On the Use of Multiple Hops in Next Generation Wireless Network Architectures

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Abstract

Multi-hop cellular architectures are being explored for use in future fourth generation (4G) cellular networks [1]. This paper is a step towards identifying desirable features of such multi-hop architectures. Towards this end, we compare two network architectures which have been proposed to improve the throughput of packet data cellular networks viz. the hybrid wireless network architecture proposed in [2] and the multi-hop cellular network architecture proposed in [3] and [4]. We extend the hybrid wireless architecture (proposed only for operation over a single cell in [2]) to multiple cells. We present an analysis of the MCN architecture to gain additional insights into its operation. We also present simulations to highlight the strengths and weaknesses of the two architectures. Based on these simulations, we suggest modifications to improve the performance of both architectures. We identify issues relating in general to the inclusion of Ad-hoc features (multiple hops) into cellular architectures.

Keywords: multihop cellular, hybrid architecture, next generation wireless networks, wireless data services, performance analysis, analytical modeling.

1 Introduction

Wireless access is widely believed to be the next step in the evolution of telecommunications. Attempts to provide wireless access have faced many challenges including restricted bandwidth, mobility, and security. Of these limitations, the first is fast becoming the bottleneck in satisfying the demand for access. Besides, the wide use of bandwidth intensive applications such as video conferencing etc. have further worsened the pressure on bandwidth. One of the products of this research has been the Cellular Network Architecture, probably the most popular wide-area mobile communication architecture today. This architecture led to the Advanced Mobile Telephone Systems (AMPS) [5], considered part of the first generation voice-oriented wireless networks. The second generation (2G) networks include Global System for Mobile Communications (GSM) [6]. Wireless data network also began gaining popularity e.g., Cellular Digital Packet Data (CDPD) [7], General Packet Radio Service (GPRS) [8]. Third generation systems (3G) systems is the generic name for a set of mobile technologies collectively known as IMT-2000 (International Mobile Communications). 3G systems is a single family of compatible standards that provide high speed radio-access, high spectrum efficiency, and packet based services in wireless networks. These include the Universal Mobile Telephony System (UMTS) based on Wideband Code Division Multiple Access (W-CDMA) and other variants based on CDMA2000. Future Fourth Generation (4G) systems [1] are expected

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to support increasing data services, multimedia traffic, efficient resource utilization and provide greater bandwidth.

Most of the present-day architectures for supporting data services over wireless networks are based on an extension of the cellular model. Today's packet data cellular networks can be classified as Single hop cellular networks (SCN). In this architecture, the nodes can reach the base by a single hop. This architecture cannot satisfy the flexible and increasing demands of packet based networks. In this context, there is a palpable need for throughput enhancement schemes which has inspired two different architectures: the hybrid wireless network architecture proposed by Hsieh and Sivakumar in [2] and the multi-hop cellular architecture (henceforth referred to as MCN) proposed by Lin and Hsu in [3], which was further extended by Padmanabha et al in [4]. This paper extends the hybrid wireless network architecture (which was initially proposed for a single cell) to multiple cells and compares the two architectures using extensive simulations analyzing throughput, power consumption, and mobility behavior.

The reason that these two architectures have been chosen for comparison is that they attempt to improve the throughput by infusing some character of Ad-hoc networks (for a brief introduction, refer to [9]) into the existing single hop architecture. Ad-hoc networks are a set of self-organized nodes communicating without the aid of any wired backbone. Their most attractive feature is their lack of need of any prior configuration, hence the name "Ad-hoc". Research in Ad-hoc networks has thoroughly explored the design space of unicast and multicast routing algorithms. Both the above architectures, the hybrid and MCN, propose to incorporate lessons learnt from Ad-hoc networks into the single hop cellular architecture. The hybrid wireless network architecture does so by using the two architectures at different times. The multi-hop cellular architecture mimics the Ad-hoc protocol by relying on multiple wireless hops. In this work, we evaluate through simulations these two architectures, on the basis of which, we suggest enhancements to these architectures.

The contributions of this paper are: extension of the hybrid wireless network architecture to multiple cells, analysis of MCN, comparison of the MCN and hybrid architectures, enhancements to both architectures. Based on this comparison, this paper helps in identifying desirable features of multi-hop cellular networks that can be used in future 4G systems.

The organization of the rest of our work is as follows: Section 2 describes the context of this work, Section 3 makes a case for multi-hop networks, Section 4 gives a short description of the hybrid wireless architecture and the basic design philosophy behind it, Section 5 describes our extensions to the hybrid network architecture for operation over multiple cells, Section 6 introduces the MCN architecture, Section 7 qualitatively compares the two architectures, Section 8 presents an analytical model of the MCN architecture, Section 9 presents simulations that corroborate the comparison in Section 7 and the analysis in Section 8, Section 10 suggests enhancements to both architectures, and Section 11 summarizes the insights gained into the problem of increasing throughput of cellular networks.

2 Context of this Work

In this section, we describe the scenario in which this work is applicable. Currently, the Single-hop Cellular Network (SCN) architecture is extensively used in the 2G and 3G networks. In these cellular networks, the base station (also referred to as base in this work) can be reached through a single hop. In this architecture, the entire service area of the operator (the service provider) is divided into cells and one base station placed per cell. Nodes send packets to the base to which they are currently registered, which are then relayed to the destination node either directly (if the destination is in the same cell) or through the base station of the destination (if the destination is in a different cell). Though numerous variations have been proposed on this architecture, this model continues to be the basis of most systems today. This is the basic model for data-oriented cellular networks we have used in this work.

In the simulations,we have experimented with both User Datagram Protocol (UDP) and Transport Control Protocol (TCP) traffic. In this context, we define *locality* to be the fraction of packets whose destination lies in the same cell as the source. Thus, higher the value of locality, higher the proportion of intra-cell traffic as compared to inter-cell traffic.

3 Why multiple hops in cellular networks?

We make a case for the use of multiple hops in cellular networks in this section. The SCN architecture has been extended with a variety of techniques, including Code Division Multiple Access (CDMA) [10], directional antennas, overlay networks, picocells etc., to provide higher throughput (for a detailed discussion, refer to [11]). Most of these techniques operate at the physical or Medium Access Control (MAC) layer (CDMA and directional antennas, for example) and hence, are applicable in the multi-hop architectures like MCN, hybrid wireless architecture as well. Overlay networks, based on the SCN architecture, have also been studied (in [12], for instance): again the idea of multiple tiers of base stations can be implemented in these extended architectures. Picocells requires additional base stations in order to support the smaller transmission radius and hence the network operator incurs greater infrastructure cost.

It is in this context, that one can appreciate the need for multi-hop cellular architectures. Such architectures can support greater throughput without requiring additional infrastructure (as has been illustrated through simulations in [2] and [4]). In our work, we evaluate the MCN and the hybrid architectures and based on that, we make suggestions on how the multi-hop characteristic of Ad-hoc networks can be infused into future cellular networks.

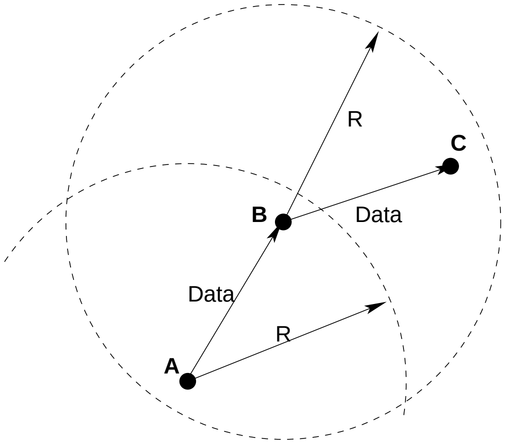

Figure 1: Hybrid Architecture in cellular mode

4 The Hybrid Wireless Network Architecture

The hybrid network architecture, a multi-hop cellular architecture, has been proposed in [2]. This architecture has been proposed only for operation in a single cell. This architecture also requires the Global Positioning System (GPS): nodes need to know their exact geographical location. They discuss two possible modes of operation in cellular networks: the Cellular mode and the Ad-hoc mode. In the Cellular mode, nodes send packets to the base which forwards them to the destination (similar to SCN). Figure 1 shows the the operation of the hybrid architecture in the cellular mode. In this mode, the node sends its packets to its base B, which forwards it to the destination C. The transmission range of every node is R (the cell radius).

In the Ad-hoc mode, nodes use Dynamic Source Routing protocol (DSR) [13] is used to discover routes — they flood *Route Request* packets, to which the receiver sends a *Route Reply* packet. The operation of the Ad-hoc mode is shown in Figure 2. The transmission range of the nodes is r, where r is chosen such that all the nodes can reach one another (no partitions will therefore occur). In this mode, the node A uses the DSR protocol to discover routes to the destination D: it floods *Route Request* packets which

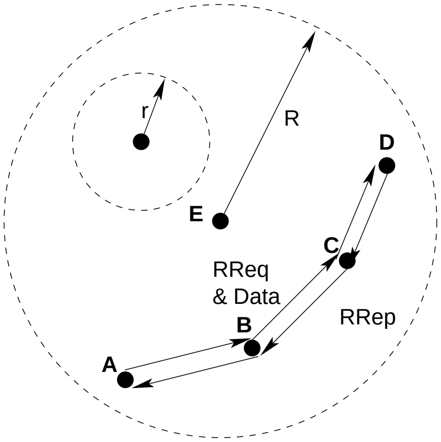

Figure 2: Hybrid Architecture in Ad-hoc mode

reach the destination D after being relayed by B and C. D now sends a *Route Reply* packet which reaches the node A, which then begins to send packets along the newly discovered route. Here, the path from A to D does not involve the base at all. Neither is the base (E in this example) necessary for finding the route.

The authors contend that the two modes, Ad-hoc and Cellular, perform well for different kinds of topologies: Ad-hoc mode works well for dense topologies and the Cellular mode is better suited to sparse topologies. The authors of [2], propose using these different modes at different times. An algorithm operates at the base which uses the network topology (GPS provided location information is sent by the nodes to the base periodically) to decide which mode the cell should operate in, so as to maximize the throughput. This decision is broadcast to all nodes. In the Ad-hoc mode, partitions are avoided by having the base periodically check the topology and broadcasting the minimum power required to keep the network connected. The authors have demonstrated that this hybrid architecture performs better than the current generation packet data networks based on the SCN architecture. Apart from throughput, battery power consumed and fairness have also been strongly emphasized in [2]. Fairness is ensured by the use of the IEEE 802.11 Point Coordination Function (PCF) in cellular mode and, the authors have suggested the use of a Medium Access Control (MAC) protocol (refer to [14]) that guarantees fair access to the common medium in Ad-hoc mode.

The switching algorithm at the base operates as follows: If the base is in cellular mode, then the base estimates the throughput if the base had been in Ad-hoc mode by simulating a packet scheduling algorithm proposed in [15]. This throughput is compared with the actual throughput achieved in the cellular mode to decide which mode to operate in. In the Ad-hoc mode, the base compares the throughput achieved in Ad-hoc mode with $B/2n$ to find out which mode the topology is best suited to (n is the number of nodes in the cell and B is the available bandwidth per cell). For additional details, refer to [2].

5 Extensions to the Hybrid Architecture

The hybrid wireless network architecture as proposed and analyzed in [2] is restricted in operation to a single cell. We extend the basic architecture to support multiple cells and subsequently compare it with the MCN architecture.

In this extension, we allow different cells to operate in different modes viz. cellular, Ad-hoc independently with different transmission powers. The alternate choice of operating all cells in the same mode does not give the flexibility independent switching allows. Allowing each cell to choose its mode of operation, based on the topology conditions in that cell, gives more flexibility: congested cells could operate at lower transmission powers, while sparsely populated cells can use higher transmission powers.

However, independent switching of different cells means that adjacent cells may have different transmission powers. This makes necessary the division of the channel (as in conventional cellular networks) to ensure the correct operation of the IEEE 802.11 Medium Access Protocol (MAC) protocol. The IEEE 802.11 MAC protocol does not support variable power ranges.

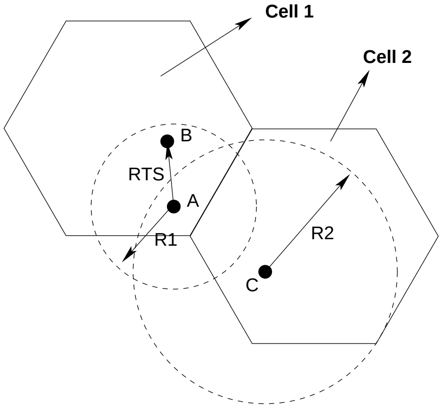

Figure 3: IEEE 802.11 does not support variable power

The RTS-CTS (Request To Send-Clear To Send) mechanism does not work because the RTS/CTS might not reach nodes whose transmissions could interfere with the ongoing transmission because of their higher transmission range. For example, in Figure 3, Cell 1 and Cell 2 both operate in Ad-hoc mode. Cell 1 uses a lower transmission range $R1$, while Cell 2 operates at a higher transmission range $R2$. When node A wishes to send a packet to B, it broadcasts its RTS on the channel. However, its RTS does not reach node C. However, even though A cannot reach C, C's transmissions can interfere at A. Thus, C can cause collisions because it did not hear the RTS. Thus, IEEE 802.11 does not support multiple transmission powers on the same channel.

Thus, the transmissions in one cell should not affect neighboring cells which might be using different powers. Hence, the mechanism of clustering becomes essential. By clustering, we refer to the division of the data channel across a set of cells called a cluster (wherein cells in the same cluster cannot use the same channel, but cells in two different clusters can). We have used the minimum possible cluster size of 3 to maximize the channel bandwidth available per cell. The switching algorithm has also been slightly modified for multiple cells. The estimated throughput in cellular mode, which is compared against the Ad-hoc throughput, is B/n because each packet is transmitted only once in the cell.

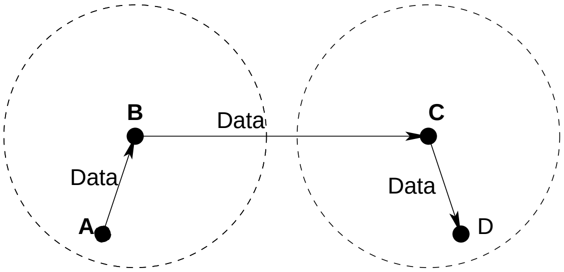

Figure 4: Both source's and destination's cell in Cellular mode

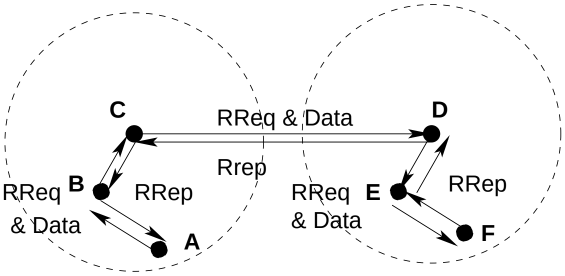

Figure 5: Both source's and destination's cell in Ad-hoc mode

Allowing different cells to operate in different modes leads to the question of how the two different modes, cellular and Ad-hoc, co-operate in order to route packets between nodes in different modes. There are two base stations involved when a source sends packets to a destination: the source's base and destination's base. We explain how these two bases co-operate with each other to facilitate packet transmission. First, we discuss the simpler case when the two cells (corresponding to the bases) operate in the same mode. For convenience, we refer to the routing packets by just the type of packet, for example, a Route Request packet is called a Route Request.

When both cells are operating in the Cellular mode (illustrated in Figure 4), routing is very similar in SCN: nodes send packets to their base station, which forwards them to the destination's base station, which in turn relays them to the destination. In Figure 4, node A sends packets to its base B, which are relayed through the base C, on to destination D.

When both cells are in the Ad-hoc mode, the source floods Route Requests to discover a route to the destination. When one such Route Request reaches the source's base, the base notices that this Route Request is meant for a node in another cell. Since the destination's cell is in Ad-hoc mode (in this case), the base forwards the Route Request over the wired network to the destination's base. From then on, the destination's base floods the Route Request in its cell. The Route Reply sent by the destination node propagates along the path taken by the Route Request (in reverse) and reaches the source. This is illustrated in Figure 5. Both the source (A) and destination (D) are in cells operating in Ad-hoc mode. A's Route Request is forwarded via the path B, C, D, E, and F. D's route reply takes the reverse path and A begins sending data along the path taken by the Route Request.

When the source's cell is in cellular mode and the destination's cell is in Ad-hoc mode, the base station of the cell in Ad-hoc mode takes the responsibility of sending the packets over possibly multiple hops to the node. It uses its route cache to find a path to the destination node, or does a Route Request to discover a path. An example is shown in Figure 6. Here, the node A (in cellular mode) sends packets to node E (in Ad-hoc mode). When the source's (A's) data is forwarded by it's base B to the base C, base C initiates a Route Request (assuming its route cache did not contain a route to E). C's Route Request is forwarded to destination E by D. The Route Reply by E reaches the base C after being relayed by D. The base C now sends the data packets from A over the path D, E. In other words, the destination's base station takes care of discovering the wireless portion of the route (except for the initial hop).

When the source is in Ad-hoc mode and the destination is in cellular mode, the source's base station plays the role of a proxy for the destination, by answering its route replies and also a route error in case it has been handed off. The sources's base station respond to a Route Request (from a node in a cell in Ad hoc mode) with a Route Reply for all nodes in other cells. This Route Request cannot be simply propagated along, because in cellular mode, Route Requests are not answered by the nodes. Consider the example in Figure 7. Here, node A (in Ad-hoc mode) sends packets to E (in cellular mode). Node A floods Route-Requests, one of which reaches its base C after being relayed through B. C realizes that E is in a cell operating in cellular mode, and so sends back a Route Reply to A. A begins to send data through B to reach C, which forwards it to base D, and then on to destination E. This information has been summarized in Table 1.

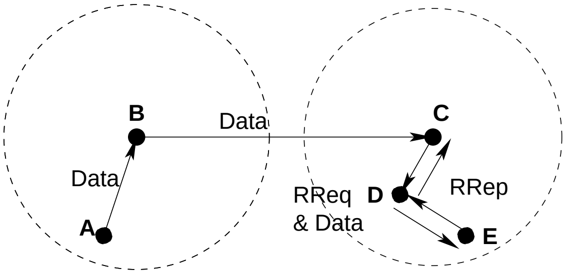

Figure 6: Source's cell in Cellular mode and Destinations' cell in Ad-hoc mode

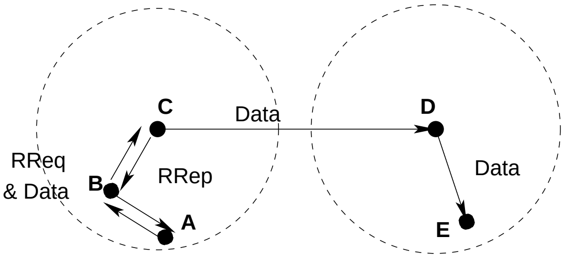

Figure 7: Source's cell in Ad-hoc mode and Destinations' cell in Cellular mode

The two kinds of routing protocols also need to cooperate in detecting route errors. This has been done via the following mechanisms. When the two cells are in the cellular mode (for example, in Figure 4), the source keeps sending to its base as before. The base forwards it to the des-

Table 1: Route discovery over multiple cells

From	To Ad-hoc
Ad-hoc	Source sends RREQ
Cellular	Destination's base does RREQ

From	To Cellular
Ad-hoc	Source's base sends RREP
Cellular	Base does routing

Table 2: Route repair over multiple cells

From	To Ad-hoc
Ad-hoc	Node detecting break sends RERR
Cellular	Destination's base handles rerouting

From	To Cellular
Ad-hoc	Destination's base sends RERR
Cellular	Base does routing

tination's base station. It is the responsibility of the source's base (B in this case) to reroute the packets as necessary. When the two cells are in Ad-hoc mode (for example, in Figure 5), a Route Error is generated by the node detecting the link break and a fresh Route Request is made by the source.

When the source's cell is in cellular mode and a destination's cell is in the Ad-hoc mode (for example, in Figure 6), the source's base station is responsible for discovering new routes in case a Route Error message invalidates the current route. Thus, link breaks from the destination's cell to the destination will be taken care of, by the source's base which plays a proxy for the source.

When the source's cell is in Ad-hoc mode and a destination's cell is in the cellular mode (for example, in Figure 7), any link breaks between the source and its base station will be taken care of by the DSR protocol itself. When the destination gets handed off to a different cell, the source's base station initiates a Route Error message back to the source. This ensures a fresh Route Request by the source to discover the new path. Here, the source's base plays a proxy for the destination. In all the above cases, the source's base helps in the inter-operation between the two modes. Table 2 summarizes this information:

6 MCN Architecture

We discuss the MCN architecture and its routing protocol in this section. The desirable effect of decreasing transmission power on the throughput in cellular networks was illustrated by analysis and simulations by Lin and Hsu [3]. This stimulated the development of a unicast routing protocol and other enhancements for such an architecture in [4]. We discuss the original proposal and move on to the modifications in [4].

Lin and Hsu have suggested that the transmission power of the mobile nodes and the base be reduced to a fraction $1/k$ of the cell radius. This means that more than one node (in fact up to a maximum of k^2) can transmit simultaneously. The node density is fairly high in typical cellular networks, which guarantees that the chances of a network partition within the cell are fairly small. Their analysis proves that the average hop count increases linearly with k and that the number of channels increases as k^2. Hence the throughput is expected to increase linearly with k. Their analysis assumes however that the straight line path between the source and destination will be available, and moreover that the routing protocol is capable of discovering it. Hence, the actual gain will be probably lower because of the overhead of the routing protocol and the possibility of absence of relaying nodes along the straight line path.

A unicast routing protocol and extensions to the above architecture were suggested in [4]. All the cells share a single data and control channel (unlike in [3] where the bandwidth is divided over clusters as in voice networks). While the transmission range on the data channel is kept at half of the cell radius, the transmission range on the control channel is the cell radius. The

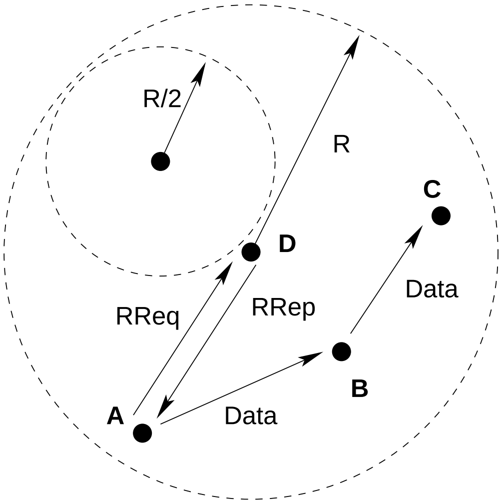

Figure 8: Data Transmission & Routing Protocol in MCN

value of 2 for the parameter k in [3] was arrived at as a compromise between increasing the spatial reuse [1] and keeping the number of wireless hops to a minimum. The routing protocol operates exclusively over the control channel. The control channel is used for delivering topology information to the base by the nodes, which recognize their neighbors by a contention-free beacon protocol. The nodes send their neighbor tables (containing the addresses of their neighbors) to the base.

The routing protocol is as follows: When a node needs to send a packet to a destination node, it transmits a *Route Request* packet containing the address of that destination, to its base over the control channel. The base uses its topology information to compute a path between the source and the destination. This route is sent back to the source using a *Route Reply* packet over the control channel. The source then embeds the source route in its data packets and begins transmission to the destination. A route cache is used to store recently obtained routes and a node makes a fresh Route Request only if it cannot find a route to the destination in its cache. The route cache is also updated with new routes when the node forwards packets (which contain the source route to the destination). All data packets are source routed, so that intermediate nodes know which nodes to forward this packet to. Figure 8 illustrates the routing protocol and the data packet transmission. When node A wishes to send packets to D, it sends a *Route Request* packet to the base D which responds with a *Route Reply* packet containing the route A, B, C. A begins to sends packets to C along this route using source

We discuss the route computation at the base: The base uses Dijkstra's shortest path algorithm on the connectivity graph that can be built using the neigbour tables sent by the nodes. The weight of the edge between two nodes has been assigned to be the number of the nodes in the capture area of these two nodes. This serves as a measure of how many nodes are likely to be affected by the transmission.

When a node is unable to reach the next hop (specified in the source route embedded in the packet), it sends a *Route Request* packet to the base and buffers the packet. The base responds with a *Route Reply* packet to the node which detected the path break, containing a new route from that node to the destination. The node, which sent the Route Error, immediately sends the buffered packets with a source route containing this newly obtained route to the destination. The base also sends a *Route Correct* packet to the source which originated the packet, containing a new route to the destination, so that subsequent packets contain the correct source route. Hereafter, we refer to the routing packets by just the type of packet, for example, a Route Request packet is called a Route Request.

This route maintenance is illustrated in Figure 9. Node B sends packets to D using a relay C. When the link C to D breaks, C buffers the packets from B and sends a Route Error to the base E, which sends a Route Reply to C and a Route Correct to B. C now sends the buffered packets using the newly obtained route to D, and B also sends packets to D with its newly obtained route to D (which need not include C).

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[1] In the packet based context, this means the number of simultaneous transmissions over the same channel.

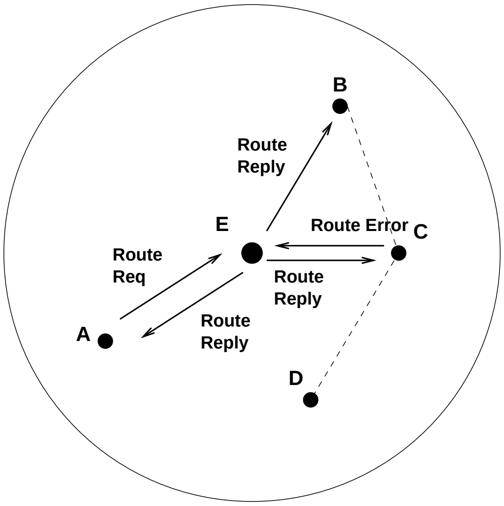

Figure 9: Route Maintenance in MCN

7 A Qualitative Comparison of the Hybrid and MCN Architectures

This section compares the two architectures qualitatively and discusses their relative merits and demerits. The hybrid wireless network architectures tries to estimate the throughput in the two modes (Cellular and Ad-hoc) and appropriately switches. It can handle a variable number of nodes and topology conditions gracefully by either operating in the Cellular mode or in Ad-hoc mode (by adjusting the power appropriately). Battery power consumed is kept at a minimum.

The demerit of the hybrid architecture lies in the fact that the usage of the minimum power required to maintain connectivity can lead to poor performance under mobility. Besides, during the switching period from cellular to Ad-hoc mode, all the routes in the DSR route cache would have probably timed out, which means that all packets will be delayed by a costly route discovery process. This can lead to a glitch in ongoing sessions.

The MCN architecture scores over conventional systems by the fact that the allocation of a dedicated control channel with greater power shifts the load of route computation onto the base station, which has up to date information about the network topology. This obviates the need for flooding, which is characteristic of the route discovery phase in Ad-hoc networks. Mobile nodes do not have to carry out intensive computation or utilize network bandwidth for routing purposes. This makes it possible even for "dumb" devices to send packets.

The main pitfall of the MCN architecture is that network partitioning within a cell is not considered, hence it is possible that a node gets cut off from the base (or other nodes). In addition, holes—regions within the cell where no signal from the base station is available due to geographical characteristics—cannot be covered. This means that it is not possible for these nodes to discover routes though they may be available. Spatial fairness suffers heavily due to the inherent contention nature of the IEEE 802.11 DCF (Distributed Coordination Function) protocol and the fact that the nodes closer to the base are heavily loaded as they are being used for relaying to the base.

In a head-to-head evaluation of the MCN architecture Vs. the hybrid architecture, the following facts come to the fore:

- The split-up of the channel in the hybrid architecture over a cluster of 3 cells means that one cell has approximately one-third the bandwidth available for a single cell in the MCN architecture. Raw network bandwidth is extremely important in increasing the throughput by reducing packet transmission times and by increasing the probability of successful transmission. Though the former is the significant factor, the latter begins to dominate at higher loads. Either way, raw network bandwidth is the major factor determining the network throughput. This can be seen in an analysis of the DCF protocol, for example in [16].
- The control channel in the case of the MCN architecture consumes about 20% of the data channel. It is a costly investment to improve overall system throughput. Net-

work partitions are simply ignored by the architecture, so holes are likely to suffer heavily.

- The use of an Ad-hoc routing protocol like DSR in the hybrid architecture without any modification leads to too much routing overhead. Ad-hoc protocols are designed with different design objectives in sight and in cellular systems where node densities are typically high, broadcasting route discovery packets can be a costly operation. The down-side of the fact that the network is always kept connected is that a single route discovery packet will be broadcasted by *all* nodes in the cell.

- Implementing real-time support in the hybrid architecture is likely to be easier since the PCF protocol in cellular mode can be used to provide QoS guarantees. However, the polling overhead in PCF might lead to scalability problems. Switching from Adhoc to cellular mode can be based on realtime requirements in addition to the topology considerations.

- Discovery of routes for nodes in other cells in the hybrid architecture can lead to excessive overhead by broadcasting discovery packets needlessly within the cell. This leads to poor performance for lower values of locality.

Table 3 summarizes the differences in performance between the two architectures.

8 Analytical Modeling of MCN Architecture

We present an analytical model of the MCN architecture to gain additional insights into its operation. The analysis in [3] does not consider non-uniform load within the cell due to the routing hot spots near the base, nor does it take into account the presence of buffers at nodes. The analysis in [4] assumes the fairness of the MAC protocol. However, the 802.11 DCF Protocol is not a fair protocol. We present the following model which does not assume fairness of the MAC protocol or uniform load across the cell. Our model holds for locality=0, in which case *all* packets are sent to other cells. We derive the expressions for any value of k and then substitute $k = 2$ to derive the expressions for the MCN architecture.

Let R be the transmission range of a node over the data channel, thus kR is the transmission range over the control channel (the cell radius). Let N denote the number of nodes in a single cell. We have used the term sub-cell k for the area containing all points within the cell satisfying $(k-1)R < r < kR$ where r is the distance of the point from the base (the region enclosed between the two concentric circles of radius kR, $(k-1)R$).

We divide the nodes into k classes based on the sub-cell they occupy. For instance, the nodes in the capture area of the base are class 1 nodes, the base itself is the only class 0 node. We first calculate N_i, the ratio of nodes in class i to the total number of nodes in the cell (we use the area of the hexagon for calculating the area of the cell):

$$
\begin{aligned}
N_i &= ((\pi i^2 R^2) - (\pi (i-1)^2 R^2))/(1.5\sqrt{3}k^2R^2) \quad (1)\\
&= \pi(2i-1)R^2/(1.5\sqrt{3}k^2R^2) \quad (2)
\end{aligned}
$$

The above equation is valid only for $1 \leq i \leq (k-1)$. We obtain N_k by the following formula:

$$N_k = 1 - (\sum_{i=1}^{i=(k-1)} N_i) \quad (3)$$

Let p_i represent the probability that a packet is successfully transmitted or received by a class i node (this includes those successfully sent or received by re-transmission). The rationale behind assigning equal probabilities to both transmission and reception is that the 802.11 DCF requirs transfer of control packets in both directions for any data transmission. Due to the fact that the nodes closer to the base have to relay packets for other nodes, the load in sub-cell i will

Table 3: Hybrid Architecture Vs. MCN Architecture

Criterion	Factors affecting it	Effect
Throughput	Data channel divided within clusters Vs. No clustering	MCN expected to provide better throughput
Power	Explicit power adjustment Vs. Fixed power	Hybrid keeps power at a minimum
Mobility	Source initiates route discovery Vs. Request to base	High mobility degrades performance of both architectures
Locality	Needless flooding for nodes in other cells Vs. Unicast to base	Hybrid expected to be affected worse by locality
Fairness	Hybrid uses PCF + Fair MAC Vs. DCF based MCN	Spatial fairness better in hybrid architecture
Latency	Flooding based Vs. Unicast route discovery	The latency in hybrid architecture expected to be higher

be greater than in sub-cell j. Hence, the following relation holds:

$$0 \leq p_0 \leq p_1 \leq p_2 \cdots \leq p_k \leq 1 \tag{4}$$

Note that in a transmission from class k to $(k+1)$, the proportion of successful packets is limited by the more heavily loaded class k which has to relay packets for a greater number of cells. Hence, we use p_k for the probability of successful transmission from class $(k+1)$ to class k or from class k to class $(k+1)$. Based on this, we define $p_{i,j}$ to be the probability of successful transmission from sub-cell i to sub-cell j (over multiple hops):

$$\begin{aligned} p_{i,j} &= \textstyle\prod_{l=j}^{l=(i-1)} p_l \qquad if\ i > j \quad (5) \\ &= \textstyle\prod_{l=i}^{l=(j-1)} p_l \qquad if\ i < j \quad (6) \end{aligned}$$

If $i > j$, the transmissions involved are $i \rightarrow (i-1) \rightarrow \cdots (j+1) \rightarrow j$ and thus we get the expression above. If $i < j$, the path of the packet of $i \rightarrow (i+1) \rightarrow \cdots (j-1) \rightarrow j$ and hence, the second expression above. It is obvious, that $p_{i,i+1} = p_{i+1,i} = p_i$ since in both cases, sub-cell i is the limiting factor. Let L_i denote the number of transmissions (not counting re-transmission; each packet from the network layer is included only once) attempted by all class i nodes per second. Let P be the number of packets generated per node per second (to nodes in other cells, since locality=0). We derive expressions for L_i using P, N_i, p_i. The number of transmissions attempted by all class i nodes is:

$$L_i = \sum_{j=(i+1)}^{j=k} L_{i,j} + PN_iN \tag{7}$$

The second term is simply the number of packets generated by all class i nodes (the number of nodes in class i is N_iN). The first term is the relaying load—packets meant for other nodes which are sent through sub-cell i. Here $L_{i,j}$ is the number of packets relayed by class i nodes for class j nodes per second. Class i nodes do relaying for packets originated by class j nodes to other cells and also relay packets from other cells to class j nodes. Thus, we split $L_{i,j}$ into packets whose *source* is class j and packets whose *destination* is class j.

$$L_{i,j} = S_{i,j} + R_{i,j} \tag{8}$$

Here, $S_{i,j}$ represents the packets generated by class j nodes which successfully arrive at a class i node, after relaying by the intermediate classes. A packet generated by a class j nodes goes through class $j-1, j-2, \cdots, i+1, i$ before arriving at class i. We can thus express $S_{i,j}$ as:

$$S_{i,j} = PN_jNp_{j,i} \tag{9}$$

where PN_jN is the total number of packets generated by class j nodes and the next term is the product of the probability of successful transmission by each of the intermediate classes. Similarly, $R_{i,j}$ represents the packets generated from other cells for class j nodes which are relayed through class i. Thus, it can be written in terms of the product of successful transmission by all sub-cells between the base and class i:

$$R_{i,j} = B_jp_{0,i} \tag{10}$$

where we have used B_j as the number of packets sent by the base whose destination is sub-cell j. Note that the number of packets generated by any node is equal to the number of packets destined to that node (assuming uniform packet generation). Hence, we can express B_j as:

$$B_j = PN_jN\sum_{l=1}^{l=k} N_lp_{l,0} \tag{11}$$

where PN_jN is the total number of packets destined to class j and N_l represented the fraction originating in class l. Thus, we can substitute $R_{i,j}$, $S_{i,j}$ from Equations 10 and 9 into (8) to get an expression for $L_{i,j}$. Thus, $L_{i,j}$ can be substituted into (7) to obtain L_i. We also calculate L_0, the number of transmissions attempted by the base:

$$L_0 = \sum_{j=1}^{j=k}(PN_jNp_{j,0}) \tag{12}$$

We then move on to derive expressions for the throughput. Let T_i denote the throughput of *a* class i node. It can be written as:

$$T_i = \sum_{j=1}^{j=k} PN_jp_{i,0}p_{0,j} \tag{13}$$

since the probability of successful transmission from sub-cell i in the source cell to sub-cell j in the destination cell is the product of the corresponding probabilities from sub-cell i to the source base station and from the destination base station to sub-cell j. The system throughput T can be written as:

$$T = \sum_{i=1}^{i=k} N_iT_i \tag{14}$$

where each T_i is weighted by the ratio of nodes in that sub-cell. For the MCN architecture, $k = 2$. We can substitute $k = 2$ in the above expressions. There are 2 sub-cells in this case:

$$N_1 = (\pi R^2)/(6\sqrt{3}R^2) = 0.30 \tag{15}$$

$$N_2 = 1 - N_1 = 0.70 \tag{16}$$

The number of attempted transmissions can be obtained by Equations 7 and 12 as:

$$L_2 = N_2PN \tag{17}$$

$$L_1 = (N_1 + N_2p_1 + N_2N_1p_0^2 + N_2^2p_0^2p_1)PN \tag{18}$$

$$L_0 = (N_1p_0 + N_2p_1p_0)NP \tag{19}$$

The class to class throughputs are derived from $p_{i,j}$:

$$p_{2,0} = p_{0,2} = p_0p_1 \tag{20}$$

$$p_{1,0} = p_{0,1} = p_0 \tag{21}$$

The end-to-end throughput and the system throughput can then be derived by Equations 13 and 14:

$$T_1 = (N_1p_0^2 + N_2p_0^2p_1)P \tag{22}$$

$$T_2 = (N_1p_0^2p_1 + N_2p_0^2p_1^2)P \tag{23}$$

$$T = N_1T_1 + N_2T_2 \tag{24}$$

The above expressions also tell us about the spatial fairness of the MCN protocol: the ratio of throughputs, T_2/T_1 is p_1, a factor which decreases at higher loads. This means that as the load increases, the class 2 nodes get a much poorer throughput as compared to the class 1 nodes.

9 Simulation Results

We have used GlomoSim [17] to simulate the MCN and hybrid architectures. It gives accurate models with precise timing for the radio layer and the 802.11 DCF. We present details of the simulation below. We have used the free space propagation model and no-capture model for the radio layer. For both these architectures, we allow 50 seconds for the nodes to get registered, wait 5 more seconds to allow the network to reach steady state condition (to fill up the route cache etc.) and then collect statistics over 15 seconds. Each data point is obtained by averaging over 10 runs of the simulation with different seeds. The values in Table 4 are used by default in all the simulations, unless different values are explicitly mentioned.

We describe the parameters for the hybrid architecture. In the Ad-hoc mode, we use the IEEE 802.11 DCF and in the cellular mode, IEEE 802.11 PCF with a round robin polling scheme is used. The DSR protocol used in the Ad-hoc mode supports gratuitous RREP, data salvage from path breaks along with promiscuous snooping. The minimum possible cluster size of 3 is used and therefore the data channel per cell is $2Mbps$ (6/3). A service area wide control channel is used for registration requests. The power adjustment algorithm increases the power so that the network remains connected. The MCN parameters follow closely those in [4]. The MAC layer used is IEEE 802.11 DCF and both data channel and control channel have a cluster size of 1. The hybrid architecture parameters are summarized in Table 5, and the MCN parameters in Table 6.

For all the simulations, we present plots for the MCN architecture, for the hybrid architectures and for a scaled version of the hybrid architecture. The scaled version has been marked as "Hybrid-Scaled" in the subsequent plots. The reason behind scaling is that the raw bandwidth per cell available to the hybrid architecture is 0.4 times less than that of the MCN architecture due to the necessity of clustering in the former. Hence, the scaled version represents 2.5 times the actual measured value. This gives an indication on how each of the architectures utilizes network bandwidth. Note that in a realistic situation, when clustering is required for the hybrid architecture, the unscaled plot is the correct picture. We have also plotted the DSR overhead in the hybrid architecture. Note that the number of DSR packets is scaled down by the ratio of the size of data packet to that of the routing packet size.

Table 4: Simulation Parameters

Description	Value
Number of Bases	7
Number of Nodes	200
Number of Nodes/Cell	40
Radius of the Cell	500m
Length of Data Packet	2KB
802.11 DIFS	$50\mu s$
802.11 SIFS	$10\mu s$
Total Bandwidth	$6Mbps$
Locality	0.4
Mobility Model	Random Way-point
Mobility	$8m/s$
UDP Rate	$8pkts/s$

9.1 Validation of Analysis

We present the following simulation results to validate the analytical model discussed in Section 6. These simulations were carried out with 80 nodes distributed over two bases. All nodes were stationary during the simulation. Twenty runs with different seeds were used to determine a single data point. We varied the load from 0.5 to 7.5 packets/sec/node with locality=0.

Table 5: Hybrid Architecture Parameters

Description	Value
MAC Layer	802.11 DCF,PCF
Power-Adjustment	Uniform power
Cluster Size	3
Data Channel per Cell	$2Mbps$
GPS Interval	$1s$
GPS Jitter	$100ms$
Control Channel	$150Kbps$
DSR Route Time-out	$30ms$
DSR Broadcast Jitter	$10ms$

Table 6: MCN Architecture Parameters

Description	Value
Mac Layer	802.11 DCF
Cluster Size	1
Data Channel	$5Mbps$
Control Channel	$1Mbps$
Beacon Interval	$1s$
Beacon Time-out	$2s$
Route-Cache Time-out	$3s$

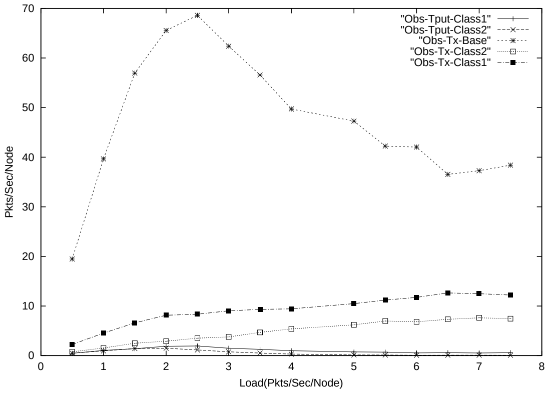

Figure 10: Attempted transmissions and throughput for different classes Vs. Load

Five parameters were measured for each load (corresponding to the parameters derived in the model): The number of attempted transmissions by a class 1 node, class 2 node, base and the throughput of a class 1, class 2 node. These parameters are plotted in Figure 10.

We plot this graph to verify the assumptions made in the model. Note that at every load, the base is the most active contender for the channel followed by the class 1 nodes and then the class 2 nodes. This supports the sub-cell saturation assumption made earlier. Observe also that the number of attempted transmissions by the base and class 1 nodes increases linearly and then starts decreasing. This marks the load at which they become saturated. The load at which the base becomes saturated is lesser than the load at which the class 1 nodes also get saturated. The observed throughput is much lesser than the hop-to-hop throughput, indicated by the attempted number of transmissions. This indicates the poor performance of the 802.11 DCF under high load conditions. Even the hop-to-hop throughput is found to start decreasing at high loads.

We now validate the analysis by comparing the measured parameters against the calculated parameters. There are two quantities p_0 and p_1, that need to be calculated. We substitute the attempted number of transmissions by the base and the throughput of the class 2 nodes measured in the simulation in Equations 19 and 23 in order to calculate p_0 and p_1. We substitute the obtained values of p_0 and p_1 in Equations 24 and 18 and compare the calculated system throughput and the attempted transmissions by class 1 nodes with the simulation values. This comparison is plotted in Figure 11.

The calculated system throughput and the observed throughput are very close to each other. A greater deviation between the attempted number of transmissions by class 1, observed and calculated, is seen. They match very closely at low loads but at higher loads, the difference is mainly because of buffer overflows and consequent packet dropping especially at the base. Note that the base packet dropping increases drastically with increase in the load. The decrease in base dropping after a point is because class 1 nodes also start dropping packets. Be-

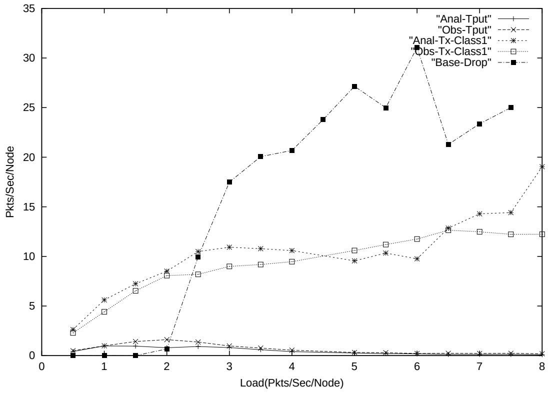

Figure 11: Throughput Vs. Load: Comparison between simulation and analysis

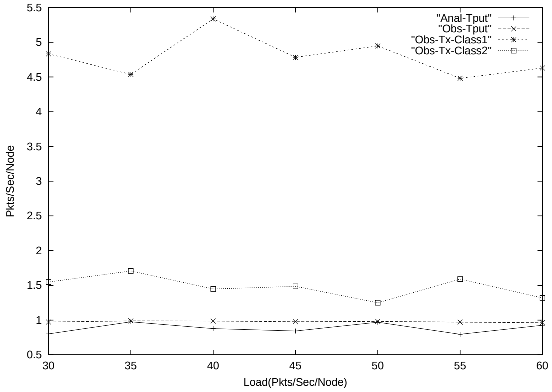

Figure 12: Throughput Vs. Number Of Nodes

cause of this, the attempted number of transmissions does not agree well with the observed value at high load.

We also varied the number of nodes fixing the packet rate at 1 packet/sec/node and plotted the throughput in Figure 12 . It can be seen that once again, the analysis is close to the observed values. In fact, even at high load, the analysis continues to yield accurate values. Along with the experimental value and the calculated value, the observed value of the number of transmission attempts have been plotted. This graph is nearly constant implying that the class 2 nodes have not reached saturation.

Thus the model using the two probabilities p_0 and p_1 is seen to be close to the actual situation. At very high loads, the accuracy of the analysis can be improved by the introduction of class 3 nodes, as in [4]. This is because, some of the class 2 nodes are also used as relays when the straight line path from a class 2 node to the base is not available. Thus even the class 2 nodes can get saturated at very high loads. The analysis proceeds the same way with probabilities p_0, p_1, and p_2.

9.2 Throughput Performance

The end-to-end throughput is the most important parameter in packet based cellular networks. QoS is provided in such environments by implementing a reliable, delay bounded transport protocol on top of these best effort routing protocols. To estimate the throughput of these architectures, we have experimented with UDP and TCP applications.

9.2.1 UDP Throughput

Each node in the simulation generates 2 to 16 packets per second. Each of these packets is directed randomly to nodes in the same cell or outside it, depending on the value of locality. Irrespective of congestion or errors, the packet generation remains constant. Thus UDP applications offer a good picture of the actual load on the network. We first present results with *locality* = 1 where all packets generated are destined to nodes within the same cell in Figure 13.

It can be observed from Figure 13 that at all loads, the MCN architecture performs much better than the hybrid architecture. This is mainly due to the greater bandwidth available to it. Another important reason is the number of wireless hops. In the MCN architecture, it is restricted to an average of four hops with a maximum of six. In a topology as dense as 40 nodes per cell, a degree (number of neighbors per node) of greater than 5 might be sufficient to keep the network connected. Hence the power is dropped drastically in the Ad-hoc mode which increases number of wireless hops as compared to the MCN

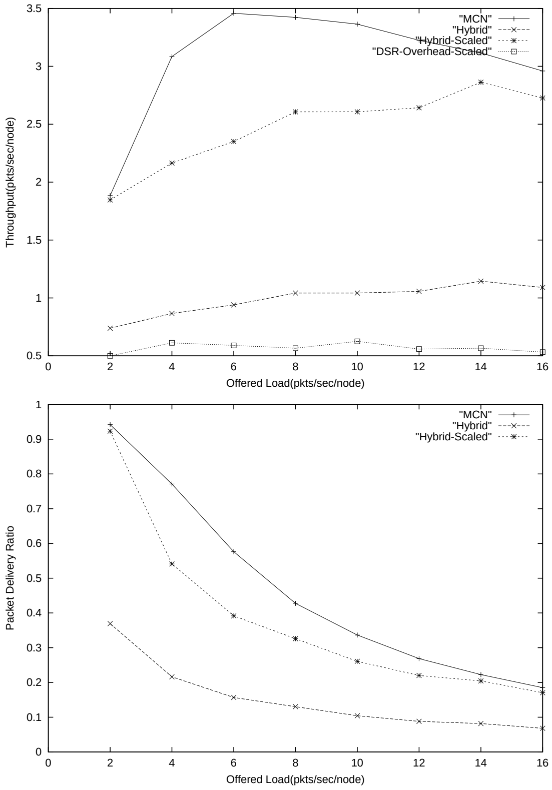

Figure 13: Comparison of the hybrid and MCN architectures (locality=1) under UDP load (i) in terms of end-to-end throughput, (ii) packet delivery ratio

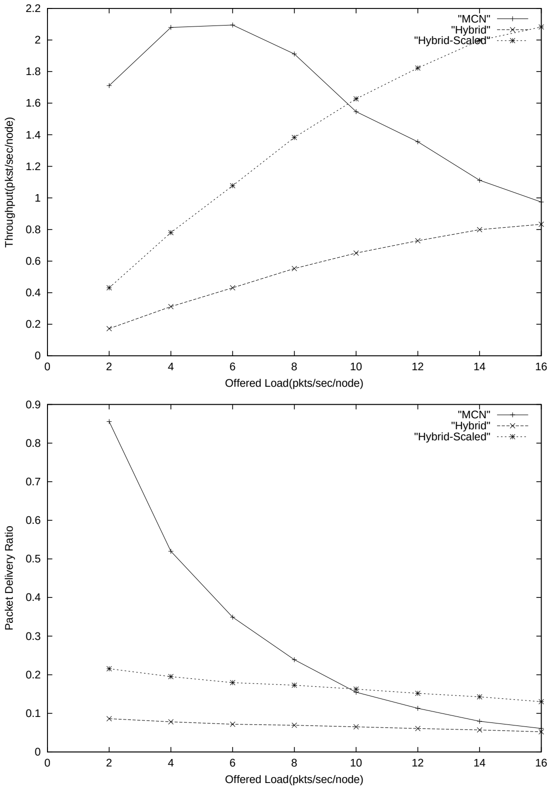

Figure 14: Comparison of the hybrid and MCN architectures (locality=0.4) under UDP load (i) in terms of end-to-end throughput, (ii) packet delivery ratio

architecture. This disadvantage of lesser bandwidth and greater number of wireless hops is seen in almost all the experiments. From the scaled plot of the hybrid architecture, we observe that MCN performs slightly better than the hybrid architecture given the same data channel bandwidth. However, the hybrid architecture scales much better with the load; observe that the throughput of the MCN architecture starts dropping after 6 pkts/sec/node. The hybrid architecture does not seem to saturate and taper down at high load.

The reason that the MCN architecture suffers at high loads is that it uses an unfair MAC layer protocol, IEEE 802.11 DCF [8]. At high loads, despite the fact that the contention is reduced by using a lower transmission range, there are an increasing number of collisions. This aggravates the contention further and the hop-to-hop throughput starts dropping and so does the end-to-end throughput. On the other hand, the hybrid architecture can resort to the PCF based cellular mode where the overhead of polling is well worth the contention traffic in DCF.

Figure 14 for the case of $locality = 0.4$ indicates that the performance of both the architecture drops upon increasing the proportion of packets to nodes in other cells. One of the reasons is the base saturation pointed out in [4], wherein the base along with the nodes in its capture area suffers heavy congestion due to the relaying of large number of packets to other cells to the base. Another reason is the near doubling of wireless hops and hence the end-to-end through-

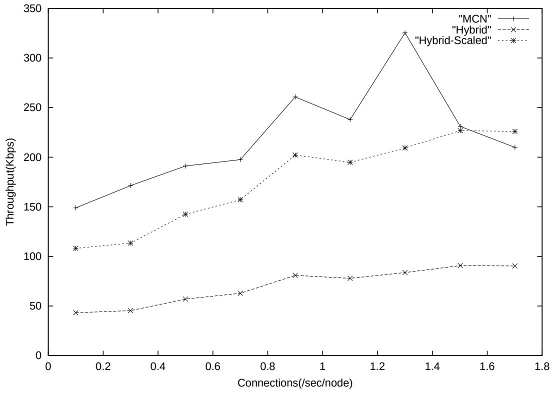

Figure 15: TCP throughput vs. Connection Initiation Rate

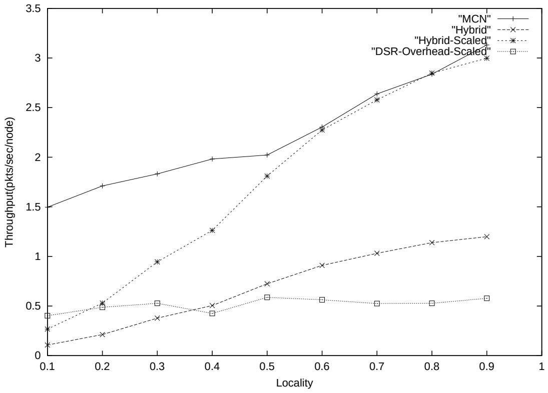

Figure 16: Throughput Vs. Locality

put suffers heavily. The hybrid architecture experiences a heavy drop at low loads but surpasses the MCN architecture at high loads. The broadcast storm of the Route Request packet over the entire cell (about N broadcasts per cell for a single Route Request packet where N is the number of nodes per cell) and the accompanying Route Reply packets drastically lower the throughput of the hybrid architecture. DSR route packets constitute a significant proportion of the end-to-end throughput achieved. Link breakages lead to this flooding again.

9.2.2 TCP Load

We have used FTP sessions to simulate TCP load. The number of connections initiated is varied from once every 10 seconds to 2 sessions per second. TCP load is difficult to interpret compared to UDP applications because of the fact that the actual load offered to the network is not linearly dependent on the connection initiation rate. This is due to the congestion induced backoffs in TCP. Extensive studies on this are available in literature [18].

Still the trends are clearly visible in Figure 15 as in the case of UDP. However there are greater ripples in the plot, suggesting the influence of TCP backoff mechanisms. There is almost a constant difference between the MCN plot and the scaled hybrid plot, corresponding to the DSR routing overhead.

9.3 Locality

Both the architectures under consideration have been simulated in detail in [2, 4] respectively for operation over a single cell. We consider the variations in performance by varying the locality from 0.1 to 0.9. We have used UDP in this experiment.

The drastic drop in performance, as seen in Figure 16, corroborates the trend observed in the UDP plots. This drop in throughput is more severe for the hybrid architecture. The number of path breaks varies exponentially with the number of wireless hops as $P_b = 1 - (1 - P_l)^n$ where P_b is the probability of a path break, P_l is the probability of a link break and n is the number of wireless hops. The increase in the number of wireless hops and the consequent increase in the number of path breaks affects the hybrid architecture more than MCN architecture because of the different responses to a link break. MCN architecture accomplishes route repair by a request to the base while the hybrid architecture has to wait for a Route Error to propagate back to the source and for the source to discover new routes by flooding.

Figure 16 also shows that at high values of locality (above 0.6) the scaled hybrid plot matches very closely the MCN plot despite the overhead

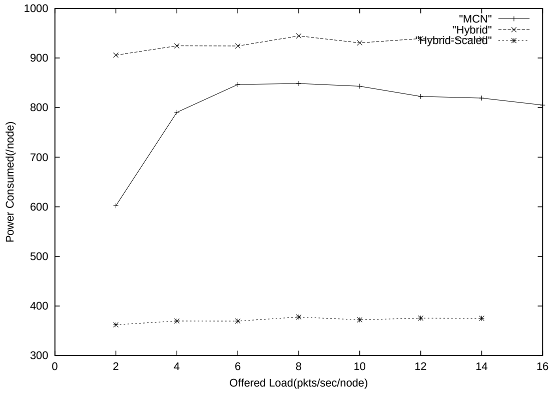

Figure 17: Power Consumed Vs. Load

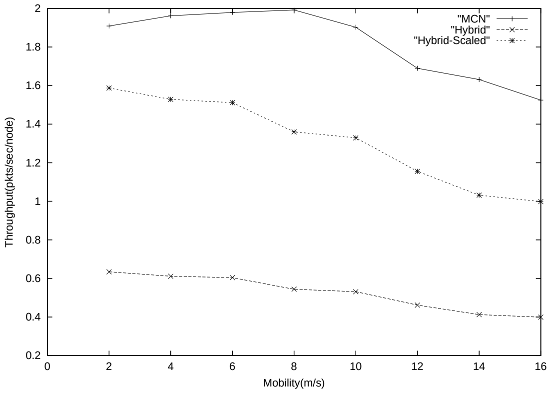

Figure 18: Throughput Vs. Speed

of the DSR routing protocol. This can be linked to the greater route inferring capabilities of DSR. In the MCN architecture, nodes simply makes a request to the base unless it has a previous cached path. In the DSR routing protocol on the other hand, the nodes knows many more routes than in the MCN architecture, because the Route Reply is sent over multiple hops and because aggressive snooping of data and routing packets helps it glean additional information about network topology.

9.4 Power

Power consumption is important for mobile devices which have to rely on batteries for radio transmission and reception. We have plotted the power consumed over the data channel for MCN and the power consumed in Ad-hoc mode for the hybrid architecture as the UDP rate is increased. Note that because of the lesser bandwidth available to the hybrid architecture, the radio transmission and reception times increase by the same proportion. So the scaled hybrid plot is obtained by multiplying by 0.4 as against 2.5 in the previous cases. This is shown in Figure 17.

The hybrid architecture performs almost on par with the MCN architecture even without considering scaling. With scaling, the power consumed in the hybrid architecture is drastically lower. This comes as no surprise because minimizing power consumed is one of the objectives of the hybrid architecture. The variation of power consumed with load is more interesting however. The power consumed by the hybrid architecture remains nearly constant suggesting that the network load (including the DSR packets) is substantial even at low UDP loads. This once again is the effect of the broadcast storms. The MCN plot shows an initial sharp increase and then saturates out. This indicates that the hop-to-hop load saturates the bandwidth at greater end-to-end loads.

9.5 Mobility

Behavior under mobility is another index of performance of a wireless architecture. We have used the random waypoint model and varied the maximum speed from $2m/s$ to $14m/s$. The plot in Figure 18 reveals an almost identical percentage drop for both the architectures. This similar performance drop in both architectures is due to the similarity in their routing protocols: Both are on-demand, caching-enhanced with Route Errors generated at the node which detects the link break. The only difference is that the routing packets are flooded in one case and directed at the base in another. This difference leads to a nearly constant performance variation between the MCN plot and the scaled hybrid plot.

Observe the sharp fall in the MCN architec-

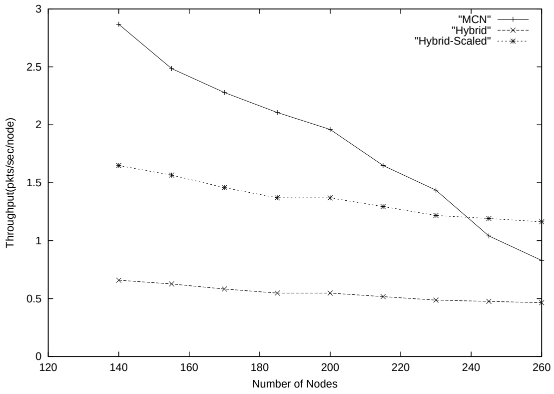

Figure 19: Throughput Vs. Node Density

ture after about $8m/s$. This reflects the bottleneck in the control channel, which gets congested due to the Route Errors, and the accompanying Route Request and Route Reply packets. The same reason holds good for the hybrid architecture, except that this drop starts occurring at lower loads indicating the effect of flooding routing protocol packets over a dense topology.

9.6 Scalability

The scalability of wireless architecture with node density another important metric for assessing a wireless architecture. For these plots, we have varied the number of nodes from 140 to 260, thus varying the number of nodes per cell over the range 28 to 52. We have shown this in Figure 19.

Observe that the scaled hybrid plot overtakes the MCN plot at very high node density again indicative of the trends observed in the UDP plots. The MCN architecture has a greater slope reflecting greater sensitivity to the node density. Even with a density as low as 28 nodes per cell, network partitions do not seem to occur with the fixed power MCN architecture. On the average, every node has a degree of 7 nodes which is sufficient to keep the network connected. Besides it is also possible to route to adjacent bases.

The reason why the hybrid architecture performs better than the MCN architecture is that the value of k chosen for the MCN architecture, $k = 2$, is dependent on node density. On the other hand, in the hybrid architecture, the base adjusts the transmission power depending on the network topology. Thus, we see that the hybrid architecture performs well at higher node densities.

9.7 Simulation Conclusions

We conclude the following from the above simulations:

- The raw bandwidth available per cell is by far the most important factor influencing the performance of the two architectures as can be seen by the differences between the MCN plot and the unscaled hybrid plot.

- The hybrid architecture outperforms the MCN architecture in terms of power but is handicapped by the broadcast storms initiated in Ad-hoc mode and the PCF limitation of greater transmission power in cellular mode. This leads to poorer performance when throughput is considered.

- The reservation of a constant proportion of the total bandwidth for control traffic is a problem which plagues all forms of out-of-band signaling. At low loads, this bandwidth might be better utilized for data traffic while at higher loads, the control channel becomes the bottleneck. This bottleneck effect is clearly visible in the mobility plots at high load.

- The performance of both architectures degrades rapidly with mobility. While this behavior resembles that of Ad-hoc networks, they still match the SCN performance as simulated in [4].

We conclude the following about desirable features of multi-hop cellular architectures, that will be used in 4G networks:

- Multi-hop cellular architectures can be designed so as to prevent performance degradation under mobility. Even though they resemble Ad-hoc networks, the presence of a centralized agent (the base) makes routing far easier. Route maintenance is also easier and packet loss during route reconfiguration can be minimised. Hence, even though multiple hops might be used, the base should be involved in the routing protocol actively: it cannot be treated as a peer to the nodes, in terms of routing. Thus, even though the base is not involved as a relay in every data packet transmission, the base should be a part of the route discovery process — this will also be convenient for implementing pricing schemes, location update etc.

- The hybrid network architecture prevents partitions even in Ad-hoc mode, by adjusting the transmission power of nodes. Partitions are simply ignored in the MCN architecture. However, the hybrid architecture requires the channel to divided over the cells in a cluster, which reduced the effective bandwidth per cell. Variable power MAC protocols (for example, in [19]) allow nodes to use *different* powers on the *same* channel. Such protocols can avoid partitions without relying on clustering.

- Pricing issues also need to be addressed in multi-hop cellular architectures before they can be used in future generation networks. Again, handling such issues will be easier if the routing protocol involves the base. In the hybrid architecture, for example, the use of DSR in the Ad-hoc mode might lead to difficulty in handling pricing issues because the nodes are capable of discovering routes of themselves — the base is not necessary to find routes. This allows the possibility of the base going unaware of certain transmissions, which can lead to difficulty in charging users.

- Using a resilient routing protocol like in MCN, one can counter the typical problems in Ad-hoc networks: poor performance under high mobility. Protocols like DSR, which rely on flooding, can lead to excessive control overhead. The routing protocols of the multi-hop architectures of the $4G$ networks will have to be similar to current cellular architectures. We can summarize this as follows: *control* protocols of multi-hop cellular architectures should be similar to those in SCN, while the *data* packet transmissions should be similar to those in Ad-hoc networks. MCN follows this principle and this is one of the reasons why MCN performs better than the hybrid network architecture.

10 Enhancements

Based on the simulations, we suggest the following enhancements to the hybrid architecture:

- Routes to the base are extremely important since the base is the relay for all packets to nodes in other cells. The power can be adjusted so that each node has at least 2 disjoint paths to the base. This especially affects performance at low values of locality when most packets are relayed through the base. The presence of a centralized agent, i.e. the base, should be exploited for routing purposes. To reduce the number of wireless hops, there should be a lower bound on the power so that dense topologies do not lead to very low powers. For example, powers like 1/5 of the cell radius will lead to large number of wireless hops.

- The DSR protocol and the cellular routing protocol can be gracefully merged into one single protocol which makes Route Requests to the base over multiple hops. This will also help the two protocols to share information thus preventing glitches during the switch period. Power adjustment can operate along with this single protocol.

- The switching algorithm needs to be enhanced in order to ensure maximum throughput. The calculation of the expected throughput in Ad-hoc mode, by simulating the packet scheduling protocol, does not take the overhead of routing packets into consideration as the cellular mode does not require them. There also needs to be some hysteresis in the mode-switching decision. The switching algorithm assumes all nodes are backlogged during the comparison of the observed Ad-hoc throughput against $C/(2n)$. This assumption might not be valid at low loads and in the case of protocols like TCP which withdraw packets for a short period due to congestion, the observed throughput will not be a true indication of the possible Ad-hoc throughput. The offered load should also be taken into consideration in the switching algorithm.

We also propose the following enhancements to the MCN architecture:

- The routing protocol should take advantage of the service-area wide data channel by routing packets through adjacent base stations if possible. This will automatically confer the hot-spot cooling ability of architectures such as iCAR [20], by performing graceful load balancing. If the nodes are not in adjacent cells, the protocol in [4] routes the packet by searching for paths from the source to its base, from the source's base to the destination's base, and finally from the destination's base to the destination. This precludes the possibility of primary, secondary, and cascading relaying capabilities described in [20].

- A dynamic load-based weight function should be used to provide the opportunity for the previous enhancement to take place. Paths to other bases should be made favorable if the current cell is heavily loaded by assigning load-based weights to the links. This will also help in reducing the spatial fairness problem for nodes far away from the base by providing them greater number of choices. Recent work exploring load aware routing in Ad-hoc networks [21] have shown that this can lead to a performance gain.

- A link cache, suggested in [22], can be used instead of a path cache. This will reduce the overhead on the control channel by allowing the nodes to infer new paths from the known paths without having to go to the base. Link breakage on a single link will not remove the whole path, instead the link will be marked as failed and the other links can be used to deduce new paths. The down-side is the computation time required at the nodes, but might be worth costly route requests.

- Reliable packet transmission is difficult to provide over multiple wireless hops. However, FEC schemes designed for wired networks, based on disjoint paths, can be used to provide reliable services.

We plan to study the effect of these enhancements to the hybrid architecture and the MCN architecture in a future work.

11 Summary

We have quantitatively and qualitatively evaluated the performance of the two next generation wireless network architectures based on a number of criteria. We have also extended the hybrid architecture proposed in [2] over multiple cells. An analytical model has also been proposed for the MCN architecture in [4]. Decreasing the transmission power to increase the spatial reuse factor is the common feature to both architectures and these simulations reflect the fact that locality affects throughput drastically for such architectures. High performance gains over SCN can be obtained by lowering the power but creates the necessity for a resilient routing protocol (as compared to the simple base forwarding in SCN). Ad-hoc routing protocols might be overkill in such an environment, due to their heavy overhead. Routing protocols of these multi-hop cellular architectures should be similar to those in SCN (to avoid excessive control overhead), while the data packet transmissions should use multiple hops like in Ad-hoc networks. In other words, the *data plane* of these networks will resemble those of Ad-hoc networks, while on the *control plane* these networks will be similar to SCN.

There are a few disadvantages in multi-hop networks: for example, the complexity of the nodes is greater, since they need to have store and forward capability. Pricing and security issues in these networks also need to be addressed.

References

[1] M. Frodigh, S. Parkvall, C. Roobol, P. Johansson, and P. Larsson, "Future-Generation Wireless Networks", in *IEEE Personal Communications 2001*, Vol. 8, No. 5, pp. 10-17, October 2001.

[2] H. Y. Hsieh and R. Sivakumar, "Performance Comparison of Cellular and Multi-hop Wireless Networks: A Quantitative Study," in *Proc. ACM SIGMETRICS 2001*, Cambridge, MA, USA, June 2001.

[3] Y. D. Lin and Y. C. Hsu, "Multi-Hop Cellular: A New Architecture for Wireless Communications," in *Proc. IEEE INFOCOM 2000*, Tel-Aviv, Israel, March 2000.

[4] Ananthapadmanabha R., B. S. Manoj, and C. Siva Ram Murthy, "Multi-hop Cellular Networks: The Architecture and Routing Protocol", in *Proc. IEEE PIMRC 2001*, San Diego, USA, October 2001.

[5] F. H. Blecher, "Advanced Mobile Phone Service", in *IEEE Trans. on Vehicular Tech.*, Vol. 29, No. 2, pp. 238-244, May 1980.

[6] M. Mouly and M. Pautet, "The GSM System for Mobile Communications", 1992.

[7] A. K. Salkintzis, "Packet Data over Cellular Networks: The CDPD Approach", in *IEEE Commun. Mag.*, Vol. 37, No. 6, pp. 152-159, June 1999.

[8] J. Cai and D. J. Goodman, "General Packet Radio Service in GSM", in *IEEE Commun. Mag.*, Vol. 24, No. 1, pp. 122-131, October 1997.

[9] Broch, D. A. Maltz, D. B. Johnson, Y. C. Hu, and J. Jetcheva, "A Performance Comparison of Multi-Hop Wireless Ad-hoc Network Routing Protocols", in *Proc. ACM/IEEE MobiCom 1998*, Dallas, Texas, USA, October 1998.

[10] W. C. Y. Lee, "Overview of Cellular CDMA", in *IEEE Trans. on Vehicular Tech.*, Vol. 40, No. 2, pp. 291-302, May 1991.

[11] T. S. Rappaport, "Wireless Communications: Principles and Practice", Prentice-Hall, 1996.

[12] L. R. Hu and S. S. Rappaport, "Personal Communication Systems Using Multiple Hierarchical Cellular Overlays", in *IEEE JSAC*, Vol. 13, No. 2, pp. 406-415, February 1995.

[13] D. B. Johnson and D. A. Maltz, "Dynamic Source Routing in Ad Hoc Wireless Networks", in *Mobile Computing* , Vol. 353, Kluwer Academic Publishers, 1996.

[14] H. Y. Hsieh and R. Sivakumar, "Improving fairness and throughput in multi-hop wireless networks," in *Proc. ICCCN 2001*, Colmar, France, July 2001.

[15] H. Luo, S. Lu, and V. Bharghavan, "A New Model for Packet Scheduling in Multi-Hop Wireless Networks," in *IEEE/ACM Transactions on Networking*, Vol. 7, No. 4, pp. 473-489, 1999.

[16] T. C. Tay and K. C. Chua, "A Capacity Analysis for the IEEE 802.11 MAC Protocol" in *ACM Wireless Networks*, Vol. 7, No. 2, pp. 159-171, March 2001.

[17] X. Zeng, R. Bagrodia and M. Gerla, "GloMoSim: A Library for Parallel Simulation of Large-scale Wireless Networks", in *Proc. PADS-98*, Banff, Canada, May 1998.

[18] H. Balakrishnan, V. N. Padmanabhan, S. Seshan, and R. H. Katz, "Comparison of Mechanisms for Improving TCP Performance over Wireless Links," in *IEEE/ACM Transactions on Networking*, Vol. 5, No. 6, pp. 756-769, 1997.

[19] J. P. Monks, V. Bharghaven, and W. M. W. Hwu, "A Power Controlled Multiple Access Protocol for Wireless Packet Networks", in *Proc. IEEE INFOCOM 2001.* Alaska, April 2001.

[20] H. Wu, C. Qiao, S. De and O. Tonguz, "Integrated Cellular and Ad-hoc Relaying Systems: iCAR", in *IEEE Journal on Selected Areas in Communications*, Vol. 19, No. 10, pp. 2105-2115, October 2001.

[21] S. Lee and M. Gerla, "Dynamic Load-Aware Routing in Ad-hoc Networks", in *Proc. IEEE ICC 2001*, Helsinki, Finland, June 2001.

[22] Y. C. Hsu and D. B. Johnson, "Caching Strategies in On-Demand Routing Protocols for Wireless Ad-hoc Networks," in *Proc. ACM/IEEE Mobicom 2000*, Boston, MA, August 2000.