Multihop Cellular: A New Architecture for Wireless Communications

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Abstract— **This work presents a new architecture, Multihop Cellular Network (MCN), for wireless communications. MCN preserves the benefit of conventional single-hop cellular networks (SCN) where the service infrastructure is constructed by fixed bases, and it also incorporates the flexibility of ad-hoc networks where wireless transmission through mobile stations in multiple hops is allowed. MCN can reduce the required number of bases or improve the throughput performance, while limiting path vulnerability encountered in ad-hoc networks. In addition, MCN and SCN are analyzed, in terms of mean hop count, hop-by-hop throughput, end-to-end throughput, and mean number of channels (i.e. simultaneous transmissions) under different traffic localities and transmission ranges. Numerical results demonstrate that throughput of MCN exceeds that of SCN, the former also increases as the transmission range decreases. Above results can be accounted for by the different orders, linear and square, at which mean hop count and mean number of channels increase, respectively.**

Keywords— **multihop, cellular, ad-hoc networks, packet radio, transmission range**

I. INTRODUCTION

Wireless communications has rapidly evolved in the recent decade. Within this field, voice-oriented services can be categorized as either [1]: (1) high-power, wide-area cellular systems, e.g. AMPS (Advanced Mobile Telephone System) [2] and GSM (Global System for Mobile communications) [3], or (2) low-power, local-area cordless systems, e.g. CT2 (Cordless Telephony) [4] and DECT (Digital European Cordless Telephone) [5]. Data-oriented services can also be categorized as either [1]: (1) low-speed, wide-area systems, e.g. ARDIS (Advanced Radio Data Information Service) [6] and CDPD (Cellular Digital Packet Data) [7], or (2) high-speed, local-area systems, e.g. HIPERLAN (Hi Performance Radio Local Area Network) [8] and IEEE 802.11 [9].

However, most services and systems mentioned above are based on the single-hop cellular architecture. Service providers must construct an infrastructure with many fixed bases or access points to encompass the service area. By doing so, mobile stations can access the infrastructure in a single hop. In a densely populated metropolitan area, to support more connections, the area that a single base, i.e. a cell, covers is shrunk and the number of bases increases. This phenomenon unfortunately leads to (1) a high cost for building a large number of bases, (2) total throughput limited by the number of cells in an area, and (3) high power consumption of mobile stations having the same transmission range as bases. Notably, (1) and (2) trade off each other. If a higher throughput in a geographical area is desired, more bases, i.e. cells, must be constructed in that area.

Another kind of network, commonly referred to as packet radio or ad-hoc networks [10], [11], is available in which no infrastructure or wireline backbone is required. In these networks, packets may be forwarded by other mobile stations to reach their destinations in multiple hops. Second generation packet radio networks, such as WAMIS (Wireless Adaptive Mobile Information System [12]), have began to address the limited bandwidth and QoS(Quality of Service) issue. An advantage of these networks is their low cost because no infrastructure is required, and, therefore, can be deployed immediately. However, these ad-hoc networks appear to be limited to specialized applications, such as battlefields and traveling groups, due to the vulnerability of paths through possibly many mobile stations. However, this vulnerability can be significantly reduced if the number of wireless hops can be reduced and the station mobility is low.

In this work, we present a new architecture, Multihop Cellular Network (MCN) as a viable alternative to the conventional Single-hop Cellular Network (SCN) by combining the features of SCN and ad-hoc networks. The implemented prototype, where mobile stations run a bridging protocol, shows that MCN is a feasible architecture for wireless LANs [13]. In MCN, mobile stations help to relay packets, which is not allowed in other variant systems of SCN, such as Ricochet network [14] and mobile base network [15]. MCN has several merits: (1) the number of bases or the transmission ranges of both mobile stations and base can be reduced, (2) connections are still allowed without base stations, (3) multiple packets can be simultaneously transmitted within a cell of the corresponding SCN, and (4) paths are less vulnerable than the ones in ad-hoc networks because the bases can help reduce the wireless hop count.

Fig. 1 shows an SCN and two possible architectures of MCN, MCN-b and MCN-p, as derived from SCN. Although the transmission range adopted in MCN-b is the same as that in SCN, the number of bases is reduced such that the distance between two neighboring bases becomes k_b times of the distance in SCN. Only four base stations, A, B, C, and D in the SCN are necessary in MCN-b. In MCN-p, although the number of bases is not reduced, the transmission ranges of base stations and mobile stations are reduced to $1/k_p$ of these adopted in SCN. Thus packets might be forwarded, in both MCN-b and MCN-p, by mobile stations to arrive destinations in multiple hops. Nevertheless, MCN-b can be viewed as a special case of MCN-p if the transmission range and the distance between

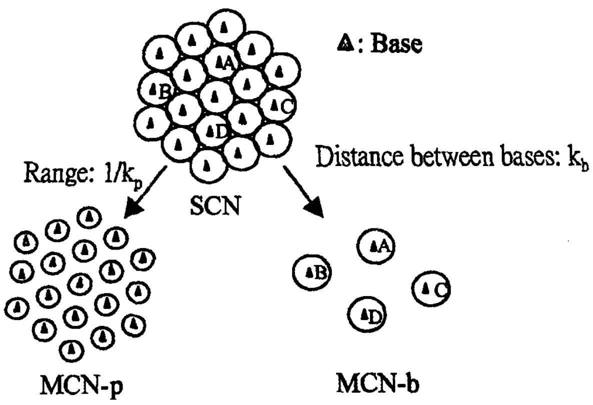


Fig. 1. Examples of an SCN and two variants of MCN, MCN-p and MCN-b.

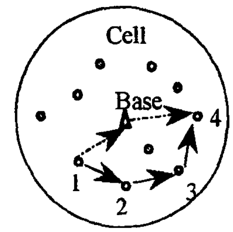


Fig. 2. Multihop routing vs single-hop routing.

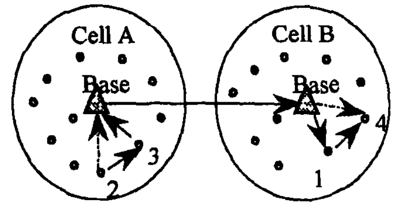


Fig. 3. Different routing paths of MCN and SCN.

bases in MCN-p are multiplied by k_p and k_b, respectively. For the example in Fig. 1, the radius of a cell and the distance between bases of MCN-b are twice as long as those of MCN-p, if $k_p = k_b = 2$. This work focuses on MCN-p while describing and analyzing the proposed architecture. In addition, MCN-b is analyzed by simple parameter substitution. MCN-p is referred to herein as MCN.

This work focuses mainly on system throughput of SCN and MCN. MCN has its merits and limitations. With respect to its merits, the throughput might be improved, since multiple packets can be simultaneously transmitted in a cell of the corresponding SCN. In terms of its limitations, the throughput might be lowered, since packets may have to be sent multiple times to arrive at bases or destinations, which consumes more bandwidth. Therefore, the end-to-end throughput of SCN and MCN must be thoroughly analyzed.

The rest of the paper is organized as follows. Section II describes the SCN and MCN architectures. Section III presents the system throughput of SCN and MCN. Section IV summarize the numerical results, indicating that the throughput of MCN is better than that of SCN. Hop count and the number of simultaneous channels or transmissions are also studied to explain the results. Finally, conclusion and areas for future research are given in section V.

II. Architecture

Single-hop Cellular Networks (SCNs) are cellular networks where bases can be reached by mobile stations in a single-hop, in contrast to Multihop Cellular Networks (MCNs) where bases can not always be reached by mobile stations in a single hop.

Before describing these two architectures, we first define the area reachable by a base in SCN as a *cell*, which is within a radius of fixed distance, say R. Incidentally, the area of a cell in MCN is also defined as the same area in SCN, which is the area *taken care of* by a base. Notably, the radius of a cell in MCN is half the distance between two neighboring bases. A *sub-cell* in MCN is defined as the area reachable in a single wireless hop by a base or a mobile station. In SCN, the area of a sub-cell is the same as the area of a cell.

A. Single-hop Cellular Network (SCN)

In SCN, base and mobile stations in the same cell are always mutually reachable in a single hop. When having packets to send, mobile stations always send them to the base within the same cell. If the destination and the source are in the same cell, such as stations 1 and 4 in Fig. 2, the base directly forwards packets to the destination. If the destination is in a different cell, the base forwards them to the base of the cell where the destination resides. The base of the latter cell then forwards packets to the destination in a single hop. Thus, the routing path resembles the dashed lines in Figs. 2 and 3.

B. Multihop Cellular Network (MCN)

The architecture of MCN resembles that of SCN except that bases and mobile stations are not always mutually reachable in a single hop. The transmission range of bases and mobile stations is reduced to $1/k_p$ of that adopted in SCN. Thus, the area reachable by a base or a mobile station is simply the area of a sub-cell. Similar to ad-hoc networks, a key feature of MCN is that mobile stations can directly communicate with each other if they are mutually reachable, which is not allowed in SCN. This feature leads to multihop routing.

If the source and the destination are in the same cell, other mobile stations can be used to relay packets to the destination, which achieves multihop routing within a cell. If not in the same cell, packets are sent to the base first, probably in multiple hops, and then be forwarded to the base of the cell where the destination resides. Packets can then be forwarded to the destination, probably in multiple hops again, within the latter

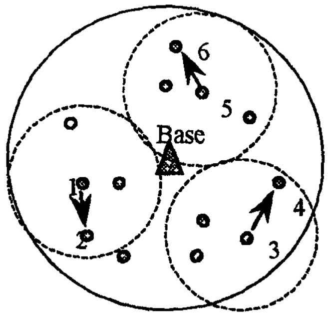


Fig. 4. Three stations in a cell transmit at the same time in MCN.

cell.

The solid lines in Figs. 2 and 3 illustrate the above two cases. These figures reveal the different routing paths of MCN and SCN by solid and dashed lines, respectively. The main advantage of MCN is the increased system throughput, as analyzed in the next section. For example, in Fig. 4, stations 1, 3, and 5 within the same cell can transmit packets simultaneously without interfering with each other; meanwhile, only one packet can be transmitted in the corresponding SCN.

TABLE I

SUMMARY OF PARAMETERS.

k_p	the transmission range in MCN-p is $1/k_p$ of the range in SCN
k_b	the distance between two neighboring bases in MCN-b is k_b times of the distance in SCN
λ_{ij}	packet generation rate at station i to station j in the same cell
λ_{io}	packet generation rate at station i to stations outside the cell
λ_{oi}	packet generation rate at stations outside the cell and destined for station i in the cell
N	the total number of stations in a cell
R	the radius of a cell
r	the maximum propagation delay in a hop
l_{RTS}	the transmission time of a RTS packet
l_{CTS}	the transmission time of a CTS packet
l_{PKT}	the transmission time of a data packet
l_{ACK}	the transmission time of an acknowledgment packet
l_{SIFS}	the time interval of SIFS
l_{DIFS}	the time interval of DIFS
rn_cycle	the expected length of a renewal interval
t_idle	the expected time until the initiation of the first transmission since a renewal point
G_s	the total packet arrival rate at mobile stations within a cell
G_{bs}	the packet arrival rate at the base
P_s	the probability of successful exchange of RTS and CTS packets

III. Modeling and Analysis

A. Underlying Assumptions and Definitions

To model the system throughput of SCN and MCN, we first assume that the up-link and down-link in a cell share the same channel for the inter-communication between mobile stations. For example, if station 2 in Fig. 3 transmits in $ch1$ and listens to $ch2$, station 3 would have to listen to $ch1$ and transmit in another channel. Thus, another control channel would be indispensable to process the complicated channel assignment when a mobile station transmits and receives packets in separate channels, making our analysis intractable. For comparison, the same assumption is also applied to SCN.

This work also applies the RTS/CTS (Request To Send / Clear To Send) access method of DCF (Distributed Coordination Function) of IEEE 802.11 [9] MAC (Medium Access Control) protocol to both architectures, while assuming that neighboring cells use different channels to avoid conflict. Hence, the need for synchronization is eliminated. Furthermore, station mobility is neglected to reduce the complexity of our analysis since the simulation results in [16] show the small effect of mobility on system throughput.

Once a channel is sensed idle and a time interval DIFS (DCF Inter-Frame Space) has elapsed, the time until a data packet is generated at station i, destined for station j in the same cell, is assumed to be exponentially distributed with rate λ_{ij}. Also, λ_{io} is denoted as the rate at which data packets are generated at station i destined for stations outside the cell. Similarly, λ_{oi} is the rate at which data packets are generated outside the cell and destined for station i in the cell. The number of stations in the cell is denoted as N and the radius of the cell is denoted as R. In addition, r, l_{RTS}, l_{CTS}, l_{PKT}, l_{ACK}, l_{SIFS} and l_{DIFS} are used to denote the maximum propagation delay in one hop, the transmission time of an RTS packet, a CTS packet, a data packet and an acknowledgment packet, as well as the time interval of SIFS (Short Inter-Frame Space) and DIFS, respectively.

Herein, the system throughput is defined using the same definition as [17], i.e. the number of successful transmissions between successive "renewal points" divided by the length of the time interval between the renewal points, referred to as a renewal interval. However, the "renewal point" is defined as the time point when all stations in a sub-cell simultaneously sense the channel being idle. Thus, the expected length of a renewal interval is defined as

$$
\begin{aligned}
rn\_cycle = & \\
& l_{DIFS} + t\_idle + l_{RTS} + r + l_{SIFS} + l_{CTS} + r \\
& + Ps * (l_{SIFS} + l_{PKT} + r + l_{SIFS} + l_{ACK} + r),
\end{aligned}
$$

where Ps denotes the probability of successful exchange of RTS and CTS packets, and t_idle represents the expected time until the initiation of the first transmission since a renewal point. Notably, both t_idle and Ps are to be derived.

Our goal is to derive the hop-by-hop throughput and end-to-end throughput in a cell for both SCN and MCN. The hop-by-hop throughput is defined as the number of successful packet transmissions per second in a cell. The end-to-end throughput is defined as the number of successful packet receptions per second in a cell by either the base, if the end destinations are outside the cell, or the end destinations, if they are within the cell. We use table I to summarize the parameters mentioned above.

B. Single-hop Cellular Network

System throughput analysis:

The system throughput of SCN is analyzed in four major steps:

1. Derive t_idle to obtain the renewal interval;
2. Derive the probability of a successful transmission at station i and the base;
3. Derive the throughput of station i and the base; and
4. Derive the hop-by-hop throughput and end-to-end throughput of SCN.

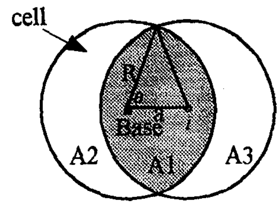
To obtain rn_cycle, the packet arrival rate at station i is computed as

$$\lambda_i = \sum_{j\neq i, j=1}^{N} \lambda_{ij} + \lambda_{io}. \tag{1}$$

Now we denote the total packet arrival rate at mobile stations within a cell by G_s which equals $\sum_{i=1}^{N}\lambda_i$. Since each packet transmitted from station i to station j is forwarded by the base, the traffic generation rate at the base is given by $G_{bs} = \sum_{i=1}^{N}\lambda_{oi} + \sum_{i=1}^{N}\sum_{j\neq i,j=1}^{N}\lambda_{ij}$. Thus, t_idle is derived as $1/(G_s + G_{bs})$, since the packet arrival process is Poisson and a sub-cell equals a cell in SCN. The renewal interval is thus given by

$$\begin{aligned} rn\_cycle = \\ & l_{DIFS} + \frac{1}{G_s + G_{bs}} + l_{RTS} + r + l_{SIFS} + l_{CTS} + r \\ & + Ps * (l_{SIFS} + l_{PKT} + r + l_{SIFS} + l_{ACK} + r). \end{aligned}$$

To analyze the probability of successful transmission from station i, at time t, to the base, we first define mean *capture area* and mean *hidden area* of station i as A1 and A2, respectively, in Fig. 5. The capture area of station i is the area within the cell reachable by station i. The hidden area of station i is the capture area of the receiver, i.e. the base station, but is hidden from station i. For convenience, $A1/\pi R^2$ and $A2/\pi R^2$ are denoted as n_h (i.e. mean percentage of capture area in a cell) and h (i.e. mean percentage of hidden area in a cell), respectively, where πR^2 represents the area of the cell. Since P(the distance between the base and station i = a) = $\frac{2a}{R^2}$, $A1$ equals $\int_0^R \frac{2a}{R^2}\cdot[2R^2\theta - Ra\sin\theta]da$, where $\theta = \arccos\frac{a}{2R}$ and $\sin\theta = \sqrt{R^2-(a^2/4)}/R$. Thus A2 is given by $\pi R^2 - A1$. Notably, A3 belongs to another cell using a different channel. Under the condition that station i is the first one who fires an RTS packet within its sub-cell, we conclude that the following conditions are necessary to obtain the probability of successful transmission from station i to the base. Notably, only the probability of successful exchange of RTS and CTS packets needs to be considered because the transmissions of the data packet and the corresponding acknowledgement packet are successful if the exchange succeeds.



A1: capture area of station i
A2: hidden area of staton i for the base

Fig. 5. Capture area and hidden area of station i in SCN.

(a) Station i has a packet to send at time t;
(b) No stations in area A1 send packets during $[t, t+r]$;
(c) The base does not send packets during $[t, t+r]$; and
(d) No stations in area A2 send packets during $[t, t + r + l_{RTS} + l_{SIFS} + r]$.

Conditions (b) and (c) imply that the RTS packet does not collide with other packets initiated by other stations in A1, since no transmission occurs during $[t, t+r]$ in the capture area of station i. Condition (d) ensures that no collision occurs due to the hidden terminal problem [18], since the base is assumed to reply the corresponding CTS packet at time $t + r + l_{RTS} + l_{SIFS}$. Hence, a pair of RTS and CTS packets is successfully transmitted.

Because no area is hidden from the base, analyzing the probability of successful transmission at the base is relatively simple under the condition that the base is the first one firing an RTS packet within its sub-cell. For the same reason discussed above, only the following two conditions need to be satisfied to completely exchange RTS and CTS packets:
(e) The base has a packet to send at time t; and
(f) No stations in the cell send packets during $[t, t+r]$.

Now the probability of successful transmission at station i and at the base, Ps_i and Ps_{bs}, is written as $[1-(1-e^{-(G_{bs}+G_s\cdot n\_h)\cdot r})]\cdot[1-(1-e^{-(G_s\cdot h)\cdot(2r+l_{RTS}+l_{SIFS})})]$, i.e. P[*both conditions* (*b*) *and* (*c*) *hold*]$\cdot P$[*condition* (*d*) *holds*], and $[1-(1-e^{-G_s\cdot r})]$, respectively. Thus, we get

$$\begin{aligned} Ps_i &= \exp\{-[r\cdot(G_{bs} + G_s\cdot n\_h) \\ &\quad + (2r + l_{RTS} + l_{SIFS})\cdot G_s\cdot h]\} \end{aligned}$$

and

$$Ps_{bs} = \exp\{-r\cdot G_s\}.$$

The probability that a transmission after a renewal point is fired by either station i or the base is $\lambda_i/(G_{bs} + G_s\cdot n\_h)$ and $G_{bs}/(G_{bs}+G_s)$, respectively. Thus, the hop-by-hop throughput of station i and the base are derived as

$$S_i = \frac{1\cdot Ps_i}{rn\_cycle}\cdot\frac{\lambda_i}{G_{bs}+G_s\cdot n\_h}$$

and

$$S_{bs} = \frac{1\cdot Ps_{bs}}{rn\_cycle}\cdot\frac{G_{bs}}{G_{bs}+G_s},$$

respectively. The total hop-by-hop throughput of SCN is eventually obtained as

$$S_h = \sum_{i=1}^{N} S_i + S_{bs}.$$

However, the end-to-end throughput of SCN equals the hop-by-hop throughput of the base, i.e.

$$S_e = S_{bs},$$

because when the base sends a packet, the receiver is simply the end destination.

C. Multihop Cellular Network

In MCN, the transmission range of the bases and stations is reduced to $1/k_p$ of that adopted in SCN. Thus, packets can be carried to the destination in multiple hops. Before analyzing the system throughput of MCN, we closely examine the mean hop count from station i to either station j or the base, in the same cell. To analyze the mean hop count, assume that station i can always find the next hop, at a distance of R/k_p, in the straight-line direction towards the destination.

Hop count analysis:

When station i sends a packet to any station in the cell, the hop count, hc, is a function of the positions of station i and the destined station. The mean hop count from station i to station j can be computed by fixing the position of one station, say i, so that the distribution of hc can be derived. When station i is located in the gray area in Fig. 6, the hop count to the base will be n because its transmission range equals R/k_p. Hence, the probability of station i being located in the nth layer of the cell is $\pi[(\frac{nR}{k_p})^2 - (\frac{(n-1)R}{k_p})^2]/\pi R^2$, which equals $(2n-1)/k_p^2$, where $1 \le n \le k_p$. The maximum hop count is known to be $k_p + n$, n hops to the base and k_p hops from the base to the station located near the boundary of the cell, allowing us to obtain $1 \le$ *hop count* $\le k_p + n$. Fig. 7 shows four different cases to compute the probability distribution of hop count, $P(hop\ count = hc)$, as derived below under the condition that station i is in the nth layer of the cell:

(case I) $P(hop\ count = hc) = \pi[(hc \cdot R/k_p)^2 - ((hc-1) \cdot R/k_p)^2]/\pi R^2$, which equals $(2hc-1)/k_p^2$, when $1 \le hc \le k_p - n$;

(case II) $P(hop\ count = hc) = (A(hc, n, k_p, R) - \pi \cdot ((hc-1) \cdot R/k_p)^2)/\pi R^2$, when $hc = k_p - n + 1$;

(case III) $P(hop\ count = hc) = (A(hc, n, k_p, R) - A(hc-1, n, k_p, R))/\pi R^2$, when $k_p - n + 2 \le hc \le k_p + n - 1$; and

(case IV) $P(hop\ count = hc) = 1 - A(hc-1, n, k_p, R)/\pi R^2$, when $hc = k_p + n$,

where $A(j, n, k_p, R)$ denotes the mean intersection area of two circles with radiuses of R and jR/k_p, i.e. the shaded area shown in Fig. 8. Since station i is in the nth layer of the cell, we have $(n-1) \cdot R/k_p < a \le n \cdot R/k_p$. Thus, we can write $A(j, n, k_p, R) = \int_{(n-1) \cdot R/k_p}^{nR/k_p} [\alpha(jR/k_p)^2 + \theta R^2 - aR \sin\theta] da$,

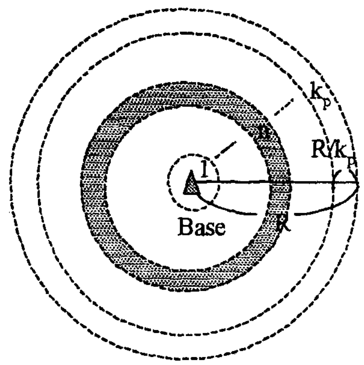


Fig. 6. The distribution of station i's position.

Legends: ○ station i

Δ base

shaded area: possiable location of station j

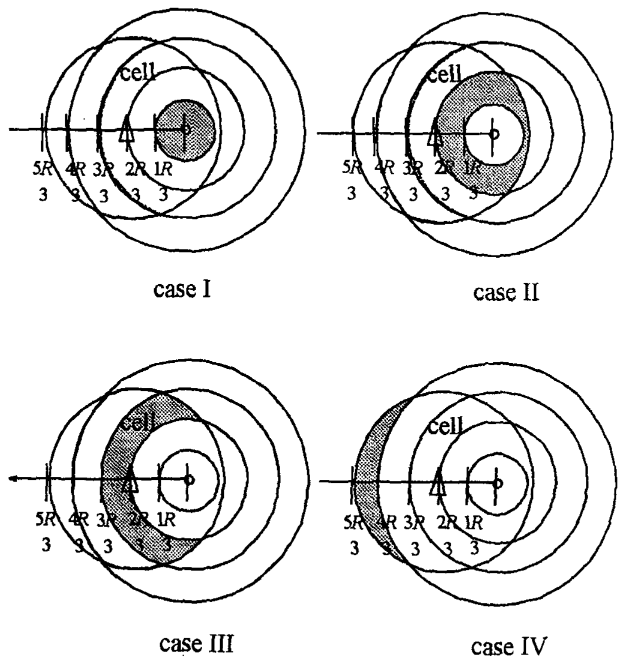


Fig. 7. Four cases to compute $P(hop\ count = hc)$, for $k_p = 3$ and $n = 2$.

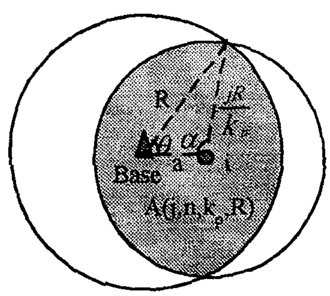


Fig. 8. Definition of $A(j, n, k_p, R)$.

where $\sin\theta = (j/k_p) \cdot \sin\alpha$, and $\cos\theta = (R^2 + a^2 - (jR/k_p)^2)/2aR$ since $R^2 - (R\cos\theta)^2 = (jR/k_p)^2 - (a - R\cos\theta)^2$.

We now get the probability of station i being located in the nth layer is $(2n-1)/k_p^2$ and the mean hop count when station i sends a packet to any station in the same cell is $\sum_{hc=1}^{k_p+n} hc \cdot P(hop\ count = hc)$. Thus, the mean hop count, which is a function of k_p, can be written as

$$avg\_hc\_ij(k_p) = \sum_{n=1}^{k_p} \frac{2n-1}{k_p^2} \cdot \sum_{hc=1}^{k_p+n} hc \cdot P(hop\ count = hc). \quad (2)$$

The mean hop count from station i to the base, $avg\_hc\_io(k_p)$, can be computed in a similar manner. However, it is much simpler to obtain $avg\_hc\_io(k_p)$ because the destination, i.e. the base, is at the fixed position. Thus, $avg\_hc\_io(k_p)$ is given by $\sum_{n=1}^{k_p}((2n-1)/k_p^2) \cdot n$, which equals

$$avg\_hc\_io(k_p) = \frac{(k_p+1)(4k_p-1)}{6k_p}. \quad (3)$$

When the base sends a packet to any station in the cell, $avg\_hc\_oi(k_p)$ obviously equals $avg\_hc\_io(k_p)$.

System throughput analysis:

For simplicity, assume that (a) the traffic is uniformly distributed within the cell, (b) stations can always find the next hop to forward packets, and (c) the base does not help forward packets if the pair of source and destination is both in the same cell. To analyze the throughput, five major steps are required:

1. Derive λ_i, G_s, and G_{bs} of MCN;
2. Derive t_idle to obtain the renewal interval;
3. Derive the probability of successful transmission at station i and the base;
4. Derive the hop-by-hop throughput of station i and the base; and
5. Derive the hop-by-hop throughput and end-to-end throughput of MCN.

By assuming that stations help forward packets, the total traffic rate at station i is given as

$$\lambda_i = \lambda_{io} \cdot avg\_hc\_io(k_p) + \lambda_{oi} \cdot (avg\_hc\_io(k_p) - 1) + \sum_{j \neq i, j=1}^{N} \lambda_{ij} \cdot avg\_hc\_ij(k_p), \quad (4)$$

because each packet is, on average, forwarded either $avg\_hc\_ij(k_p)$ times if the destination is in the same cell, $avg\_hc\_io(k_p)$ times if the destination is outside the cell, or $avg\_hc\_oi(k_p) - 1$ times when the source is outside the cell and the first transmission is done by the base. Notably, λ_i is intuitively equivalent to the traffic rate handled, i.e. pumped or forwarded, by station i because the traffic rate, to the cell, contributed by station i should equal the traffic rate, contributed by others, station i should take care of. Now we denote the traffic rate at all stations and the base by G_s and G_{bs}, which equal $\sum_{i=1}^{N} \lambda_i$ and $\sum_{i=1}^{N} \lambda_{oi}$, respectively.

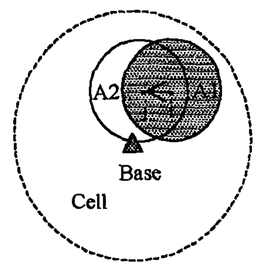


Fig. 9. Capture area and hidden area of station i in MCN.

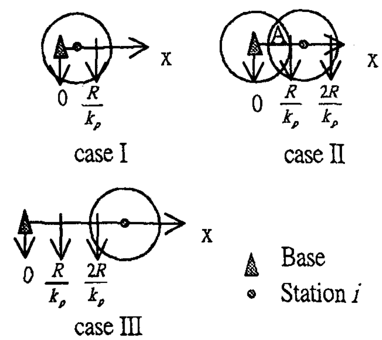


Fig. 10. Three cases to compute Ps_i.

In MCN, t_idle is derived as $1/((G_s + G_{bs})/k_p^2)$ which equals $k_p^2/(G_s + G_{bs})$, where the area of a sub-cell is $1/k_p^2$ of the area of a cell. The mean length of a renewal interval is thus defined as

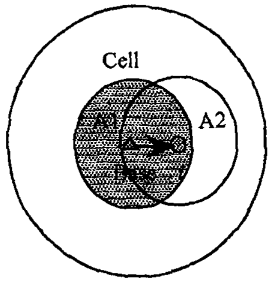
$$rn\_cycle = l_{DIFS} + \frac{k_p^2}{G_s + G_{bs}} + l_{RTS} + r + l_{SIFS} + l_{CTS} + r + Ps * (l_{SIFS} + l_{PKT} + r + l_{SIFS} + l_{ACK} + r). \quad (5)$$

For convenience, we again denote n_h and h as $A1/\pi R^2$ and $A2/\pi R^2$, where A1 and A2 are the mean capture area and the mean hidden area, respectively, of station i when it sends a packet to the next hop, say j, as shown in Fig. 9. Now the probability of successful transmission at station i can be derived similarly as done in SCN. However, the relative positions of station i and the base have three cases to be considered as shown in Fig. 10:

(case I)

$$Ps_{i1} = \exp\{-[r \cdot (n\_h \cdot G_s + G_{bs}) + (2r + l_{RTS} + l_{SIFS}) \cdot h \cdot G_s]\},$$

when the distance between station i and the base is smaller than R/k_p so that the base is in the capture area of station i;



A1: capture area of the base
A2: hidden area of the base for station i

Fig. 11. Capture area and hidden area of the base in MCN.

(case II)

$$Ps_{i2} = \exp\{-[r \cdot n\_h \cdot G_s + (2r + l_{RTS} + l_{SIFS}) \cdot (h \cdot G_s + P_A \cdot G_{bs})]\},$$

when the distance between station i and the base station is larger than R/k_p but smaller than $2R/k_p$ so that the base would be in the hidden area of station i, with probability P_A, when the receiver is positioned in the area A as shown in case II of Fig.10; and
(case III)

$$Ps_{i3} = \exp\{-[r \cdot n\_h \cdot G_s + (2r + l_{RTS} + l_{SIFS}) \cdot h \cdot G_s]\},$$

when the distance between station i and the base is larger than $2R/k_p$ so that the base does not affect the transmission of station i.

From above discussion, we can obtain that the mean probability of successful transmission at station i is

$$Ps_i = \frac{1}{k_p^2} \cdot Ps_{i1} + \frac{3}{k_p^2} \cdot Ps_{i2} + \frac{k_p^2 - 4}{k_p^2} \cdot Ps_{i3}.$$

Notably, the hidden area, i.e. A2 in Fig. 11, within the cell should be considered to analyze the probability of successful transmission of the base. We thus write

$$Ps_{bs} = \exp\{-[r \cdot n\_h \cdot G_s + (2r + l_{RTS} + l_{SIFS}) \cdot h \cdot G_s]\}.$$

Before deriving the throughput of MCN, we define the local traffic rate as the mean traffic rate within a sub-cell. Thus, the local traffic rates at station i and the base are $\lambda_{local\_i} = (G_s + G_{bs})/k_p^2$ and $\lambda_{local\_bs} = (G_s/k_p^2) + G_{bs}$, respectively. Notably, the term G_{bs} in λ_{local_i} is multiplied by $1/k_p^2$ because the probability that the base is in the sub-cell of station i is $1/k_p^2$. Hence, the probability that a transmission after a renewal point is fired by either station i or the base is $\lambda_i/\lambda_{local\_i}$ and $G_{bs}/\lambda_{local\_bs}$, respectively. We thus derive the hop-by-hop throughput of station i and the base as

$$S_i = \frac{1 \cdot Ps_i}{rn\_cycle} \cdot \frac{\lambda_i}{\lambda_{local\_i}},$$

and

$$S_{bs} = \frac{1 \cdot Ps_{bs}}{rn\_cycle} \cdot \frac{G_{bs}}{\lambda_{local\_bs}},$$

respectively. Eventually, the hop-by-hop throughput of MCN is obtained as

$$S_h = \sum_{i \in cell} S_i + S_{bs}. \tag{6}$$

The end-to-end throughput can be written as

$$S_e = S_h \cdot F,$$

where F is given by

$$F = \frac{A + B}{A \cdot avg\_hc\_ij(k_p) + (B + C) \cdot avg\_hc\_io(k_p)}, \tag{7}$$

in which A, B and C are $\sum_{i=1}^{N} \sum_{j=1, j\neq i}^{N} \lambda_{ij}$, $\sum_{i=1}^{N} \lambda_{oi}$ and $\sum_{i=1}^{N} \lambda_{io}$, respectively. This is because each packet from station i to station j in the same cell is, on average, transmitted $avg\_hc\_ij(k_p)$ times and each packet from the base to station i or from station i to the base will be transmitted $avg\_hc\_io(k_p)$ times in MCN. However, only λ_{ij} and λ_{oi} are going toward those end destinations in the same cell.

For the end-to-end throughput of MCN-b, the equations can be obtained by substituting k_p by 1 and R by $k_b \cdot R$ because, in MCN-b, the transmission range remains the same as the one in SCN. However, the distance between bases is multiplied by k_b.

IV. Numerical Results

Analysis and simulation results for system throughput of SCN and MCN are presented as follows. For simulation results, the SCN and MCN environments are simulated by PARSEC [19], a C based discrete-event simulation language developed at UCLA. The values of r, l_{PKT}, l_{ACK}, l_{RTS}, l_{CTS} are obtained by using the following parameter values: the data rate is $1.5Mbps$, propagation velocity of signals is $3*10^8 m/s$, and the length of data, acknowledgment, RTS and CTS packets are 1024, 14, 20 and 14 bytes, respectively. However, the value of propagation delay, r, is much smaller than the others and, therefore, is neglected in simulations. The other parameter values are as follows: the radius of a cell, R, is 150 meters, the number of mobile stations, N, is 250, $l_{DIFS} = 0.149$ ms, and $l_{SIFS} = 0.042$ ms. The total traffic rate in a cell is 167 packets per second, which is about $1.5Mbps$ while considering DIFS, SIFS, RTS and CTS packets, and we normalize this traffic rate, G, to 1, which is the default value.

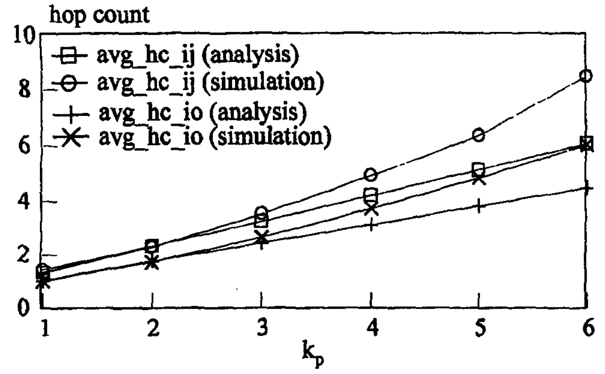


Fig. 12. Mean hop count for internal and external traffic in MCN.

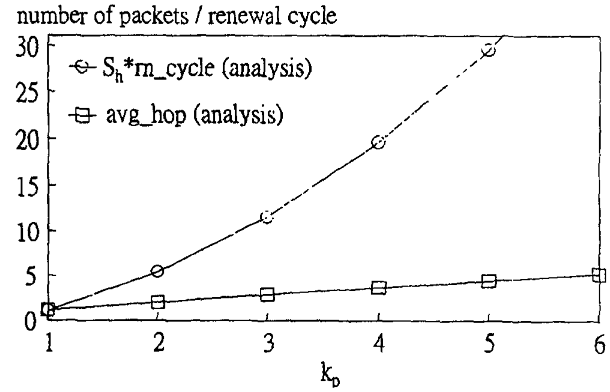


Fig. 13. Mean number of channels vs mean hop count.

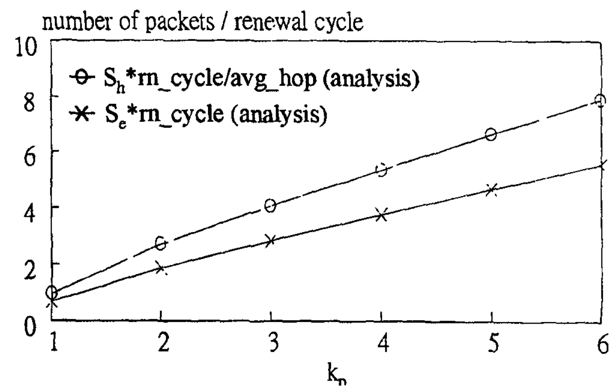


Fig. 14. End-to-end throughput vs ratio of mean number of channels to mean hop count.

Traffic *locality*, $\sum_{i=1}^{N}\sum_{j\neq i,j=1}^{N}\cdot\lambda_{ij}/\sum_{i=1}^{N}\lambda_i$, is defined to compare the end-to-end throughput of SCN and MCN, indicating that the percentage of packets generated by any station i, where $1 \leq i \leq N$, is destined for stations in the same cell. According to the values of the above parameters, we choose $\lambda_{ij} = 0.0008955$, $\lambda_{io} = 0.223$ and $\lambda_{oi} = 0.223$ so that $locality = 0.5$, and the default value of *locality* is 0.5. In simulations, the routing table is pre-computed using the all-pairs shortest path algorithm, Floyd-Warshall algorithm [20].

A. Mean hop count vs mean number of channels in MCN

Two important factors, mean hop count and mean number of channels, are presented first, which significantly affect the throughput of MCN. Fig. 12 shows the results of mean hop count for internal traffic, i.e. $avg\_hc\_ij(k_p)$, and for external traffic, i.e. $avg\_hc\_io(k_p)$, in MCN. The curve for external traffic is lower than the curve for internal traffic because the maximum hop count from station i to the base is $R/(R/k_p) = k_p$ and the maximum hop count from station i to station j is $2R/(R/k_p) = 2k_p$. For both cases, the hop count increases almost *linearly* as the transmission range decreases. When $k_p = 1$, the value of $avg\_hc\_io(k_p)$ equals 1 because each station i can reach the base in a single hop. However, the value of $avg\_hc\_ij(k_p)$ is in the interval between 1 and 2 because the hop count may be either 1 or 2 when station i wants to send a packet to station j in the same cell. Simulation results show higher values than those of analysis results owing to the assumption when analyzing mean hop count, i.e. station i can always find the next hop, at a distance of R/k_p, in the straight-line direction towards the destination. The simulation model removes this assumption to reflect the real situation and examine its influence.

Fig. 13 shows the mean number of channels, $S_h \cdot rn\_cycle$, i.e. the mean number of packets that can be simultaneously transmitted per renewal cycle within a cell of MCN, and the mean hop count of a packet which is computed as $(locality) \cdot avg\_hc\_ij(k_p) + (1-locality)\cdot avg\_hc\_io(k_p)$. Fig. 14 shows the number of simultaneously received packets at destinations per renewal cycle, i.e. $S_e \cdot rn\_cycle$, and the ratio of mean number of channels to mean hop count. The former curve is lower than the latter one because of the lack of the term, C, in numerator in equation (7). As k_p increases, Fig. 13 reveals that the number of channels increases much more rapidly at the order close to k_p^2 than the mean hop count, which increases at the order close to k_p. This result can be explained by closely examining equations (2), (3), (5), and (6). The order of mean hop count, i.e. $[(locality)\cdot\sum_{n=1}^{k_p}((2n-1)/k_p^2)\cdot\sum_{hc=1}^{k_p+n} hc \cdot P(hop\,count = hc)]+[(1-locality)\cdot((k_p+1)(4k_p-1)/6k_p)]$ from equations (2) and (3), is close to k_p. However, the order of mean number of channels, i.e. $(5)\cdot(6) = k_p^2\cdot[Ps_i\cdot G_s/(G_s+G_{bs}) + Ps_{bs}\cdot G_{bs}/(G_s + k_p^2 G_{bs})]$ from equations (5) and (6), is close to k_p^2 because G_s is usually much larger than G_{bs}.

B. SCN vs MCN

Of particular interest is the difference of the throughput between SCN and MCN. In SCN, each packet is transmitted exactly twice, one for upstream and another for downstream, if the destination is in the same cell. However, such a packet is transmitted either once or twice in MCN when $k_p = 1$. When traffic locality is 0, i.e. all packets are sent to the base, the

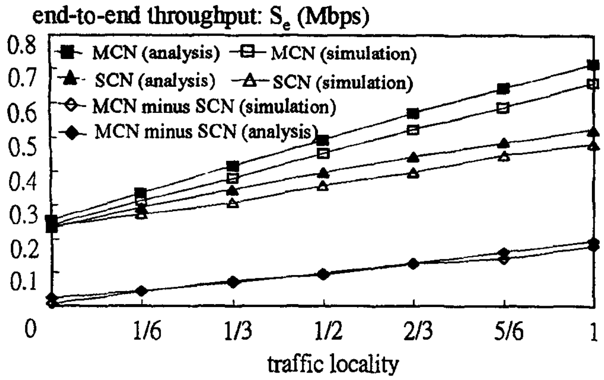


Fig. 15. Impact of traffic locality on throughput for $k_p = 1$ and $G = 1$.

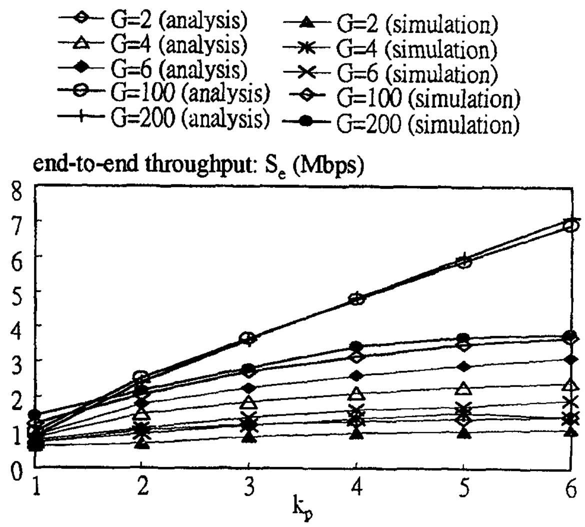


Fig. 16. End-to-end throughput under various offered loads in MCN.

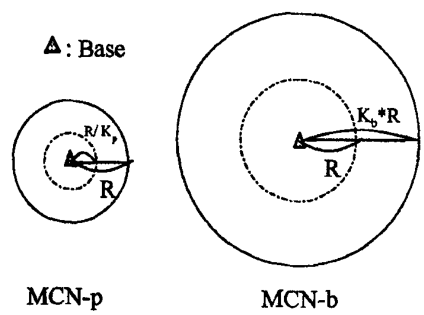


Fig. 17. MCN-p and MCN-b for $k_p = k_b = 2$.

mean hop count in MCN and SCN are both exactly 1, i.e. no difference between MCN and SCN. However, if traffic locality is 1, i.e. the destination is within the cell, the mean hop count in MCN is smaller than the one in SCN as shown in Fig. 12. Hence, the end-to-end throughput is higher in MCN than in SCN. Thus, we predict that a higher ***locality*** would increase the difference between MCN and SCN. Both "MCN minus SCN" curves of analysis and simulation results in Fig. 15 confirm our prediction. For the lack of the term, C, in numerator in equation (7), higher ***locality*** will increase throughput of both MCN and SCN. However, the end-to-end throughput of simulation results are lower than those of analysis results is caused by the higher value of mean hop count, as shown in Fig. 15.

The curves in Fig. 16 are ascending because the mean number of channels increases much more rapidly than the mean hop count. Figs. 15 and 16 confirm that MCN has a superior throughput than that of SCN. Analysis results in Fig. 16 indicate that the upper bound of end-to-end throughput of MCN is reached when G is over 100.

C. MCN-p vs MCN-b

After comparing SCN and MCN, MCN-p and MCN-b are compared as follows. In Fig. 17, the dashed circles denote sub-cells, i.e. the transmission ranges of bases, and the solid circles denote cells. Notably, the base of a cell is the closest base for any stations within the cell. Assume that the following two conditions hold:

1. $k_p = k_b$ and the number of stations are the same, i.e. N, and uniformly distributed within the solid circles of MCN-p and MCN-b, respectively.
2. The values of λ_{ij}, λ_{io}, and λ_{oi} are the same in both MCN-p and MCN-b.

We believe that the end-to-end throughputs of MCN-p and MCN-b are the same, except for the slight difference due to the different propagation delays. In Fig. 18, the two coincided curves, "MCN-p" and "MCN-b (un-normalized)", confirm above statement. However, the parameters used in MCN-b should be normalized to compare the throughput of MCN-p and MCN-b, i.e. under the same station density and traffic load within a unit area. Consequently, to compute the throughput of normalized MCN-b, N is multiplied by k_b^2, and the final result of throughput should also be divided by k_b^2.

The probability of successful transmission rapidly decreases in MCN-b because the transmission range is k_p times of that in MCN-p, i.e. the number of stations in a sub-cell is k_p^2 times of that in MCN-p. Above observations account for why the curve of "MCN-b (normalized)" in Fig. 18 descends so quickly, implying that, given the densities of bases, i.e. R, stations, i.e. N, and traffic, i.e. λ, our formulas help determine the transmission range for the desired throughput level.

V. Conclusion

This work presents a new architecture, Multihop Cellular Network (MCN), and derives the throughput of MCN and its counterpart, Single-hop Cellular Network (SCN), based on the RTS/CTS access method. The throughput is analyzed by mod-

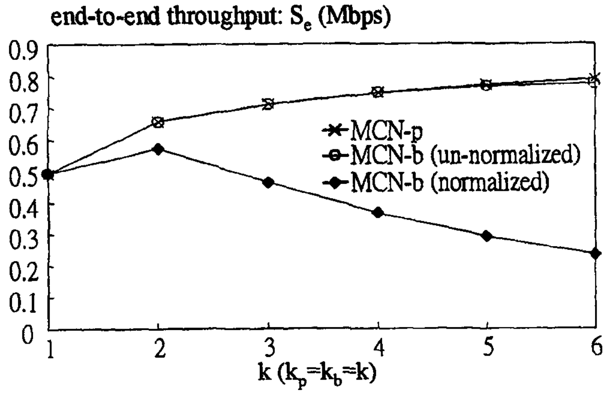


Fig. 18. The difference between MCN-p and MCN-b.

eling the packet departure process as a renewal process, in which the renewal point is defined as the time point when all stations in a sub-cell simultaneously sense that the channel is idle. Furthermore, *mean hop count* is analyzed because it significantly influences the throughput of MCN, as confirmed by the numerical results.

Analysis and simulation results for the throughput of SCN and MCN lead to three important observations. First, the throughput of MCN is superior to that of the corresponding SCN. Second, the throughput of MCN increases as the transmission range decreases. We explain these two observations by illustrating the different increasing orders, k^2 and k respectively, of mean number of channels, i.e. simultaneous transmissions in a cell, and mean hop count, as the transmission range decreases by k times. Third, given the densities of bases, i.e. R, stations, i.e. N, and traffic, i.e. λ, our formulas help determine the transmission range for the desired throughput level. When the transmission range and distance between bases in MCN-b are k_p times of those in MCN-p, the number of stations in a sub-cell becomes k_p^2 times of that in MCN-p and throughput hence descends quickly.

Although MCN shows a higher throughput than SCN, some related issues must be further studied. The first thing is how to obtain an appropriate operational value of k while considering both throughput performance which favors large k and path vulnerability which favors small k. Furthermore, the mobility of stations cannot be neglected in the environment with high mobility. Thus, future research should develop an efficient routing algorithm and more closely examine the issues of handoff and mobility management in the MCN environment.

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