuse yielding acceptable GoS with 399 RS's having 8 channels on each RS, and 19 BS with 8*3 channels on each BS providing U-cells, show a figure of 326 users/MHz/Km^2.This calculation is done for scenario where available spectrum is equally split between BS and RS to provide links to MS. And BS-RS links are provided by either out of band spectrum or through optical fibre.

VI. RELATIVE SYSTEM COST ANALYSIS

Although the comparison of absolute costs of CCN and MCN is complex task, but the fact that over all cost of a cellular network is proportional to the number of access points i.e. BS's or RS's [8] can be exploited to make the comparative cost analysis relatively simpler. Since the number of sites required per unit area, can roughly be assumed as measure of overall system cost. So an approximate comparison of costs of CCN and MCN can be achieved if the relationship between the average cost of BS and RS is established. The total cost TC of an access point i.e. BS or RS is dependent on some major factors as follows.

TC= f(PC(h), AC(n,g), SC(l,s), BHC(d,t), HC(t), OMC **)**

PC=Pole/Tower cost further dependent on its height h
AC=Antenna cost dependent on number n and gain g
SC=Site cost dependent on location l and size s of installation
BHC=Backhauling cost dependent on distance backhaul link distance d and traffic t
HC=Hardware cost dependent on traffic t to be handled
OMC=operational and maintenance cost.

Almost all of these cost factors shown in above expression reduce many folds for RS compared to BS because of the following facts about RS (compared to BS)

1. Relatively very smaller height so lower TC
2. One omni directional antennas compared to three directional antennas so much lower AC
3. Small space required for installation so lower SC
4. No back haul cost so BHC~0
5. Lesser traffic to be handled, hence lower HC
6. Lower space and power consumption so lower OMC

Dependent on these facts a 5 to 10 Cost Reduction Factor ($CRF=TC_{BS}/TC_{RS}$) can be achieved. For the subsequent comments in next section we assume a CRF of 7.

VII. COMPARISON OF PERFORMANCES AND COSTS

Table III surmises all the results obtained in this study. Relative cost estimation is presented in terms of number of standard BTS sites required per unit area for each system configuration. GoS offered by each system is presented as sum of soft blocking (left I the column) and Erlang blocking (right in the column) for two different PR's of 9dB and 17dB.Optimisation of CCN gives better QoS i.e. SINR threshold of 17dB instead of 9dB and almost (236-59)/59*100=300% more capacity but at about (3-.75)/.75*100=300% higher system cost compared to initial system design in Table I. This optimised capacity and performance is used as base line for comparison with MCN architectures studied. The 1st case of MCN with out of band spectrum/optical fibre used for BS-RS links gives highest capacity increase of(236-633/236*100)~170 % compared to optimised capacity of CCN at a relative (4.6-3)/3*100=50 % increase in system cost .

Table III
SUMMARY OF RESULTS

System type & major Simulation Parameters	Freq. Reuse	Total Blocking (Soft +Erlong) PR=9B	Total Blocking (Soft +Erlong) PR=17dB	Capacity Users/MHz /Km2	Relative Cost i.e. No. of standard sites per km2
CSS, R=600m, HT=30m	3*3=9	2+2=4%	19+1=20%	19600/1.8/80 =136	~0.75
CSS R=600m, HT=30m	7*3=21	0+2=2%	3.5+1.5=4%	48600/4.2/196 =59	~0.75
CSS Optimized R=300m,, HT=10-15m	3*3=9	2+2=4%	7+2=9%	19600/1.8/20 =544	~3
CSS, Optimized R=300m, HT=10-15m	7*3=21	0+2=2%	0+2=2%	48600/4.2/49 =236	~3
MCN (out of band spectrum Or Opt.Fiber for BS-RS) R=450m,r=100m, ht=10m	21	0+2=2%	7+1=8%	48600/4.2/18.2 =633	4.6
MCN(in band spectrum) R=450m,r=100m, ht=10m	21	0+2=2%	6+1=7%	48600/8.4/18.2 =316	4.6
MCN (Out of band spectrum Or opt. Fiber BS-RS) With U-cells R=450m,r=100m HT=20m, ht=10	21 +2*7=42	0+2=2%	0+2=2%	50004/8.4/18.2 =326	~5

For 2nd case of MCN when same available spectrum is split between the BS-RS and RS-MS links, and no complex spectrum sharing is technique is deployed, capacity is estimated to be about (316--236)/236*100=~34% higher than that of optimised CCN for same cost increase of 50%. And in case of complex spectrum sharing this figure will should lie between 170% to 34% depending on how dexterously the spectrum is shared and reused among BS-RS and RS-MS links. Cost of such a system will be still about 50% higher than optimised CCN. 3rd case of MCN with U-cells, having out of band/optical fibre BS-RS links, provide (326-236) /236*100=38% compared to that of optimised CCN for a cost increase of ((5-3)/3*100)=67%.

VIII. CONCLUSIONS

This paper compared the performance and cost of Conventional Cellular Network (CCN) with the three different architectures of Multihop Cellular Network (MCN) assessed through rigorous system level simulations. GSM being the most well known cellular system is considered as a case study. CCN design is first optimised for the best capacity and performance it can yield. The optimum capacity CCN and its cost thus assessed are used as base line of comparison.

MCN without umbrella cells (U-cells) can offer capacity a around 34% higher than optimum CCN capacity for simplistic spectrum split between BS-RS and RS-MS links. A capacity increase of up to 170% over optimum CCN is possible with intelligent most spectrum sharing or if BS-RS links are established by out of band spectrum or optical fibre. Cost of such a MCN is estimated to be about 50% higher than that of optimised CCN.

MCN with U-cells and with BS-RS link established by out of band spectrum/optical fibre, capacity up to 38% higher than optimised CCN is possible, for an estimated system cost increase of about 67%.

The results obtained by considering specific case of GSM can also be useful to provide a foresight of loose upper bound and lower bound on the performance of different MCN configurations for UMTS and WiMAX. Particularly cost analysis is quite general.

In future, it would be interesting to investigate the performance of MCN architectures specifically for broadband OFDM standards e.g. WiMAX.

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