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A Cross Layer Routing Protocol for Multihop Cellular Networks

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Abstract We propose a cross-layer routing protocol for a Code Division Multiple Access (CDMA) Multihop Cellular Network (MCN). In designing the routing protocol for MCN, multiple constraints are imposed on intermediate relay node selection and end-to-end path selection. The constraints on relay nodes include willingness for cooperation, *sufficient neighbourhood connectivity* and the level of interference offered on the path. Path constraints include end-to-end throughput and end-to-end delay. A facile incentive mechanism is presented to motivate the cooperation between nodes in call forwarding. In addition, we present a route resilience scheme in the event of dynamic call dropping. In particular, a fast neighbour detection scheme for route resilience is proposed. Instead of using periodic HELLO messages as in traditional ad-hoc routing, the proposed neighbour detection scheme adopts an explicit handshake mechanism to reduce neighbour detection latency. We conclude the paper by demonstrating the superior performance of the proposed routing protocol compared with the other well known routing algorithms.

Keywords Cross layer routing · End-to-end throughput · End-to-end delay

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1 Introduction

The radio frequency bandwidth used for mobile communications has become a scarce and expensive resource as the number of mobile user increases. Given the limitation on the spectrum, many researchers have attempted to develop a scheme for effective frequency bandwidth utilisation. Probably the greatest single architectural concept in improving bandwidth utilisation is the cellular network, allowing frequency reuse. In conventional single hop networks, frequency reuse is largely a function of the transmission range of individual mobile nodes or the transmission radius of the base stations. That means one can achieve greater frequency reuse either by reducing the transmission range of mobile nodes or by deploying many base stations with smaller transmission ranges. However, deploying a larger number of basestations with smaller range will eventually increase the infrastructural cost to an unacceptable level. Therefore, it is desirable to try and achieve the lowest transmitted power possible by changing the transmission path from a direct link into a series of smaller hops using other users, or strategically placed relays (multihop relaying). Placing strategic relays may again create an infrastructural issue and also raise the problem of optimal placement of relay nodes. Therefore, it is clear that multihop relaying through other users' mobile nodes could present an attractive solution for transmission power reductions and allow more effective reuse of bandwidth.

In addition to the above, conventional single hop cellular networks still have some areas where coverage is yet to be provided. These areas are often referred to as *dead spots*. Dead spots include subway train platforms, indoor environments and underground areas. Moreover, in areas of dense subscriber populations, known as *hot spots*, such as downtown areas and amusement parks, subscribers tend to experience higher call dropping/blocking. Increase the number of basestations may not be of complete and long time futuristic solution for these problems [2]. Multihop relaying has been proven to be effective in increasing the capacity, coverage, reducing the call blocking probability and decreasing the per node transmission power [3–6]. Furthermore, with a conventional system if the user has a poor channel established directly to the base station, they may have no choice but to change location to achieve communication. However, in multihop relaying, mobiles with no good path to any base station may instead relay their calls through one of the neighbour mobile nodes.

Encouraged by the above facts there has been interests in incorporating multihop relay communications into cellular networks. i.e. mobile node to mobile node multihop communications or mobile node to basestation multihop communications. Such a network is often referred to as Multihop Cellular Network (MCN). This is the concept behind Opportunity Driven Multiple Access (ODMA) proposed in 3GPP [7]. The provision of a relaying capability service in next-generation ad-hoc GSM (AGSM) is also under study [8]. For data networks also, multihop cellular networks have been proposed in [9].

For becoming an effective solution, MCN has many issues which have to be resolved such as:

1. It is necessary to understand the properties of the topology which minimises the total transmit power in the presence of interference.
2. Finding a suitable routing strategy and route resilience scheme are still an open problem in MCN. This problem is computationally intractable and heuristic algorithms are mainly used.
3. Suitable medium access mechanisms, resource scheduling (for example dynamic CDMA code allocation and CDMA code reuse in distant mobile nodes) and optimal selection of transmission power are some of the issues which are not yet resolved.

In this paper the fundamental issue we investigate is that of finding a multi-hop routing path, route resilience scheme and neighbourhood detection scheme in order to achieve satisfactory end-to-end performance. The major contributions of this paper are:

1. We propose a unified, cross-layer routing protocol, satisfying multiple constraints for MCNs. We do not assume full cooperation in call forwarding and present a facile incentive mechanism to motivate cooperation between mobile nodes acting as relays. In the routing protocol design, multiple constraints are imposed on intermediate relay node selection and end-to-end path selection. The relay node constraints include cooperation, *sufficient neighbourhood connectivity* and level of interference. Path constraints for route selection are end-to-end throughput and end-to-end delay.
   We define the end-to-end throughput using physical layer parameters: received power, signal to interference and noise ratio (SINR) and probability of successful transmissions. The interference metric involves MAC layer and physical layer parameters, and these metrics are used in the network layer for routing protocol design. Therefore, the proposed routing algorithm is a cross-layer protocol in nature, between network, medium access control (MAC) and physical layers.
2. A route resilience scheme is introduced to cope with dynamic call dropping events. If we assume a route consists of multiple hops or links, then dynamic call dropping occurs when one of the links breaks. Link breakage may be caused by node mobility or energy drainage of a node, resulting in a non-forwarding node. In the proposed resilience scheme we bypass the non-forwarding node and route the call via one of the cooperative neighbours such that all the routing criteria are satisfied.
3. We present a fast neighbour detection mechanism. The neighbour detection mechanism is localised and operates in a distributed fashion at each node. Instead of using *periodic* HELLO messages, the proposed scheme adopts an explicit handshake mechanism to reduce the latency in neighbour detections.

2 Related Work

An integrated Cellular and Ad-hoc relaying (iCAR) system was presented in [6] with a set of fixed relays and fixed routes through these relays. Shortest-path-first algorithm was adopted in route selection in the MCN architectures proposed in [4,5]. A routing protocol for hybrid networks based on a spanning-tree was proposed in [10], and selection of relay-nodes based on finding a route that has the smallest bottleneck was presented in [11]. A charging and rewarding policy in routing for MCNs was proposed in [12] where dynamic source routing (DSR) is used as the routing protocol. A route selection algorithm based on call status, signal strength, battery power and round-trip time (RTT) was proposed in [13]. There are a number of power-aware ad hoc routing protocols which use energy as the critical parameters [14–20]. Our proposed routing protocol introduces a new dimension to the work listed above interms of unique cross layer routing strategy and route resilience.

3 Assumptions and Proposed MCN Architecture

For the start of our analysis, we assume a single cell with n number of mobile nodes distributed according to a Poisson point process. The base station and the nodes use CDMA as the access method for their interconnections as CDMA is considered for third generation 3GPP,

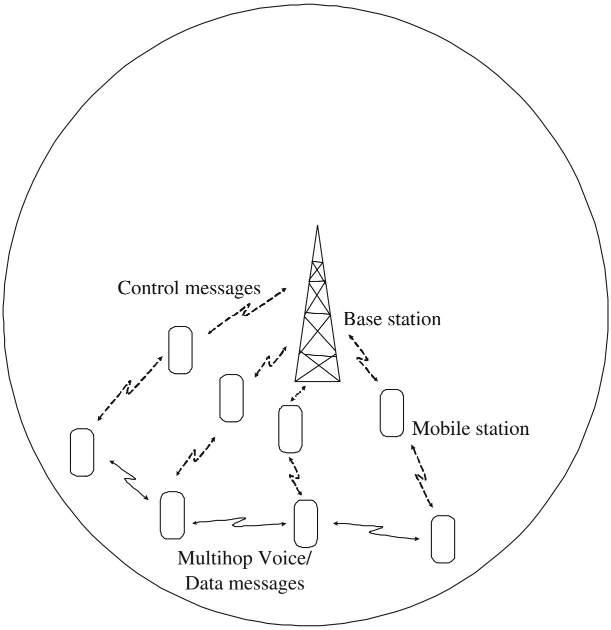


Fig. 1 Proposed single cell system model showing Control Channel (CCH) as a *dashed line*, and Traffic Channel (TCH) as a continous line

3GPP2 and UMTS systems. Also CDMA for multihop communications is widely explored in literature for example in [7,21–23]. Every node is assigned with a CDMA code and the dynamic allocation of CDMA code and its reuse in far-away nodes are not considered in this paper, since such an analysis merits a separate paper. Base station is assumed to have enough resources to compute the route in real time. Perfect power control is used in this CDMA network so that all the transmitters use just the transmission power level that is required to let the receiver decode the signal with proper quality. However, the nodes transmit HELLO messages with fixed power p_{HELLO} for neighbour detection. We assume that nodes do not transmit and receive in the same time slot to avoid primary collision at receive nodes [24]. Also cell phone nodes are assumed to have sophisticated receiver to reduce the receiver noise so that the error propagation across the route path can be minimized. The propagation channel between the mobile nodes are flat fading, independent and identically distributed (iid) Rayleigh. The logical channel is divided into Control Channels (CCHs) and Traffic Channels (TCHs). The CCH handles only signaling, while the TCH carries speech and data traffic. Control messages containing the source ID and the destination ID, are exchanged between the nodes and base station using the CCH. Control messages are routed based on Dijkstra's algorithm, as they are very short and exchanged only at the time of call initialisation. TCH channels follow the unified cross-layer routing scheme proposed in Sect. 4. Figure 1 shows such architecture with dashed lines for CCHs and continuous lines for TCHs.

4 Proposed Cross Layer Routing Protocol

In our proposal, when a node wants to initiate a packet transmission to a destination node, it will send a call initiation request or *Route Request* (RReq) containing the IDs of the source and destination to its basestation over a CCH. The basestation uses the strategy proposed in this section to compute a route between the source node and the destination node. This route information is sent back to the source using a *Route Reply* (RRep) packet over the CCH. The source node then inserts this route information into its data packets and transmits these data packets.

The constraints used in the proposed routing protocol are divided into *node constraints* and *path constraints*. The constraints considered for relay node selection are:

1. *Cooperation*: All of the selected relay nodes must cooperate to forward the call.
2. *Connectivity*: The selected relay nodes must have a sufficient number of connected neighbours (*sufficient neighbourhood connectivity*) in order to increase the connectivity [25].
3. *Interference*: Interference caused in the network due to communication between any two nodes in the path must be below a certain threshold I_{max}.

The constraints for path selection are:

1. *End-to-end throughput*: End-to-end throughput in the selected path must be above a certain threshold.
2. *End-to-end delay*: End-to-end delay in the selected path must be below a certain threshold.

4.1 Node Selection Criteria

4.1.1 Co-operation Metric and Proposed Incentive Mechanism

An essential component in the MCN is the co-operation of mobile nodes in relaying data packets from other mobile nodes. In our proposal, each node has a *willingness status* [26] flags for packet relaying as follows:

1. will_status = 0 for non co-operation
2. will_status = 1 for co-operation

In conventional cellular networks, mobile nodes by default do not agree for packet relaying since packet relaying consumes scarce resources such as battery power, processor time and bandwidth. Hence, the default willingness status of a node is 0 (i.e. non-cooperation for packet relaying) [26]. Therefore, it is clear that a node must be stimulated in some way to change their willingness status from 0 to 1. The proposed incentive mechanism works as follows:

Whenever a node wants to initiate a communication, it sends an RReq to the base station through a CCH. Upon receiving the RReq, the base station broadcasts a *Cooperation Request* (CReq) to the entire region (cell) through a broadcast CCH. The CReq contains source ID, destination ID and the *incentive amount* per node that is to be ‘paid’ after communication. Those nodes that are interested in the incentive offer will change their willingness status from 0 to 1 and reply to the base station using a CCH. Let us assume $\bar{\Phi}(n)$ is the network of co-operating nodes (nodes with will_status = 1). It makes sense that the incentives for multihop routing to be ‘paid’ by service providers since:

- MCN promises enormous user capacity improvement which is advantageous for the service provider [4].
- Routing path is found by the base station, which has the option of switching to single hop when it finds multihop is inefficient and more costly.

We do not discuss here the exact nature of the payment, but clearly the existing ‘credit-back’ schemes for subscribers could be easily adapted as required.

4.1.2 Neighbourhood Connectivity and Detection

In [25], it is shown that in a network of n randomly placed nodes, each node should be connected to $\Theta(log(n))$ nearest neighbours. If a node has less than $0.074(log(n))$ connected neighbours, then the network is asymptotically disconnected with probability 1 as n increases. Hence, *sufficient neighbourhood connectivity* is an important criterion to establish communication within an MCN.

We define *sufficient neighbourhood connectivity* of nodes as follows: If a node $m \in \bar{\Phi}(n)$ has k neighbours from $\bar{\Phi}(n)$ and if:

$$k > \Theta(log(n))$$

then node m satisfies *sufficient neighbourhood connectivity* criterion and consequently, it is an eligible relay node. In our work we choose Θ as a function of number of nodes in the network. Let us construct a subset $\hat{\Phi}(n)$ from $\bar{\Phi}(n)$ with nodes satisfy our *sufficient neighbourhood connectivity* criterion. Every node will build its own neighbour table and will notify this information to the base station. However, the MCN topology may change frequently and hence the time delay involved in neighbour detection is critical. We address the problem of neighbourhood detection with low latency in the following section.

4.1.3 Proposed Neighbourhood Detection Scheme

Traditionally, ad-hoc routing protocols such as Optimised Link State Routing (OLSR) detects neighbour changes by exchanging periodic HELLO messages [26]. Although the HELLO based neighbour detection is simple to implement and robust in the presence of message loss, there have been concerns about its performance in the dynamic environments like MCNs:

1. *Detection latency*: The HELLO based mechanism has a relatively large delay in neighbour detection. For example, it takes around 3 seconds on an average for OLSR nodes to detect established connections [26]. Such latency might lead to unnecessary increase in end-to-end delay, especially in high mobility networks.
2. *Resource wastage*: Periodic HELLO messages are broadcast even if no link changes occur, which wastes bandwidth and battery life. Smaller HELLO intervals result in increased frequency of HELLO messages which will increase channel contention and lead to congestion.

In our proposal, instead of relying on periodic HELLO messages, we use an explicit route handshake mechanism, which reduces the latency in connection establishment and improves path availability. In particular, we propose a unicast based handshake (*UHS*) option. i.e. the handshake packets are transmitted as unicast messages between the neighbouring nodes. For example, when node A receives its first HELLO message from B, it sends ACK messages only to node B.

Outline: Traditional ad-hoc routing protocols only use symmetric links in route calculations. The established (physical) connections would not be available for data transfer until identified as *symmetric* links by the routing protocols. Therefore, a delay in neighbour detection might lead to routing performance degradation. The neighbour detection latency of HELLO based routing protocols is caused by the periodic nature of HELLO messages. After receiving the first HELLO message from a neighbour, the node does not respond until it broadcasts its own HELLO message. Essentially, the neighbour handshake process is *implicit* through exchanging periodic HELLO messages.

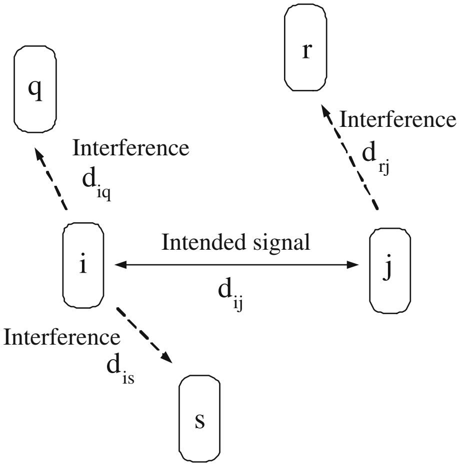


Fig. 2 Interference metric

In our scheme, we use an *explicit* handshake messages to facilitate connectivity detection. More specifically, in addition to periodic HELLO messages, a node sends explicit handshake messages to its neighbours. The basic process is described as follows:

1. Each node broadcasts periodic HELLO messages to its neighbours.
2. When node A receives its first HELLO message from its unknown neighbour B, it creates a new entry for directed link ($B \rightarrow A$), and responds with an ACK message *immediately* to node B, with the status of the new link ($B \rightarrow A$).
3. When node B receives such an ACK message, it infers the existence of bi-directional link ($B \leftrightarrow A$); then node B sends *immediately* an ACK message to node A, confirming the symmetric link ($A \leftrightarrow B$) status between them.
4. If, for any reason, the ACK message from A is lost or dropped, the following periodic HELLO messages would recover such a loss and complete the neighbour detection as normal.
5. Similarly, if the ACK message from B to A is dropped, the next periodic HELLO message recovers the loss and acknowledges A normal.

Additionally, to reduce control traffic overhead, we propose that nodes only transmit their neighbour table to the base station (using a CCH) when there is a *change* in the neighbour connectivity.

4.2 Interference Metric

Interference reduction in CDMA networks is achieved by controlling the transmission power. However, the transmission power levels of the nodes depend on the distance of the other intermediate nodes in the route. Let us consider the communication between a particular node i and any other node j as shown in Fig. 2. The average interference received at some node r due to transmission from node i to node j is given by:

$$\frac{\rho_{ir}^2 p_{ij}}{d_{ir}^{\gamma}}$$

where ρ_{ir} is the time-correlation between the signature waveforms of nodes i and r, γ is the path loss coefficient, d_{ir} is the distance between node i and node r, p_{ij} is the transmitted power from node i to node j. Note that the average received power in a Rayleigh flat fading channel always follows a distance-decay law [27]. Let us assume G is the direct sequence CDMA (DS-CDMA) processing gain. Then, the sum of the interference received in all neighbour nodes in the network due to the transmission from i to j is given by:

$$I = \frac{1}{G}\left(\sum_{r=1, r\neq\{i,j\}}^{n} \rho_{ir}^2 \frac{p_{ij}}{d_{ir}^{\gamma}}\right)$$

Let us construct a subset $\ddot{\Phi}(n)$ from $\hat{\Phi}(n)$ such that the communication between any two nodes in $\ddot{\Phi}(n)$ causes interference in the network which is below certain threshold I_{max}. We call the nodes in $\ddot{\Phi}(n)$ as *potential relay nodes*.

4.3 Path Metrics Formulation

Let $\chi = \{x_1, x_2, x_3, \ldots, x_M\}$ denote the set of paths available between a source node and a destination node along the *potential relay nodes*. The following are the metrics used in choosing a particular path from the set χ:

1. End-to-end throughput
2. End-to-end delay

4.3.1 End-to-End Throughput Metric

End-to-end throughput is defined as the probability of successful transmission from a source node to a destination node which involves successful transmission at each and every intermediate node. The successful single hop transmission from node i to its neighbour node j $(\forall i, j \in \ddot{\Phi}(n))$ occurs when the received power at node j from node i is stronger than interference plus noise power by a factor of β (i.e $SINR \geq \beta$). The probability of successful transmission from node i to node j is:

$$\mathrm{P}(C_{i,j}) = \mathrm{P}(SINR_{i,j} \geq \beta) = \mathrm{P}\left(\frac{r_{i,j}}{(I_{i,j} + N)} \geq \beta\right) = \mathrm{P}(r_{i,j} \geq \beta.(I_{i,j} + N))$$

where $r_{i,j}$ is the received power at node j from the intended node i and $I_{i,j}$ is the interference at node j due to other communications. Let $r_{k,j}, k = 1, \ldots, K(k \neq i, j)$ be the received power at node j from the kth interferer, then the interference at node j from all interferers is:

$$I_{i,j} = \frac{1}{G}\left(\sum_{k=1, k\neq\{i,j\}}^{K} \rho_{k,j}^2 r_{k,j}\right)$$

Erroneous detection occurs when $SINR_{i,j} < \beta$, this probability $\mathrm{P}(E_{i,j})$ is given by:

$$\mathrm{P}(E_{i,j}) = \mathrm{P}(r_{i,j} < \beta \cdot (I_{i,j} + N))$$

The propagation channel between mobile nodes is different from a conventional wireless channel. However, the envelope still follows a Rayleigh distribution [28]. When the channel envelope is Rayleigh then the received power $r_{i,j}$ follows an exponential distribution. Hence:

$$\mathrm{P}(r_{i,j}) = \frac{1}{R_{i,j}} e^{\frac{-r_{i,j}}{R_{i,j}}} \tag{1}$$

where $R_{i,j}$ denotes the average received power $R_{i,j} = \frac{p_{i,j}}{d_{i,j}^{\gamma}}$ [27,29].

1. *Case I*: Number of hops > 1
   Let us say $x_m = \{1, 2, 3, \ldots, h\}$ is the path selected to relay the packets from source node 1 to the destination node h and number of hops in the communication is $h - 1$. The probability $\mathrm{P}(C_{1,h})$ that the message is successfully transmitted from source 1 to destination h is given by:

$$\mathrm{P}(C_{1,h}) = \mathrm{P}\left(\bigcap_{i=1}^{h-1} C_{i,i+1}\right) = 1 - \mathrm{P}\left(\bigcup_{i=1}^{h-1} E_{i,i+1}\right) \geq 1 - \sum_{i=1}^{h-1} \mathrm{P}(E_{i,i+1}) \geq 0 \qquad (2)$$

   where the last bound on 0 is from the fact that $\mathrm{P}(C_{1,h}) \geq 0$. Let us consider communication between node i and its closet neighbour $i + 1$ in the routing path:

$$\mathrm{P}(E_{i,i+1}) = \mathrm{P}(SINR_{i,i+1} < \beta) = \mathrm{P}(r_{i,i+1} < \beta \cdot (I_{i,i+1} + N))$$

   Now the probability of error conditioned on the interference is:

$$\mathrm{P}(E_{i,i+1})|_{I_{i,i+1}} = \frac{1}{R_{i,i+1}} \int_{0}^{\beta \cdot (I_{i,i+1}+N)} \left(e^{-\frac{r_{i,i+1}}{R_{i,i+1}}}\right) dr_{i,i+1} = 1 - \left(e^{\frac{-\beta(I_{i,i+1}+N)}{R_{i,i+1}}}\right)$$

   where $I_{i,i+1}$ itself is a random quantity, therefore, the probability of error $\mathrm{P}(E_{i,i+1})$ after removing the condition on $I_{i,i+1}$ is:

$$\begin{aligned}\mathrm{P}(E_{i,i+1}) &= \mathrm{E}_{I_{i,i+1}}\left[1 - e^{-\frac{\beta(I_{i,i+1}+N)}{R_{i,i+1}}}\right] \\ &= \int_{0}^{\infty} \cdots \int_{0}^{\infty} \left(1 - \left(e^{-\frac{\beta[\frac{1}{G}\sum_{k=1,k\neq\{i,i+1\}}^{K} \rho_{k,i+1}^{2} r_{k,i+1} + N]}{R_{i,i+1}}}\right)\right) \\ &\quad \cdot \prod_{k=1,k\neq\{i,i+1\}}^{K} P(r_{k,i+1}) dr_{k,i+1}\end{aligned}$$

   where $\mathrm{E}_{I_{i,i+1}}[.]$ is the expectation of [.] with the random variable $I_{i,i+1}$. By substituting $\mathrm{P}(r_{i,j})$ from (1) and by invoking the independence assumption of $\mathrm{P}(r_{i,j})$, the above equation can be written as:

$$\mathrm{P}(E_{i,i+1}) = 1 - \left[e^{\left(-\frac{\beta N}{p_{i,i+1} d_{i,i+1}^{-\gamma}}\right)} \prod_{k=1,k\neq\{i,i+1\}}^{K} \frac{1}{1 + \frac{\beta}{G} \frac{\rho_{k,i+1}^{2} p_{k,i+1}}{p_{i,i+1}} \left(\frac{d_{i,i+1}}{d_{k,i+1}}\right)^{\gamma}}\right] \qquad (3)$$

   From (2) and (3) the lower bound on end-to-end throughput can be written as:

$$\mathrm{P}(C_{1,h}) \geq 1 - \sum_{i=1}^{h-1} \left(1 - \left[e^{\left(-\frac{\beta N}{p_{i,i+1} d_{i,i+1}^{-\gamma}}\right)} \prod_{k=1,k\neq\{i,i+1\}}^{K} \frac{1}{1 + \frac{\beta}{G} \frac{\rho_{k,i+1}^{2} p_{k,i+1}}{p_{i,i+1}} \left(\frac{d_{i,i+1}}{d_{k,i+1}}\right)^{\gamma}}\right]\right) \qquad (4)$$

2. *Case II*: Number of hops = 1

$$\mathrm{P}(C_{1,2}) = \mathrm{P}(r_{1,2} \geq \beta \cdot (I_{1,2} + N))$$

Now the conditional probability of correct detection is:

$$\mathrm{P}(C_{1,2})\Big|_{I_{1,2}} = \frac{1}{R_{1,2}} \int\limits_{\beta\cdot(I_{1,2}+N)}^{\infty} \left(e^{-\frac{r_{1,2}}{R_{1,2}}}\right) dr_{1,2} = e^{\frac{-\beta\cdot(I_{1,2})+N}{R_{1,2}}}$$

After averaging over $I_{1,2}$ the probability of correct detection is:

$$\mathrm{P}(C_{1,2}) = \left[e^{\left(-\frac{\beta N}{p_{1,2}d_{1,2}^{-\gamma}}\right)} \cdot \prod_{k=1,k\neq\{1,2\}}^{K} \frac{1}{1+\frac{\beta}{G}\frac{\rho_{k,2}^{2}p_{k,2}}{p_{1,2}}(\frac{d_{1,2}}{d_{k,2}})^{\gamma}} \right]$$

From the set of paths χ, we construct a set $\{\mathbf{X}\}$ such that the constraint on end-to-end throughput is satisfied.

4.4 End-to-End Delay Metric

The major contributions to the end-to-end delay are the transmission delay induced by the relay nodes and the propagation delay over the multihop communications. In our routing algorithm, we ensure that the end-to-end delay is minimal by introducing an additional path constraint. We select a path from the set $\{\mathbf{X}\}$ such that the selected path has minimal end-to-end delay and satisfies end-to-end delay constraint.

4.5 Summary

So, a summary of the process for the routing protocol is:

1. From n nodes, select a set of co-operative nodes and construct a set $\bar{\Phi}(n)$.
2. From $\bar{\Phi}(n)$ nodes, select a set of nodes which have *sufficient neighbourhood connectivity* and build a set $\hat{\Phi}(n)$.
3. From $\hat{\Phi}(n)$ choose a set of nodes which satisfy interference criterion and construct a set $\ddot{\Phi}(n)$.
4. From $\ddot{\Phi}(n)$ select source to destination paths $\{\mathbf{X}\}$ such that the lower bound on $P(C_{1,h})$ is above a certain threshold.
5. From $\{\mathbf{X}\}$ choose a source to destination path which has minimal end-to-end delay and having end-to-end delay below a certain threshold.

When a node wants to start data transmission, it sends a *Route Request* (RReq) containing source ID and destination ID to the base station through a CCH (node → base station). The base station broadcasts within the entire cell the Co-operation Request (CReq) which contains the ID of the source node, the destination node and the *incentive amount* (node ← basestation). Those nodes that are willing to co-operate make their response through the CCH with their neighbour details (node → basestation). Now the base station will find a source to destination path using *sufficient neighbourhood connectivity*, interference, end-to-end throughput and end-to-end delay constraints, and will convey this route information to the source node using CCH (node ← basestation).

5 Dynamic Call Dropping and Proposed Route Resilience Scheme

The forced termination of the call against the will of the subscriber is called *dynamic call dropping*. Dynamic call dropping may be caused by various reasons including node mobility, energy drainage, and an emergency or priority requirement of an intermediate relay node to make its own call.

The proposed solution for dynamic call dropping is as follows: since each selected relay node has sufficient number of connected neighbours (*sufficient neighbourhood connectivity* criterion), whenever any of the above stated situation arises in any of the relay node, the corresponding relay node (defined as *dynamic non-forwarding* node) will notify the base station using CCH about its sudden inability to forward the call. For example we assume a lower threshold of energy e_{th} (which is sufficient to connect to base station) on every node. The moment energy level goes below e_{th} the corresponding relay node will change its status from cooperating node to dynamic non-forwarding node and will notify the base station about its status. The base station can then pick up one of the neighbours of that particular dynamic non-forwarding node as a substitute such that the constraints on all the metrics are satisfied. Subsequently the corresponding dynamic non-forwarding node will be removed from the path. Therefore, the route can be repaired on the fly by locally redirecting the packets through an alternate route constituted by the cooperating neighbour of the dynamic non-forwarding node. Basestation can pay partial incentive to the dynamic non-forwarding node depending upon the duration of its participation in relaying.

6 Routing Metric Analysis

Let us more closely examine the constraints used for route selection.

1. In the co-operation constraint, as the number of intermediate nodes increases, the incentive offered also increases. Hence, the service providers will prefer having a direct link from source to destination.
2. If we look at end-to-end throughput:
   Case I: *Number of hops is very large*
   $P(C_{1,h}) \geq \left(1 - \sum_{i=1}^{h-1} \mathrm{P}(E_{i,i+1})\right) \to 0$. This will lead to negligibly smaller end-to-end throughput.
   Case II: *Number of hops=1*
   The end-to-end throughput is a function only of SINR. Hence, it is possible to achieve end-to-end throughput of 1 as long as the transmitted power is large enough to guarantee that $SINR > \beta$. Hence, end-to-end throughput metrics also favour a direct link from source to destination.
3. The end-to-end delay for a path is a direct function of the queuing delay at each node, and data propagation delay between hops, and so increases linearly with the number of intermediate nodes. Hence, the end-to-end delay constraint always favours fewer intermediate nodes, and ideally a direct path from source to destination.

In summary, all the above constraints favour direct source-to-destination paths in a single hop fashion. However, let us look at the interference constraint more closely. Assume that the transmitted power levels at node i is adjusted such that the destination node j receives a power level of p_{ref}, i.e.:

$$p_{ij} = p_{ref} d_{ij}^{\gamma}$$

The interference received at neighbour nodes as a function of d_{ij} is:

$$I(d_{ij}) = \frac{1}{G}\left(\sum_{r=1, r\neq\{i,j\}}^{n} \rho_{ir}^2 \frac{p_{ref} d_{ij}^{\gamma}}{d_{ir}^{\gamma}}\right)$$

where p_{ref} and d_{ir} are fixed quantities and the only variable is d_{ij}.

Therefore, the interference constraint favours a shorter hop length (d_{ij}). However, shorter hop lengths may lead to more hops in the path. This conflicts with other constraints. Hence, it is critical to find the balance between the number of hops and the hop length such that the constraints on all metrics are satisfied.

6.1 Route Discovery Delay Analysis

The delay involved in route discovery includes:

1. The delay in exchanging control messages
2. The delay in route calculation
3. The delay in neighbour detection

From Section 4.5 each route discovery process involves the exchange of four control messages. The computational complexity at the base station involves finding an optimal route that satisfies all the proposed metrics. Let us assume T_{CH} is the total delay in sending one control message from source node to base station, $T_{computational}$ is the computational delay and $T_{neighbour}$ is the neighbour detection latency of each node. Now the total route discovery delay T_{route}:

$$\begin{aligned} T_{route} &= 4 \times T_{CH} + T_{computational} + max(T_{neighbour}) \\ &= 4 \times T_{PCH} + 4 \times T_{QCH} + T_{computational} + max(T_{neighbour}) \end{aligned}$$

where T_{PCH} is the total propagation delay of control message from source node to basestation, T_{QCH} is the total queuing delay of control messages in nodes (or in base station) and $max(T_{neighbour})$ is the maximum latency in neighbour detection of any node. Generally T_{PCH} is negligible due to relatively shorter distance communications, and $T_{computational}$ can also be considered negligible as basestation is assumed to be equipped with sufficient computational resources. Hence, T_{route} can be approximated as:

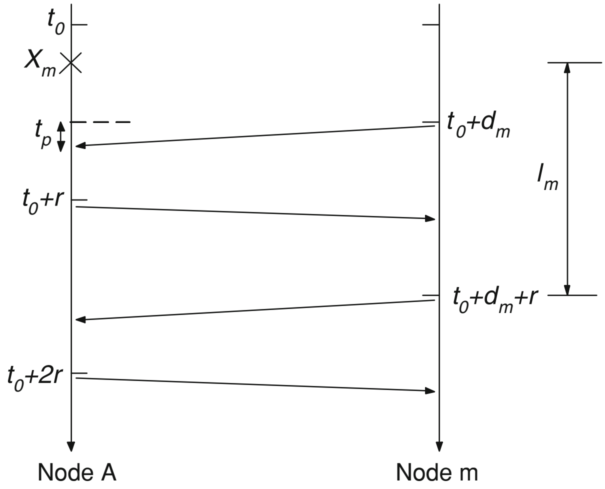
$$T_{route} \approx 4 \times T_{QCH} + max(T_{neighbour})$$

7 Neighbourhood Detection Latency Analysis $T_{neighbour}$

In this section, we compare the link detection latency of HELLO-based neighbour detection mechanism with the proposed fast neighbour detection scheme. In the following discussions, we assume that:

1. The arrival of a link establishment event is an iid Poisson process with arrival rate λ.
2. The delays in packet transmission and propagation (i.e. t_p) are small enough (compared with link detection latency) to be ignored.

Fig. 3 HELLO based neighbour detection



7.1 HELLO Based Neighbour Detection

Let us consider a node A and its neighbour m as shown in Fig. 3. Assume that node A generates periodic HELLO packets at every r seconds (the *HELLO interval*) starting from time instant t_0, and to avoid primary collision at A, node m starts generating the periodic HELLO packets after d_m time, i.e. starting from time instant $t_0 + d_m$. Let X_m be the time when the *first* symmetric link is established after t_0. Then the link discovery latency of a particular link (l_m) can be approximated by:

$$l_m = t_0 + d_m - X_m + r = r + d_m - (X_m - t_0)$$

Assume a particular node A has N neighbours. Since the link arrivals are Poisson distributed with parameter λ, the inter-arrival time $(X_m - t_0)$ will be exponentially distributed with parameter λ [30]. Let us assume the collision avoidance offset time d_m $(1 \leq m \leq N)$ for various nodes are exponentially distributed with parameter λ in the interval $(t_0, t_0 + r]$. Now, let us calculate the total path detection latency. The total latency to detect a path is, in the worst case, the sum of the detection latencies for all the individual links at each hop. We assume the link detection process is time slotted and at a given time only one link detection can occur. Then the latency involved in N link detections, (l_N), in a collision free condition is:

$$l_N = \sum_{m=1}^{N} [r + d_m - (X_m - t_0)] = N \times r + \sum_{m=1}^{N} [d_m - (X_m - t_0)] \tag{5}$$

Since $(X_m - t_0)$ and d_m are exponentially distributed $[d_m - (X_m - t_0)]$ will also be exponentially distributed with parameter λ and $\sum_{m=1}^{N} [d_m - (X_m - t_0)]$ will follow *Gamma* $(N, \frac{1}{\lambda})$ [30]. Therefore, the statistical average link latency of total N link detections (L_N) in a collision free condition can be approximated by:

$$T_{neighbour} = E[l_N] = N \times r + E\left[\sum_{m=1}^{N} (d_m - (X_m - t_0))\right] = N(r + \frac{1}{\lambda}) \tag{6}$$

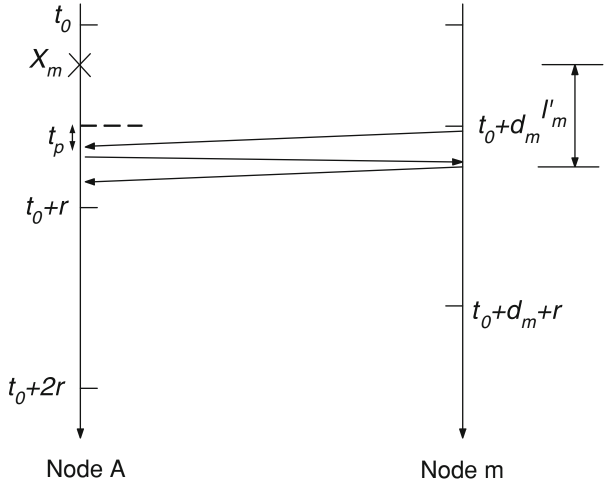


Fig. 4 Proposed fast neighbour detection

7.2 Proposed Fast Neighbour Detection Scheme

As explained in Sect. 4.1.2, neighbour detection consists of exchange of one HELLO message and two handshake signals as shown in Fig. 4. Let the latency involved in a link detection be l'_m, then, under our proposed scheme, the link discovery latency can be approximated as:

$$l'_m = t_0 + d_m - X_m = d_m - (X_m - t_0)$$

Now the total link detection latency of N neighbours is:

$$l'_N = \sum_{m=1}^{N} (d_m - (X_m - t_0))$$

By following procedures similar to the development of (5) and (6), the statistical average link detection latency of N neighbours (L'_N) in a collision free condition is:

$$T_{neighbour} = E\left[l'_N\right] = E\left[\sum_{m=1}^{N} (d_m - (X_m - t_0))\right] = N\frac{1}{\lambda} \tag{7}$$

From (6) and (7) we can conclude that the latency involved in the proposed fast neighbour detection scheme is much lower than that of the HELLO based neighbour detection scheme.

8 Base Station Complexity Analysis

The proposed algorithm of Sect. 4.5 is heuristic in nature and therefore it has linear complexity with respect to number of nodes. In determining metrics only interference and end-to-end throughput will constitute complexity as the remaining metrics involves only exchange of CCHs. If we assume equal 1 operation for addition, division and multiplications then the total number of operations required to determine the interference metric for a source to destination path is $4Kh$ where h is the number of intermediate nodes in the communication. Also if we assume equal 1 operation for exponential, addition, multiplication and division then the total number of operations required to determine the end-to-end throughput metric of (4) is $15Kh$

where K and h are upper bounded by n. Therefore, the complexity involved in determining the end-to-end throughput metric is upper bounded by n^2 and also the total complexity with respect to number of nodes is in the order of n^2. As base station is assumed to have enough computational resources this complexity can be handled.

9 Simulations and Results

We simulate a single-cell of radius 1 Km with nodes distributed as a two dimensional Poisson process with mean 0.5. We assume equal distribution of incentives for all intermediate relay nodes. For illustration purpose end-to-end delay threshold is considered as 100 ms, SINR threshold (β) for throughput calculation is taken to be 0.1 dB and the end-to-end throughput threshold is assumed to be 0.9. The CDMA codes are near-orthogonal with the correlation coefficient of 0.1 and the spreading factor (G) is taken to be 32. The Interference threshold (I_{max}) is chosen as 0 dBm. To validate the performance of the proposed model, a brute-force, Monte-Carlo simulation was carried out by randomly selecting the source and destination nodes, and the results were averaged over at least 500 realisations of the node distributions. The simulation results are presented with error bars. $[\mu - \sigma, \mu + \sigma]$ is the interval for error bars, where μ is the sample mean and σ is the standard deviation of the samples. In this underling simulation environment we compare our proposed algorithm with:

- Interference Aware Routing (IAR) proposed in [31]
- Optimum Hop Size Routing (OHSR) proposed in [21]
- Nearest neighbour routing

9.1 Total Power Analysis

The transmission power model used for our analysis is:

$$p_{ij} = \alpha d_{ij}^4 + \psi$$

where ψ is a constant to represent minimum transmit power (p_{min}), and α is the normalisation constant. For simulation purposes, let us assume $\psi = 0.1$. Since the radius of the cell is 1 Km and the maximum transmitted power from mobile handset will be of the order of 2 Watts, we can rewrite the above equation as:

$$p_{ij} = 1.9 \times 10^{-12} \times d_{ij}^4 + 0.1$$

Apart from the transmission power, we also consider receive power in our power analysis, since the power spent in the local oscillators and bias circuitry of the low-power transceivers will be considerable in receiving the packets [32]. We assume a constant power of 50 mWatts per packet per node in receiver circuitry in our simulations. Figure 5 compares the total power spent per packet transmission in various algorithms. From Fig. 5 we can infer that the proposed routing algorithm has significantly less total power requirement per packet transmission. Moreover, as the number of nodes increases the total power spent per packet transmission in the nearest neighbour algorithm and the IAR algorithm increase considerably. This is because though the single hop transmission power in both the algorithms is less, these algorithms result in many intermediate nodes as the node density increases; hence the total transmitted power and the power spent in receiving will be significantly higher. The OHSR algorithm minimises the maximum hop length. However, most of the time it gives a path with a greater number of hops of significantly large length.

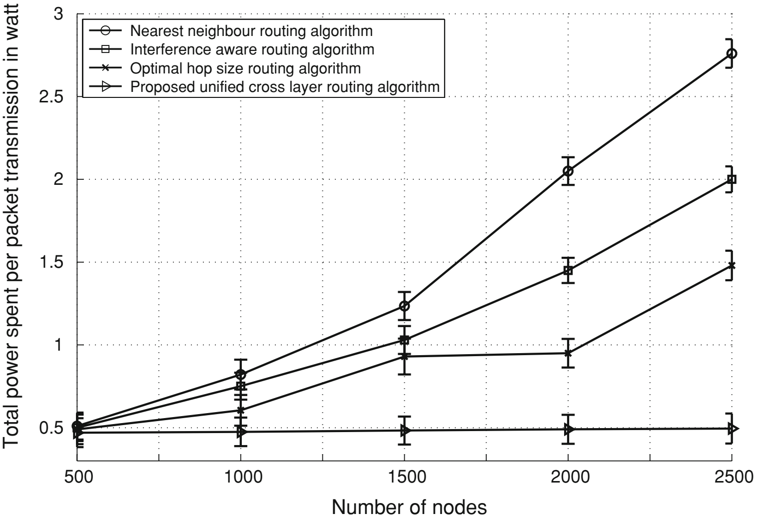


Fig. 5 Total power spent per packet transmission versus number of nodes

9.2 End-to-End Throughput Analysis

We assume 50 (i.e. $K = 50$) fixed nodes of uniformly distributed interferers for ongoing communications. We have plotted the lower bound on end-to-end throughput by varying the number of nodes in Fig. 6. From Fig. 6 we can deduce that the lower bound on end-to-end throughput in the case of the proposed algorithm is considerably higher. This is because from (4) it is clear that lower bound on end-to-end throughput reduces as the number of hops increases. All nearest neighbour, IAR and OHSR algorithms result in a greater number of hops. Moreover, as the node density increases the number of hops increases in all the three algorithms. However, in our proposed algorithm we maintain the end-to-end throughput by incorporating a constraint on it.

9.3 Incentives and End-to-End Delay Analysis

In the end-to-end delay, transmission delay (including queuing delay) in the intermediate nodes is a more significant than the propagation delay. Therefore, when the number of intermediate nodes increases, the end-to-end delay will also increase. Moreover, the incentives paid also increases linearly as the number of intermediate nodes increases. Hence, the algorithm behaves similarly in terms of the end-to-end delay and incentives paid. We assume a constant transmission delay of 30 ms per node. Figure 7 shows end-to-end delay performance of various routing algorithms. From Fig. 7 we can infer that the end-to-end delay in the case of nearest neighbour routing algorithm and IAR algorithm are at intolerable levels for voice communication, while the end-to-end delay in the proposed approach is around 100 ms, which is insensitive to human ears. Also, as the number of nodes increases the delay increases because as the node density increases the number of hops increases in each of the nearest neighbours, IAR and OHSR algorithms as explained above. The incentives offered also will behave similar to end-to-end delay.

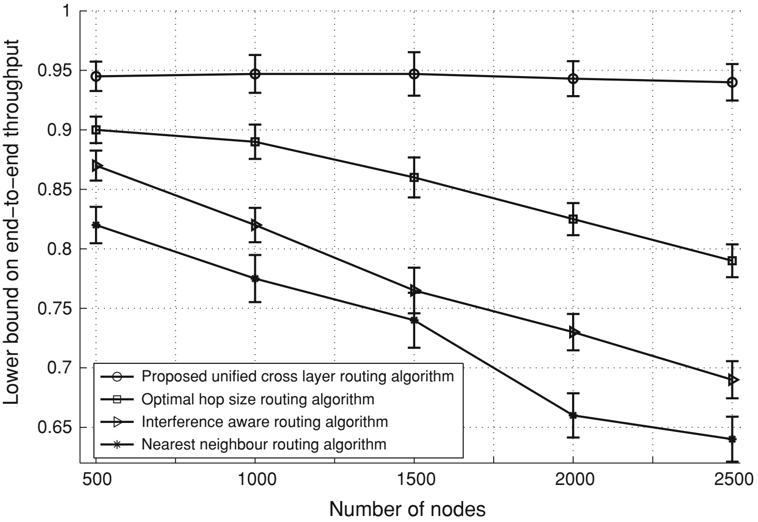


Fig. 6 Lower bound on end-to-end throughput versus number of nodes

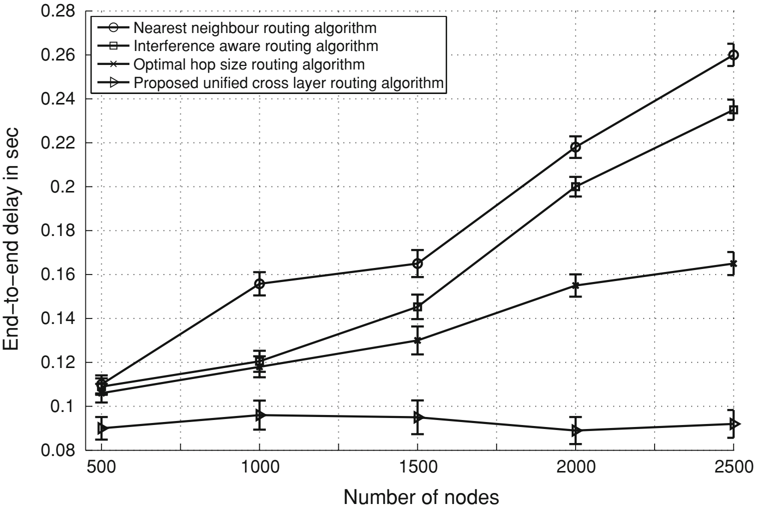


Fig. 7 End-to-end delay versus number of nodes

10 Conclusion

This paper proposes a unified cross-layer routing protocol for MCNs by taking necessary performance metrics into account. The proposed algorithm is compared with the existing MCN routing algorithms (such as the interference aware routing algorithm, nearest neighbour algorithm and optimum hop size routing algorithm). We find that, compared to other algorithms, the proposed algorithm has better performance in terms of overall power consumption, end-to-end throughput, end-to-end delay and incentives paid.

We also present a fast neighbour detection scheme and route resilience scheme. Instead of using periodic HELLO messages, the proposed scheme adopts an explicit handshake mechanism to reduce the latency in neighbour detection. An analytical study of neighbour detection latency shows that the proposed scheme reduces the link detection latency compared to HELLO based neighbour detection algorithm such as OLSR and [33].

One of the drawbacks of the proposed routing mechanism is the potential extra traffic overhead introduced in dense networks with high node mobility. In order to mitigate the side effects of the proposed algorithms, in our ongoing work, we have been working on an adaptive solution to adjust the delay in sending handshake messages on the CCH dynamically based on network conditions. This is to balance the trade-off between throughput and control traffic overhead.

Also the hardware issue in designing handsets to enable mobile node to mobile node/base station multihop communications has to the addressed to realise the multihop cellular communications in practice. We hope that the revolution in the hardware miniature design will address this issue in near future.

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