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Geographic Multicast and Multiratecast for Wireless Sensor and Actuator Networks

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Geographic Multicast and Multiratecast for Wireless Sensor and Actuator Networks

by

Xue Hong Liu

Thesis submitted to the
School of Information Technology and Engineering
in partial fulfillment of
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Master of Applied Science

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Abstract

Abstract - We introduce fully localized protocols Geographic multicast routing (GMR) and Multiratecast routing (MRC) for wireless sensor networks. Geographic multicast routing (GMR) efficiently delivers multicast messages to multiple destinations. Each forwarding node selects a subset of its neighbours as relay nodes towards destinations. GMR optimizes the cost over progress ratio where the cost is equal to the number of relaying neighbours and the progress is the overall reduction of the remaining distances to destinations. GMR's cost-aware greedy neighbour selection achieves a good tradeoff between the bandwidth of the multicast tree and the effectiveness of the data distribution. It also achieves $O(Dn \min(D, n)^3)$ computation time, where n is the number of neighbours of current node and D is the number of destinations. Simulation results show that GMR outperforms position based multicast in terms of cost of the trees and computation time over a variety of networking scenarios. Multiratecast routing protocols (MRC) are first fully localized multicast algorithms to solve the multiratecast problem in wireless sensor networks, where source node sends reports to a fixed number of sink nodes at different frequencies (rates). We propose two multiratecast algorithms. The first is Rate Cost Multicast routing (RCM) that applies destination set partition, and calculates best relay neighbour sets with minimum rate cost. Three different rate cost calculation methods are studied to get the best choice of the overall rate cost metrics. The second is Maximum Rate Multicast (MRM) protocol that simplifies the forwarding decision. It selects next forwarding neighbour that provides maximum progress for destinations with the highest rate. Simulation results show that RCM provides best performance in network with small destination number while MRM has comparable performance for network with large number of destinations. As in traditional geographic routing algorithms, deliveries to all destinations in both GMR and MRC are guaranteed by applying face routing when necessary.

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List of Acronyms

GFG	Greedy Face Greedy routing protocol
GG	Gabriel Graph
GMP	distributed Geographic Multicast routing Protocol
GMR	Geographic Multicast Routing protocol
GPS	Global Positioning System
MAC	Medium Access Control
MRC	Multiratecast routing protocol
MRM	Maximum Rate Multicast routing protocol
RCM	Rate Cost Multicast routing protocol
PBM	Position Based Multicast routing protocol
SPBM	Scalable position Based Multicast routing protocol
UDG	Unit Disk Graph
WSN	Wireless Sensor Network

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Chapter 1

Introduction and Motivation

A wireless sensor network (WSN) is a type of self-configured, self-organized, static or mobile network that consists of a set of networked sensor nodes. Sensor nodes are usually small size, inexpensive wireless equipments with limited communication, computation and energy resources. They sense environment and communicate among each other using wireless links. They work in a distributed way, and collaborate to perform automated tasks requiring sensing capabilities. The number of such sensors in a WSN is expected to be large, in the order of hundreds or thousands. The wireless sensor communication is usually performed through wireless channel in a multi hop way. Data is sampled at source node, transmitted to neighbour node and relayed by intermediate node until destination node is reached. "Routing protocols for wireless sensor networks are used to transmit messages from sources to destinations. They can be classified as unicast, broadcast or multicast. Unicast routing is used to send a message generated by a sensor node to a single destination or sink. Broadcasting is used to send a message from a sensor node to every other node in the network. Multicasting is used to deliver messages from a single source to a set of destinations." [3]

1.1 Geographical Multicast Routing

Possible applications of WSNs are endless, including habitat monitoring, wildfire detection, pollution monitoring, etc. In many of these scenarios, there are applications in which a single sensor needs to send the same data to multiple destinations. Those applications can benefit from the use of multicast communications to reduce bandwidth consumption in the network. Examples of those applications include data replication, assignment of tasks or sending of commands (especially in sensor and actuator networks) to a specific group of sensors, queries to multiple sensors, etc. For instance, one real application we are using is the control of water sprinklers for water irrigation, in which, in many cases, sensors may need to send the same information to multiple actuators. Actuators

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are in charge of opening or closing valves depending on the need to water some areas based on information measured from sensors. Some of these applications are data-intensive; therefore, it is of paramount importance for them, to count on an efficient multicast mechanism being able to alleviate the overall consumption of resources in the network. Multicasting is a technique used to deliver messages efficiently from a source to a set of destinations. Multicasting protocols try to minimize the consumption of network resources taking advantage of the fact that some parts of the paths from the source to the destinations can be shared by multiple destinations. The larger the path shared, the lower overall bandwidth consumption is obtained.

There have been a lot of multicast routing proposals for ad hoc networks [30], each of them based on different design decisions. Unfortunately, they cannot fulfill the unique requirements of WSNs effectively. They are mostly designed to deal with highly mobile nodes, with higher processing and storage capacity, and a much limited amount of nodes. In addition, WSNs are characterized by their topological changes due to node failures or duty-cycle operation. These characteristics make localized routing algorithms [38] more appropriate for WSNs. Unlike centralized ones, localized algorithms do not need to know the complete topology to take routing decisions. Furthermore, centralized algorithms introduce too much overhead to be used in WSNs.

Providing efficient multicast routing in WSNs poses special challenges compared with unicast data delivery. In fact, the problem of computing a minimal bandwidth consumption multicast tree in wireless multihop networks was recently proven [7] to be NP-complete. This becomes specially challenging when overhead needs to be kept low due to the limited battery, storage capacity, bandwidth, and processing power of sensor nodes.

A number of multicast routing protocols have been proposed to enable the multicast applications. They can be divided into two main groups: multicast protocols that requires global structure such as tree based [8, 9, 14, 15, 16] or mesh based protocols [10, 11, 12, 13], and protocols that use only local information such as geographic routing or position based routing [6, 1, 3].

Multicast protocols that require global structure need to construct and maintain a routing distribution table before and during routing processing. They are considered very

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challenging for wireless sensor networks for two reasons: First, the network nodes in sensor network normally have limited CPU power and memory so it is challenging to store the routing table in a node. Secondly, some characteristics such as the node failures, the membership changes, the topology changes all makes it very expensive for routing table update on each node.

In this thesis, a new multicast geographic routing protocol GMR is presented in which the main contribution is a new cost-aware heuristic neighbour selection scheme. The new scheme requires a low computational cost and is able to compute very efficient multicast paths. In addition, the protocol does not require any type of network-wide flooding. It is solely based on local geographic information obtained from neighbouring nodes. By selecting neighbours based on our cost-aware metric, the proposed protocol is able to outperform previous schemes in terms of the cost of multicast packet delivery, and the computational cost of computing such trees.

GMR is to design a multicast protocol that focus on localized construction of bandwidth optimal multicast trees. Thus, given that the focus is on the efficient neighbour selection function, positions of destinations are assumed to be known to multicast sources. Furthermore, given that the number of destinations is expected to be low for the multicast scenarios considered for sensor networks, the proposed scheme is mainly concerned with an enhanced neighbour selection criterion. The proposed multicast protocol GMR selects neighbours based on the cost over progress framework that was first introduced by Kuruvila *et al.* [19] (for routing problem) integrated with a greedy neighbour selection. The cost function considers the number of transmissions based on the results of Ruiz *et al.* [7], that showed that the optimality of a multicast tree in terms of bandwidth consumption needs to be evaluated in terms of the minimization of the number of transmissions performed. GMR avoids hard-to-tune parameters, has lower computational costs, and computes multicast paths with a lower overall cost. Moreover, GMR scheme is general enough to be easily coupled with any scalable group management scheme.

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1.2 Multiratecast Routing

There are WSN applications that a single sensor needs to sample data and propagate them to potential consumers at different required rate. For instance, when an environment monitor sensor network monitors weather change in a forest, sample temperature or earth vibration data may be reported at different rate to different sinks. Multiratecast protocols are proposed in this thesis to try to minimize the consumption of network resources by taking advantage of sharing some of the paths from the source to the destinations while each destination's specific rate requirement can still be satisfied.

One important multiratecast application is for network with backup base stations or backup sinks. Data are collected by sensor nodes and are transmitted and stored in base station (sink) nodes for further analyze and study. Data rate for sending to primary sink is high. Data rate for second sink is medium rate and rate is lower for third sink node and further lower for rest of back up sinks. If primary sink fails, second sink node should take over the network. If second sink fails, the third sink node takes over the network and it continues... The total backup network requires that data are captured and sent to different sink nodes by different rate range from high to low.

There are scenarios that infrastructure network does not exist. The backup sink nodes may need wireless data transmission for whole processing. For example the backup sinks can be a few laptops in special circumstances to capture temperature or chemical data. Human observers may check data on laptops for certain action. If primary sink failed, human observer may need collect information from backup sink and still receive useful information.

Sinks may run a separate protocol which checks if primary sink is fail. If so, other sinks may remove it from the network, select new primary sink, and send new reporting rates requirements to all sensors. Once rates for every sink are determined, a dynamic routing protocol should be designed to support multiratecast efficiently. The protocol also should be able to adapt to rate change quickly when the sink nodes join or leave the network or when network topology is changed.

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As the following example: There are three sink nodes in the network “a”, “b”, “c” which requires data rate 10, 5, 8 respectively. Sink “a” is the primary node, source node S collects data and sends full information to sink “a” at rate 10. Data will also be split and sent to backup node “b” and “c” at rate 5 and 8. When a relay node branches message to next forwarding nodes at different rate, data diffusion and reassemble may be required. Paper [21] describes a data-centric routing that is related to data content processing. However, the data process part is another research topic and we focus on routing path study in this thesis.

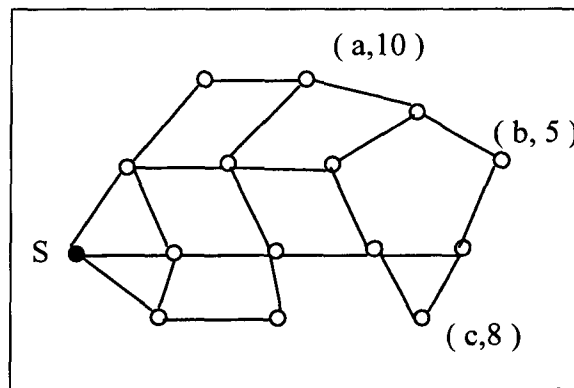


Figure 1 Network with Multiple rate destinations

For the network example in Figure 1, there can be two different routing paths as showing in picture (a) and (b). They have same transmission number 6 (hop count). Protocols that use hop count as performance guidance could not tell the difference of routing paths in picture (a) and (b). However, if we consider sum of data rate as routing cost, total data transmission rate cost at routing paths in (b) is 51 while total rate cost in (a) is 60. Routing path is (b) is more efficient in rate cost metric.

Introduction and Motivation

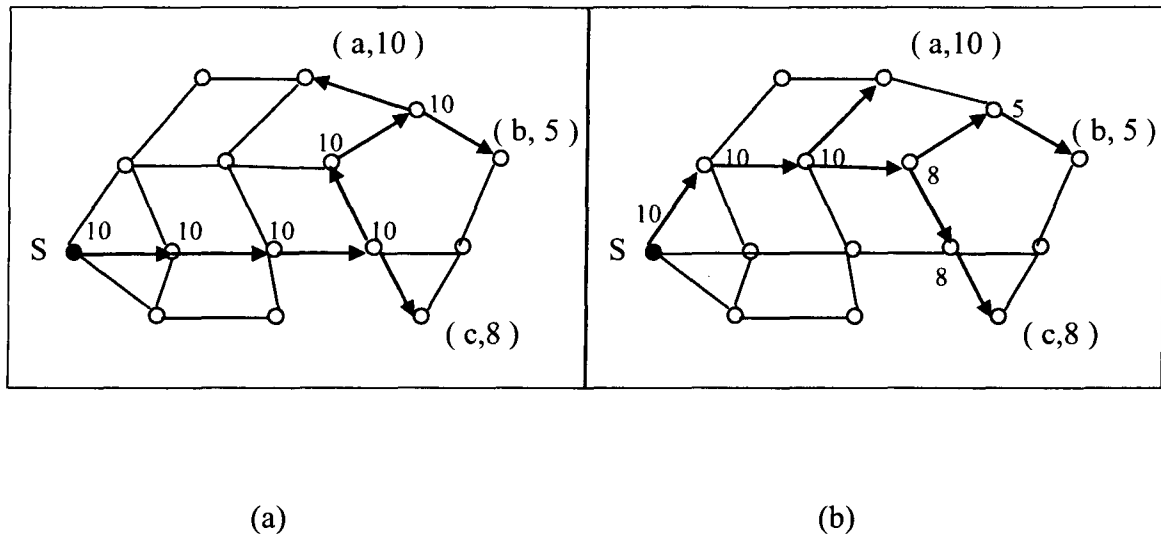


Figure 2 Different rate cost paths

There are multicast protocols that use only local information for multicast routing. Existing multicast protocols include PBM [2], GMR [3], and GMP [1]. However, they do not satisfy multiratecast in common that they do not consider the specific multi-rate routing requirement in routing decision. They mainly use hop count as the routing performance metrics, it may not reflect correct routing cost for multiple data transmission where paths with same hop count may transmit data at different data rate at each transmission.

There are also existing rate aware multicast protocols. However, they are either protocols working on changeable rate or protocols requiring global tree construction suitable for wired sensor network. They do not fulfill the application requirement this thesis studies. Protocol proposed in [4] is a protocol that monitors wireless link and adapts data transmission rate to achieve lowest total transmission time. It does not provide solution for the specific application requirement that each destination request multiratecast data by a different rate. Protocol in [17] is the only existing protocol that related to the multiratecast, however, it is a tree based non-localized algorithm based on edge cost calculation. In this protocol, the source node constructs multicast tree by sending and receiving explore/ack messages to destinations. As mentioned above, it has amount of overhead control messages and is not efficient in wireless sensor networks.

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Routing protocols that support multiratecast should consider data rate in routing path selection and also considering the wireless multicast advantage. In wireless network, a message transmitted by a node is received by all its neighbours. This means that one single message is sent at certain rate, it is received by all the relays nodes. This property is commonly known as the wireless multicast advantage. The relay node may continue data forwarding at same rate, or it may forward selective part of coming data at a reduced rate for destinations that only require lower data rate. Splitting data and lower transmission rate according to destinations' requirement can reduce overall routing cost. However, existing multicast protocols are not able to achieve rate based optimization because considering only hop count in performance metrics may not reflect the optimal path for network with multiple rate destinations.

In this thesis, two purely localized network layer multiratecast protocols are proposed to support for dynamic multiple rate routing in wireless sensor networks. The first protocol proposed is Rate Cost Multicast routing protocol (RCM). At each forwarding node, RCM applies destination set partition and then calculates rate cost to select best next forwarding nodes. This algorithm explores three different RCM rate cost calculation functions and compares their routing performance. RCM ensures that at each forwarding process, the rate-based cost to next hops is minimal. The second protocol proposed is maximum rate multicast (MRM). It has a rate prioritized greedy multicast with simpler calculation. It has comparably good performance and is very suitable for dense network with large number of destinations.

The MRC protocols have three unique characteristics: Firstly, they are purely strict localized algorithms that use only node position information to make routing decision. Secondly, they should consider destination data rate when making routing decision, ensure paths that each destination receives data at its requested rate. Thirdly, they aim at overall multicast paths from single source to multiple destinations that use minimum network resources; we define it as rate based cost including hop count and data rate consideration.

The Multiratecast protocols are unique from existing multicast protocol in that they adjusts routing paths according to data rate as well as hop count and distance. They are the first protocols that explore data rate as a major parameter in a localized routing performance

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metric. For a network with multiple rate requirements in destinations, they are able to efficiently find optimal paths for all destinations with lowest overall rate cost.

1.3 Network Model and Assumptions

In this paper, we model a WSN as an undirected graph $G = (V, E)$, where V is the set of vertices and E is the set of edges. The model, known as unit disk graph (UDG), assumes that the network is two-dimensional (every node $v \in V$ is embedded in the plane) and wireless nodes are represented by vertices of the graph. Each node $v \in V$ has a transmission range r , which is equal for all nodes. Let $\text{dist}(v_1, v_2)$ be the distance between two vertices $v_1, v_2 \in V$. An edge between two nodes $v_1, v_2 \in V$ exists $\Leftrightarrow \text{dist}(v_1, v_2) \leq r$ (i.e., v_1 and v_2 are able to communicate directly).

Both Geographic Routing (GMR) and Multiratecast (MRC) Algorithms are generalized position based multicast protocols. We assume that in the network, any node knows its own position, its neighbors' position. Source node knows all destinations' positions and the required data rates. Sensor nodes may periodically exchange "hello" message between neighbors to update position information or use other types of location updates methods [45] to get neighbor's position. The destinations' position information available to sender is standard assumption that many localized distributed routing protocols are based. [1][2][3][43][47][48][49][50][51][51][52]. A survey of location update can be found in [45]. Multicasting and multiratecasting to a set of destination addresses and to a set of group addresses are separate problem statements, corresponding to different scenarios and applications. We are interested only in scenarios with relatively limited number of destinations, when positions of destinations are known to reporting sensor, and therefore we do not address group scenario cases. How sensor learns these positions is a separate problem, also beyond the scope of this work. One possible application and justification for not using group addresses, and for providing positions to reporting sensor, is reporting to few sinks from a sensor networks, with same (multicasting) or different rates (multiratecasting), where there is no infrastructure network available to assist. These sinks can, in preprocessing step, inform all sensors about their position. This could be done by

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sending strong signals reaching all sensors; or by flooding that starts from each of sinks and propagates inside sensor networks. Other multicast routing protocols may not need position information but this is normally at the expense of flooding the whole network in search for possible sources or destinations, thus introducing a different kind of overhead compared to overhead related to location service here. In this thesis, we follow the common assumption of many localized research that positions of neighbors and destinations are available.

We also assume there is no movement of destinations during routing process. This is because sensor networks are static most of the time. Although in the future advanced study stage, mobility should be included in routing algorithm analysis; simulation in this thesis do not consider movement to get the simplified first sets of results. Besides, we need to approve that performance of algorithms on a static special case is good before we move on to study algorithms in mobile situation.

We assume network nodes are capable of forwarding message at any data rate that destinations require. Each relay node receives message at the maximum rate it needs forward to and is capable of forwarding message at any rates required by its next forwarding nodes. Data diffusion and reassemble may be applied in MRC when a relay node branches message to next forwarding nodes at different rate. Paper [21] describes a data-centric routing that is related to data processing. However, the data process part is another research topic and we focus on routing path study in this thesis.

Data routing starts from source node when it selects first forwarding neighbours. It then sends out message to the selected forwarding nodes. The message contains routing information related to destinations it needs forward to, including positions, data rates etc. The forwarding nodes make similar forwarding selections; retransmit the message to its next forward nodes until the message reaches destinations. Forwarding selection is solely based on local neighbour positions and routing information contained in message. There is no global routing table that needs to be established. Each node makes routing decision purely based on local calculation. We assume that the network has ideal MAC and physical layer and there is no packet loss during transmission.

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Summary of network assumptions:

- An ideal MAC and Physical layer provide reliable transmission.
- No packet loss during packet forwarding. Each time a node transmits a packet; all its selected next forwarding neighbours receive this packet with probability 1.
- A static network while multicasting is in progress. Node mobility is not considered for simulation. The positions of nodes do not change during routing.
- No transmission delay.
- Any node knows its own position, its neighbour's positions.
- Source node knows destinations' positions by a type of location service.
- Source node knows destinations' request data rate.
- Each node in the network is capable of routing at the maximum data rate of destinations.
- Message is able to be replicated at relay node at any rate required by destinations, proper data processing is available to assist next data forwarding at lower rate

1.4 Publications related to this thesis

Out of this thesis we made one publication and another one is in preparation:

1. Bandwidth-Efficient Geographic Multicast Routing Protocol for Wireless Sensor Networks
2. Multiratecast in Wireless Sensor Networks

1.5 Thesis Organization

The remainder of the thesis is organized as follows: Section 2 gives literature review of related multicast protocols. Section 3 described the Geographic Multicast Routing Protocol (GMR). Section 4 provides the GMR performance evaluation. Section 5 describes

Introduction and Motivation

the two proposed Multiratecast Routing Protocols (MRC). Section 6 provides routing performance analysis for MRC. Section 7 summarizes and discusses future work.

Chapter 2

Literature Review

There have been a lot of routing protocols developed for wireless sensor networks. Based on different data distribution, they can be divided to Unicast, Multicast, and Broadcast protocols. Unicast routing is a one-to-one routing that a message generated by a sensor node is sent to a single destination or sink. Broadcasting is one-to-all routing that is used to send a message from a sensor node to every other node in the network. Multicast routing is used to deliver messages from a single node to a set of destinations. Due to the limitation of wireless sensor networks such as limited energy resources, high cost of transmission, limited processing capabilities and restricted lifetime, it is inefficient to use broadcast (flooding) as a routing scheme in sensor networks. Multicasting protocols try to minimize the consumption of network resources by taking advantage of the fact that some parts of the paths from the source to the destinations can be shared by multiple destinations.

2.1 Unicast protocols in WSN

Based on how routing path is found from source node to destination, Unicast protocols can be divided to two main categories: Non-Geographical and Geographical routing.

Most Unicast protocols are non-geographical routing protocols. They do not directly use geographical information in routing decision. They can be further divided into three approaches: the proactive approaches, the reactive approaches and hybrid approaches. The proactive routing protocols have characteristic that each node in the network maintains a route to every other node in the network at all times. Periodic routing information update and maintenance is required for each node. Examples of proactive routing protocols are DSDV [24] and OLSR [25]. The reactive routing protocols are also called on-demand routing. Routing path is discovered and computed based on routing demand. It has less overhead compared to proactive approaches but have longer route acquisition latency.

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Examples of reactive routing protocols are AODV [26] and DSR [27]. Hybrid routing approaches combine the proactive and reactive routing protocols in various ways to allow flexible routing based on network characteristics.

Geographical unicast routing protocols [29][39][6][40][38][41][42][23] had characteristics that network nodes are able to continually obtain geographical information through a type of Location Service such as GPS and the geographical information is used in routing path selection. Geographical routing can be further divided into non-localized protocols and localized protocols. Non-localized protocols utilize geographical coordinate to perform global routing discovery from source node to destination node such as LAR [29]. Localized geographical routing protocols [39][6][40] have proven to be very effective in providing unicast routing in the common resource-constrained scenarios [38][40][42] that WSNs present. They work with local information, require a low computational cost, adapt very fast to changing network conditions, and are able to route messages with a very low control overhead. Each node taking part in a routing process takes decisions about which neighbour is the best one to be selected as next forwarder in order to carry the message as nearer to the position of the destination as possible. Thus, the information about position is fundamental. Although the use of hardware-based positioning systems such as GPS might be possible, there are scenarios (e.g., indoor) in which they cannot be effectively used. However, they can also work based on virtual coordinates, as shown in [22] and [18]. Similarly, the proposed multicast protocols in this thesis can also work based on these virtual coordinates. GFG [6] is an example of localized geographical routing that is duplicated as in GPSR [23]. The routing in GFG [6] composes two schemes: greedy forwarding mode for nodes that have neighbours closer to destination than itself and recovery mode for nodes do not have closer neighbours to destination. In recovery mode, GFG [6] applies face routing until greedy mode routing can be resumed.

2.1.1 GFG [6]

GFG [6] is location-based Unicast routing protocol for wireless network. It guarantees packet delivery in a connected planar graph. It consists of two routing modes:

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greedy routing mode and recovery mode. Packet routing starts from greedy mode. Each GFG packet contains destination's location. Every node in network periodically broadcasts a beacon packet within its own radio range which contains its current location information. Every node stores its neighbors' location information after receiving beacon packets. Starting from original node, each greedy mode forwarding node calculates the distances from every neighbour node to the destination node. The neighbour node located closest to the destination node is selected as next hop. When a forwarding node cannot find any node that is closer to destination than itself, the routing is known as local optimum situation and is changed from greedy mode to recovery mode. Packet routing in recovery mode traverses along faces of a planar sub-graph of original network graph. The most common planar sub-graph used is the Gabriel Graph (GG), which contains an edge CA if the disk with diameter CA contains no other nodes inside it. Note that node C may decide which of its edges belong to GG based on the position of itself and its neighbours, without sending any message for the purpose of constructing GG. Face routing continues along faces until the packet reaches a node that is closer to the destination than the node where greedy mode failed. Then the routing resumes to greedy mode. Packet is routing in either greedy mode or recovery mode until reaches destination.

2.2 Multicast protocols in WSN

Providing efficient multicast routing in wireless sensor networks has specific challenge compared to Unicast routing. Besides the common resource limitations of sensor network, multicast routing need compute efficient multicast distribution paths that making use of a minimal amount of control information, sending as few as possible duplicate packets, and consuming minimal overall network resources to all destinations.

There have been a lot of multicast routing proposals for wireless sensor networks; each of them based on different design decision. Most of them are non-geographical routing protocols and are not designed to work in a localized way. Based on the routing paths structure they employ, they can be divided into tree-based protocols, mesh-based protocols and hybrid protocols [9, 15]. Tree based protocols have one shared path from source node to

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each destination. They use lower number of relay nodes compared to mesh based protocols but the tree need to be reconstructed when links break due to node mobility. In addition, they also rely on periodic flooding that is a costly operation for sensor network. Examples of tree based protocols are MAODV [14], ADMR [31], and AMRIS [32]. Mesh-based protocols expand a multicast tree with additional paths so that they have multiple paths from source node to each destination. They have more redundancy in routing structure compared to tree-based protocols and the additional paths can be used to forward multicast data packets when some of the links break. The mesh-based protocols have proven to be particularly suited for scenarios with high mobility rates. However, the maintenance of these structures through periodic broadcasts and the large amount of duplicate forwarding makes them impractical for sensor network. Examples of mesh-based protocols are CAMP [10], ODMRP [11], NSMP [12], and DCMP [13]. Hybrid protocols are mix of tree and mesh protocols such as AMRoute [9] and MCEDAR [15]. For all above three types of protocols, their non-localized operation produces an excessive control overhead for wireless sensor network.

There have been multicast protocols for wireless sensor networks that take geographical information to perform multicast routing. They are also called Geo-Multicast protocols. However, applying geographical routing in multicast faces specific challenges such as how to select next forwarding nodes and perform efficient routing based on position information for multiple destinations. Various geographical multicast protocols have been proposed such as [1, 2, 3, 8, 33, 34, 35] to explore different ways to perform efficient Multicast. DDM [8] combines Unicast data tables for multicast data forwarding which requires additional overhead and makes it best suitable only for small multicast groups. LAM [34] makes use of broadcast so that it is impractical for wireless sensor networks. Protocol in [33] uses position information to build a multicast tree that aims at minimize the number of links. However, its cost calculation is not optimal because the wireless medium is one-to-many communication and cost should be better characterized by number of transmission nodes instead of number of links. Because of the design challenges of multicast, localized protocols are believed to be better suitable for wireless sensor networks

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[36]. PBM [2], GMR [3], GMP [1] are examples of localized geographical multicast protocols.

2.2.1 Localized Geographical Multicast

Localized multicast protocols usually use local geographical positions information of nodes to make routing decision. The position information can be acquired by location service such as GPS or virtual coordinates as in [18] and [22]. The position information is included in message header and is used at each forwarding node in next routing nodes selection.

2.2.1.1 PBM [2] and SBPM [43]

Position Based Multicast (PBM) [2] is one of the localized geographical multicast protocols. Although it is not initially thought for sensor networks, it fulfils most of the desired design criteria of localness and limited network overhead. PBM is a generalization of GFG[6] (Greedy-Face-Greedy) routing to operate over multiple destinations. It builds a multicast tree, whose shape can vary from the shortest path tree, to an approximation of a minimum cost multicast tree depending on a parameter denoted as λ . Authors in [6] try to find a good trade-off between the total number of nodes forwarding the message and the optimality of individual paths towards the destinations. Each node evaluates all possible subsets of neighbours (W) using a function to evaluate each $w \in W$. $f(w) = \lambda N + (1 - \lambda)S$, $0 \leq \lambda \leq 1$, where N is the number of neighbours in the considered subset ($|w|$) divided by the total number of neighbours (n), and S is the summation of the minimal distances from nodes in W to destinations, normalized by the summation of distances from the current node to all destinations. From all possible subsets of neighbours (W), the current node selects the one with optimal $f(W)$. If the best subset of neighbours is a single node, then that node will be the only relay for all the destinations. If a subset of neighbour nodes is selected, then each of the nodes in the subset will take care of routing the data messages to part of the destinations. If at some node there is no node provides advance towards one or more destinations, the

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authors use, only toward those destinations, a variant of face routing like the one we describe in 2.1.1 face routing. The main problem with this approach is that determining the optimal value for λ is not a trivial task. In fact, the authors evaluated different values of λ but they never came out with a determination of an optimal value. An additional issue is the fact that the algorithm is computationally expensive. Evaluating all possible neighbour subsets has an exponential computational cost as the number of neighbour's increases.

For networks with a very large number of multicast receivers, PBM may not scale well due to the need to include all destinations in multicast data packets. To improve the scalability, another protocol called scalable position based multicast for mobile ad hoc networks (SPBM) [43] was designed. It uses the geographic position of nodes to provide a scalable group membership scheme and to forward data packets. SPBM is mainly focused on the task of managing multicast groups in a scalable way. However, they fail to provide efficient multicast forwarding, because they use one separate unicast geographic routing for each destination. In addition, the interchange of routing tables between neighbours makes the protocol not as scalable to the number of multicast groups as PBM is.

2.2.1.2 GMP [1]

GMP [1] is another localized geographical multicast protocol proposed by Shibo Wu and K. Selcuk Candan. Starting from source node, it tries to build a virtual multicast Steiner tree by applying a stateless reduction ratio heuristic calculation. It traverses all destinations and tries to find a pair of destinations with highest reduction ratio and then creates a virtual destination node to represent the two destinations. It then repeats the calculation for new destination set including new virtual node and all rest of destinations to create next best virtual node until all destinations are represented by one final virtual node. After that, the multicast routing is simplified as Unicast from current node to final virtual node. GMR tries to find neighbour node closest to the final virtual node as next hop and sends message to the neighbour node. After neighbour node receives the message, it applies same reduction ratio heuristic calculation again to construct virtual tree and forwards message to next final virtual nodes. Same calculation continues until message reaches destinations. If no neighbour can

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provides forwarding to final virtual node or if it is not beneficial to create a virtual destination node, message is split and same algorithm applies on each of the split message routing.

The advantage of GMP is that it simplifies multicast routing to unicast by a linear virtual node calculation at each forwarding node. The disadvantage of GMP is that it calculates virtual destination by two destination nodes at a time. The created new virtual node may change the virtual destination topology. It will be less efficient routing if destinations are scattered around source node and may end of a virtual node on opposite direction of some destination nodes.

2.2.2 Multiple Rate Transmission Protocols

All the above routing protocols discussed in Section 2.1 and 2.2 are focus on single rate multicast routing where they consider all packages transfer in same rate from any forwarding node in the network. There are some protocols that perform routing at variable rate. However, none of existing rate aware protocols solve the same multiratecast problem we are discussing in this thesis: finding optimal localized multicast paths for destination with rate requirement.

Uyen and Xiong proposed a rate-adaptive multicast protocol for MANET [4]. The protocol constructs multicast tree that selects the paths with lowest total transmission time. It was based on simple routing metrics: among several paths between a sender and a receiver, the routing protocol selects the path with the lowest total transmission time. It has the reason that low transmission time helps increase throughput and reduce energy consumption. It monitors the quality of wireless links and suggest optimal transmission rate that helps to reach its goal. This protocol considers data rate adaption in routing path selection, but as mentioned above, it does not consider multiratecast requirement and is quite different from the problem we are trying to solve.

Gurdip, Sandeep and Sanjoy proposed a rate based propagation protocol [17] for sensor networks. In this paper, it tried to solve the similar problem that multiple destinations require data at different data rate. However, it is not a localized algorithm and does not have

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the assumption that network nodes know destinations position and rate information. It tries to construct a tree that has optimal total cost. The cost is calculated as sum of all edge cost that is the rate of sending data multiplied by the length of the edge. The path selection is based on a tree that is constructed by flooding Explore message and calculating the Ack messages at each network node. Starting from source node, Explore messages that contains current node's data sending rate are broadcasted to all current node's neighbours. Because destinations have multiratecast requirement, each node in the multicast tree must receive data at the rate which is equal or larger than the rate it need forward to its children. The initial Explore message from source node has rate 0. When the explore messages reach destinations, Ack messages are sent back including the required rate. When a relay node first receive a Ack message, it will set the rate in Ack as its planned rate and accepts the node that sent Explore message as its parent node and broadcast the same Explore message to all its neighbours. A relay node waits for all responses of its received Explore messages before sending back to its parent to update its rate. When a node receives more than one Explore message, it need process a cost compare calculation to decide if it needs switch parent node. It will calculate the cost of adding the new rate for current child and the cost of removing existing rate. By comparing the two costs of adding and removing parent results, the node can decide if it needs switch parents to the low cost node.

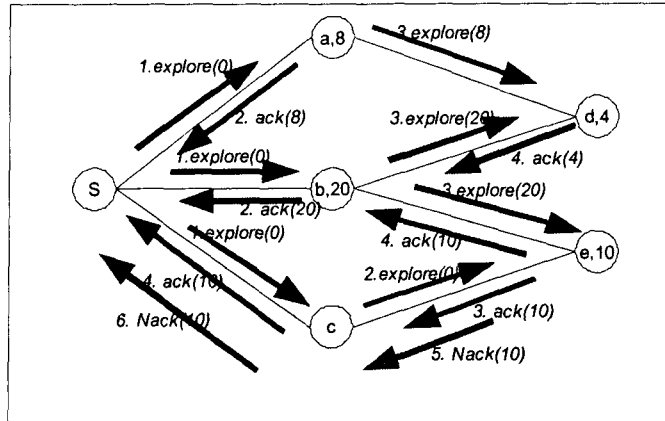
The following pictures show an example of the rate-based data propagation algorithm on unweighted graph. The data is sent from source node s to destination node a , b , d , e that request data at rate 8, 20, 4, 10 respectively. From the picture (a), we can see that source node s sends out explore message with rate 0 to all its neighbours. "The numbers next to the nodes in the figure denote the rate requirements of the nodes, and the index before the message denotes the sequence in which the messages are being sent." [17] Nodes a , b reply $ack(8)$ and $ack(20)$ message to node s and continue send out $explore(8)$ and $explore(20)$ message to all their neighbours. Node c is not a destination node, it simply continue the flooding with $explore(0)$ message. Node d receives explore message from a and b , it selects the node with higher rate as parent node and sends back $ask(4)$ message to b . Node e first receives $explore(0)$ message from node c and accepts c as parent node by sending back $ack(10)$ to node c . Later, after node c receives $explore(20)$ message from node b , it finds

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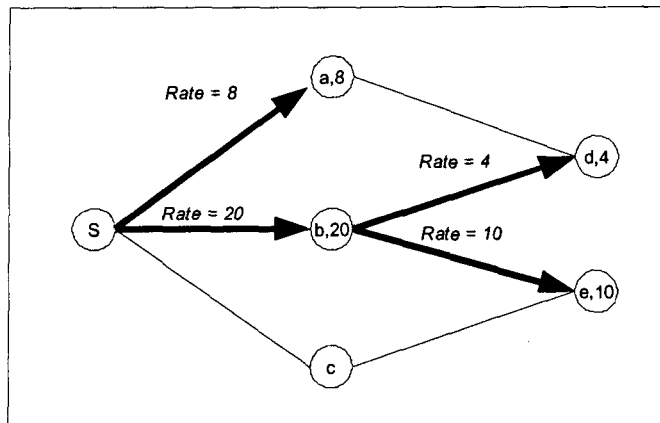
switching parent node from c to b will lower the cost of tree. Node c then sends $ack(10)$ to b to accept b as parent. Node c also sends out $Nack(10)$ message to c to remove it as parent node. The picture (b) shows the rate-based data propagation tree construction results. The edges in bold belong to data propagation tree and the rates listed beside those edges are the data rates need to be sent on the edges. The rate based propagation protocol [17] defines cost of the tree as the sum of cost of all tree edges, where the cost of the tree edge is rate of sending the data multiplied by the weight of the edge [17] which can be listed as $w(i, j) * r_e$, where $w(i, j)$ is the edge from i to j , r_e is the rate of sending data on the edge. For an unweighted graph as the example, if we use all edge weight as 1, the tree cost can be sum of data rate on all tree edges. Picture (c) shows the final routing paths and the cost based on all weight equal to 1 scenario. "In the case of weighted networks, the cost of using an edge is the weight of the edge multiplied by the rate at which data is sent over the edge." [17] The tree construction algorithm will be modified when accepting and switching parents because it needs new edge cost calculation to decide which operation takes lower cost. However, the paper [17] did not give a clear definition of the edge weight or the detail description of tree construction process on weighted graph.

As we can see from the Figure 3 example, the rate-based data propagation protocol [17] needs globally broadcast explore/ack messages to build the data propagation tree. It needs complex procedure to complete the tree construction. The complexity of tree calculation increases rapidly when there is large number of network nodes or large number of destinations. The tree structure is also fragile to maintain. It needs to be built before routing. If network is broken anywhere in the tree, it needs to be fully rebuilt before routing can be performed again. Mesh based solutions also need to be rebuild reporting tree when anything breaks and tree is extracted from mesh. Compared to tree or mesh based protocols, the proposed localized protocols have advantage that if there is any link broken, they need only locally update neighbor position information and routing process should be able to dynamically do different neighbor selection based on current neighbors' position.

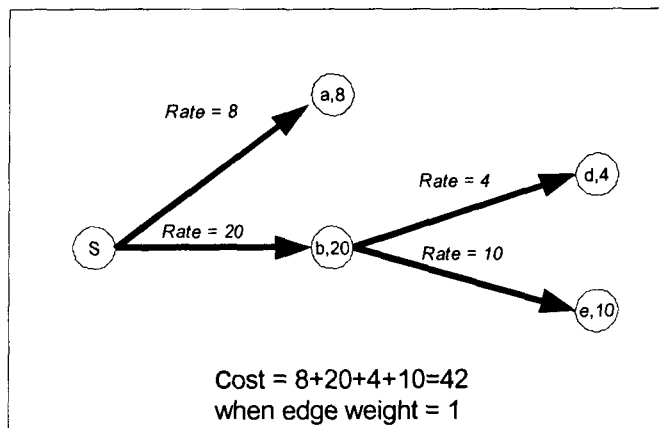
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(a) Tree construction process



(b) Tree construction result



(c) Final routing paths and cost

Figure 3 Illustration of the rate-based data propagation algorithm

Geographic Multicast Algorithm Description

Chapter 3

Geographic Multicast Algorithm Description

3.1 Overview

Geographic Multicast Routing (GMR) is a new multicast routing protocol for WSNs. The problem it tries to solve can be described as follows: given a multicast message generated by a source node, find a subset of nodes in the network so that the message is delivered to all destinations (sinks) with a very low consumption of bandwidth. To achieve the goal, the number of messages sent must be minimized, which means using a limited bandwidth and using as few sensors as possible to route the message to the destinations. It is important to design algorithms with a low computational cost, and constrained memory consumption. The protocol will be based on the idea of geographic routing, which is able to meet those requirements. We adapted it to deal with multiple destinations. As described in previous section, the sensor nodes are assumed to know their position, and they communicate their position to neighbours using periodic beacons. If real position (e.g. GPS coordinates) is not available, virtual coordinates can also be used effectively [18]. The source is also assumed to know the position of the destinations as in previous geographic routing protocols. To do that, schemes such as ALS [44] can be used.

Sensor nodes running GMR use the position of their neighbours to select which subset of them is the best to propagate the message towards the destinations. In our case, the selected subset is the one with the lowest total distance to destinations per unit of cost. When several neighbours are selected, each of them takes care of routing towards part of the overall set of destinations. Of course, due to the use of local information only, it may happen that the decision taken by a node is not always right. For instance, voids can make the protocol fall into a local minima scenario, reducing thus its performance. When that happens, (i.e., for some destinations no neighbour of the current node can reduce the distance) the algorithm uses face routing to exit the local minima until a new node providing advance is found. Within the remainder of this section, we will explain the general operation of the protocol in detail.

Geographic Multicast Algorithm Description

3.2 Cost Over Progress Metric

The cost over progress concept was first introduced by Kuruvila in unicast [19]. In Unicast routing, current forwarding node C tries to select a best neighbour node N that is closer to destination and has minimum cost over progress ratio. For each Unicast forwarding, the cost is 1 which is the hop count based on the assumption and metrics. The progress is the distance progress toward to destination.

We will now explain how the cost over progress metric can be used to select next hops towards destinations when nodes know their positions.

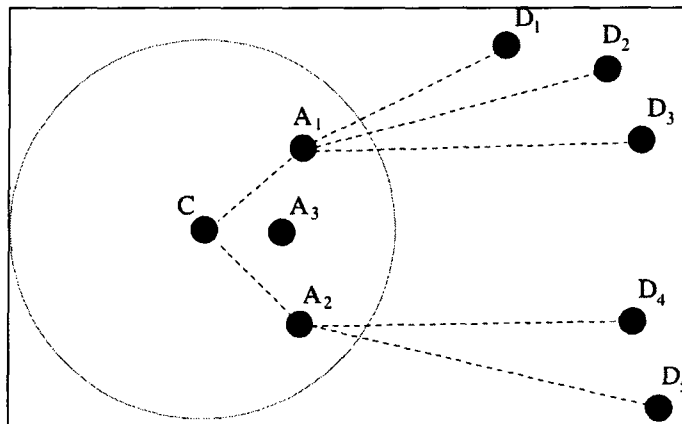


Figure 4 GMR cost over progress

Evaluating the candidate forwarding from C to A_1 and A_2

Consider the case in Figure 4 as illustration of the general principle. As we can see, a source wishes to send a packet to a number of destinations (sinks) with known positions. Unlike PBM, we describe here a solution that does not need any parameter. Assume that a node C , after receiving a multicast message, is responsible for destinations D_1, D_2, \dots, D_5 , and that it evaluates neighbours A_1, A_2 as possible candidates for forwarding. The whole task could be sent to one neighbour only (if there exist one that is closer to all destinations

Geographic Multicast Algorithm Description

than C), or could be split to several neighbours, each with a subset of destinations to handle. Hop count is expected to be proportional to distances.

As example in Figure 4, the current total distance for multicasting from node c is $T_1 = |\overline{CD_1}| + |\overline{CD_2}| + |\overline{CD_3}| + |\overline{CD_4}| + |\overline{CD_5}|$. If C considers A_1 and A_2 as forwarding nodes, covering D_1, D_2, D_3 and D_4, D_5 respectively, the new total distance is $T_2 = |\overline{A_1D_1}| + |\overline{A_1D_2}| + |\overline{A_1D_3}| + |\overline{A_2D_4}| + |\overline{A_2D_5}|$, and the progress made is $T_1 - T_2$ which is equal to the total distance progress of A_1 ($|\overline{CD_1}| + |\overline{CD_2}| + |\overline{CD_3}| - |\overline{A_1D_1}| + |\overline{A_1D_2}| + |\overline{A_1D_3}|$) and A_2 ($|\overline{CD_4}| + |\overline{CD_5}| - |\overline{A_2D_4}| + |\overline{A_2D_5}|$). Our aim is also to minimize the consumption of bandwidth, which is proportional to the total number of forwarding nodes selected. Thus, the cost is the number of selected neighbours, which in the above example is 2. Thus, the cost over progress of forwarding set $\{A_1, A_2\}$ is evaluated as $(2)/(T_1 - T_2)$. Among all candidate forwarding sets, the one with minimal value of this expression is selected. If there is no neighbour closer than C towards one or more of the destinations, then we have to enter into face mode. Section 3.3 describes how to proceed in this case.

As we can see from the above example, GMR extended the cost over progress to multicast scenario. Instead of select one best forwarding neighbour, it selects a best neighbour set with minimum cost over progress ratio. In general, the destination set partition could be $\{M_1, M_2, \dots, M_m\}$ with each destination being in exactly one of these subsets. Each M_i has its own cost-progress ratio, and the whole set partition also has its own cost-progress ratio as we explained before. The cost-progress ratio for the subset in Figure 4 can be computed as follows: The current total distance for multicasting is $T_1 = |\overline{CD_1}| + |\overline{CD_2}| + |\overline{CD_3}|$. The new total distance is $T_2 = |\overline{A_1D_1}| + |\overline{A_1D_2}| + |\overline{A_1D_3}|$, and the progress made is $T_1 - T_2$. The cost is the number of selected neighbours, which in the above example is 1. Thus, the forwarding cost over progress ratio for the subset is evaluated as $(1/T_1 - T_2)$.

Let P_i be the progress in M_i (each P_i is from above explanation). The cost in each M_i is 1 since all destinations in a given subset are served by the same (one) neighbour. The cost for the destination set M is total number of selected forwarding neighbour m which is equal

Geographic Multicast Algorithm Description

to the total number of subsets in set partition. The progress for set partition M is the total distance progress to all destinations in M . The cost over progress ratio can be calculated as following function:

$$C = \frac{|m|}{\sum_{i=1}^{|m|} P_i}$$

Where:

m is the number of selected forwarding nodes or subset number

P_i is the distance progress of each selected neighbour node

3.3 Multicast GFG

Multicasting is normally expected to proceed in greedy mode. That is, a node selects neighbours closer to the destinations than itself. However, a node C currently routing a message might not have any neighbour providing advance towards some of the destinations included in the message header. This situation is known as a local optimum for the greedy mode. Those destinations are included in a list called *multicast face list*. In unicast geographic routing, a recovery scheme called face routing [6] can be applied. It describes how to find an alternative route to escape from the local optimum until the message reaches a node where greedy mode can be continued. The route toward that particular destination is said to be in perimeter mode during the change from greedy to perimeter mode, and during the search for a node closer to the destination than the node that experienced local minima.

When a node C has to route in perimeter mode for some of the destinations included in the message, it decides the next hop or every destination in the face list according to GFG routing [6]. The protocol first decides which of the edges incident to belong to a planar subgraph. The most common planar subgraph used is the Gabriel Graph (GG), which contains an edge CA if the disk with diameter CA contains no other nodes inside it. Note that node C may decide which of its edges belong to GG based on the position of itself and its neighbours, without sending any message for the purpose of constructing GG. Face routing

Geographic Multicast Algorithm Description

is applied independently toward each destination in the face list. However, it may happen that the next selected neighbour is the same for several destinations. One single message is sent, including the list of all such destinations in perimeter mode.

When a message with some destinations being routed in perimeter mode arrives at a node C , it checks whether its position is closer to any of the destinations than the node where the multicast perimeter mode started. If the test is positive, such destination is removed from the multicast face list and added to the list of destinations to be routed in greedy mode. Multicast perimeter mode ends when the multicast face list is empty.

It is also possible that the current node uses the same neighbour to forward traffic to different modes. That is, greedy routing may be in progress for some destinations, while perimeter mode can be in progress for others. Current node C , in fact, transmits a single message (counted as one in the overall cost), listing all destinations, the mode being applied to each of them, and the neighbours that need to handle each of these destinations. As a result, a particular neighbour may be assigned to handle some destinations in greedy mode and some destinations in the perimeter mode.

3.4 Packet format

When multicast data is being forwarded, only those neighbours selected by the current node have to process the message. A GMR header is added to data messages to allow these nodes to realize that they are selected. It is also used to mark which destinations require perimeter mode.

That header is made of the position of the sender and a list of records, with one record associated to each relay. A message transmitted by a node is received by all its neighbours. This wireless multicast advantage can help us to further reduce the overhead of our protocol. Every record contains information about the identifier of the selected relay and a list of the destinations it is responsible for either in greedy or in perimeter mode.

The GMR message is in following format:

- **Message Head**
 - Source Node: The source node position information

Geographic Multicast Algorithm Description

- **Current Node:** The current forwarding node information
 - **Next Node:** The next forwarding nodes information
 - **Greedy Information:** Greedy routing information include a list of all neighbour nodes that will forward message in Greedy mode, the destinations that each neighbour node covers, their positions and required data rates
 - **Face Information:** Face routing information include a list of neighbour nodes that will forward message in Face node, the destination that each neighbour node covers, their positions, data rates, face start points.
- **Message Data**
- Data that need to be forwarded to destinations

3.5 Greedy Neighbour Selection

To reduce the calculation, GMR applies greedy neighbour selection process. It is concrete algorithm used by the current node to decide which subset of its neighbours will forward multicast data messages towards which subset of destination. Instead of traverse all neighbour nodes to find a best neighbour node for each subset, GMR defines a initial destination partition set M , and then merges the subsets in rounds to get a best set with lowest cost over progress ratio. In this section, we describe that part of the protocol, showing the benefit in terms of computational cost compared to previous works.

Given k destinations, a possible algorithm can consider all S_k partitions of the set of destinations. For each subset in a given set partition, the node checks whether it is possible to find a neighbour that is closer to all destinations in that subset than the current node C . If this is not possible for a subset, then this partition is ignored. If this is possible for each subset in the given set partition, then we measure the cost/progress ratio. Finally, after all the evaluations, we choose the best among all measured ones. This solution is applicable for a small number of destinations, e.g., up to five. For a larger number, it becomes exponential in k , and therefore a faster greedy solution like the one presented below is needed.

We start with the set of destinations $\{D_1, D_2, \dots, D_k\}$ for which there is a neighbour of the current node providing advance. We first group together, into the same subset, those

Geographic Multicast Algorithm Description

destinations for which the neighbour providing the most advance is the same. For instance, in Figure 4, the initial set partition to consider would be $\{\{D_1, D_2, D_3\}, \{D_4, D_5\}\}$, where A_1 serves D_1, D_2, D_3 and A_2 serves D_4, D_5 . The algorithm for initial destination set partition is as following:

Initial Greedy Destination Set

Greedy destination set partition starts with finding initial destination set $DS = \{M_1, M_2, \dots, M_k\}$ for the destinations list $\{D_1, D_2, \dots, D_m\}$. Those destinations, for which the neighbour providing the most advance is the same, are grouped together into same subset.

The

1. given destination list $D = \{D_1, D_2, \dots, D_m\}$, create empty destination set DS
2. for each destination D_k , do
3. find out closest neighbour N_k , save as pair (D_k, N_k)
4. for each neighbour N_i , do
5. create empty subset M
6. for all pair (D_k, N_k) , do
7. if $N_i = N_k$
8. add D_k to subset M
9. end if
10. end do
11. If M is not empty, append M to DS

Geographic Multicast Algorithm Description

12. end do
13. Get initial greedy destination set $DS = \{M_1, M_2, \dots, M_k\}$

The greedy set partition selection algorithm for multicast works as follows. First, the initial partition set $\{M_1, M_2, \dots, M_m\}$ is initialized as we explained before. The current cost-progress ratio is computed accordingly as $|m| / \sum_{i=1}^m P_i$ as we described in 3.2. The selection process then proceeds in rounds. In each round, all pairs are checked for possible improvement over previously best cost over progress ratio. Two partitions can be combined only if there are neighbours of the current node, providing advance towards all the destinations in both partitions M_i and M_j . However, their merging, if possible, may not result in a better cost over progress ratio. The pair that provides the best improvement is selected and merging is performed, creating the new set partition M . The process advances to the next round and starts over again with the new set M . If no pair provided any improvement then the process stops and the best set partition is found.

Greedy Destination Set partition Selection Algorithm

1. Initial set $DS = \{M_1, M_2, \dots, M_k\}$, $M_i = \{D_j \mid \text{same neighbour provides most advance}\}$
2. Calculate set cost for initial set $C(DS)$
3. Repeat
4. $BestReduction = 0$
5. for all pairs $\{M_i, M_j\}$ do
6. Find new set cost of new set DS' by merging of $\{M_i, M_j\} \in DS$
7. $reduction = C(M) - C(M')$

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8. if $reduction > BestReduction$ then
 9. $BestReduction = reduction$
 10. $BestMerge = \{M_i, M_j\}$

 11. end if
 12. end for
 13. if $BestReduction > 0$ then
 14. $DS' = \{M_1, M_2, \dots, \{M_i, M_j\}, \dots, M_m\}$

 15. $Cost = C(DS')$
 16. end if
 17. Until $BestReduction = 0$
-

We now explain in more detail how two partitions merge, and how is reduction calculated. In order to merge two subsets M_i and M_j as one single set M_{ij} , the algorithm considers the set of neighbours that are closer to all destinations in M_i and M_j than the current node C . If that set is empty, then merging is not possible, and $reduction = 0$. Otherwise, among all such neighbours, we select the one which provides the best cost over progress ratio for this new subset M_{ij} (that is, the one that maximizes the corresponding progress $Best\ Reduction = T_1 - T_2$).

This algorithm, instead of testing all possible subsets, only needs to test $O(D^3)$ of them (in the worst case), D being the total number of destinations. As discussed in the next section, when the number of the neighbours of the current node is lower than the number of destinations, there is no need to test more than n^3 subsets, n being the number of the neighbours.

We merge two subsets of destinations because it reduces the cost of retransmitting from 2 to 1. A node providing advance toward all destinations in the merged set may not improve overall progress significantly, but reduces retransmission cost in half, and the overall cost over progress ratio improves. We will now elaborate on this in more detail. Let

Geographic Multicast Algorithm Description

us assume that $DS = \{M_1, M_2, \dots, M_i, M_j, \dots, M_m\}$ is the initial set partition in which all destinations in every M_i are served by the same closest node (B_i) among all neighbours of the current node A . Let $N(A)$ be the set of A 's neighbours. Given two subsets $M_i, M_j \in M$, we will analyze the conditions under which some neighbour with a lower progress can still provide a better tradeoff.

Let m be the cost of the initial partition, and $\sum_{k=1}^m P_k$ be the progress made with such election. If we merge M_i and M_j into a single set served by a single node $B_{i,j} \in N(A)$, $B_{i,j} \neq B_i, B_{i,j} \neq B_j$, the cost of the new subset $M_i \cup M_j$ is 1. The overall cost after merging is then $m-1$. In addition, the new progress made after merging would be $\sum_{k \neq i, k \neq j} P_k + P_{i,j}$, where $P_{i,j}$ is the progress made by the $B_{i,j}$ towards destinations in $M_{i,j}$.

For the new cost-progress to be better than before merging, the following inequality must be satisfied:

$$\frac{m}{\sum_{k=1}^m P_k} > \frac{m-1}{\sum_{k \neq i, k \neq j} P_k + P_{i,j}}$$

Thus, the new overall progress of candidate neighbours to merge subsets must satisfy

$$\sum_{k \neq i, k \neq j} P_k + P_{i,j} > \frac{m-1}{m} \sum_{k=1}^m P_k$$

This means that all those nodes $x \in N(A)$ whose progress towards destinations satisfy above inequality can provide a better cost over progress ratio than the initial selection, even though they do not provide the best progress for any of the destination sets. Every reduction of cost by merging two subsets decreases the progresses made up to $(\sum_{k=1}^m P_k / m)$.

Geographic Multicast Algorithm Description

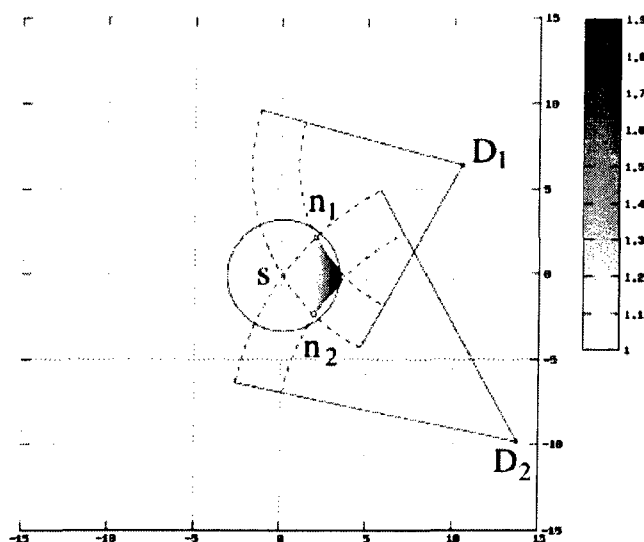


Figure 5 Identification of nodes according to their goodness

In Figure 5, we can see the current node S and two neighbours n_1 and n_2 within its radio range. We also see destinations D_1 and D_2 , where n_1 and n_2 are the neighbours providing the best progress to D_1 and D_2 , respectively. The shaded zone is the one in which there may exist other neighbours that can improve the overall cost over progress ratio. They do not provide the best advance for any of the individual destinations, but they can provide a better tradeoff. The legend of the graph represents the amount of improvement in cost/progress ratio over the configuration before merging.

3.6 Algorithm Complexity

In this section, we evaluate the worst case complexity of the neighbour selection algorithm and we show that it is asymptotically lower than that of PBM for most of the cases.

Theorem 1: The complexity of GMR is $O(Dn \min(D, n)^3)$, where D is the number of destinations and n is the number of neighbours of the node currently multicasting the message.

Proof: The first step of the algorithm builds initial partition set $M = \{M_1, M_2, \dots, M_i, M_j, \dots, M_m\}$ by dividing destinations in subsets. Every subset consists of those destinations

Geographic Multicast Algorithm Description

whose closest neighbour of the current node is the same. That is, if a neighbour gives the best progress to two different destinations, that two destinations will be in the same initial subset. This stage will need $D * n$ comparisons.

If the number of destinations is lower than the number of neighbours, $D < n$, then the number of subsets in M is, in the worst case, of size D (i.e., every subset contains only a single destination). If the number of destinations is greater than the number of neighbours, $D > n$, then the number $m = |M|$ of subsets in the initial partition M is $\leq n$ because it is impossible to have more subsets than neighbours. In this case, $|M_i| > 1$ for one or more $M_i \in M$. Thus, $0 \leq m \leq \min(D, n)$.

The process of computing the best subsets $M_i, M_j \in M$ to merge requires testing each pair of subsets. The number of tested pairs is $(m * (m - 1) / 2)$. The largest number of iterations occurs when at every step it is always possible to find two subsets to be merged that improve the ratio. The total number of iterations in that case is $m - 1$. Then, m may range from 1 to $\min(D, n)$. Given that iteration with m subsets may test $O(m * (m - 1) / 2)$ pairs, the worst case number of merging operations is $(m^3 - 6m^2 - m) / 6$. This gives us an algorithm with $O(m^3)$ merging steps. Merging two subsets may involve verifying all n neighbours for their feasibility, and testing $O(D)$ destinations in two subsets being merged. Thus, in the worse case, the algorithm has a complexity of $O(Dn \min(D, n)^3)$.

In the case of PBM, in all cases (i.e., worst, average, or best one), all possible subsets of neighbours (and not the subsets of destinations) are computed to select the best one. These neighbours are called forwarding nodes, and, for each destination, one of them takes responsibility for forwarding. Given n neighbours, the number of possible subsets is $\sum_{k=0}^n \binom{n}{k} = 2^n$. This leads to an exponential time complexity, which is much higher than the time complexity of selecting forwarding neighbours for GMR.

In addition, we must consider that in the average case of our algorithm, the cost is expected to be much lower. The computation time is evaluated experimentally in the next section.

Chapter 4

GMR Performance Evaluation

Our simulations compare our proposed cost over progress scheme, with six variants of the position-based multicast routing PBM [2]. The reason for choosing PBM, is that it is, to the best of our knowledge, the best localized geographic multicast routing algorithm to date. These variants correspond to different values of the λ parameter. Being more specific, we use values of $\lambda = 1, 0.8, 0.6, 0.4, 0.2, 0$. The reason is that PBM behaviour varies significantly depending on the value of λ , and there is no mechanism to find the best for a particular scenario. Authors of PBM showed that $\lambda = 0.4$ in their simulations is the one that seemed to provide the best performance. However, as we will see in this section, the best value of λ depends on specific network parameters. In addition, we also compare the quality of the trees produced by GMR with shortest path trees (SPTs). We consider a perfect MAC layer without collisions, and a UDG model. That is, a message sent out by a node is received by every other node in its radio range.

4.1 Simulation Setup and Testing parameters

In order to observe the routing algorithm performance in different scenarios, we simulated different network by alternating following parameters:

- D (Average degree): In order to test the average degree impact on the routing performance, we tested the network from sparse to dense network by using average degree: 5,6,7,8,9,10.
- DN (destination number): in order to test the destination number impact on the routing performance, we choose destination number 5,10,25,50. Receivers were also randomly selected from the set of sensor nodes.
- N (Number of nodes): We choose network 1000 nodes randomly placed in an area of 1000×1000 m. The radio range id varied in order to achieve different network

GMR Performance Evaluation

densities in terms of a mean number of neighbours. Note that this is equivalent to using a fixed radio range and increasing the simulation area.

- T (Test execution time): For each test scenario, our results are the mean over a total number of 50 simulation runs, which proved to be sufficient to provide a small 95% confidence interval.

4.2 Performance Metrics

To assess the performance of the proposed schemes, we considered the following performance metrics.

- Number of transmissions. This metric measures the efficiency of the multicast paths selected. The lower the number of transmissions, the lesser the network resources consumed to deliver the data message to all destinations. This is the most important performance parameter.
- Stretch factor. The stretch factor is the maximum difference in hops between the SPT to a receiver and the actual path. This metric provides an indication of how much does the protocol diverge from shortest paths.
- Computation time. This metric evaluates how costly in terms of computational power the protocol is. It is also useful to compare the mean case performance of the different protocols in comparison with the theoretical worse case results we obtained in the previous section.

4.3 Simulation Results

4.3.1 Number of Transmissions

We analyze in this section the effectiveness of neighbour selection schemes. We shall see that our proposed scheme achieves a good trade-off between the lengths of individual paths, and the overall number of transmissions. That is, our scheme only splits

GMR Performance Evaluation

paths to multiple destinations, when there is no cost-effective next hop towards the whole set of destinations. By using that cost-based path splitting strategy, we are able to identify when it is really interesting to create different paths.

To study the impact of the density in GMR and showing its performance against traditional ad hoc routing protocols such as MAODV [14] and ODMRP [11], we simulate both GMR and SPTs at increasing densities. Figure 6 shows that, as expected, GMR has a lower performance in very sparse scenarios because of the extensive use of face routing, due to a high number of void areas. Nevertheless, since usually WSNs are densely deployed, this should not be a concern in real deployments. As the figure shows, the higher density, the better the performance obtained by GMR. As expected, when the mean density is high enough to let the protocol work in greedy mode most of the time, the cost of multicast trees found out by GMR is much lower than those of traditional ad hoc routing protocols, since they create shortest paths towards each destination.

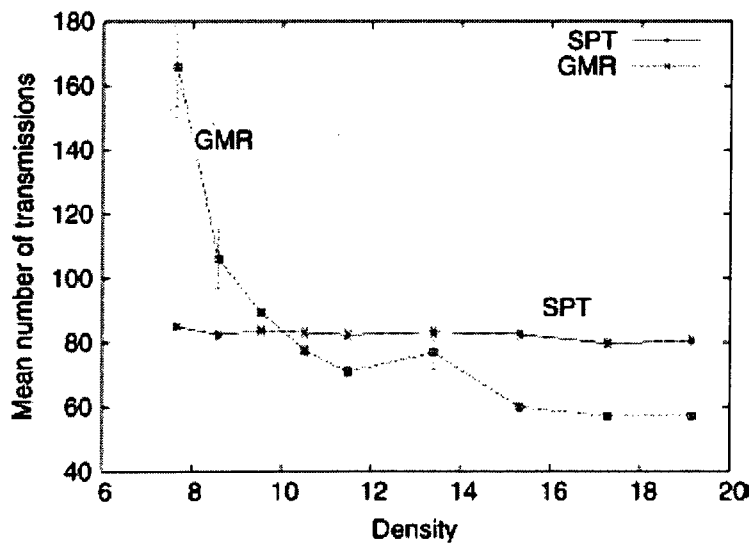


Figure 6 Mean number of transmission for ten destinations at varying density

Figure 7(a) shows that GMR outperforms PBM regardless of the values of the λ parameter and in a variety of network densities. The higher the density, the bigger the

GMR Performance Evaluation

improvement obtained over PBM. As expected, the value of λ has an influence on PBM's performance. For values of λ close to 0 PBM tends to create shortest paths. However, those paths are not optimal in terms of the number of transmissions. When λ approaches 1, PBM tries to minimize the number of transmissions regardless of the length of the paths. The problem with $\lambda = 1$ is that by not considering progress to destinations, paths may become very large in terms of number of hops and overall number of transmissions. As we can see, even for those values of λ , GMR manages to outperform PBM because GMR not only minimizes the number of transmissions but at the same time the mean path length. We can see in Figure 7(a) that GMR achieves an improvement between 2%–35% for a mean density of five neighbours per node. The higher the density the biggest the improvement obtained by GMR. For instance, for a mean density of ten neighbours per node, the improvement ranges between 30%–95%. In general, GMR is 2%–25% better than the best case of PBM (using $\lambda = 0.2$) and 38%–95% better than the worse case of PBM (using $\lambda = 1$). The key to that improvement is the goodness of the neighbour selection function used by GMR. For higher densities, most of the routing is performed in greedy mode (almost no face routing is required). Thus, the better neighbour selection function achieves its higher advantage. For a different number of destinations, results follow a similar trend. The higher the number of destinations, the higher the number of transmissions required. However, in general, the improvement achieved by GMR compared with PBM is within the same percentages.

Figure 7 (b) shows the rate at which destinations are reached for a mean density of 7. From it we can assess the efficiency of the transmissions for each tested protocol. The lower the number of transmissions needed to reach a certain number of destinations, the better the efficiency of the protocol. As we showed before, GMR clearly needs fewer messages to reach 100% of destinations than PBM using different λ values. This figure also shows that GMR makes a very efficient use of its transmissions because for a given number of transmissions, the percentage of destinations reached is higher. The reason for that is that GMR's neighbour selection algorithm manages to efficiently delay the splitting of paths to approximate the minimum number of transmissions trees, while still providing a good advance toward destinations. Figure 8 illustrates the different behaviours of GMR as density increases. As expected, the higher the density of the network, the better the performance

GMR Performance Evaluation

obtained. The reason is that with higher densities, the probability of entering into face mode drops rapidly. Hence, the neighbour selection algorithm becomes even more effective. Figure 9 compares transmission number between GMR and the sum of unicast in the same network configuration with density at 10. With the destination number increase from 5 to 50, we can see that sum of unicast cost increase sharply while GMR transmission number only has mild increase. We can conclude that GMR provides better multicast routing efficiency. The larger the destination number, the better performance GMR shows.

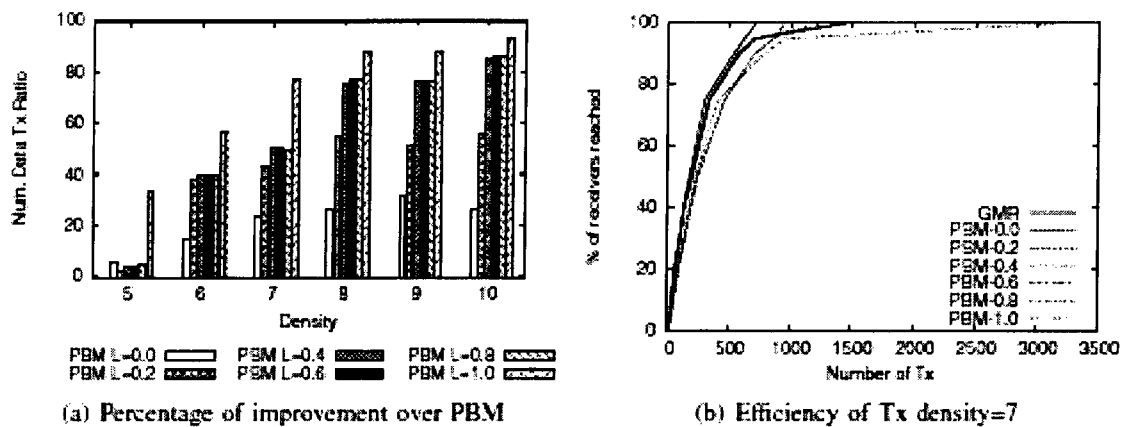


Figure 7 Improvement in number and efficiency of transmissions for 25 destinations.

(a) Percentage of improvement over PBM. (b) Efficiency of Tx density=7

GMR Performance Evaluation

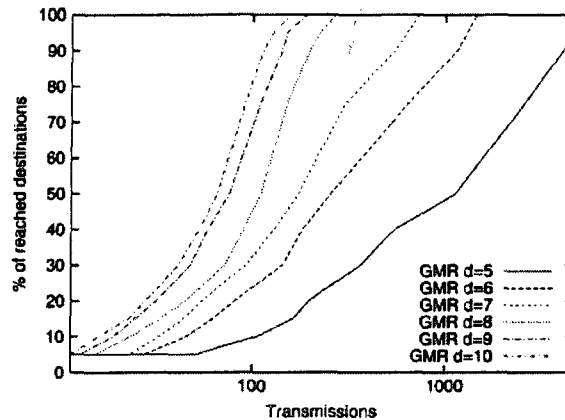


Figure 8 Efficiency of Tx for GMR for 25 destinations and different densities

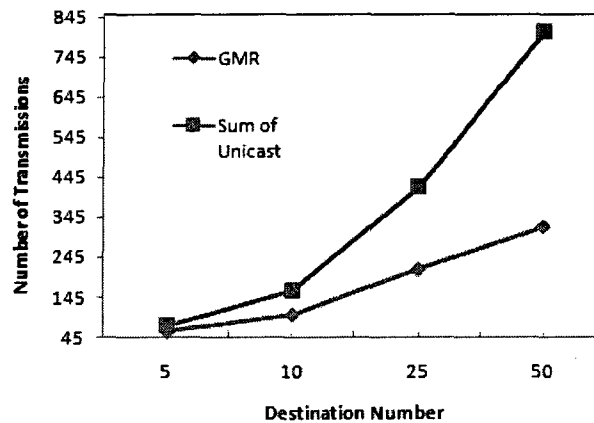


Figure 9 Comparisons of GMR and sum of Unicast

Summing it up, GMR is an efficient multicast protocol and behaves always better than the best case for PBM. Unlike PBM, GMR does not need to adjust any parameter. GMR is a self-adapting algorithm that is able to find out only with local information the right point in which to split multicast messages in order to maintain a good tradeoff between path length and total number of messages transmitted.

4.3.2 Stretch Factor

GMR Performance Evaluation

achieves. This is due to the fact that when λ approaches 0, PBM tries to compute a SPT. In general, GMR is getting better stretch factor values than PBM for most of the tested configurations. Only in a few configurations in which $\lambda = 0$, GMR does not outperform PBM. The reason in those few cases is that the goal of GMR is not to find the shortest path but a good tradeoff between the length of the paths and the overall consumption of network resources. As we can see in the figures, the tradeoff obtained by GMR is very good because it is superior to PBM for every $\lambda \geq 0.2$, while still needing a lower number of transmissions. In Figure 10 (b), we can see that the improvement in stretch factor achieved by GMR over PBM is bigger than 40% for every $\lambda > 0.2$. For lower λ values, GMR still performs around 15% better than PBM except in some particular cases.

4.3.3 Neighbor Selection Computation Time

As we showed before, the computational cost of PBM is exponential in n , while the one of GMR is polynomial in n and D . Given that the average number of neighbours in our experiments is small (the highest density is 10), this may not translate into better performance for GMR. However, we show in our experimental results that the average case performance of GMR is very consistent and scalable across network parameters. To measure the computational time, we execute one single step of the routing algorithm. This step makes the first neighbour selection (the initial one at the source node). For each set of parameters, we executed the single step 50 times and measured the total time of those 50 executions. We performed execution over 50 different graphs. The time is the mean on the 50 graphs. Figure 11 shows the results for the case that would be the best case for PBM. As we can see from the pictures, the computation time of GMR at each node is around 50ms. It may still be heavy computation time at sensor node although GMR has already clearly showed better performance than PBM. This is current limitation of GMR. Future study should try to further reduce the computation time. We discuss GMR limitation in Chapter 7.

GMR Performance Evaluation

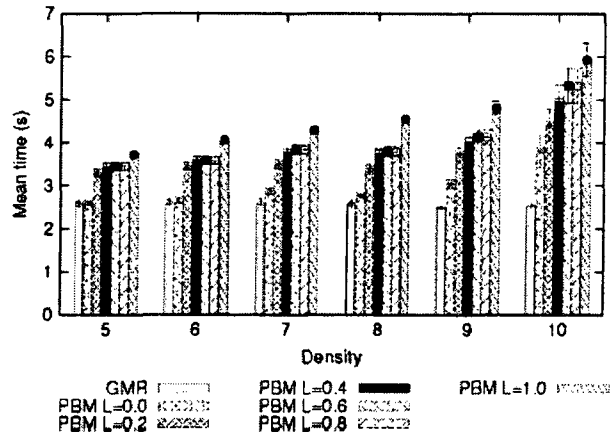


Figure 11 Computational time comparisons for varying destinations

We can see that the mean execution time for GMR is stabilized between 2–3 s regardless of the density of the network. However, PBM's mean execution time grows exponentially with density. This is because the proposed neighbour selection algorithm is able to compute a good set of neighbours efficiently, thanks to the heuristic for subset merge. In fact, the algorithm shows a good performance in the mean case.

Multiratecast Algorithm Description

Chapter 5

Multiratecast Algorithm Description

The proposed multiratecast algorithms are purely localized stateless multicast protocols for WSN. They are generalizations of multicast GFG and can be efficient in both static and dynamic sensor networks. The routing path selection is not only based on distance, but also on destination data rate requirement. The detail algorithm description is in following sections.

5.1 Rate cost metric

The problem that multiratecast (MRC) algorithms are facing can be described as following: given a multicast message generated by a source node S , a group of destination nodes $\{D_1, D_2, \dots, D_m\}$ (sinks) which each destination node requests to receive data at specific rate, MRC need to find a set of relay nodes in the network so that the message is delivered to all destinations (sinks) with a minimum consumption of network resources and at the same time, assures each destination receives data at its required rate.

To achieve these goals, we must minimize the number of messages sent which means using as few sensor relay nodes as possible. We must also efficiently branch multicast paths so that paths transmission in higher rate can be shared as much as possible to reduce network bandwidth consumption. Traditional routing protocols use hop count or transmission number as a major performance metric. This metric is not suitable for multiratecast routing performance evaluation. According to Nyquist-Shannon sampling theorem, the bandwidth is directly proportional to the data transmission rate. For one forwarding node, the higher data rate it sends out a message, the more network resource it uses. Considering Unicast routing scenario, when destination requires data at specific rate, the total routing network resource consumption is proportional to the total transmission number and the data rate in routing path. Combine the two factors: hop count and rate, the routing cost for single rate Unicast routing can be evaluated as following equation:

Multiratecast Algorithm Description

$$\text{cost } C = kr$$

where C is total single rate cost ,

r is the data rate required by destination,

k is the total hop count number (transmission number)

Considering a network with multi-rate destinations, different from Unicast routing, the multiratecast message may split and transmission rate may change at relay nodes when routing path branches. Multiratecast require that each destination receives data at its request rate, so that message forwarding has to be at the maximum rate among those destinations it covers, it has to fulfill following rate requirements:

- $r_p \geq r_c$
- $r_p = \max(r_{p1}, r_{p2}, \dots, r_{pn})$
- $r_c = \max(r_{c1}, r_{c2}, \dots, r_{cm})$

Where r_{p^*} is parent node, $(r_{p1}, r_{p2}, \dots, r_{pn})$ is data rates for destinations that parent node covers

Where r_{c^*} is child node, $(r_{c1}, r_{c2}, \dots, r_{cm})$ is data rates for destinations that child node covers

The start rate at source node S is the maximum rate for all destinations. When message reaches next forwarding nodes, the next forwarding nodes will retransmit message at the equal or less rates depends on their covered destinations. The total routing consumption can be evaluated as following equation:

$$C = \sum_{j=1}^k r_j$$

where C is total multirate cost,

r_j is the transmission rate at forwarding node j ,

Multiratecast Algorithm Description

j is the forwarding node number,

k is the total hop count.

A performance metric by considering both transmission number and transmission rate will better reflect the network resource consumption for multiratecast routing. As shown in the following example, the routing path A and B are for same network with same number of destinations with same destination rate. Routing path A completes routing with 9 transmissions. Routing path B completes routing with 7 transmissions. However, path A has more data transmission in lower data rate so its total rate cost is smaller than that of routing path B:

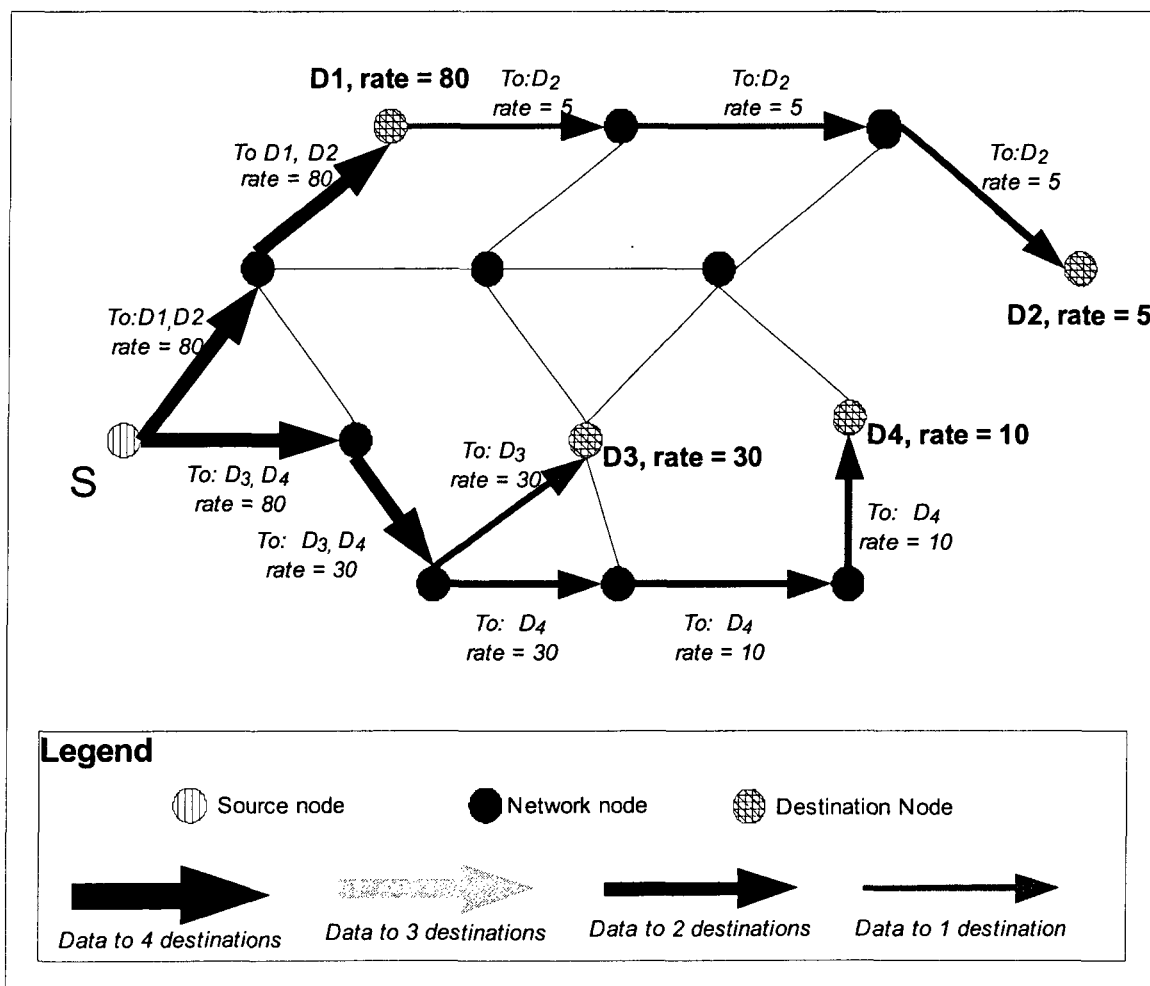


Figure 12 Multiratecast Routing Path A

Total transmission Number : 9

Multiratecast Algorithm Description

Rate Cost: $80+80+5+5+5+30+30+10+10 = 255$

In the above picture, the data transmission was separated at source node. Data was transmitted more in lower rate and total rate cost is 255.

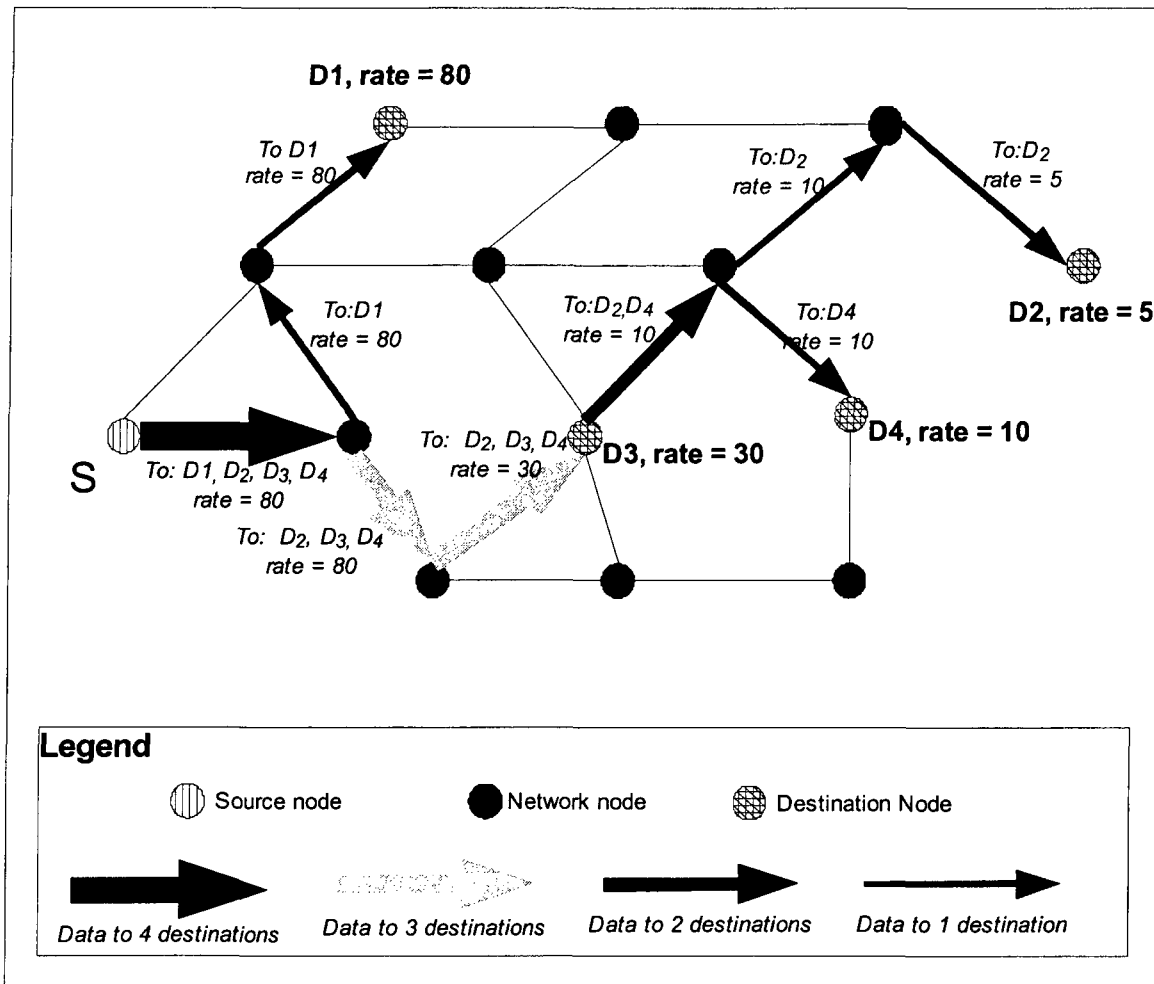


Figure 13 Multiratecast Routing Path B

Total transmission Number : 7

Rate Cost: $80+80+80+30+10+10+5 = 295$

Multiratecast Algorithm Description

In the above picture, the data transmission was grouped together and separated later. Data was transmitted more in higher rate and total rate cost is 295. This rate cost is more than that in routing path A.

Suppose we keep everything the same in the above two pictures, just change data rate between D_1 and D_2 , the hop counts will not change but rate cost will show different results for the two pictures.

We believe the rate cost metric is more suitable for multiratecast and reflects the overall routing efficiency. We will use this metric to evaluate Multiratecast (MRC) protocols.

5.2 Multiratecast Algorithms: RCM and MRM

5.2.1 Overview

Multiratecast algorithms (MRC) apply multicast Greedy Face Greedy (GFG) routing and include data rate as parameter in routing path selection. As described in previous section, the multiratecast problem can be described as: a source node S needs forward message to destination set $D = \{D_1, D_2, \dots, D_m\}$ in which each destination requires data rate $R_i (i = 1, 2, \dots, m)$.

Starting from source node, each forwarding node should select a set of next forwarding nodes, to efficiently branch message to cover all or part of destinations so that the overall routing rate cost can be minimal.

At each forwarding node, Both RCM and MRM separate destinations into two lists: Greedy destination List and Face destination List. Any destination that has at least one neighbour node closer to it than the current forwarding node will be put in a greedy routing list. RCM or MRM Greedy routing will be applied to those destinations. Any destination that does not have any neighbour node closer to it will be put to face routing list and face routing will be applied for those destinations.

Multiratecast Algorithm Description

Greedy Routing:

The difference between RCM and MRM is in Greedy routing part.

RCM greedy:

The key of RCM greedy routing is to apply destination set partition, group destinations into different sets and to find out a best set partition that has lowest rate cost. Message will be transmitted at the highest rate among destinations that the current node covers to all neighbour nodes. The selected next forwarding nodes in the best set will acquire message at its assigned rate and continue next forwarding to cover its assigned destination subset. To get optimal branch and lowest overall rate cost, RCM calculates local rate cost not only by considering distance advances towards destinations and the number of subset groups, but also different data rate to cover different destination groups. The more distance progress to destinations in each message forward, the higher possibilities that there will be less transmission number in the total routing. Because RCM routing makes forwarding decision completely based on local information, it is an optimal local forwarding and may not guarantee the overall routing rate cost is minimum. The network density, topology, destination positions or rate distribution change can all impact the local forwarding decision and thus overall performance. The distance advance towards part of destinations may have more or less impact in total routing performance. To find out which local routing decision has overall better performance, RCM uses a parameter called rate cost factor to evaluate the rate vs. distance progress ratio. It explores three different set rate cost methods and they focus on different aspect of the rate cost factor calculations. RCM_A calculates rate cost factor that focus on efficient distance advance towards destinations in each subset and get set cost as sum of best subset cost. RCM_B focus more on getting best individual rate cost factors and tries to get subset and set cost as sum of best individual rate cost factors. RCM_C evaluates rate cost factor based on the whole set. The three RCM rate cost factors methods are implemented in a simulation, the routing results are analyzed and compared in Chapter 6 Performance and Evaluation.

Multiratecast Algorithm Description

To reduce the calculation complexity for network with large number of destinations, RCM applies a flexible routing calculation. It applies complete destination set partition only for network with small number of destinations and applies a faster greedy destination set partition for network with large number of destinations.

Detail description of RCM is in section 5.2.3.

MRM greedy:

MRM greedy routing gives priority to maximum rate destination. It tries to find a best neighbour node that is closest to the destination requires highest rate. It then let the neighbour node cover all other possible other destinations. The maximum rate destination is then removed from current greedy routing list and the MRM processes destination with the second maximum rate. This process continues until all destinations are covered and each destination in greedy routing list has one and only one next forwarding neighbour.

Detail description of MRM is in section 5.2.4.

Face routing for both RCM and MRM:

Both RCM and MRM apply same face routing for destinations that have no neighbour node that provides distance progress. The face routing is based on individual destination as described in [6]. For each destination in face list, face routing calculation will be applied individually to get a next face forwarding neighbour node. It is similar to GMR as described as in 3.3. Face routing message that reaches next forwarding node will continue be processed in face routing mode until finally it reaches destination or reaches a node that is closer to destination than the node that face routing started, then greedy mode routing can be resumed.

When a next forwarding node is selected to do Greedy routing for some destinations and Face routing for other destinations, the related neighbour-destination routing information will be contained in one message and sent out from current forwarding node.

Multiratecast Algorithm Description

5.2.2 Message transmission and format

After independently execute the MRC greedy and face part routing calculation, forwarding node sends out one message at the highest rate among the destinations it covers to all its neighbours. The message can include both greedy and face forwarding information in message head. A next forwarding neighbour may be selected as greedy forwarding node for some destinations and face routing node for another destination. All related routing information is contained in the message head. The selected next forwarding neighbours will capture the message; continue MRC routing calculation and forwarding until message reaches destinations.

- **Message Head**

- Source Node: The source node position information
- Current Node: The current forwarding node information
- Data rate: the data sending rate from current node to next node
- Next Node: The next forwarding nodes information
- Greedy Information: Greedy routing information include a list of all neighbour nodes that will forward message in Greedy mode, the destinations that each neighbour node covers, their positions and required data rates
- Face Information: Face routing information include a list of neighbour nodes that will forward message in Face node, the destination that each neighbour node covers, their positions, data rates, face start points.

- **Message Data**

- Data that need to be forwarded to destinations

5.2.3 The rate cost multicast protocol (RCM)

The RCM applies complete set partition in greedy routing for network with small number of destinations and applies greedy set partition in greedy routing for network with large number of destinations. Set costs are calculated for every destination set. Then either a

Multiratecast Algorithm Description

simple loop or a set merge and compare process will be applied to choose the best set with lowest cost.

To better describe the RCM algorithm, we use following picture as an example. Suppose we have current node S needs transfer data to 4 destinations D_1, D_2, D_3 and D_4 . Each destination requests data rate at R_1, R_2, R_3 and R_4 respectively. We will go through the all the stages in the algorithm and describe RCM routing calculation.

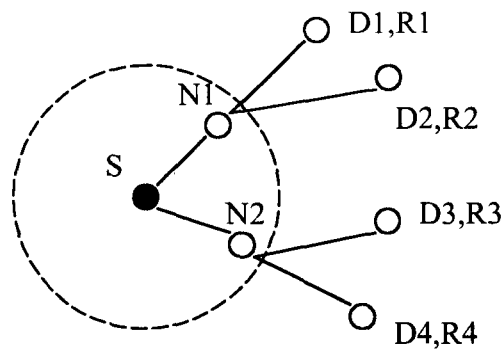


Figure 14 Example of RCM Forwarding

5.2.3.1 RCM greedy routing (for 5 or less destinations)

The RCM greedy routing network for network with small number of destinations can be divided into three stages:

- 1> First stage is complete destination set partition.
- 2> The second stage is to calculate set cost for every destination set.
- 3> The third stage is to compare and find out the destination set with lowest cost.

5.2.3.1.1 Stage 1: Destination Set partition

The complete set partition algorithm is from paper [20] [37] which calculates all the possible set partitions for a given destination list.

For example as in above Figure 14, Node S needs forward package to 4 destinations

Multiratecast Algorithm Description

$D_1 - D_4$. The destination set partition will give following possible 15 destination sets:

$$\text{Set 1} = DS_1 = \{\{D_1, D_2, D_3, D_4\}\}$$

$$\text{Set 2} = DS_2 = \{\{D_1\}, \{D_2, D_3, D_4\}\}$$

$$\text{Set 3} = DS_3 = \{\{D_2\}, \{D_1, D_3, D_4\}\}$$

$$\text{Set 4} = DS_4 = \{\{D_3\}, \{D_1, D_2, D_4\}\}$$

$$\text{Set 5} = DS_5 = \{\{D_4\}, \{D_1, D_2, D_3\}\}$$

$$\text{Set 6} = DS_6 = \{\{D_1, D_2\}, \{D_3, D_4\}\}$$

$$\text{Set 7} = DS_7 = \{\{D_1, D_3\}, \{D_2, D_4\}\}$$

$$\text{Set 8} = DS_8 = \{\{D_1, D_4\}, \{D_2, D_3\}\}$$

$$\text{Set 9} = DS_9 = \{\{D_1\}, \{D_2\}, \{D_3, D_4\}\}$$

$$\text{Set 10} = DS_{10} = \{\{D_1\}, \{D_3\}, \{D_2, D_4\}\}$$

$$\text{Set 11} = DS_{11} = \{\{D_2\}, \{D_3\}, \{D_1, D_4\}\}$$

$$\text{Set 12} = DS_{12} = \{\{D_2\}, \{D_4\}, \{D_1, D_3\}\}$$

$$\text{Set 13} = DS_{13} = \{\{D_3\}, \{D_4\}, \{D_1, D_2\}\}$$

$$\text{Set 14} = DS_{14} = \{\{D_1\}, \{D_4\}, \{D_3, D_2\}\}$$

$$\text{Set 15} = DS_{15} = \{\{D_1\}, \{D_2\}, \{D_3\}, \{D_4\}\}$$

5.2.3.1.2 Stage 2: calculate set cost for every destination set

After complete destination set partition for m destinations $D = \{D_1, D_2, \dots, D_m\}$, there can be a list of destination sets DS . For a given destination set DS_i , it may contain one or more destination subsets. There can be total k destination subsets where: $DS_i = \{M_1, M_2, \dots, M_k\}$, $1 \leq k \leq m$. Each destination subset M_i may includes one or more destinations. Any destination D_j should be in one and only one subset.

Subset M_i has following characters:

- $M_i = \{D_{i1}, D_{i2}, \dots, D_{ip}\}$, where $1 \leq i \leq k$, $1 \leq p \leq m$
- $M_i \cap M_j = \Phi$, where $i, j = 1, 2, \dots, k$
- $M_1 \cup M_2 \cup \dots \cup M_k = D$

Multiratecast Algorithm Description

The set cost calculation for given destination set is described in detail in section 5.2.3.3.

5.2.3.1.3 Stage 3: Find out best destination set

The process of selecting best destination set is to loop through all destination sets and compare set costs and pick the set with lowest cost. The rate cost for a destination set DS_i set is listed as $RC(DS_i)$. The best set fulfills following equation:

$$RC(DS_s) \leq RC(DS_k)$$

Where,

DS_s is the selected best destination set, $1 \leq s \leq n$

DS_k is any other destination sets, $1 \leq k \leq n$

5.2.3.2 RCM greedy routing (for more than 5 destinations)

The RCM greedy routing network for network with small number of destinations can be divided into three stages:

- 1> First stage is to find initial destination set. The initial set is found similar as GMR routing as described in 3.5 Greedy Neighbour Selection.
- 2> The second stage is to do subset merge and compare to find out the set with lowest cost

Take the destinations in Figure 14 as an example, neighbour node N_1 provides most distance advance for D_1 and D_2 . Node N_2 provides most distance advance for D_3 and D_4 . So that the initial set partition to consider would be $\{ \{ D_1, D_2 \}, \{ D_3, D_4 \} \}$, where N_1 serves $\{ D_1, D_2 \}$ and N_2 serves $\{ D_3, D_4 \}$.

$$Set\ 1_greedy = \{ M_1, M_2 \}$$

Multiratecast Algorithm Description

$$\text{where } M_1 = \{D_1, D_2\} \quad M_2 = \{D_3, D_4\}$$

After the initial set is formed, RCM calculates the set cost for the initial set. The set cost for greedy set partition is similar as described in GMR protocol section 3.5. However, different from GMR, the set cost in RCM is calculated as rate cost instead of simply cost over progress. The greedy subset merge and compare is preformed in rounds. In each round, all subset pairs $\{M_i, M_j\}$ are checked for possible improvement over previously calculated rate cost. Two partitions can be combined only if there are neighbours of the current node, providing distance advance towards all the destinations in both subset M_i and M_j . However, their merging, if possible, may not result in a better new rate cost. The pair of subset that provides the best rate cost improvement is selected and merging is performed, creating the new subset M' . The new subset M' and all remaining unmerged subsets forms new destination set DS' . The greedy set cost calculation/ merge process advances to the next round and starts over again with the new set DS' . If no pair provided any improvement then the process stops and the best set is found.

RCM routing greedy destination set partition uses following algorithm that is similar as in [3]:

RCM Greedy Destination Set partition

1. Initial set $DS = \{M_1, M_2, \dots, M_k\}$, $M_i = \{D_j \mid \text{same neighbour provides most advance}\}$
2. Calculate rate set cost for initial set $RC(DS)$
3. Repeat
4. $BestReduction = 0$
5. for all pairs $\{M_i, M_j\}$ do
6. Find new set cost of new set DS' by merging of $\{M_i, M_j\} \in DS$
7. $reduction = RC(M) - RC(M')$

Multiratecast Algorithm Description

8. if $reduction > BestReduction$ then
 9. $BestReduction = reduction$
 10. $BestMerge = \{M_i, M_j\}$

 11. end if
 12. end for
 13. if $BestReduction > 0$ then
 14. $DS' = \{M_1, M_2, \dots, \{M_i, M_j\}, \dots, M_m\}$

 15. $Rate\ Cost = RC(DS')$
 16. end if
 17. Until $BestReduction = 0$
-

5.2.3.3 RCM set cost Calculation

We describe the RCM set cost calculation in this section.

The set cost is a value to reflect the local routing efficiency for multiratecast when current node split message to the next forwarding nodes with different data rate. After set partition, for each given set, the next forwarding data rate for every subset is a defined value. The value is the maximum data rate among destinations in the subset. RCM tries to find a best neighbour to cover all destinations for each subset. RCM introduces a parameter rate cost factor to reflect the local rate cost efficiency towards selected destinations. The rate cost factor rcf is defined as rate vs. distance progress ratio $R/\Delta D$. R is the data rate cost towards the selected destinations, ΔD is the distance progress towards selected destinations.

$$rcf = \frac{R}{\Delta D}$$

R is data rate cost for all the selected destination(s)

ΔD is the distance progress towards the selected destinations

Multiratecast Algorithm Description

The rate cost factor can be calculated based on each individual destination, on each subset or on the whole set. The routing path and message split may be different when apply different rate cost factor calculation thus result in different overall routing performance. Because there is no existing study show which rate cost factor calculation method is most suitable for multiratecast routing, RCM explores the three different methods to calculate set cost. For a given destination set, RCM applies three types rate cost factors to get set cost. Their simulation results and performance analysis are presented in Performance Evaluation part in chapter 6.

5.2.3.3.1 RCM_A: set cost focus on subset

RCM_A focus on finding minimum rate cost factor for each subset. The rate cost factor in RCM_A is calculated as the maximum rate in subset divided by total distance towards all destinations in the subset. Because the maximum rate for subset is same value for all neighbours, so that among all neighbour nodes that provide distance progress to subset destinations, RCM_A tries to find a best neighbour node that provide maximum distance advance to all destinations in the subset. This will result in a best neighbour with minimum rate cost factor. RCM_A uses the minimum rate cost factor as subset cost, and then calculates set cost as sum of all subset costs.

Suppose we have a set partition DS_i with total k destination set that $DS_i = \{M_1, M_2, \dots, M_k\}$. For each destination subset M_j suppose we have p destinations $M_j = \{D_{j1}, D_{j2}, \dots, D_{jp}\}$. RCM_A calculates the rate cost factor for each neighbour node as following equation:

$$rcf_{subset} = \frac{Rmax_{subset}}{\Delta D} = \frac{Rmax_{subset}}{\sum_{i=1}^p (|SD_i| - |nD_i|)}$$

The best forwarding neighbour node N should have lowest subset rate cost factor, or maximum distance progress to all destinations in subset because the maximum rate of the subset is a constant value. The best forwarding node N should full fill following equations:

$$\frac{Rmax_{subsetj}}{\sum_{i=1}^p (|SD_{ji}| - |N_jD_{ji}|)} \leq \frac{Rmax_{subsetj}}{\sum_{i=1}^p (|SD_i| - |n_jD_{ji}|)}$$

Multiratecast Algorithm Description

Or

$$\sum_{l=1}^p \left| |SD_{jl}| - |N_j D_{jl}| \right| \geq \sum_{l=1}^p \left| |SD_l| - |n_j D_{jl}| \right|$$

Where,

$R_{max_{subsetj}}$ is highest rate of all the selected destination(s) in a subset M_j

$|SD_{jl}|$ is the distance between current node S to the destination D_{jl}

$|n_j D_{jl}|$ is the distance between any other neighbour node n to the destination D_{jl}

$|N_j D_{jl}|$ is the distance between best forwarding node N_j to the destination D_{jl}

p is the total number of destinations in the subset M_j

After each subset M_j has a best forward node, RCM_A calculates its set cost for destination set DS_i by sum of all subset rate cost factors as following equation:

$$RC1 = \sum_{j=1}^k \frac{R_j}{\sum_{l=1}^{jp} (||SD_{jl}| - |N_j D_{jl}||)}$$

Where,

$RC1$ is the set cost for a destination set DS_i by RCM_A calculation

k is the number of subsets in DS_i , $DS_i = \{M_1, M_2, \dots, M_k\}$.

j is the subset number, $1 \leq j \leq k$

R_j is max rate of destinations within the subset M_j

jp is the number of destinations in subset M_j , $M_j = \{D_{j1}, D_{j2}, \dots, D_{jp}\}$.

$D_{j1}, D_{j2}, \dots, D_{jp}$ are destinations in subset M_j

N_j is the best forward node for subset M_j

Multiratecast Algorithm Description

$|SD_{ji}|$ is the distance between current forwarding node S to destination D_{ji} in M_j

$|N_j D_{ji}|$ is the distance between best forward node N_j to destination D_{ji} in M_j

Based on RCM_A calculation methods, the rate set cost for example listed in Figure 14 is:

$$RC1 = \frac{\max(R1, R2)}{||SD_1| - |N_1 D_1|| + ||SD_2| - |N_1 D_2||} + \frac{\max(R3, R4)}{||SD_3| - |N_2 D_3|| + ||SD_4| - |N_2 D_4||}$$

An in following two figures, suppose we have two different destination sets for 4 destinations, we can calculate set cost by RCM_A and get different set cost for each of them.

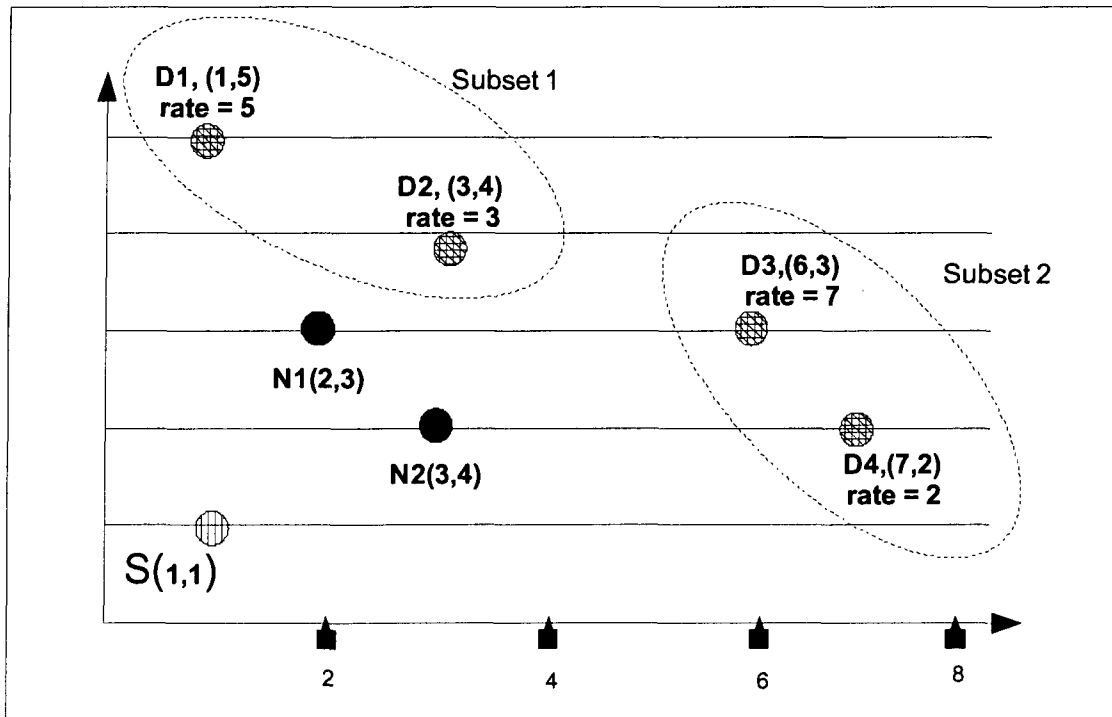


Figure 15 Example of RCM Set Cost Calculation (A)

Multiratecast Algorithm Description

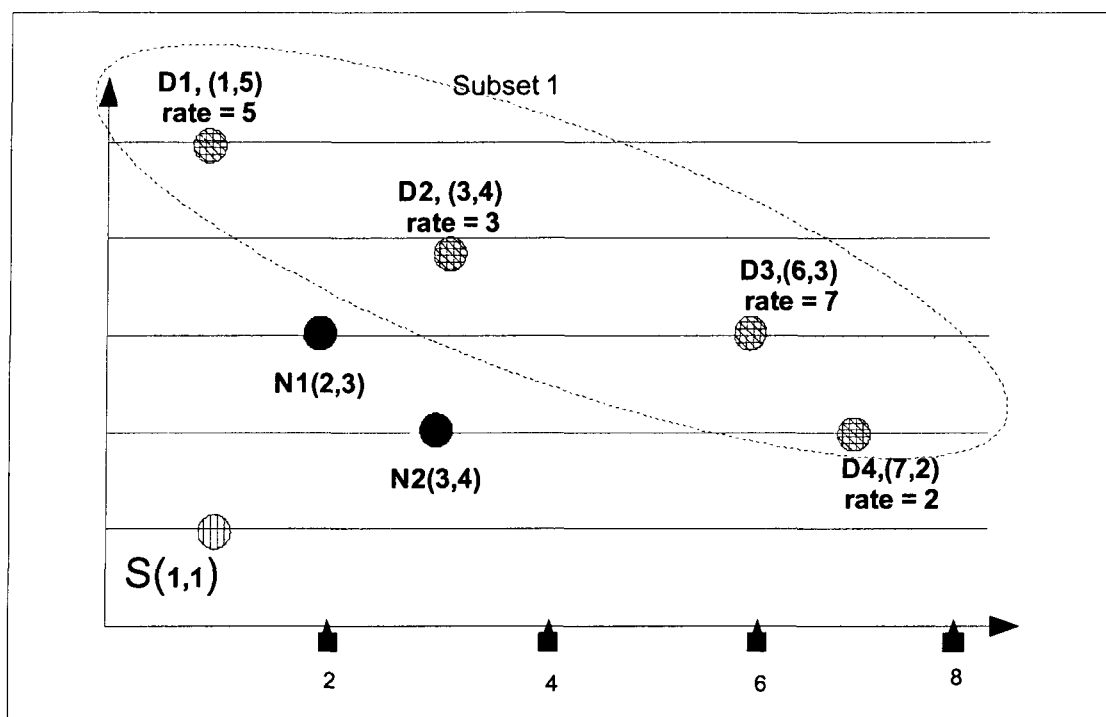


Figure 16 Example of RCM Set Cost Calculation (B)

The above two figures list two possible destination sets for a given network with 4 destinations. Forwarding node S has two neighbour nodes N1 and N2. By calculating the set cost for figure A and B, we may get different next forwarding set cost by RCM_A.

RCM_A set cost calculation for Figure 15

For the above Figure 15, we have destination set with two subset $DS = \{\{D_1, D_2\}, \{D_3, D_4\}\}$. RCM_A calculates set cost as following steps:

For subset M_1 , it calculates the distance advance from N_1 to $\{\{D_1, D_2\}\}$, and then N_2 to $\{\{D_1, D_2\}\}$, and then compares the results to find out the best neighbour for subset M_1 .

$$\begin{aligned} \Delta DN_1 (\text{subset } 1) &= \left| |SD_1| - |N_1D_1| \right| + \left| |SD_2| - |N_2D_2| \right| \\ &= |4 - \sqrt{5}| + \left| \sqrt{2^2 + 3^2} - \sqrt{1+1} \right| \end{aligned}$$

Multiratecast Algorithm Description

$$= 3.89$$

$$\begin{aligned} \Delta DN_2 (\text{subset } 1) &= ||SD_1| - |N_2D_1|| + ||SD_2| - |N_2D_2|| \\ &= |4 - \sqrt{13}| + ||\sqrt{2^2 + 3^2}| - |\sqrt{2^2 + 2^2}|| \\ &= 3.21 \end{aligned}$$

Best Neighbour node for subset M_1 is : N_1

For subset M_2 it calculates the distance advance from N_1 to $\{\{ D_3, D_4\}$, and then N_2 to $\{\{ D_3, D_4\}$, and then compares the results to find out the best neighbour for subset M_2 .

$$\begin{aligned} \Delta DN_1 (\text{subset } 2) &= ||SD_3| - |N_1D_3|| + ||SD_4| - |N_1D_4|| \\ &= |\sqrt{29} - 4| + ||\sqrt{2^2 + 3^2}| - |\sqrt{37} - \sqrt{5^2 + 1}|| \\ &= 2.37 \end{aligned}$$

$$\begin{aligned} \Delta DN_2 (\text{subset } 2) &= ||SD_3| - |N_2D_3|| + ||SD_4| - |N_2D_4|| \\ &= ||\sqrt{5^2 + 2^2}| + |\sqrt{3^2 + 1}|| + ||\sqrt{6^2 + 1^2}| - |4|| \\ &= 4.31 \end{aligned}$$

Best Neighbour node for subset M_2 is : N_2

Set cost for Figure 15 by RCM_A is:

$$\begin{aligned} RC1_I &= \frac{\max(R1, R2)}{||SD_1| - |N_1D_1|| + ||SD_2| - |N_1D_2||} + \frac{\max(R3, R4)}{||SD_3| - |N_2D_3|| + ||SD_4| - |N_2D_4||} \\ &= \frac{5}{\Delta DN_1 (\text{subset } 1)} + \frac{7}{\Delta DN_2 (\text{subset } 2)} = \frac{5}{3.89} + \frac{7}{4.31} = 2.90 \end{aligned}$$

RCM_A set cost calculation for Figure 16

For the above Figure 16, we have one subset, so the calculation by RCM_A is:

Multiratecast Algorithm Description

$$\begin{aligned}\Delta DN1(subset) &= \left| |SD_1| - |N_1D_1| \right| + \left| |SD_2| - |N_1D_2| \right| + \left| |SD_3| - |N_1D_3| \right| + \left| |SD_4| - |N_1D_4| \right| \\ &= 3.89 + 2.27 = 6.26\end{aligned}$$

$$\begin{aligned}\Delta DN2(subset) &= \left| |SD_1| - |N_2D_1| \right| + \left| |SD_2| - |N_2D_2| \right| + \left| |SD_3| - |N_2D_3| \right| + \left| |SD_4| - |N_2D_4| \right| \\ &= 3.21 + 4.31 = 7.52\end{aligned}$$

Select best Node : N_2

Set cost for Figure 16 by RCM_A is:

$$RC1_{FI} = \frac{7}{\Delta DN2(subset)} = \frac{7}{7.52} = 0.93$$

5.2.3.3.2 RCM_B: set cost focus on individual destination

In RCM_B calculation methods, we focus more on individual destination rate cost factor.

The individual destination rate cost factor is defined as forwarding rate to a destination divided by the distance progress from a neighbour node to the destination as following equation:

$$rcf_{individual} = \frac{R_{forwarding}}{\Delta D} = \frac{R_{forwarding}}{\left| |SD_i| - |nD_i| \right|}$$

Where,

$R_{forwarding}$ is the forwarding rate that the destination requires

$|SD_i|$ is the distance between current node S to the destination D_i .

$|nD_i|$ is the distance between neighbour node n to the destination D_i .

For every destination in a subset, $R_{forwarding}$ is a constant value equal to the maximum data rate among all destinations in the subset $R_{max_{subsetj}}$ because RCM_B tries to find a best forwarding neighbour node that covers the subset. The best node should provide minimum total individual destination rate cost factors for all destinations in the

Multiratecast Algorithm Description

subset. RCM_B then calculates subset cost as the sum of individual costs of the best forwarding node, and then calculate set cost for destination set as the sum of all subset cost.

For subset M_j , the best forwarding node N fulfills following equation:

$$\sum_{i=1}^p \frac{Rmax_{subsetj}}{\left| |SD_{jl}| - |N_j D_{jl}| \right|} \leq \sum_{i=1}^p \frac{Rmax_{subsetj}}{\left| |SD_i| - |n_j D_{jl}| \right|}$$

Or

$$\sum_{i=1}^p \frac{1}{\left| |SD_{jl}| - |N_j D_{jl}| \right|} \leq \sum_{i=1}^p \frac{1}{\left| |SD_i| - |n_j D_{jl}| \right|}$$

Where,

$Rmax_{subsetj}$ is highest rate of all the selected destination(s) in a subset M_j

$|SD_{jl}|$ is the distance between current node S to the destination D_{jl}

$|n_j D_{jl}|$ is the distance between any other neighbour node n to the destination D_{jl}

$|N_j D_{jl}|$ is the distance between best forwarding node N to the destination D_{jl}

p is the total number of destinations in the subset M_j

For the whole destination set DS_i , RCM_B calculates set cost as sum of all best individual rate cost factors of every subset. Equation is as below:

$$RC2 = \sum_{j=1}^k \sum_{l=1}^{jp} \frac{R_j}{\left| |SD_{jl}| - |N_j D_{jl}| \right|}$$

Where,

$RC2$ is the set cost for a destination set DS_i by RCM_B calculation

k is the number of subsets in DS_i , $DS_i = \{M_1, M_2, \dots, M_k\}$.

j is the subset number, $1 \leq j \leq k$

R_j is max rate of destinations within the subset M_j

jp is the number of destinations in subset M_j , $M_j = \{D_{j1}, D_{j2}, \dots, D_{jp}\}$.

$D_{j1}, D_{j2}, \dots, D_{jp}$ are destinations in subset M_j

N_j is the best forward node for subset M_j

Multiratecast Algorithm Description

$|SD_{j_l}|$ is the distance between current forwarding node S to destination D_{j_l} in M_j

$|N_j D_{j_l}|$ is the distance between best forward node N_j to destination D_{j_l} in M_j

As for example listed in Figure 14, RCM_B has rate cost as following:

$$RC2 = \frac{\max(R1, R2)}{||SD_1| - |N_1 D_1||} + \frac{\max(R1, R2)}{||SD_2| - |N_1 D_2||} + \frac{\max(R3, R4)}{||SD_3| - |N_2 D_3||} + \frac{\max(R3, R4)}{||SD_4| - |N_2 D_4||}$$

RCM_B set cost calculation for Figure 15

For the destination set in Figure 15, RCM_B calculates set cost as following steps:

For subset M_1 , it calculates rate cost factor from N_1 to $\{\{D_1, D_2\}\}$, and then N_2 to $\{\{D_1, D_2\}\}$, and selects the neighbour with lower total rate cost factor.

$$\begin{aligned} rcf(N_1, subset 1) &= \frac{\max(R1, R2)}{||SD_2| - |N_1 D_1||} + \frac{\max(R1, R2)}{||SD_2| - |N_1 D_2||} \\ &= \frac{5}{||4 - \sqrt{5}||} + \frac{5}{||\sqrt{2^2 + 3^2}| - |\sqrt{1+1}||} = 5.12 \end{aligned}$$

$$\begin{aligned} rcf(N_2, subset 1) &= \frac{\max(R1, R2)}{||SD_2| - |N_2 D_2||} + \frac{\max(R1, R2)}{||SD_2| - |N_2 D_2||} \\ &= \frac{5}{||4 - \sqrt{13}||} + \frac{5}{||\sqrt{2^2 + 3^2}| - |\sqrt{2^2 + 2^2}||} = 14.59 \end{aligned}$$

Best Neighbour for subset M_1 is: N_1

For subset M_2 , it calculates rate cost factor from N_1 to $\{\{D_3, D_4\}\}$, and then N_2 to $\{\{D_3, D_4\}\}$, and selects the neighbour with lower total rate cost factor.

Multiratecast Algorithm Description

$$\begin{aligned}
 rcf(N_1, subset\ 2) &= \frac{\max(R3, R4)}{\left| |SD_3| - |N_2 D_3| \right|} + \frac{\max(R3, R4)}{\left| |SD_4| - |N_2 D_4| \right|} \\
 &= \frac{7}{\left| \sqrt{29} - 4 \right|} + \frac{7}{\left| \left| \sqrt{2^2 + 3^2} \right| - \left| \sqrt{3^2} - \sqrt{5^2 + 1} \right| \right|} = 12.1
 \end{aligned}$$

$$\begin{aligned}
 rcf(N_2, subset\ 2) &= \frac{\max(R3, R4)}{\left| |SD_3| - |N_2 D_3| \right|} + \frac{\max(R3, R4)}{\left| |SD_4| - |N_2 D_4| \right|} \\
 &= \frac{7}{\left| \left| \sqrt{5^2 + 2^2} \right| + \left| \sqrt{3^2 + 1} \right| \right|} + \frac{7}{\left| \left| \sqrt{6^2 + 1^2} \right| - 4 \right|} = 6.52
 \end{aligned}$$

Best Neighbour for subset M_2 is: N_2

Set cost I by RCM_B for Figure 15 is :

$$\begin{aligned}
 RC2_I &= \frac{\max(R1, R2)}{\left| |SD_1| - |N_1 D_1| \right|} + \frac{\max(R1, R2)}{\left| |SD_2| - |N_1 D_2| \right|} + \frac{\max(R3, R4)}{\left| |SD_3| - |N_2 D_3| \right|} + \frac{\max(R3, R4)}{\left| |SD_4| - |N_2 D_4| \right|} \\
 &= 5.12 + 6.52 = 11.64
 \end{aligned}$$

 RCM_B set cost calculation for Figure 16

For the destination set in Figure 16, RCM_B calculates set cost as following steps:

$$\begin{aligned}
 rcf(N_1, subset) &= \frac{\max(R)}{\left| |SD_2| - |N_2 D_2| \right|} + \frac{\max(R)}{\left| |SD_2| - |N_2 D_2| \right|} + \frac{\max(R)}{\left| |SD_3| - |N_2 D_3| \right|} + \frac{\max(R)}{\left| |SD_4| - |N_2 D_4| \right|} \\
 &= 12.197
 \end{aligned}$$

$$\begin{aligned}
 rcf(N_2, subset) &= \frac{\max(R)}{\left| |SD_2| - |N_2 D_2| \right|} + \frac{\max(R)}{\left| |SD_2| - |N_2 D_2| \right|} + \frac{\max(R)}{\left| |SD_3| - |N_2 D_3| \right|} + \frac{\max(R)}{\left| |SD_4| - |N_2 D_4| \right|} \\
 &= 26.95
 \end{aligned}$$

Best Neighbour for subset is: N_2

Set cost II by RCM_B for Figure 16 is :

Multiratecast Algorithm Description

$$RC2_{II} = rcf(N_{1,subset}) = 12.197$$

5.2.3.3 RCM_C: rate cost based on destination set

In RCM_C method, rate cost factor is based on the whole destination set. The set rate cost factor is calculated as sum of all subset rate divided by sum of all maximum subset distance progress. The rate cost factor is as in following equation:

$$rcf_{set} = \frac{\sum_{j=1}^k R_j}{\sum_{j=1}^k \Delta D_j} = \frac{\sum_{j=1}^k R_j}{\sum_{j=1}^k (\sum_{i=1}^{jp} ||SD_{ji}| - |n_j D_{ji}||)_j}$$

Where,

k is the number of subsets in DS_i , $DS_i = \{M_1, M_2, \dots, M_k\}$

j is the subset number, $1 \leq j \leq k$

R_j is max rate of destinations within the subset M_j

jp is the number of destinations in subset M_j , $M_j = \{D_{j1}, D_{j2}, \dots, D_{jp}\}$.

$D_{j1}, D_{j2}, \dots, D_{jp}$ are destinations in subset M_j

$|SD_{ji}|$ is the distance between current forwarding node S to destination D_{ji} in M_j

$|n_j D_{ji}|$ is the distance between neighbour node n to destination D_{ji} in M_j

Because given a destination set, the sum of subset rate is a fixed value that equals to the sum of maximum data rate of all subsets, so in order to lowest set rate cost factor, RCM_C need select best neighbour node for each subset that provide maximum distance progress for all destinations in each subset. The best forwarding node for subset M_j should fulfill following equation:

$$\sum_{i=1}^p ||SD_{ji}| - |N_j D_{ji}|| \geq \sum_{i=1}^p ||SD_i| - |n_j D_{ji}||$$

Where,

Multiratecast Algorithm Description

$|SD_{jl}|$ is the distance between current node S to the destination D_{jl}

$|n_j D_{jl}|$ is the distance between any other neighbour node n to the destination D_{jl}

$|N_j D_{jl}|$ is the distance between best forwarding node N_j to the destination D_{jl}

p is the total number of destinations in the subset M_j

After selecting best forwarding node for each subset, The rate cost of the destination set DS_i that contains k destinations $DS_i = \{M_1, M_2, \dots, M_k\}$ can be gotten by following method:

$$RC3 = \frac{\sum_{j=1}^k R_j}{\sum_{j=1}^k (\sum_{l=1}^{jp} |SD_{kl}| - |N_j D_{jl}|)}$$

Where,

k is the number of subsets in DS_i , $DS_i = \{M_1, M_2, \dots, M_k\}$

j is the subset number, $1 \leq j \leq k$

R_j is max rate of destinations within the subset M_j

jp is the number of destinations in subset M_j , $M_j = \{D_{j1}, D_{j2}, \dots, D_{jp}\}$.

$D_{j1}, D_{j2}, \dots, D_{jp}$ are destinations in subset M_j

$|SD_{jl}|$ is the distance between current forwarding node S to destination D_{jl} in M_j

$|N_j D_{jl}|$ is the distance between best forwarding neighbour node N_j to destination D_{jl}

As for example listed in Figure 14, RCM_C calculates rate cost as following:

$$RC3 = \frac{\max(R1, R2) + \max(R3, R4)}{||SD_1| - |N_1 D_1|| + ||SD_2| - |N_1 D_2|| + ||SD_2| - |N_2 D_3|| + ||SD_3| - |N_2 D_4||}$$

RCM_C set cost calculation for Figure 15

For the set example in Figure 15 RCM_C selects best neighbour node as same as RCM_A:

Multiratecast Algorithm Description

It calculates distance progress from N_1 N_2 to the destinations in the two subsets, and selects N_1 for subset M_1 and N_2 for subset M_2 .

The set cost I by RCM_C for Figure 15 is :

$$RC3_I = \frac{\max(R1,R2) + \max(R3,R4)}{||SD_1|-|N_1D_1|| + ||SD_2|-|N_1D_2|| + ||SD_3|-|N_2D_3|| + ||SD_4|-|N_2D_4||}$$

$$= \frac{5+7}{3.89+2.87+2.22+2.08} = 1.14$$

RCM_C set cost calculation for Figure 16

For the example in Figure 16, RCM_C calculates selects best neighbour node N_2 for all destinations in the subset because it provides the most distance progress for all destinations. This result is same as in RCM_A.

set cost II by RCM_C for Figure 16 is :

$$RC3_II = \frac{\max(R1,R2) + \max(R3,R4)}{||SD_1|-|N_2D_1|| + ||SD_2|-|N_2D_2|| + ||SD_3|-|N_2D_3|| + ||SD_4|-|N_2D_4||}$$

$$= \frac{5+7}{0.39+2.82+2.22+2.08} = 1.60$$

5.2.3.4 Example of RCM Greedy routing best set selection

In this section, we will give example of the RCM best set selection process.

As mentioned before, for network with small number of destinations, RCM applies complete destination set partition, calculates set cost for every set and choose the best set with lowest cost.

For example, suppose we only consider two destination set as in Figure 15 and Figure 16. After set cost calculation, RCM_A, RCM_B, RCM_C may select better set and forwarding node as following:

Multiratecast Algorithm Description

	RCM_A	RCM_B	RCM_C
Set cost A	2.90	11.64	1.14
Set cost B	0.93	12.19	1.60
Final selection (forwarding nodes)	Figure B (N_2 for all destinations)	Figure A (N_1 for subset 1, N_2 for subset 2)	Figure B (N_2 for all destinations)

Table 1 Example of set cost results compare

RCM_A and RCM_C both select set in Figure B with N_2 as forwarding node to cover all destinations while RCM_B select set in Figure A with N_1 cover subset M_1 and N_2 cover subset M_2 .

This example only shows routing forwarding difference with 4 destinations and 2 nodes. For network with larger number of destinations and more neighbour nodes, the routing selection and branch can be quite different for RCM_A , RCM_B and RCM_C methods.

For network with more than 5 destinations, after creating initial destination set, RCM applies rounds of subset merge and set cost recalculation/compare process until find out the best set with lowest cost.

For example, suppose we have an initial greedy set $DS_0 = \{\{D_1, D_2\}, \{D_3, D_4\}, \{D_5, D_6\}\}$ and its set cost is 5. Following the above greedy set merge, there can be three possible subset merge results:

	Merge 1	Merge 2	Merge 3
Initial Set	$DS_0 = \{\{D_1, D_2\}, \{D_3, D_4\}, \{D_5, D_6\}\}$ Initial set cost = 5		
New set	$\{D_1, D_2\}$ $\{D_3, D_4, D_5, D_6\}$	$\{D_3, D_4\}$ $\{D_1, D_2, D_5, D_6\}$	$\{D_5, D_6\}$ $\{D_1, D_2, D_3, D_4\}$
New set cost	10	3	7

Multiratecast Algorithm Description

Selected new set	No	Yes	No
------------------	----	-----	----

Table 2 Subset merge example 1

From this table, after the three possible merge, we get new possible set cost as 10,3,7 respectively. The merge 2 provides lower new set cost than the initial set, so that new set is formed as $\{\{D_1, D_2, D_5, D_6\} \{D_3, D_4\}\}$.

Further merge on new set:

	Merge 1
Current set	$\{D_3, D_4\} \{D_1, D_2, D_5, D_6\}$
New set	$\{\{D_3, D_4, D_1, D_2, D_5, D_6\}\}$
New set cost	9
Selected new set	No

Table 3 Subset merge example 2

Further set merge has higher set cost than the current set, so the greedy destination partition will have final destination set as $\{\{D_1, D_2, D_5, D_6\} \{D_3, D_4\}\}$ with set cost 3.

5.2.4 Maximum Rate Multicast protocol (MRM)

Compared to RCM, MRM is simpler when calculating the next forwarding nodes in greedy mode. It is still a general Greedy Face Greedy Algorithm, the Greedy routing selecting gives priority to maximum data rate destination.

In MRM greedy routing part, when a node S wants to find a routing node to multiple destinations with multiple rates, it applies multiple relay point (MRP) strategy. The strategy works at following:

MRM algorithm

Multiratecast Algorithm Description

Step 1: For all the destinations in greedy list, found one destination that requires highest rate, say it is D_m .

Step 2: Figure out the neighbour nodes that can provide most distance progress towards the just picked destination D_m , mark this neighbour node as N_m .

Step 3: For rest of the destinations in greedy routing list, as long as node N_m can provide greedy routing to the destinations, use N_m as forwarding nodes for those destinations.

Step 4: If there are still destinations that cannot be forwarded by N_m , repeat step 1 to 3 to find next forwarding node until all the destinations are covered.

If there is face routing involved, the face routing is similar as in RCM routing, the greedy routing can be resumed whenever the forwarding node is closer to destination than the face routing start node.

Since there is no destination set partition required, this algorithm requires much less calculation. It is very suitable for the situation where they are high number of destinations or sensor nodes have very limited power consumption requirement.

Chapter 6

MRC Performance Evaluation

6.1 Simulation Network

We simulated and compared all the MRC algorithms in simulation networks. The networks use Unit Graph Model and were generated by CRUG (Connected Random Unit Graph) algorithm. The algorithm requires number of nodes (N) and the average density degree (d) as input, and runs as follows:

For a given interval, each node is placed randomly first. There are total $\frac{N \times (N-1)}{2}$ edges among all the N nodes, sort them by their length in increasing order. The radius R that corresponds to a chosen average degree of d can be set to equal to the length of $\frac{N \times d}{2}$ -th edge in the sorted order. Any edge that is not longer than R will remain in the graph, while other edges are eliminated from the graph.

Once the graph is generated, Dijkstra's *shortest path algorithm* (from one node to all other nodes) is used to check the connectivity of the graph. Only connected graphs are saved and used for simulation. The unconnected graphs are discarded.

The source node and destination nodes are randomly selected in the connected network. We test the network routing from one single source node to multiple destinations because MRC algorithms are designed to base on this one-way, point-to-multipoint transmission. The data rate required by each destination node is able to be changed as user input when testing simulation network.

6.2 Testing Parameters

In order to observe the routing algorithm performance in different scenarios, we simulated different network by alternating following parameters:

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- D (Average degree): The efficiency of the multiratecast may depend on different network density. In order to test the average degree impact on the routing performance, we tested the network from sparse to dense network by using average degree: 8, 12, 16, 20, 24, 28, 32
- DN (destination number): in order to test the destination number impact on the routing performance, we choose destination number 2, 3, 4, and 5 to study the routing performance for network with small number of destinations and destination number 10, 20, 30, 40, 50 to study performance for networks with large number of destinations.
- N (Number of nodes): We choose network with 100, 300, 500 nodes to study the protocols performance with small number of destinations (2-5 destinations). We choose network with 500, 800, 1000 nodes to study the protocols performance with larger number of destinations. (10 – 50 destinations)
- SD (Standard Deviation): To study the destination rate distribution's impact on routing performance, we studied network with same average destination rate but with different rate standard deviation. For networks with only 5 destinations, two data rate groups are applied. One has average rate 1000 and rate standard deviation 0, 7.14, 16.9, 14.3, 33.9 as listed in Table 4 Destination rate group1 for network with 5 destinations. The other group has relatively more drastic data rate. The second group has average rate 2222.2 and rate standard deviation 26.1, 361.23, 790.57, 2104.02, 4368.04 as listed in Table 5. For networks with larger number of destinations, we studied network with 10, 20, 30, 40, 50 destinations. We applied destination rate with average rate 1000 and standard deviation 100,300,500,700 as list in Table 7. To study the impact of more drastic rate distribution, we applied a group of more drastic rate distribution for network with 6 destinations. The average rate for all 6 destinations is 18518.5. The rate standard deviation is 403.73, 7567.17, 14066.17, 20894.2, 40108.36 as list in Table 6.
- T (Test execution time): For each test scenario with given protocol, given network nodes, average degree, given destination nodes and rate, we generate 50 network

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graphs and perform routing on every one of them. We save and use the average routing results of 50 executions as final result to do analysis.

- P (Protocols): We tested protocol RCM and MRM. For RCM protocol, we applied three different rate cost factors methods RCM_A, RCM_B and RCM_C as described in previous chapter and compare results to find out which rate cost factor is more efficient in overall multiratecast routing performance. To conveniently list routing results, we list name RCM_A, RCM_B and RCM_C in picture and result analysis. However, they all belong to RCM algorithm.

Mild Destination Rate Distribution					Average Rate	SD
D1	D2	D3	D4	D5		
100	100	100	100	100	100	0
97	103	111	96	93	100	7.141428
90	80	115	120	95	100	16.95582
70	110	127	79	114	100	24.32077
130	120	50	120	80	100	33.91165

Table 4 Destination rate group1 for network with 5 destinations

Drastic Destination Rate Distribution					Average Rate	SD
D1	D2	D3	D4	D5		
2190	2208	2223	2230	2222	2222.2	26.11
1822	2022	2223	2422	2622	2222.2	361.23
1222	1722	2223	2722	3222	2222.2	790.57
380	751	1500	2920	5560	2222.2	2104.02
1	10	100	1000	10000	2222.2	4368.04

Table 5 Destination rate group2 for network with 5 destinations

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Drastic Destination Rate Distribution						Average Rate	SD
D1	D2	D3	D4	D5	D6		
18518.5	18518.5	18518.5	18518.5	18518.5	18518.5	18518.5	0
18001	18200	18400	18600	18800	19110	18518.5	404.7339
8511	12500	16500	20500	24500	28600	18518.5	7507.171
2011	6900	13200	20000	30000	39000	18518.5	14066.17
751	2010	8300	14550	30500	55000	18518.5	20894.2
1	10	100	1000	10000	100000	18518.5	40108.36

Table 6 Drastic rate distribution for network with 6 destinations

Destination	Average Rate	SD			
D1-D10	1000	100	300	500	700
D1-D20	1000	100	300	500	700
D1-D30	1000	100	300	500	700
D1-D40	1000	100	300	500	700
D1-D50	1000	100	300	500	700

Table 7 Rate distribution for network with large number of destinations

6.3 Performance metric

To assess the performance of the proposed algorithms we used total rate cost as performance metric which is defined as the total transmission rate in routing paths as described in 5.1. As mentioned, the proposed multiratecast protocols are novel multicast protocols designed for the routing requirement in wireless sensor networks that each destination request data at different rate. Existing common performance metric like hop count does not reflect the efficiency for multiratecast routing. In simulation, we record the transmission rate at each forwarding node and use the sum of transmission rate as performance metric to evaluate the different protocols.

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6.4 Simulation Results

6.4.1 The Impact of Number of Nodes

To evaluate the impact of network node number on the routing protocol performance, we studied the routing data based on the networks that had same average degree, same destination number and same rates but only different number of network nodes. The test result shows that with the increase of network nodes, the routing cost increase and the increase ratio is similar to all MRC protocols. We select some of the results list in below as examples.

The following pictures show an example of routing cost for networks with 5 destinations. The destination rate distribution is equal to 7.14. The average degrees for the two simulation network are equal to 12 and 24. The left two pictures show RCM_A, RCM_C and MRM had similar costs but RCM_B obviously has more routing costs. The right two pictures show routing results with RCM_B removed. We can see that RCM_C slightly outperform others. The increase ratio is similar to all the protocols.

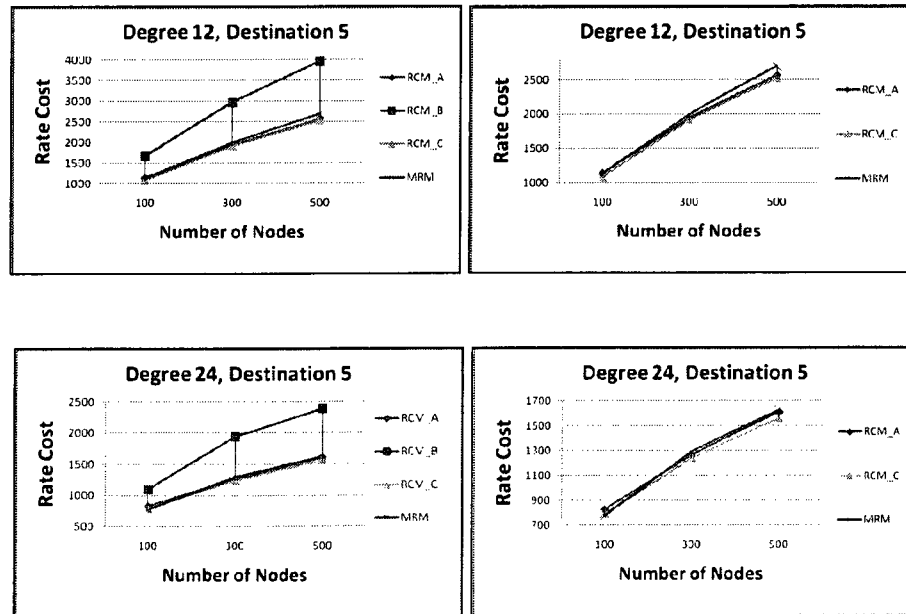


Figure 17 Rate Cost at Varying Node Number

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For Network with small number of destinations

N=100, 300, 500

For network with large number of destinations, routing cost also increase with network nodes. The following two pictures show examples of two network routing results. One is for a sparse network with 10 destinations and average degree 8, the other is for a dense network with 50 destinations and average degree 32. The result show that no matter if the network is sparse or dense network, rate cost increase with the node number increase, RCM_B has worst performance while MRM protocol outperforms RCM. The number in larger number of destinations, with the network node number increase, the performance difference between MRM and RCM increases. MRM shows more advantage in network with more destination numbers.

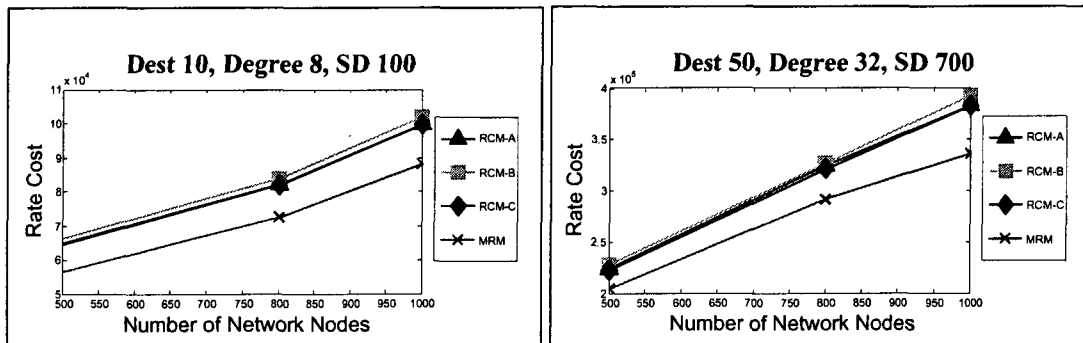


Figure 18 Rate Cost at Varying Node Number

for Network with large number of destinations

N = 500, 800, 1000

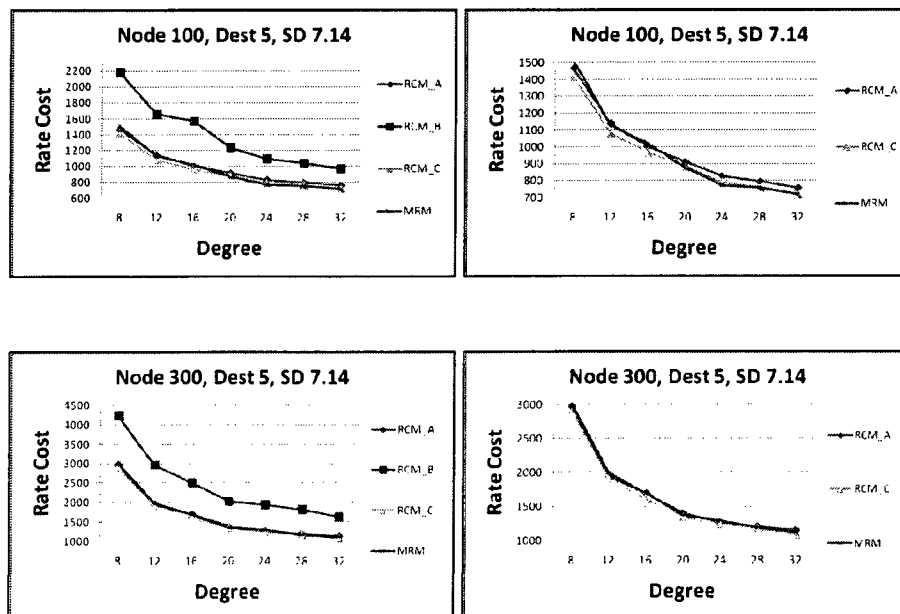
6.4.2 The Impact of Average Degree

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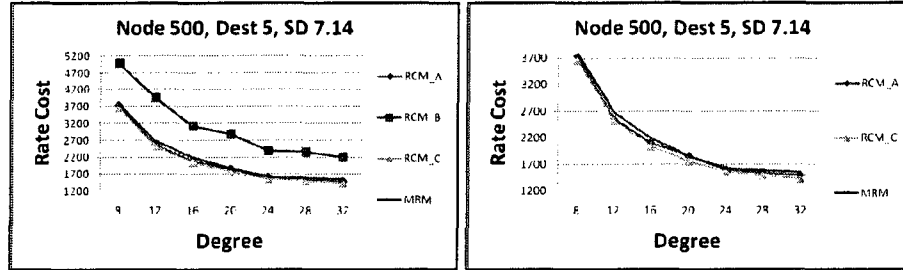
To measure the protocol's performance under different network density, we analyzed the routing cost from sparse network to dense network with increasing average degree. For network with same destination number, same destination rate, same number of network nodes, we studied routing results with average degree 8, 12, 16, 20, 24, 28, 32.

Simulation results show that with the increase of network degree, the multiratecast routing costs decrease dramatically. We can see that the proposed MRC protocols are more efficient and suitable for high density networks because they more chances to select the best next forwarding node in greedy and have less chances of face routing.

The following pictures are examples of routing cost for small network with 5 destinations and average rate 100, distribution standard deviation 7.14. For network with 100 nodes, 300 nodes and 500 nodes, with the network degree increase, all MRC protocols routing cost decrease. RCM_B is the worst performer that has larger cost than others while the other three RCM_A, RCM_C and MRM show similar performance, RCM_C slightly outperform others.



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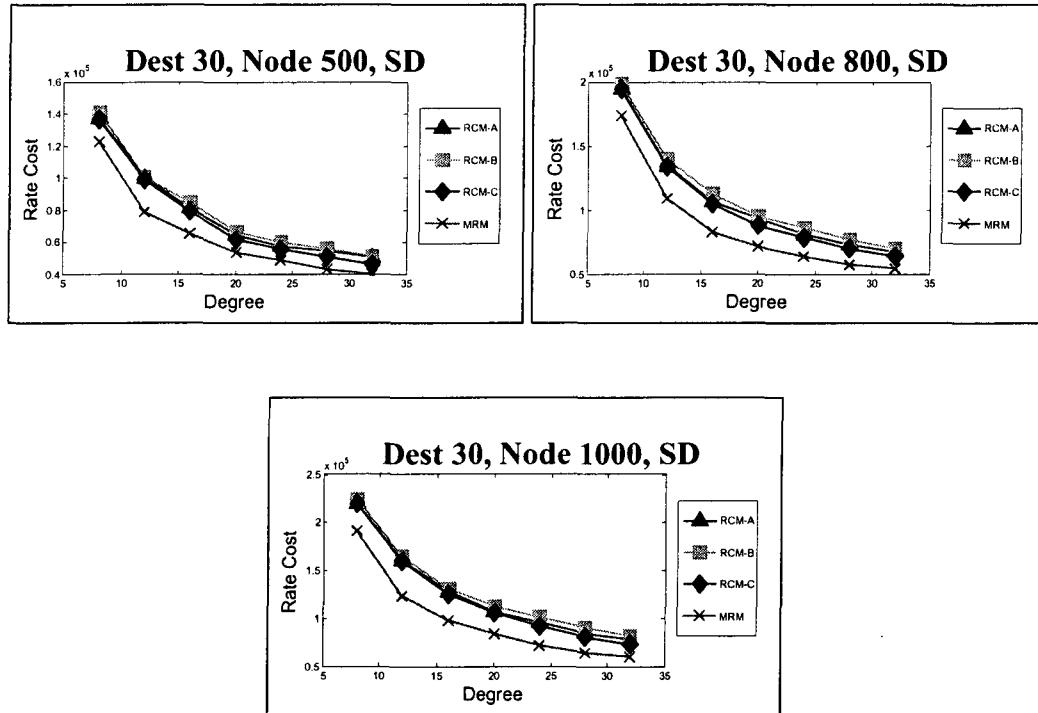
**Figure 19 Rate Cost at Varying Degree
for Network with small number of destinations**

D = 8, 12, 16, 20, 24, 28, 32

The following pictures are examples of routing cost for large network with 30 destinations and average rate 1000, distribution standard deviation 300. For network with 500 nodes, 800 nodes and 1000 nodes, with the network average degree increase, all MRC protocols routing cost decrease. RCM_B is still the worst performer however its rate cost difference so not so large as compared to that in small number of destinations. We can see the RCM_A, RCM_B, and RCM_C have similar cost while MRM obviously outperform them.

From the simulation results, we can conclude that both RCM and MRM have good routing performance for large and dense network while MRM has more advantage. This partly because we apply greedy set partition for large network, the routing with greedy set partition may depend on initial set partition. A non-optimal set partition may results more routing cost.

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**Figure 20 Rate Cost at Varying Degree
for network with large number of destinations**

D = 8, 12, 16, 20, 24, 28, 32

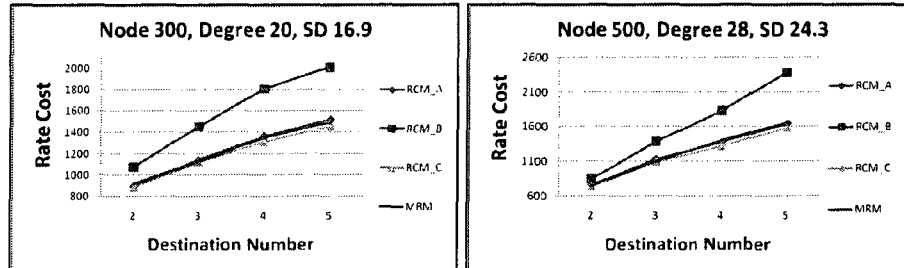
6.4.3 The Impact of Destination Numbers

To study the destination number's effect on the routing performance, we studied routing results with same network scenario except only destination number difference. As expected, the routing costs increase with the increase of destination numbers in both small and large number of networks. However, the ratio of cost increase speed is slower than that of the destination number increase.

As in the following two pictures, we have two networks with small number of destinations. One is a network with 300 nodes, average degree 20, average rate 100 and rate distribution 16.9. The other is a network with 500 nodes, average degree 28, average rate

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100 and rate distribution 24.3. By increasing destination number from 2 to 5, which is 150% increase, the average cost only increase from 900 to 1500 which is 66% increase.



**Figure 21 Rate Cost at Varying Destination Number
for network with small number of destinations**

DN = 2, 3, 4, 5

For network with large number of destinations, we list two example networks in following pictures. The first network is with 500 nodes, average degree 28, average rate 1000 and rate distribution 500. The second network is with 800 nodes, average degree 16, average rate 1000 and rate distribution 300. We can see from both the two pictures, when destination number increases 5 times from 10 to 50, the rate cost only increase less than 3 times.

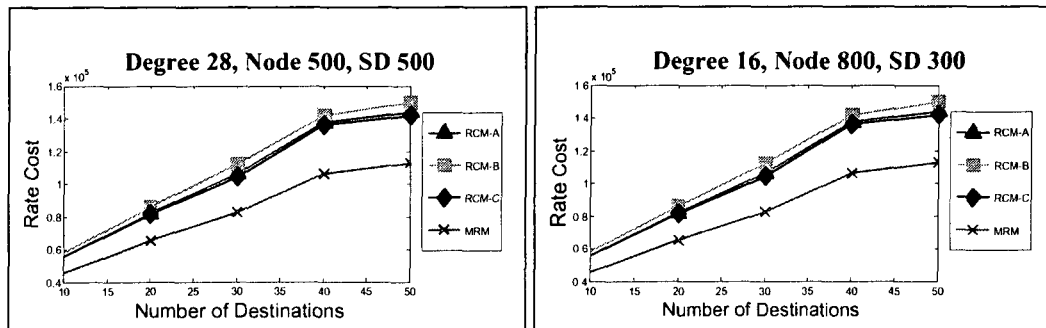


Figure 22 Rate Cost at Varying Destination Number

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for network with large number of destinations

DN = 10, 20, 30, 40, 50

The MRM has better performance in network with large number of destinations. It is reasonable: the RCM applies greedy destination set partition instead of complete destination set partition. Therefore, RCM rate cost calculation is partly based on the selection of initial destination set. Although RCM_C always outperforms MRM in complete destination set partition in network with small number of destinations, it cannot always find out best forwarding set based on set merge in network with large number of destinations.

The results show that multiratecast protocols reduce overall routing cost by sharing paths. From the results we can conclude that both RCM and MRM are efficient multicast protocols and MRM have better performance than RCM with greedy set partition and is a practical protocol suitable for large network with large number of destinations.

6.4.4 The Impact of Standard Deviation

Multiratecast protocols are specially designed to fulfill the requirement that destinations request data at different rate. To evaluate the impact of destination rate change to routing performance, we studied networks with same degree, same network node numbers, same destination number, same average destination rate but only different rate distributions.

We first study the network with small number of destinations and mild rate change. RCM routing in this scenario apply complete destination set partition. The following pictures show routing results for network with 5 destinations with mild rate distribution. Routing results for networks with small network nodes (100), medium network nodes (300) and large network nodes (500) are displayed. The degrees for these networks are low(8), medium(24) and high(32). For each simulation network graph, 5 groups of different data rates are used. The average data rate for all destinations are set to same number 100, the rate distribution standard deviation is set in increasing order from 0 to 33.9. The left three pictures include RCM_B while right three pictures do not include RCM_B. It is observed

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that algorithm RCM_C has lowest total rate cost and algorithm RCM_B has the highest cost. With the increase of rate standard deviation, the costs slightly increase for algorithm RCM_A, RCM_C and MRM. The cost for RCM_B keep flat or slightly decrease although its cost is always larger the other three algorithms.

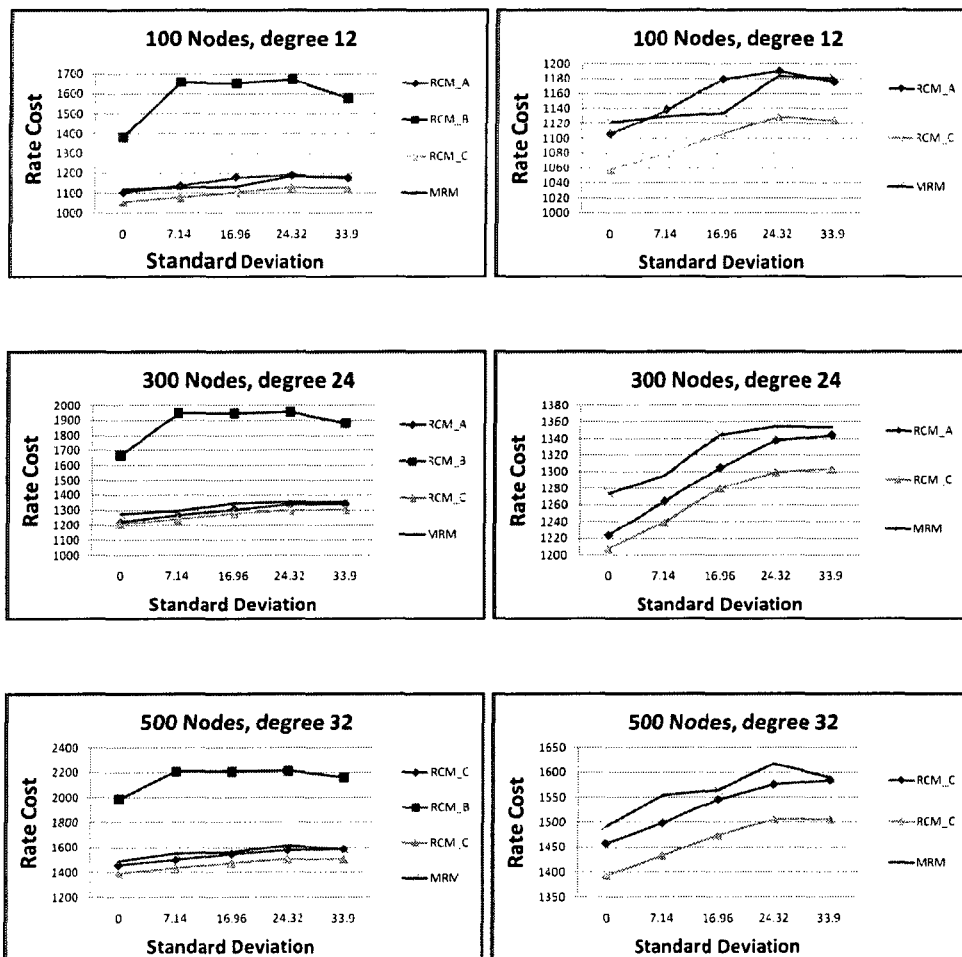


Figure 23 Rate Cost at Group 1 Rate Distribution

for network with 5 destinations

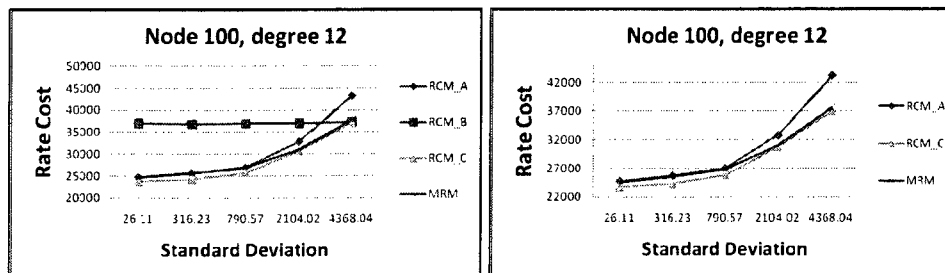
SD = 0, 7.14, 16.96, 24.32, 33.9

Average rate = 100

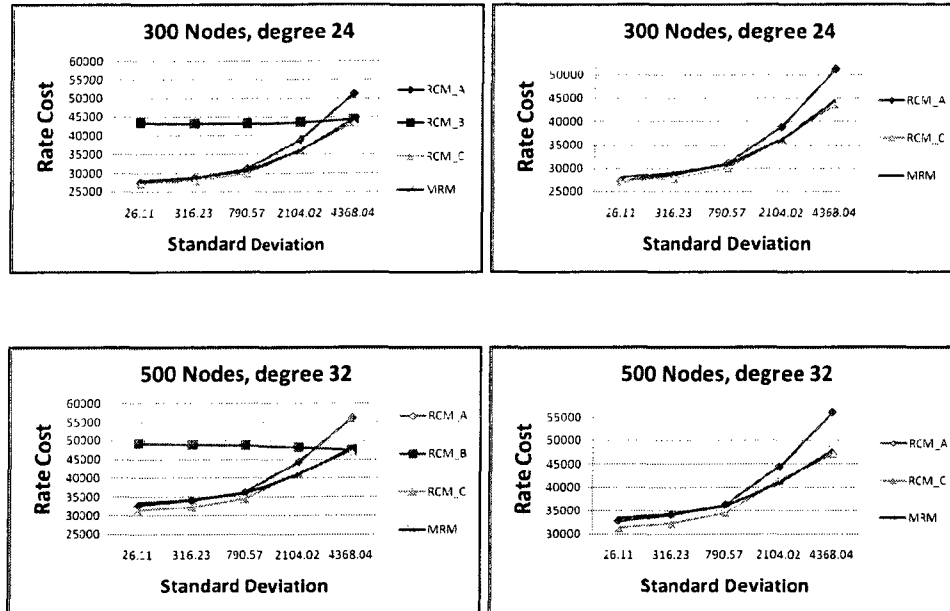
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Secondly, we study the same networks with 5 destinations but more drastic rate distribution. Simulation results show that when the destination's data rate differences are more drastic, destination data rate distribution does affect the routing performance for RCM and MRM algorithms.

The following pictures show the algorithms performance with increasing rate distribution in three network configurations similar as we studied before but with average data rate change to 2222.2 and rate standard deviation in increasing order from 26.11 to 4368.04. The left three pictures include RCM_B while right three pictures do not include RCM_B. It is observed that with the data rate difference increase, all the algorithms' rate cost increase. However, the routing performance's difference between RCM and MRM, and the difference between three RCM methods are decreased. When the destinations have most data rate differences, the three methods RCM_A, RCM_C and MRM have similar performance. RCM_C is still the best among all the algorithms, but the cost differences among the three algorithms are not as big as in previous mild rate distribution scenario. RCM_A costs increase more with the rate distribution's increase and it becomes the worst performer in the network with largest rate distribution. RCM_B keeps flat rate cost and is still the worst algorithm compare to others. RCM_C slightly outperform MRM. The results show that when data rates have relatively more drastic differences among destinations, the routing algorithms that consider the destination with maximum data rate is most important in routing decision. We can conclude from the results that RCM_C with complete set partition is the best for network with small number of destinations but MRM is also very competitive.



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**Figure 24 Rate Cost at Group 2 Rate Distribution
for network with small number of destinations
SD = 26.11, 316.23, 790.57, 2104.02, 4368.04**

Average rate = 2222.2

Thirdly, we study the network with large number of destinations. RCM apply greedy set partition in this scenario. We ran simulation on networks with same network nodes (500,800,1000), same degree (8,12,16,20,24,28,32) , same destination number (10,20,30,40,50) , with only destination rate change. Simulation results show that destination's rate distribution has direct impact on routing cost. The following example pictures show results for network with 500 and 1000 nodes, with destination number 10 and 50, and with degree 24 and 32. The average rate for both of the networks is 1000 and rate distribution standard deviation is from 100 to 700. It is observed that with the rate distribution increase, all protocols have obvious rate cost increase. MRM outperforms all RCM with 3 methods.

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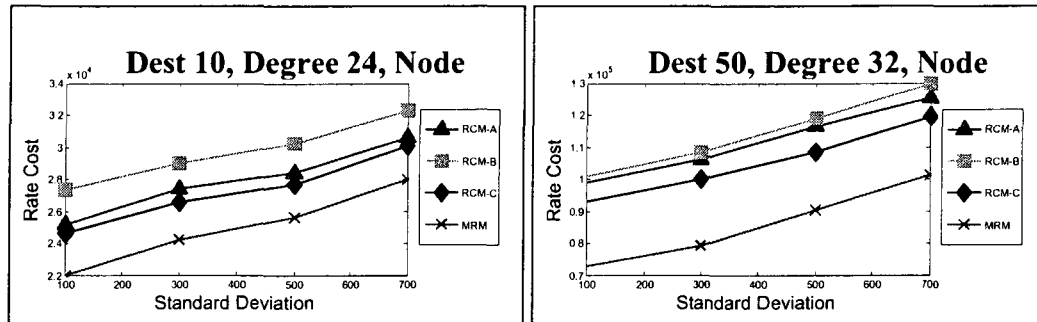


Figure 25 Rate Cost at Varying Rate Distribution

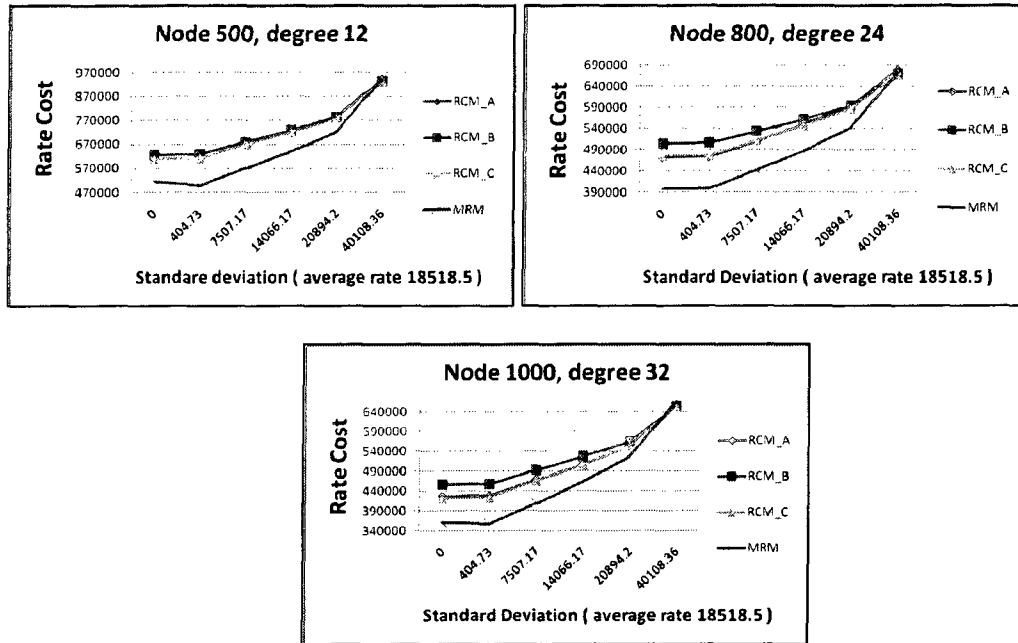
for network with large number of destinations

SD = 100,300,500,700

Average degree = 1000

Although different protocols show different rate cost and the costs increase with the increase of standard deviation, when the standard deviation is big enough, or in other words, the rate distribution is drastic enough, all the routing protocols have similar rate cost. The following pictures show a group of drastic rate distribution for network with 6 destinations. The average rate for all 6 destinations is 18518.5. The rate standard deviation is 0, 403.73, 7567.17, 14066.17, 20894.2, 40108.36 as list in Table 6. From the pictures we can see that MRM outperforms RCM protocol however, the difference of their performance gets smaller with the increase of rate standard deviation. When the standard deviation is big enough, all the protocols have similar rate cost. These are reasonable results because when the rate distribution is extremely unbalanced, the one destination that has much higher rate decides the total routing path selection. Compare to the highest rate destinations, the rate cost of paths to other destinations have little impact to the overall routing rate cost.

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**Figure 26 Rate Cost at Varying Rate Distribution
for network with 6 destinations**

SD = 0, 404.73, 7507.17, 14066.17, 20894.2, 40108.36

We can also see from the simulation results that for network with large number of destinations where RCM apply greedy set partition, MRM has less rate cost than RCM no matter at which destination rate distribution. This is different from the results for network with small number of destinations where RCM_C with complete set partition has less rate cost than MRM. We believe it is because the greedy set partition is not as optimal as complete set partition. We compared the RCM_C and MRM's performance in 6.4.6 and the performance of greedy and complete set partition in 6.4.7.

6.4.5 Comparison of Three RCM rate cost factors

RCM explores three rate cost factor in greedy routing calculations. The routing results show that all of them have more advantage in dense network. For all of them, the

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average routing cost decreases with the increase of network degree. Network nodes number does not affect their performance very much. Algorithm RCM_C outperforms others in almost all test cases. Algorithm RCM_B has the worst performance. The cost differences for algorithm RCM_C and RCM_A are not large. We can conclude from simulation results that RCM_C is the best among three.

The three pictures below are examples of the RCM algorithms performance with increasing average degree. Three different network graphs are selected. The first graph is for network with 100 nodes, 3 destinations and standard deviation 0. The second graph is for network with 300 nodes, 4 destinations and standard deviation 17. The third graph is for network with 500 nodes, 5 destinations and standard deviation 33.9. The results show consistently that RCM_C is the best performer.

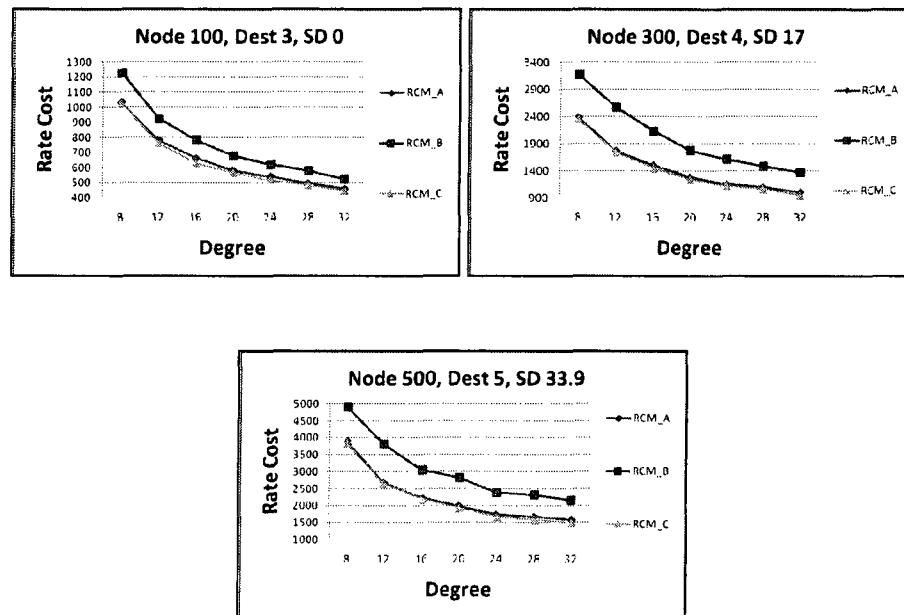


Figure 27 Comparisons of Three RCM Rate Cost Methods

Degree = 8,12,16,20,24,28,32

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6.4.6 Comparison of RCM and MRM

MRM is a very competitive algorithm. For network with small number of destination, compared to RCM_C that applies complete destination set partition, it has slightly more routing cost and is the second best algorithm. However, the cost differences between algorithm RCM_C and MRM are not large. The following three pictures show that in the three different networks listed as above, routing difference for MRM and RCM_C is not larger than 7%.

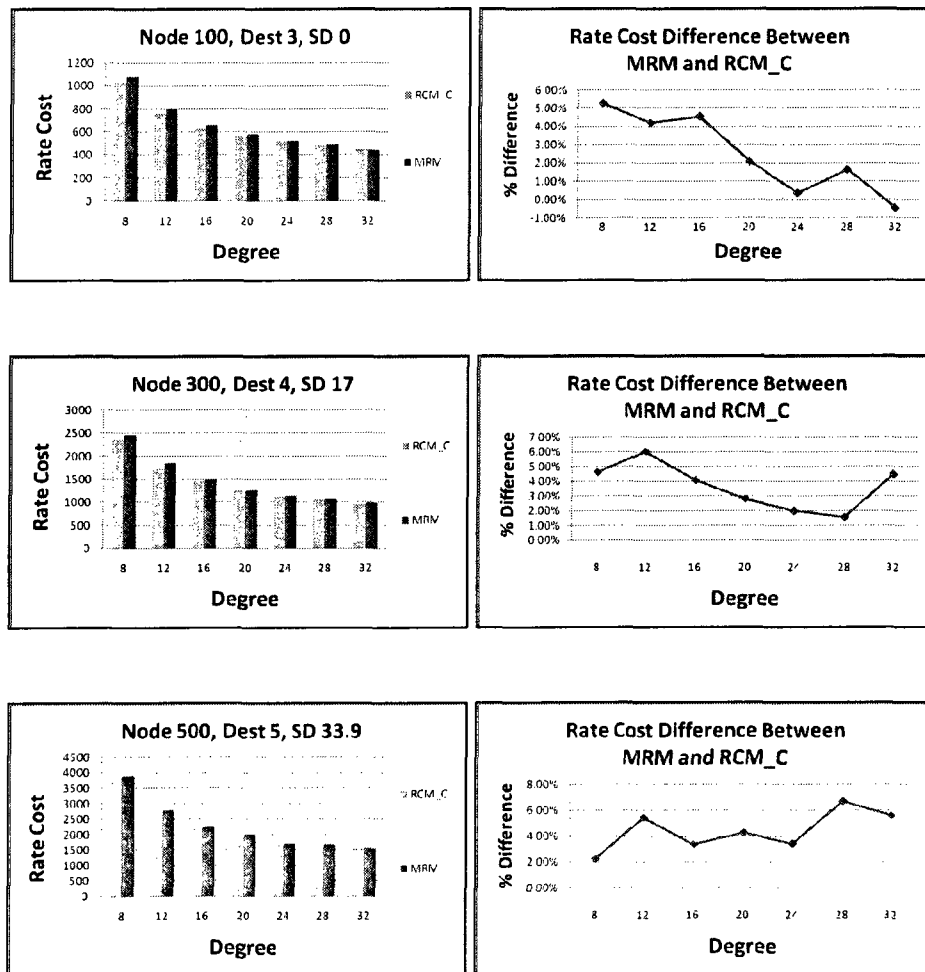


Figure 28 Comparisons of MRM and RCM_C

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Degree = 8,12,16,20,24,28,32

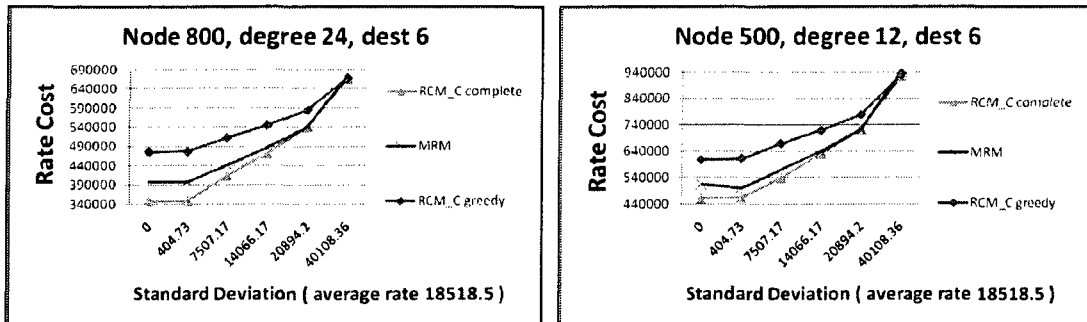
However, for network with large number of destinations, MRM outperforms RCM_C with greedy set partition in almost all network condition. We can see simulation results for varying network nodes, destinations, degree, and standard deviation from 6.4.1 to 6.4.4. Also, compared to RCM algorithm, MRM has advantage that its calculation is simple. It does not need destination set partition calculation.

We believe that for multi-rate sensor networks that have small number of destinations, RCM_C is an appropriate protocol because it provides best routing performance among all the protocols we study. For networks with large destination numbers, MRM is more suitable because RCM greedy set partition in large network is less efficient than MRM. MRM has better performance and needs less computation.

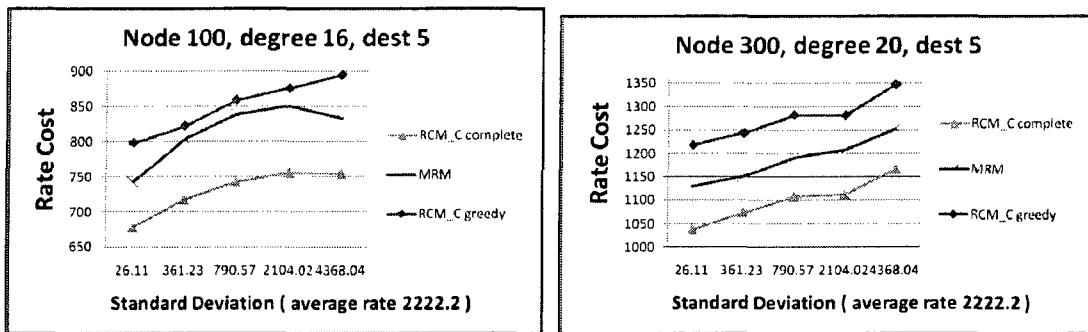
6.4.7 Comparison of Greedy and Complete set partition in RCM

RCM applies complete set partition for network with small number of destinations and a faster greedy set partition for networks with large destination numbers. The previous simulation results show that RCM_C with complete set partition outperforms MRM however RCM_C with greedy set partition is less efficient than MRM. To study the cost difference of greedy and complete set partition, we did RCM_C routing with both greedy and complete simulation on network with 5 and 6 destinations. Except set partition function, all other simulation parameters are exactly the same including network nodes, degree, destination number and rates, routing protocols. The only difference in simulations is that one routing simulation used complete set partition; the other routing simulation used greedy set partition. The following pictures show the routing cost difference between RCM_C with greedy set partition and complete set partition. We also listed MRM rate cost in the picture as a reference.

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(a)



(b)

Figure 29 Comparisons of greedy and complete set partition

(a) Average rate = 18518.5 DN = 6

SD = 0, 404.73, 7507.17, 14066.17, 20894.2, 40108.36

(b) Average rate = 2222.2 DN=5

SD = 26.11, 361.23, 790.57, 2104.02, 4368.04

The first two pictures are for networks with 6 destinations. The network nodes are equal to 800, 500 and degrees are equal to 24, 12. The second two pictures are for networks with 5 destinations, the networks nodes are equal to 100, 300 and degrees are equal to 16, 20. We can see from the pictures that rate cost of RCM_C with both types of set partition increase with the destination rate standard deviation increase. RCM_C with complete set partition always has less rate cost than MRM however RCM_C with greedy set partition always has

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higher rate cost. This is because complete set partition considers all possible destinations' combination and finds the best one among them. It can get the best destination set with lowest rate cost in each forwarding thus result in better overall routing paths. The greedy set partition starts from the initial destination set and tries to find better set based on the initial set by merging the subset. If an initial destination set is not optimal, there is no other way to correct the partition to get a better routing selection. We can also see from the pictures that when the standard deviation is high enough, routing results with either RCM_C greedy or RCM_C complete function have similar rate cost. This is because the highest rate destination has large impact on the rate cost as we described in 6.4.4.

6.4.8 Comparison of GMR and RCM_C

To study the routing efficiency of multiratecast protocols, we compare the RCM_C routing rate cost to the non rate based routing protocol GMR in same network configuration scenarios. We select GMR because it is the localized multicast protocol that does not consider destination rate in routing path selection. We also select RCM_C because it is the localized multicast protocol that consider destination rate in routing decision. Based on greedy destination set partition and set cost calculation focus on whole set, RCM_C has most similar cost calculation function compare to GMR. We did simulation on network with 6 destinations and 500 nodes. The average rate is 18518.5. The destination rate standard deviation is changed from 0 to 404.73, 7507.17, 14066.17, 20894.2 and 40108.36. The simulation results show that when destination rates are equal, GMR and RCM_C had same rate cost. RCM_C had lower cost for network with higher standard deviation. The rate cost difference increase when the destinations rate standard deviation increases. This shows that multiratecast protocols are more efficient for network with unbalanced destination rate.

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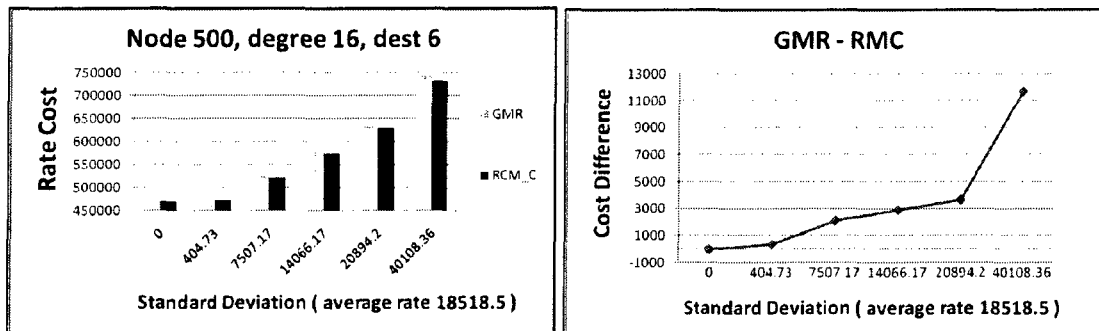
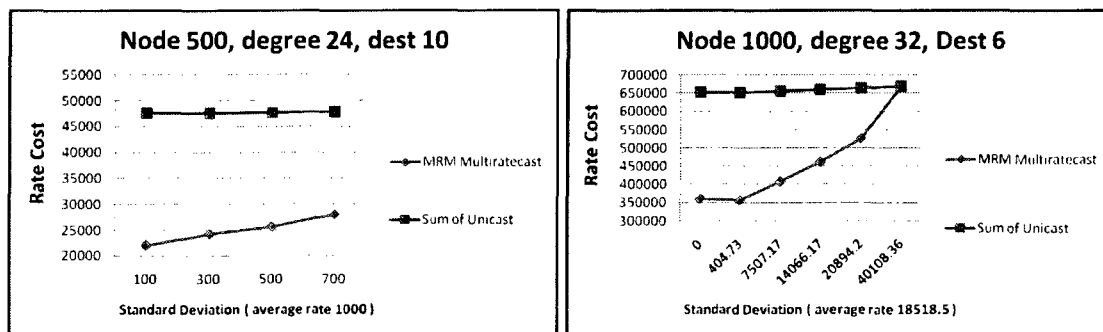


Figure 30 Comparisons of GMR and RCM_C

6.4.9 Comparison of Multiratecast and Sum of Unicast

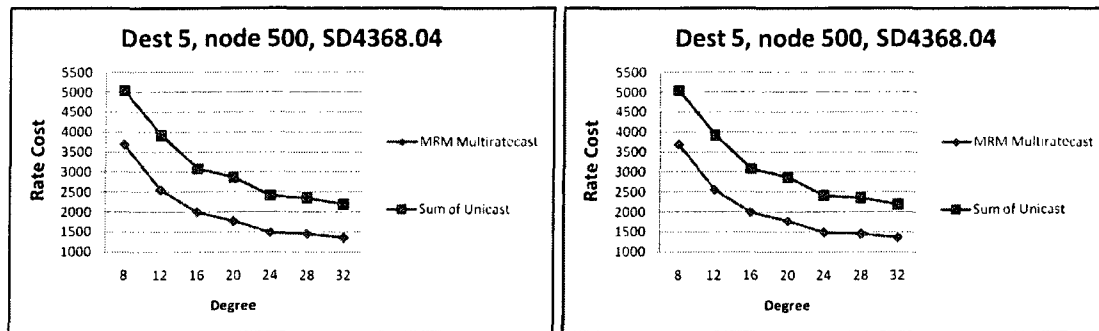
To study the routing efficiency of the multiratecast protocols, we compare the MRM multiratecast rate cost to the sum of unicast rate cost in the same network configuration. The reason to select MRM is that: based on previous simulation data analysis, we found among the protocols we study, MRM is the best routing protocol for network with large number of destinations and it is better than the RCM_C with greedy set partition. Besides, it is also a very competitive protocol for network with small number of destinations. It is the second best one compared to RCM_C with complete set partition. We believe compare MRM and the sum of unicast rate cost will give a proper representation of the multiratecast routing efficiency.



(a)

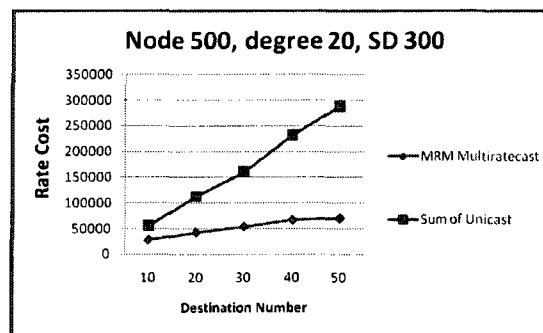
(b)

MRC Performance Evaluation



(c)

(d)



(e)

Figure 31 Comparisons of MRM and sum of Unicast

The above 5 pictures give examples of MRM and sum of unicast cost based on networks with one changing parameter. The unicast routing is performed from source node to each destination node individually. From source node and at each forwarding node, the neighbour node that is closest to destination node will be selected as next relay node until message reaches the destination node. The sum of transmission rate at each relay node on the unicast path to the destination is the rate cost for the destination. The total rate cost for all destinations is the sum of unicast rate cost that we use to compare with MRM. We can see from the above pictures that MRM has lower rate cost than sum of unicast rate cost in all simulation scenarios.

The first two pictures show the rate cost when the destination rate standard deviation increase. Picture (a) shows network with 500 nodes, average degree 24, 10 destinations and average destination rate 1000. It has relatively mild standard deviation 100, 300,500,700.

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The MRM rate cost shows slightly increase with the SD increase however the sum of unicast cost almost remains same. Picture (b) shows network with relatively drastic standard deviation. The network is with 1000 nodes, average degree 32, 6 destinations and average rate is 18518.5. We used rate standard deviation from 0 to 40108.36. From the picture, we see the sum of unicast cost only slightly increases but there is big MRM rate cost increase with the SD increase. At the highest standard deviation, the MRM cost is almost the same as sum of unicast cost. This is because the destination with highest rate has most impact for the overall routing cost, other destination's rate cost are too small compared to the highest rate cost so that multiratecast has similar rate cost as unicast.

The third picture (c) shows rate cost change with only number of network nodes increase. We studied network with 5 destinations, average degree 20, SD 361.23 and average rate is 18518.5. With the network nodes increase from 100 to 300 and 500 nodes, the simulation results show that rate cost increase with the network nodes. However, the MRM rate cost increase is slower than the sum of unicast cost increase. We can conclude that the MRM shows more efficiency in network with large number of network nodes.

The picture (d) shows rate cost change with only the average degree change. The network is with 5 destinations, 500 nodes, SD 4368.04 and average rate 2222.2. Both MRM rate cost and sum of unicast cost decrease with the degree increase in the picture. This is because with average degree increase in same 500 nodes network, there are more directly connected nodes in the network so there are less chance of message relay and face routing.

The picture (e) shows rate cost change with destination number change. We studies network with 500 nodes, average degree 20, SD 300 and average rate 1000. With the destination number increase from 10 to 50, we can see that sum of unicast cost increase sharply while MRM only has mild increase. The larger destination number, the bigger difference between MRM and unicast rate cost. We can conclude that the destination number has a large impact for the routing performance. MRM shows more efficiency in network with large number of destinations.

Conclusion and Future Work

Chapter 7

Conclusion and Future Work

We introduced geographical multicast routing protocol GMR and multiratecast protocols MRC for WSNs. Both GMR and MRC are purely localized multicast protocols. They do not require the use of extensive broadcast to route messages to a set of destinations. GRM is designed to perform bandwidth efficient multicast. It uses a cost-based neighbour selection at each routing step, allowing it to find a good tradeoff between the optimality of the multicast tree and the efficiency of data delivery. MRC protocols aim to resolve the efficient multiratecast routing problem where destinations request data at different rate.

Computing the optimal multicast tree in terms of bandwidth consumption is similar to finding the multicast tree with the minimum number of forwarding nodes, and was shown to be NP-complete (see [7]). Thus, the use of the greedy forwarding scheme is fully justified. In addition, using this greedy neighbour selection is also a good idea for sensor networks because the routing decision at each single node is performed based on the current network topology. Thus, both GMR and MRC are able to adapt to topological changes due to sensors operating in a duty cycle. However, individual sensors are assumed to be static.

One of the key aspects of GMR is the cost-aware neighbour selection function. The reason is that the shape of the tree is one of the key parameters governing the overall optimality of the tree. Given that the complexity of testing all possible neighbour subsets grows exponentially, we proposed a heuristic algorithm which has shown to be efficient compared with PBM.

For GMR, we did simulation from small to large number of destinations, with varying density. We compared the GMR and PBM's performance in terms of the efficiency of the resulting trees, the deviation from SPTs (stretch factor), and on the computational time. The simulation performance results show that GMR outperforms PBM.

MRC protocols further extend geographical multicast routing to multi-rate scenario. Besides the GMR's cost-aware bandwidth efficiency advantage, MRC explore rate cost solutions to ensure optimal routing paths to multiple destinations at variable rate. A new

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parameter rate cost metric is proposed to evaluate the multiratecast protocols because traditional parameter hop count does not reflect the efficiency of variable rate routing paths.

Two multiratecast protocols RCM and MRM are proposed in this thesis. RCM algorithm calculates rate cost at each forwarding node, tries to select best forwarding nodes with lowest rate cost so that over all routing cost is can be optimal. Three different rate cost factor calculations are proposed and tested by simulation. The method RCM_C outperforms rest of two in all aspects. It is observed that RCM_C would be the best one for any RCM related task. Simulation results show that RCM_C algorithm based on complete destination set partition is able to find lowest rate cost routing paths and is best choice for network with small number of destinations. MRM algorithm always tries to firstly find best forwarding node for the destination with maximum data rate so that the routing paths are optimized to suit for maximum data rate and distance progress. It has competitive routing performance in network with small number of destinations and shows more efficiency in network with large number of destinations. MRM's simple calculation made it more practical for wireless sensor network.

For MRC, we did simulation for network with small and large number of destinations. We analyzed routing results based on destination number change, network node number change, average degree change, rate distribution change. We compared RCM three methods and MRM protocols performance and found their best suitable application scenario. We also compared MRM rate cost and sum of unicast rate cost.

The above studies are based on a list of assumptions as in 1.3 including we assume the position of destinations is known by the source, idea MAC layer, no packet loss, every node is capable of transmit data at destination required rate... We do not consider node failure or movement scenario.

GMR and MRC have common limitation as other existing position based protocols [1][2][3][6][43] that the destinations' position information is included in message head. The encoding overhead will be significant if destinations increase to large number. We do not compare the message overhead in our simulation because overhead increase does not change from one to the other position based protocols used in comparisons. The overhead can cause heavy computation time at forwarding node. As we discussed in 4.3.3, although GMR had

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showed better computation time than PBM, the time still a limitation of GMR protocol. A new recently proposed location based protocol [46] optimizes coding efficiency by destination grouping and hierarchy. Reduce message overhead and computation time will be future research topics related to position-based multicast. Other protocols are based on different assumptions and are inherently not comparable.

Future work related to geographical multicast and multiratecast can be the following several areas:

- 1> We plan to analyze different alternatives to optimize multicast face routing.
- 2> The cost-aware functions can be changed to deal with energy efficiency and realistic physical layers.
- 3> GMR works perfectly when the number of receivers is small or medium. Dealing with larger number of receivers needs to consider new approaches to the problem.
- 4> Sensor node movement or node join/leave network may cause routing loop, we may study the delivery rate in this situation.
- 5> Power and energy efficiency metrics can be used to compare different routing protocols
- 6> If the assumption that every node can provide maximum data rate for destinations is not valid, if some relay node has lower transmission rate, how to adapt multicast routing path selection.
- 7> Multiple sources to multiple destination data routing may require data merge. Multiratecast protocols may need support the many-to-many routing request.
- 8> If several destinations request same rate, destinations can be grouped by rate, the multiratecast routing protocols can be changed based on rate groups.

Reference

Chapter 8

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