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On the performance of time division multiple access-based multihop fixed cellular networks with respect to available frequency carriers

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Abstract: In multihop cellular networks (MCN), the user nodes can act as relays and forward other nodes' traffic to/from base stations. There are several advantages of MCN such as the improved signal quality and higher coverage. However, it is known that multihop relaying networks require extra radio resources. Therefore the performance of MCN depends to a great extent on the availability of adequate radio resources. The performance of a time division multiple access (TDMA)-based multihop fixed cellular network is analysed with highlighting the dependence of the system performance on the amount of available radio resources, namely, the number of frequency carriers. Results show that in a fixed cellular network, the multihop architecture significantly outperforms the traditional single-hop architecture in terms of the outage probability and throughput if an adequate amount of frequency carriers is available in the network. Otherwise, the multihop fixed cellular networks architecture loses its superiority and might even lead to performance degradation, particularly at high loading levels.

1 Introduction

Growing wireless multimedia applications are demanding high data rates and stringent quality of service (QoS) requirements. In order to provide these requirements in a cost-effective manner, wireless-network designers and service providers are exploring new network architectures such as multihop cellular networks (MCN). Like other multihop wireless networks, nodes in MCN act as relays that forward other nodes traffic to/from base stations (BSs). However, unlike other multihop wireless networks, MCN enjoy the availability of network infrastructure [1].

Recently, multihop communications in the context of MCN have gained enormous interest. The capacity gain of MCN in CDMA networks is quantified in [2] using interference analysis. Results in [2] show that a capacity gain of at least 10% can be achieved without degrading the signal quality. Power and rate control in multihop CDMA cellular networks has been discussed in [3]. Two algorithms for power and rate control (minimum total power and maximum channel gain and transmission rate ratio) have been proposed in [3] and shown to be able to improve the throughput significantly (25.92–108.58% for the former and 2.5–16.79% for the latter) compared with that of traditional single-hop cellular systems.

The throughput gain due to MCN is analysed in [4]. Lower and upper bounds for the throughput gain are reported. Results show that the throughput gain increases with the number of hops. Also, it is found that the throughput gain is limited by the quality of the link between the BS and the closest set of relays. The resource allocation in terms of packet scheduling, routing and load balancing is addressed in [5]. An integrated resource allocation approach is proposed to maximise the system throughput without overloading some relays. A significant throughput gain due to MCN is also reported in [5].

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In [6], coverage enhancement in MCN is investigated. The authors studied single-cell and multiple-cell scenarios. In the single-cell case, multihop relaying is found to be always useful in improving the coverage even if the BS and relay nodes use the same channel. However, in the multiple-cell scenario, multihop relaying is found to be useful in terms of coverage enhancement only if BSs use different channels than those used by the relay nodes. This is because the signal degradation due to the interference between the BSs and relaying nodes (if they use the same channel) can exceed the signal enhancement due to the multihop relaying.

The impact of relay selection policy on the capacity enhancement of MCN is discussed in [7]. Random and smart relay selection schemes are analysed. It was found that there is no much difference in performance gains from each. Therefore the overheads and complex processing associated with the smart selection schemes do not justify, and a simple relay selection scheme can give similar gains.

This paper considers multihop fixed cellular networks (MFCN) as shown in Fig. 1. Nodes with good-quality links to the BSs support other nodes having poor-quality links by forwarding their traffic to/from the BSs. Hence, the MFCN architecture can help nodes get connected to the BSs even if they are remote from these BSs as in the case of rural areas. Due to the relaying capability, MFCN can make links shorter and reduce shadowing, which leads to smaller path-losses. Since the radio links in MFCN have smaller path-losses (in comparison to the conventional single-hop cellular network), it may be possible to operate with lower transmit power levels, or to use high modulation levels to increase the link spectral efficiencies.

However, there are a number of implementation challenges associated with MFCN such as the signalling overhead, the additional latency due to relaying, the need for routing to/from BSs, more complex user nodes, and resource over-utilisation (due to the extra channels needed for relaying). Therefore more investigation is needed to determine under what conditions and at the cost of which resources MFCN do provide performance enhancements.

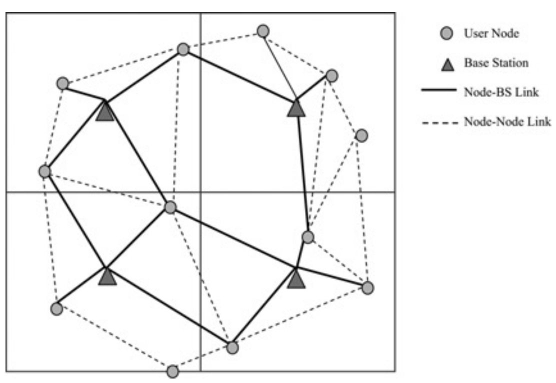

Figure 1 *MFCN architecture*

This paper investigates the performance of a MFCN and its dependence on the number of frequency carriers. The performance metrics used here are the node throughput and outage probability. The results are compared with those from the conventional single-hop cellular network. The system model is presented in the next section. Section 3 provides the simulation parameters and assumptions. The results and performance analysis are discussed in Section 4. Finally, the summary and conclusions are given in Section 5.

2 System description

2.1 Network architecture

The MFCN architecture considered in this study is shown in Fig. 1. As mentioned above, user nodes (in addition to handling their own traffic) act as relays which means that no new network infrastructure is needed. Both, user nodes and BSs, have directional switched beam antennas. This is a reasonable assumption as stationary nodes are assumed.

We use hybrid multiple access technique, time division multiple access (TDMA)/frequency division multiple access (FDMA). As directional switched beam antennas are used at the nodes as well as the BSs, aggressive frequency reuse can be achieved. Hence, a frequency reuse factor of one is assumed here. Synchronous TDMA has been considered such that all node transmissions are concurrent and slot synchronised.

A user node in a particular cell can be served through any BS in the network and can take relaying assistance from any node in its cell or in any other cell. This approach is complex in terms of control information processing, implementation and management. However, it leads to optimum utilisation of spectral resources due to the high trunking efficiency.

2.2 Routing

In this work, we use a simple route ranking/selection scheme in order to find multiple multihop routes for each node (to BSs). All possible routes with three or less hops between each node and the BSs are explored. Bad links are avoided by rejecting any route that includes a link with path-loss greater than a certain path-loss threshold (PL_{th}). The remaining routes are ordered based on the number of hops; single-hop routes are ranked first then two-hop routes and finally three-hop routes. Within the set of routes with the same number of hops (links), routes are ranked in an ascending order using the following cost function

$$f = \max(PL_i) \tag{1}$$

where $i = 1, 2$ for two-hop routes and $i = 1, 2, 3$ for three-hop routes. This min–max ranking tries to minimise

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the maximum path-loss of the links of the selected route. This approach aims to eliminate the bottlenecks, that is, the routes, which include bad links. After ranking all routes, these ranked routes between the node and the BSs are saved to be used whenever the node has traffic to send to the BSs. Since nodes are mainly stationary, this process (route ranking) can be done offline in the network planning phase or whenever new nodes/BSs are added to the network. This approach avoids the overhead and complications associated with the frequent routing-table updates or the dynamic route discovery. The only drawback is the needed storage space to save the routing tables. However, this is not a major concern since the additional overhead and cost, due to memory and storage devices, is very limited. The reason for limiting the number of hops to three is to avoid excessive delay and resource over-utilisation.

When a node has traffic to send, it checks the best route in the table to see whether free slots in that route are available. The values of the achievable signal-to-interference-plus-noise ratio ($SINR_{ach}$) in the free slots over all hops of the candidate route are compared with the threshold SINR ($SINR_{th}$). $SINR_{ach}$ has to be higher than $SINR_{th}$ in at least one slot in each hop of the candidate route. If this condition is not fulfilled, the next best route in the table is explored until we find a route with at least one free slot with $SINR_{ach} > SINR_{th}$ in each hop. If there is more than one slot available in a hop, the best one (in terms of $SINR_{ach}$) is assigned to the connection. Time-slots across the whole route are reserved until the burst is completely transmitted. Fig. 2 shows a flow chart illustrating the route-selection and time-slot assignment.

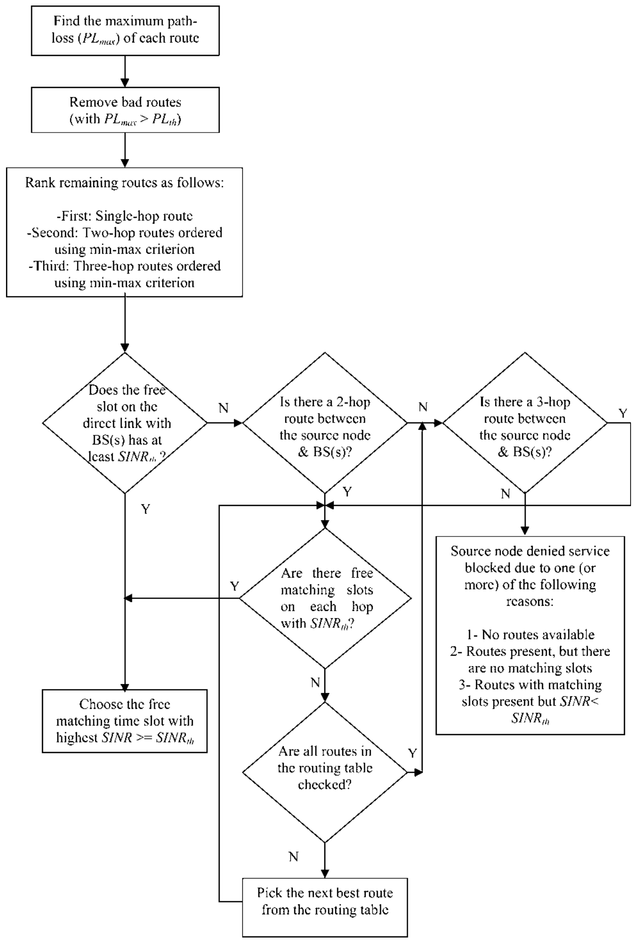

Figure 2 *Route-selection and time-slot assignment*

Fig. 3 shows an example of route selection. As shown, node 1 finds the single-hop (from node 1 to the BS) unavailable ($PL = 135$ dB $> PL_{th} = 120$ dB). Then, two-hop and three-hop routes between node 1 and the BS are ranked as discussed above. There are two two-hop routes (1–4–BS and 1–2–BS). The first one has smaller cost function ($f = 73$ dB). When node 1 has traffic to send to the BS, it checks the best route (1–4–BS). If free time-slot with $SINR_{ach} > SINR_{th}$ is found then this route will be selected, otherwise node 1 selects the second best route (1–2–BS). If free time-slots with acceptable SINR are unavailable in the second best route, node 1 will check the free slots of the third best route (1–4–2–BS) and so on.

2.3 Matching free time-slots

The matching free time-slots problem means that common time-slots have to be free or available in both the transmitting and receiving nodes/BSs [8]. In traditional single-hop TDMA, a node can use any time-slot to send to the BS as long as that time-slot is free at the BS. However, in a MFCN, there is no guarantee that the free time-slots at the BS are also free at the transmitting node. This is due to the fact that at the transmitting node, some time-slots can already be occupied to relay the traffic of other nodes.

As shown in Fig. 3, node 1 tries to get node 4 to relay its traffic to BS (1–4–BS). There are free matching time-slots available in the first hop between node 1 and node 4 (time-slots: 3, 5, 9 and 10). In the second hop, although the BS has free slots available (time-slots: 1, 4 and 8), there is no matching free slots between node 4 and the BS. Obviously, node 1 still can use route (1–4–BS) if the burst can be buffered at node 4 until a matching time-slot becomes available between node 4 and the BS. However, this approach is not always preferable because of the additional buffering delay until a matching

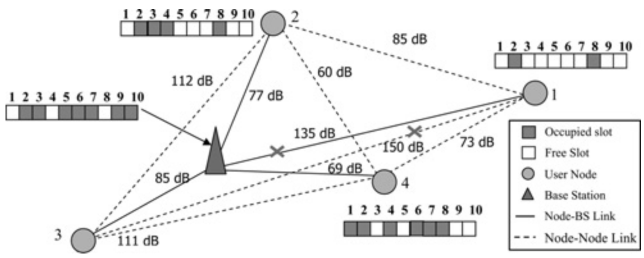

Figure 3 *Example of route selection and matching time-slot problem*

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Table 1 Mapping of adaptive coding and modulation to SINR

SINR dB	Spectral efficiency, bps/Hz	Coding rate-modulation scheme
>26.0	6	1 — 64 QAM
21.94–26.0	5.25	7/8 — 64 QAM
19.0–21.94	4.5	3/4 — 64 QAM
17.7–19.0	4	2/3 — 64 QAM
15.0–17.7	3.5	7/8 — 16 QAM
14.02–15.0	3	3/4 — 16 QAM
12.0–14.02	2.67	2/3 — 16 QAM
10.93–12.0	2	1/2 — 16 QAM
7.45–10.93	1.5	3/4 — 4 QAM
4.65–7.45	1	1/2 — 4 QAM
<4.65	0	—

time-slot is released. Hence, node 1 checks the second best hop route (1–2–BS) and finds matching free time-slots on the first hop (time-slots: 1, 5, 6, 7, 9, 10) and on the second hop (time-slot: 1) so it can use this route.

2.4 Traffic model

The user nodes are considered to generate bursty traffic sessions, typical of the Internet and multimedia applications. The overall network traffic arrival follows Poisson distribution with a mean arrival rate of λ burst/sec. Burst size is exponentially distributed with a mean of μ k bits.

2.5 Transmit power, modulation and coding

Fixed transmit power is considered on each hop. Adaptive coding and modulation are utilised using 11 combinations of coded Mary quadrature amplitude modulation (M-QAM) as shown in Table 1. The coding rate and modulation level combination is selected on each hop of the route independently based on the SINR level. Mapping of adaptive coding and modulation with respect to SINR is based on bit interleaved coded modulation (BICM) [9] at BER $= 10^{-6}$.

3 Simulation parameters and assumptions

3.1 Simulation parameters

As shown in Fig. 1, a network of four square shaped cells, each of size 3×3 km^2 is considered, with 200 nodes uniformly distributed in the entire network. Multiple frequency carriers at 2.5 GHz and a signal bandwidth of 5 MHz each are employed. Synchronous TDMA/FDMA access technique (with ten time-slots per frame) is considered so that all node transmissions on the uplink are slot synchronised. Simple Automatic Repeat Request (ARQ) scheme is used to take care of high frame outage links.

This study considers a suburban environment like a moderately dense residential area. The average signal power received at the BS or relay node (in dBW) can be represented by the following formula

$$P_r(d) = P_t + G_t + G_r - \mathrm{PL}(d) \qquad (2)$$

where P_t is the transmit power (in dBW), G_t and G_r are the transmitter and receiver antenna gain values (in dB), respectively, d is the distance between the transmitter and receiver and PL(d) is the path-loss (in dB)

$$\mathrm{PL}(d) = 20\log\left(\frac{4\pi d_0}{\lambda}\right) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma \qquad (3)$$

where d_0 is the reference distance, λ is the wave length of the carrier frequency, n is the path loss index and X_σ is the lognormal shadowing with standard deviation of σ.

The antenna beam-width (at the nodes and the BSs) is 30° with 7 dB gain in the main lobe and 0 dB gain in the side lobe. Node–BS and node–node links have exponential path-loss with an exponent of 3.8 and 4, respectively. Shadowing is modelled using a lognormal random variable with zero mean and $\sigma_s = 4$ dB for the node–BS links and 6 dB for the node–node links.

The difference between node–BS and node–node links in terms of propagation parameters (path-loss exponent and shadowing standard deviation) is mainly because node–BS links usually enjoy more favourable radio links in comparison to the node–node links mainly due to the BS antenna elevation. As the transmitter height increases the chance of the link being above the ‘clutter’ also increases; this results in reduced path loss, which in turn may be modelled by a lower propagation exponent and a lower shadowing standard deviation [10].

Fixed transmit power of 3 dBW is used on all hops and the system noise figure is 5 dB. Network traffic is bursty in nature with a Poisson distributed arrival. Burst size is exponentially distributed with mean of 15 k bits. Bursts are served in the form of frames at the rate of 100 frames/s. Each burst is assigned one slot per frame on each hop of the entire route. Table 2 lists the simulation parameters used in this work.

3.2 Simulation assumptions

Independent and fixed shadowing on all links: Since node density is low, it is reasonable to assume that there is no spatial correlation between shadowing values at different nodes, on both node–node and node–BS links. Also, fixed shadowing is assumed based on the stationary nodes assumption.

Table 2 System parameters used in the simulation

System parameter	Type	Simulation value
network architecture	cellular	4 square shaped cell, each 3 × 3 km^2; 200 nodes uniformly distributed in the network
carrier frequency		2.5 GHz
frequency carriers		no. of carriers = 2, 4, or 6, with a bandwidth of 5 MHz each
noise power	AWGN	noise power = −125 dBW and noise figure = 5 dB
multiple access	synchronous TDMA	all node transmissions are slot synchronised
link analysis	uplink	
transmit power	fixed	$P_t = 3$ dBW
path loss	exponential path loss plus independent and fixed shadowing	node–BS links: reference distance $d_0 = 10$ m; propagation exponent n = 3.8; zero mean lognormal shadowing with $\sigma = 4$ dB node–node links: reference distance $d_0 = 10$ m; propagation exponent n = 4; zero mean lognormal shadowing with $\sigma = 6$ dB
antenna type	directional switched beam at both BSs and nodes	30° beam width; main lobe gain = 7 dB; side and back lobe gain = 0 dB
maximum permissible number of hops		3
max. acceptable path loss for multihop relaying	propagation path loss + shadowing	$PL_{th} = 126$ dB
node buffer size		unlimited
traffic model	bursty	burst arrival rate: Poisson distributed with mean $\lambda = 400$–8400 burst/s; burst size: exponentially distributed with mean $\mu = 15$ kbits.
frame specs	fixed time slot duration	frame duration = 10 ms no. of slots per frame = 10
adaptive coding and modulation	code rate and modulation level mapped to SINR	11 levels (as listed in Table 1)
frame error	$SINR_{ach} < SINR_{th}$ on any hop	$SINR_{th} = 4.65$ dB
automatic repeat request (ARQ)	continuous ARQ	upper limit on consecutive frame dropping before ARQ = 2; retransmit entire burst

Unlimited buffer capacity on each node: This is assumed for modelling and simulation simplicity. In addition, the low cost of memory chips can justify this assumption.

Uplink transmission: The analysis focuses on the uplink transmission (from nodes to BSs through intermediate nodes). This is due to the fact that with the expected multimedia applications such as video conferencing, telemedicine and interactive remote training sessions, the uplink transmission will also require high data rates like downlink and will meet QoS requirements. Moreover, uplink performance analysis is considered relatively more complex than downlink, because of the distributed nature of traffic generation, multiple concurrent transmission and highly variable interference levels.

All nodes are active: Each node generates the above specified average node traffic. Moreover, the nodes are always on, irrespective of whether they are sending data or

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not, to make sure that nodes are available to serve as relays whenever needed.

Resource pooling: This means that a user node in a particular cell can be serviced through any BS in the network and can take relaying assistance from any node in any cell. This approach is practical in MFCN since some nodes can be served with any BS if there are some relaying nodes between the node and the BS.

Continuous ARQ: A receiver (intermediate node or destination BS) sends an acknowledgment to the transmitter for every frame. This acknowledgment shows whether the frame was received in error or not. The ARQ process is performed per hop (not per route) to minimise the delay.

4 Simulation results

In this section, the performance of the MFCN is analysed for different values of the number of available frequency carriers. The same network, but with single-hop connections, is also analysed for comparison. The system performance is measured in terms of outage probability, connectivity and normalised throughput.

4.1 Outage probability

In this work, we consider the outage due to either poor coverage ($SINR_{ach} < SINR_{th}$) or resource unavailability.

Fig. 4 shows the outage probability at a different number of frequency carriers (two, four and six). The single-hop network, due to poor coverage, has consistently high outage (38–40%) when the network has four and six frequency carriers irrespective of the generated node traffic. This means that if some nodes do not have single-hop coverage to BSs, then no matter how many frequency carriers are provided, they just cannot be served because of the poor coverage. This outage probability (due to poor coverage) can also be approximated by [11]

$$P_{\text{out-poor coverage}} = \frac{1}{\text{cell area}} \int_{\text{cell area}} P(\text{SINR}_{\text{ach}} < \text{SINR}_{\text{th}})\, dA = \frac{1}{2}\left(1 + \text{erf}(a) + \exp\left(\frac{1-2ab}{b^2}\right) \times \left[1 - \text{erf}\left(\frac{1-ab}{b}\right)\right]\right) \quad (4)$$

where $a = (\text{SINR}_{\text{th}} - \overline{\text{SINR}}(R)/\sigma\sqrt{2})$, $b = 10n\log(10n\log e/\sigma\sqrt{2})$, R is the cell radius and $\overline{\text{SINR}}(R)$ is the average SINR (SINR without shadowing) at distance R given by

$$\overline{\text{SINR}}(R) = \overline{P}_{\text{r}}(R) - \text{NF} - N \quad (5)$$

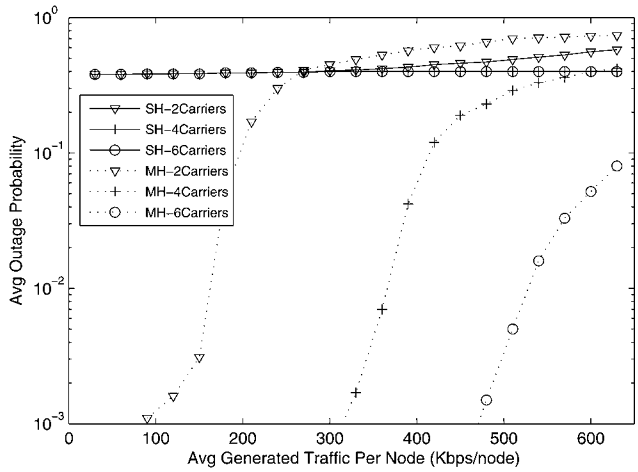

Figure 4 *Outage probability of single-hop and MFCN (signal bandwidth = 5 MHz and no. of nodes per network = 200)*

where $\overline{P}_{\text{r}}(R)$ is the average received power given by (2) and (3) without shadowing, NF is the noise figure, and N is the noise power.

This expression in (4) gives the same value found by simulation in Fig. 4 (38%) for a single-hop at low traffic values.

If frequency carriers are few like in the case of two frequency carriers, then at low node traffic the outage probability is similar to that of four and six frequency carriers while at high node traffic levels, the impact of limited resources also adds up, resulting in increased outage probability (up to 0.6).

The capability of the MFCN to improve the outage probability is obvious in Fig. 4. However, it is evident that the MFCN outage probability increases monotonically and steeply with the increase in the traffic level due to the resource over-utilisation problem associated with MFCN. With two frequency carriers only, a significant reduction in the outage probability is achievable at low traffic levels due to the coverage enhancement. Nevertheless, at medium and high traffic rates, the performance of MFCN becomes inferior to the single-hop network because of the lack of enough resources.

If the number of frequency carriers is increased to four, the superimority of the MFCN outage performance can be extended to medium and high traffic levels (up to 0.12 bps/node/Hz). However, at higher traffic levels, the performance of MFCN approaches that of the single-hop network. Increasing the number of frequency carriers to six results in extending the superiority of the MFCN outage performance to high traffic levels.

4.2 Connectivity

In MFCN, the connectivity of different nodes to the BSs can be achieved using a single-hop or multihop (two- or three-hop) routes. The contribution of single-hop, two-hop and three-hop routes in the connectivity is presented Fig. 5.

As shown in Fig. 5*a*, at low traffic levels, nodes with no single-hop connectivity are fully supported by two-hop connections; therefore three-hop connections are never needed. As the traffic level increases, more concurrent two-hop connections become active; this leads to higher co-channel interference. This, in turn, means a new connection request may find it hard to get a two-hop route with good SINR on both hops; as such, it may start seeking three-hop connections with shorter link. However, more three-hop routes will cause more co-channel interference. Thus, this leads to a sort of chain reaction of higher co-channel interference to the extent that connectivity of the MFCN becomes worse than that of the single-hop cellular network.

As the number of frequency carriers increases to four, chances of finding a two-hop route with acceptable SINR on both hops is extended to medium traffic levels, hence the need to switch to a three-hop connection is limited to high traffic levels, as shown in Fig. 5*b*.

As shown in Fig. 5*c*, increasing the number of frequency carriers to six almost eliminates the need for a three-hop connection throughout the range of traffic levels considered. This simply means that a two-hop route with viable SINR is always available.

4.3 Node throughput

Fig. 6 compares the average net delivered node throughput of the single-hop network and the MFCN. As depicted in Fig. 6, traffic generated from poorly covered nodes in the single-hop cellular network is not fully supported; hence a lower slope of ~ 0.62 is observed for light to medium generated traffic levels, irrespective of the number of available frequency carriers. However, as traffic grows, the impact of resource limitation comes into play resulting in degradation of node throughput. As the number of the frequency carriers is increased to four in the single-hop cellular network, not only is the degradation in node throughput shifted further on the traffic scale, but it also becomes less steep in comparison with that of the two-frequency carrier case. A further increase in the number of frequency carriers to six ensures full throughput for all nodes under the coverage, even at the highest offered load considered.

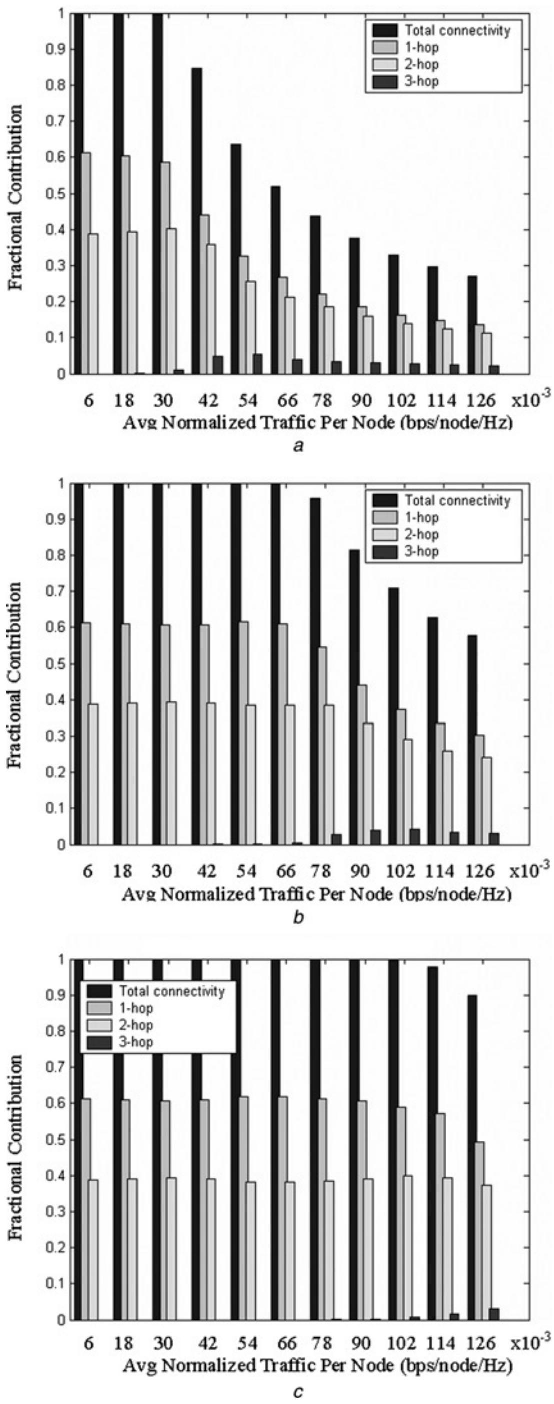

Figure 5 *Contribution of i-hop (i = 1, 2, 3) connectivity in MFCN network (signal bandwidth = 5 MHz and no. of nodes per network = 200)*

a with 2 frequency carriers
b with 4 frequency carriers
c with 6 frequency carriers

In the MFCN, full coverage and high spectral efficiencies due to short links, leads to a full-support and 100% delivered throughput for light to medium traffic levels. Later, at high traffic levels, increased interference leads to degraded spectral efficiency and resource exhaustion, resulting in relatively lower throughput; nevertheless, this is still superior to the corresponding single-hop cellular network, except for the two-frequency carrier case (at normalised traffic level >0.1 bps/node/Hz). However, it should be noted that the throughput of the MFCN with four and six

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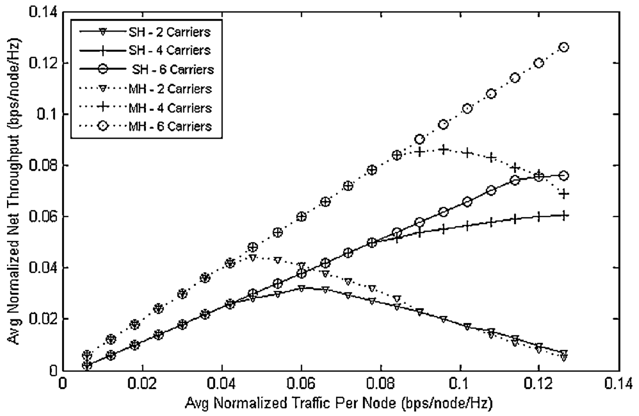

Figure 6 *Average normalised net throughput of single-hop and MFCN with 2, 4 and 6 frequency carriers (signal bandwidth = 5 MHz and no. of nodes per network = 200)*

carriers will eventually become less than that of the single-hop cellular network if the loading levels are increased even further (to values greater than those shown in Fig. 6).

4.4 Spectral-efficiency coverage

In this work, spectral-efficiency coverage in the single-hop cellular networks and MFCN is defined as follows [12]:

Spectral-efficiency coverage in single-hop network: 'Percentage of total number of nodes with 95% probability of $SINR_{ach}$ greater than or equal to targeted SINR ($SINR_t$) for a specific modulation level on any time-slot (free or occupied) of the BS'

Spectral-efficiency coverage in multihop network: 'Percentage of total number of nodes with 95% probability of $SINR_{ach}$ greater than or equal to $SINR_t$ for a specific modulation level on any time-slot (free or occupied) of the relay(s) and BS'

In this work, we map the $SINR_{ach}$ to a certain spectral efficiency using adaptive coding and modulation as mentioned above in Table 1. Therefore if a node has $SINR_{ach}$ of 4.65–7.45 dB for 95% of the time, then this node has spectral-efficiency coverage of 1/2-QPSK or 1 bps/Hz. Similarly for $SINR_{ach}$ of 14.02–15.0 dB for 95% of the time, a node has spectral-efficiency coverage of 3/4-16QAM or 3 bps/Hz, and so on. $SINR_t$ can vary depending upon the service type and required QoS. By calculating SINR on both free and occupied slots, we present the potential in single-hop cellular and MFCN to achieve certain transmission rate (or equivalently SINR) coverage. In other word, if more frequency carriers are provided, such coverage can be practically guaranteed.

Fig. 7 shows the spectral efficiency coverage for single-hop network and MFCN with two-carriers. As can be ascertained, MFCN have 100% node coverage of 1/2-QPSK (1 bps/Hz) over the entire range of traffic level, as

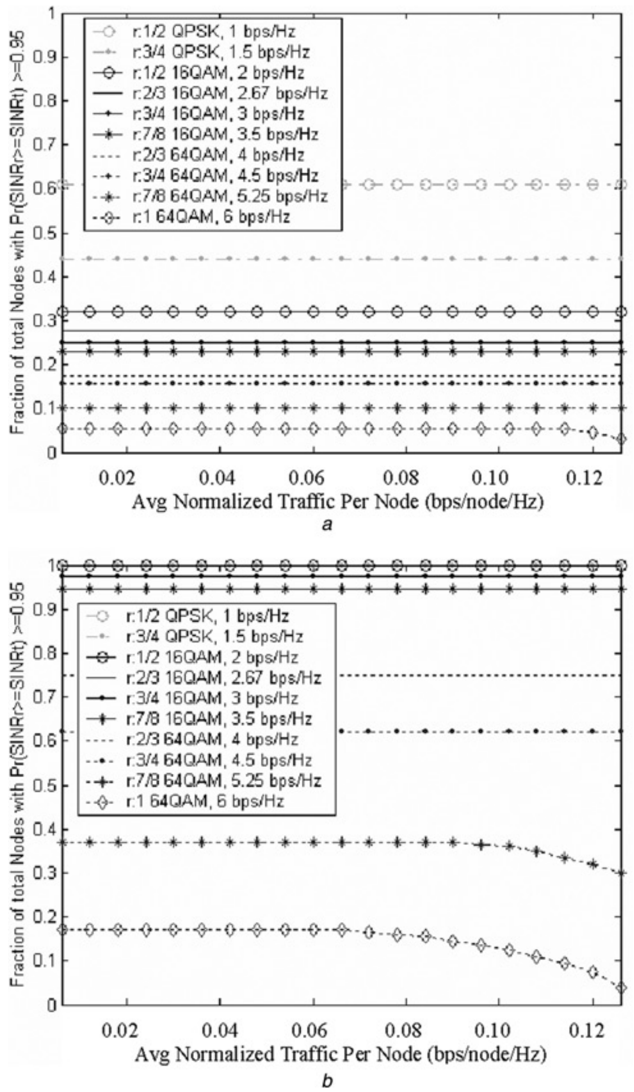

Figure 7 *Spectral efficiency coverage with 2 carriers (signal bandwidth = 5 MHz and no. of nodes per network = 200)*

a in Single-hop cellular network
b in MFCN

compared to only 62% in the corresponding single-hop network. In addition, the 100% node coverage is extended up to 2/3-16QAM (2.67 bps/Hz). This is followed by 98% node coverage of 3/4-16QAM (3 bps/Hz), and 95% node coverage for 7/8-16QAM (3.5 bps/Hz), compared with only 25 and 23% node coverage in the corresponding single-hop cellular network. This trend continues for higher spectral efficiency coverage too. However as traffic grows, more and more concurrent multihop routes exist in the MFCN network, which causes higher co-channel interference and more resource utilisation. Therefore coverage for high spectral efficiency starts degrading at medium to high traffic levels. In case of 7/8-64QAM (5.25 bps/Hz), coverage drops from 37 to 30%, while in 1-64QAM (6 bps/Hz), it drops from 17 to 3%.

If the number of frequency carriers is increased to four and six, it is found that there is no change in the coverage probabilities, except that the degradation of the 7/8-64QAM and 1-64QAM coverage at high traffic levels does not exist any more. (Figures of spectral-efficiency coverage with 4 and 6 carriers are not shown because of the limited space). This is because, with more available carriers, nodes can find more time-slots to choose from to achieve the required SINR.

5 Summary and conclusions

This paper investigates the performance of a TDMA-based MFCN in comparison with the conventional single-hop cellular network. The performance is evaluated in terms of the outage probability, connectivity and average node throughput, with a special emphasis on the dependence of the performance on the number of frequency carriers.

From the discussion above, it can be concluded that for a network in the start-up phase with low upfront infrastructure and poor coverage, implementing multihop relaying provides not only significant coverage boost but also high throughput. The superior performance of MFCN is found to be directly related to the number of available frequency carriers. If the network has a large number of frequency carriers, the advantages of the MFCN structure in terms of high throughput and low outage can be realised. On the other hand, if the network has a limited number of frequency carriers, the performance gain can not be obtained, particularly at high loading values.

These findings demonstrate that the incorporation of the multihop feature can provide more flexibility in the cellular network design as bandwidth can be utilised towards attaining high data-rate coverage. Such a bandwidth-coverage exchange is often not possible in single-hop networks; that is, when there is a coverage problem, having additional frequency carriers will not help in any significant way.

We will extend this work by considering the following issues: The impact of the design parameters (e.g. user node density and the number and locations of BSs), route selection policy, non-uniform traffic distribution (hotspots), asynchronous up-link transmission and multi-carrier access systems (OFDM/OFDMA).

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