# ON IMPROVING RELIABILITY IN MULTICAST ROUTING PROTOCOL FOR WIRELESS SENSOR NETWORK

**T. Sampradeepraj,**
Department of Computer Science and Engineering
Sethu Institute of Technology, Madurai
Email id: sampradeepraj@gmail.com
**S.P. Raja,**
Department of Computer Science and Engineering
Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology,
Avadi, Chennai, Tamil Nadu, India
**S. Beatrice,**
Department of Computer Science and Engineering
Xavier Institute of Technology, Mumbai
**N. Narayanan Prasanth,**
Department of Computer Science and Engineering
Vellore Institute of Technology, Vellore, Tamilnadu, India
**V. Anusuya Devi,**
Department of Computer Science and Engineering
National Engineering College, Kovilpatti, Tamilnadu, India

***Abstract:***

*Multicast routing becomes the most challenging problem in Wireless Sensor Networks (WSN). Multicasting is an effective way to facilitate group communication in which the multicast data need to be sent from a source node to multiple receivers. In this paper, a simple and efficient algorithm Minimum Connected Dominating Set (MCDS) is used to form a virtual backbone as forwarding group of the network. The MCDS aims at minimizing the number of nodes, where few nodes should be dominated, which are responsible for forwarding the multicast packets by applying Random Linear Network Coding (RLNC). RLNC has great potential to improve the performance of multicast routing protocol. The objective of this paper is to improve the performance of On-Demand Multicasting Routing Protocol (ODMRP) with respect to reliability using RLNC over MCDS for WSN, so that bandwidth utilization can be increased in the network. The proposed approach is named as*

*RLNMCDS-ODMRP, which deliver multicast data in high reliable. Experimental results and performance analysis show that the proposed protocol outperforms the classical multicast routing protocols that use MCDS or RLNC.*

***Keywords**: Wireless sensor network, Multicast routing, Network coding, Minimum Connected Dominating Set, Reliability.*

## 1. INTRODUCTION

Wireless Sensor Network (WSN) is a wireless network consisting of relatively large number of sensor nodes to monitor environmental or physical conditions [1]. WSN is currently receiving significant attention due to their broad applications such as environment monitoring, building structures monitoring, habitat monitoring, traffic surveillance, information gathering, military sensing, wildfire detection and pollution monitoring, etc [1]. Multicast is the transfer of same data to multiple receivers at the same time. Multicasting is a more efficient method of supporting group communication than broadcasting. Applications of multicasting are conference meetings and military control operations to multicast tactical information [2].

The multicast routing protocol is mainly classified into three categories: reactive, proactive and hybrid [3]. The reactive routing protocol is called as on-demand routing protocol. It creates routes only when desired by the source node. Example for reactive multicast routing protocol is: ODMRP [4]. The proactive routing protocol is called as table-driven. In which, the route for other node is maintained in the routing table. The hybrid routing protocol is a combination of both reactive and proactive multicast routing protocol.

In WSN, network backbone formation and channel capacity are some networking issues [5]. To solve these issues two most popular techniques were used, they are, (1) Minimum Connected Dominating Set (MCDS), (2) Random Linear Network Coding (RLNC).

A Dominating Set (DS) *S* of graph *G = (V, E)* is a subset of *V*, such that each node is either in the DS or adjacent to some node in the DS [6]. Connected Dominating Set (CDS) is a DS and all the nodes in the DS are connected. The most redundant transmission can be reduced by forming a CDS as a virtual backbone in the network [7]. In CDS, DS nodes are relaying the messages, maintain routing tables, reduce the communication cost, reduce the redundant traffic, localize the routing information, save storage space and it provides reliable connectivity between the nodes. The MCDS is a connected dominating set with minimum cardinality [8]. Finding a minimum sized connected dominating set is NP-Hard [9]. In real time environment, the virtual backbone of the network as small as possible, in order to decrease the protocol overhead, to save life time, energy consumption and cost of construction etc. Hence, it is desirable to form a minimum sized CDS. Constructing minimum sized CDS in WSN is an important issue because it reduces unnecessary multicast message transmission in the network. This paper provides an algorithm to find MCDS in Unit Disk

Graph (UD Graph) based on computation of Convex Hull (CH) of sensor nodes [10]. MCDS improves the reliability of the network, because limited number of sensor nodes are engaged in multicast message transmission.

Network coding is a technique where forwarding nodes mix the packets using mathematical operations, which reduces the number of transmissions and save the bandwidth in wireless network [11]. Network coding can be classified as either inter or intra-session. In the inter session network coding, the coded packets are received from different sources to be mixed to solve the bottleneck problem. In the intra-session network coding, the coded packets are received and mixed from same source to address the packet loss problem [12]. Network coding also can be classified into XOR (binary) coding, Reed-Solomon and Random Linear Network coding (RLNC).

### 1.1 Motivation and justification

In this work, MCDS and RLNC techniques are used in ODMRP to send code updates or other data from a sink node to a group of sensor nodes for WSN. Finding MCDS of the network is a promising approach. Recently, some researchers have proposed MCDS alone to construct a virtual backbone for multicast operation and to improve performance of multicast routing protocols in WSN [13, 14, 15]. In general, MCDS can be constructed and calculated by using either global or local network information and centralized or distributed way respectively. However, due to the characteristics of WSN, it is hard to obtain and maintain global network information also MCDS calculation in a single node is not efficient [16]. Therefore, the proposed multicasting routing protocol focuses on local information and distributed way to construct and calculation of MCDS in WSN.

Javad A.T et al. [5] proposed weighted Steiner connected dominating set (WSCDS) of the network graph for multicast routing in wireless ad-hoc networks. Shuai Wang et al. [17] explored energy minimal broadcast protocols in wireless ad hoc networks proposed by combining network coding and connected dominating set (CDS). Zhao zhang et al. [18] introduced polynomial time approximation scheme (PTAS) for minimum CDS in WSN. Hongjie Du et al. [19] presented distributed algorithm to construct weakly connected dominating set in distributed sensor network. Xiaoyan kui et al. [20] investigated the problem of constructing a energy balanced CDS based network backbone to extend the network life time in data collection.

Using routing, the multicast data cannot be communicated to destination nodes at a time. However, if the member nodes of the network have been allowed to perform linear network coding operations in addition to routing, the multicast data can be communicated to destination nodes at a time and achieves the maximum capacity of multicast network [21]. Ahlswede [11] illustrated this through famous “butterfly network”. Therefore, RLNC is essential to communicate a source to multiple receivers at a time. Most of the researchers has been applied RLNC alone for various multicast applications and increases the capacity of the network in MANET and Wireless Mesh Network (WMN) [22-27]. In which, RLNC has great potential to improve the performance in terms of throughput, reliability and minimize the transmission delay in MANET. Arash. Ghafouri et al. [28] improving the ODMRP protocol performance using power-based method. Mallapur, S.V. et al. [29] proposed multi-constrained reliable multicast routing protocol (MRMRP) using network coding.WSN differ from the MANET in terms of performance metrics, traffic patterns, and their amount of available memory and processing resources. These differences are considered in RLNC and it makes some of the network coding approaches proposed for WSN [30-34]. RLNC provides loss recovery in low quality wireless links and economical path diversity in WSN [35].

Multicasting with network coding was investigated quite intensively in recent years. Ahlswede et al. [11] proposed network coding in information theory to improve throughput in wireless networks and showed that network coding can achieve maximum multicast rate in the network. S. Katti et al. [36] presented the core idea of mixing packets by the XOR operation to increase the network throughput. Tracey Ho et al. [37] presented a distributed random linear network coding approach. Rout, RR et al. [32] attempted to enhance the lifetime of WSN using duty cycle and NC. Zhu et al. [38] applied network coding to overlay network to improve capacity by constructing a 2-reduandant multicast graph. Dumitrescu et al. [39] proposed a layer multicast with network coding. Jaggi et al. [40] presented a polynomial time construction showing that network coding at intermediate nodes could obtain larger rates than without coding. Zhi-jie Han et al. [31] proposed a set of distributed algorithms for improving the multicast throughput in WSN.

The proposed protocol RLNMCDS-ODMRP aims to develop efficient and high reliable multicast routing protocol. WSN protocols must be simple in both computation and communication load and should be easily implemented also it should be scalable, efficient and adaptive in terms of minimizing redundant retransmissions in various situations. Efficient multicast routing protocols are important for achieving throughput, reliability, packet delivery ratio, minimum end-to-end delay, security and energy efficiency, therefore all the aforementioned conditions are considered in the proposed protocol. So far, there is no work on ODMRP with RLNC over MCDS for WSN. Thus, the proposed protocol is essential to develop efficient multicast routing protocol for WSN.

**1.2 Outline of the paper**

This paper first presents a comprehensive investigation of MCDS and RLNC, also discusses details of their operations. Second, implementation of the proposed protocol has two phases as shown in Figure 1. In the first phase, the source node discovers the route and constructs the MCDS using convex hull, in the second phase, the source node transmitting the data by applying RLNC through the constructed MCDS in ODMRP to its receivers. At the end of this research work, performance of proposed protocol is evaluated.

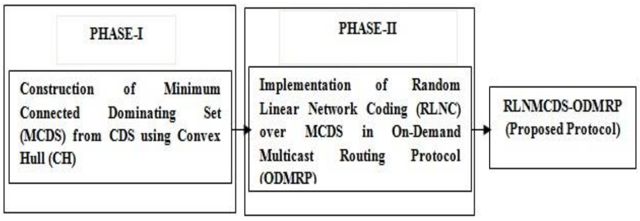



**Figure1** Outline of the paper

### 1.3 Organization of the paper

The rest of the paper is organized as follows: Proposed methodology is given in section 2. Section 3 discusses about the experimental results of proposed approach. Finally, conclusion about the proposed approach is given in section 4.

## 2. PROPOSED METHODOLOGY

In this paper, two most popular techniques were used, they are, (1) Minimum Connected Dominating Set (MCDS), (2) Random Linear Network Coding (RLNC).

### 2.1 Construction of Minimum Connected Dominating Set

The concept of the MCDS comes from the graph theory [41]. It defines a set of nodes for a given connected graph (network). The CDS network is shown in Figure 2. In this network, nodes in blue form a MCDS and they are connected through the blue bold lines, which represent the backbone of the network. All other nodes that are marked in white and green node (receiver) can be reached by the blue nodes in the MCDS. MCDS dramatically reduce the redundant transmissions by sending multicast messages forwarded by nodes in the MCDS in order to reach all the receivers [42]. MCDS is constructed from CDS using convex hull in the following steps as shown in the Figure 3,

STEP 1: Find the minimum degree vertex in CDS. Degree of vertex C is 3, Degree of vertex E is 4, Degree of vertex G is 3, Degree of vertex F is 5 and Degree of vertex D is 4. Now consider the minimum degree vertex C

STEP 2: Calculate Convex hull of N[C] ([]-closed neighbourhood, ( ) – open neighbourhood) as shown in Figure 4. CH(N[C]) is {E, C, D}

STEP 3: Calculate convex hull of N[i] as shown in Figure 5.

$$\bigcup_{i} CH(N[i])$$

STEP 4: Check if Convex hull of N[C] is contained in where i ϵ N(C) = {E, B, D} as shown in Figure 6.

STEP 5: If Step 4 is true, then remove the vertex C from CDS and go to step1

STEP 6: Select the next minimum degree vertex i.e. G and repeat the process from step 1 to step 5. By above process, remove the vertex G and go to step 1

STEP 7: Select the next minimum degree vertex i.e. D

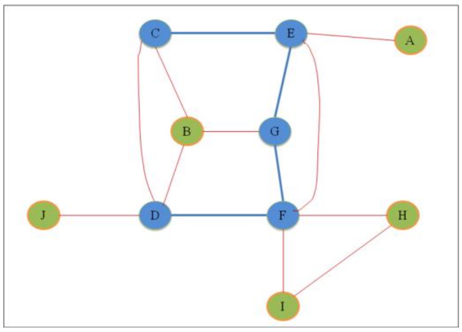



**Figure 2** The CDS Network

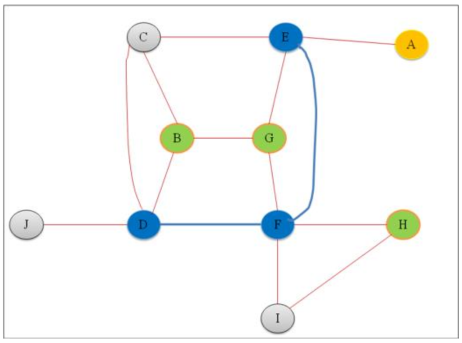



**Figure 3** The MCDS Network

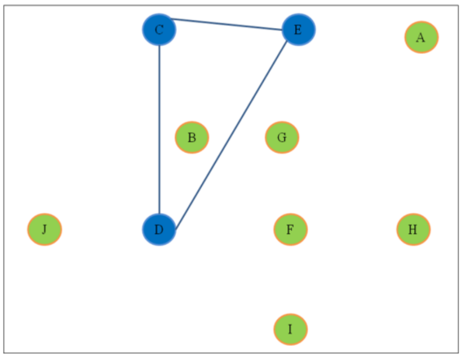
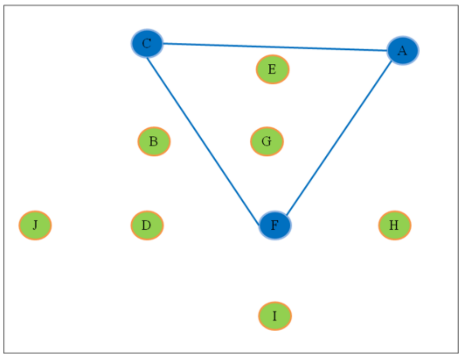
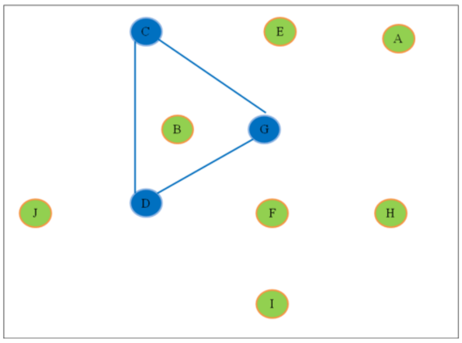


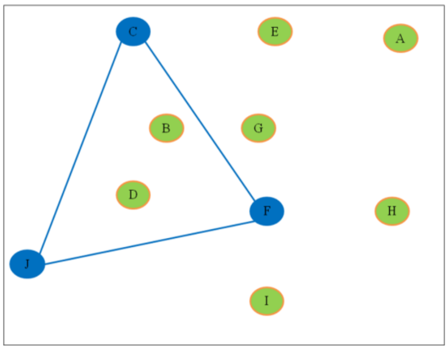

**Figure 4.** CH(N[C]) is {E, C, D}




**(a)**

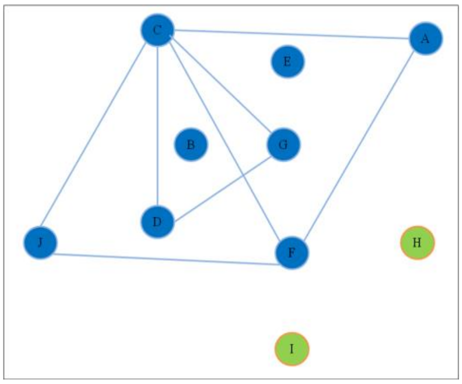



**(b)**

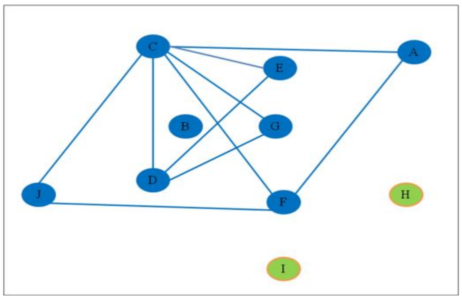



**(c)**

**Figure 5** (a) Convex hull of N[E] – ACF (b) Convex hull of N[B] – GCD (c) Convex hull of N[D] – CFJ




**(a)**




**(b)**

**Figure 6** (a) $\bigcup_i CH(N[i])$ (b) $CH(N[C]) \subseteq \bigcup_i CH(N[i])$

STEP 8: Calculate CH(N[D]) and Convex hull of N[D] is CFJ

$$CH(N[D]) \not\subset \bigcup_i CH(N[i])$$

STEP 9: Calculate CH(N[i]) for all i ϵ N(D) = {B,F,C,J}

STEP 10: CH (N[D]) is not contained in *where* i ϵ N(D) = {B, F, C, J}

STEP 11: If step 10 is false , don't remove the vertex D from CDS and go to step 1

STEP 12: Select the next minimum degree vertices E and F, and go to step 1. Likewise two vertices E and F are not deleted from CDS. Finally CDS left with the vertices E, D and F

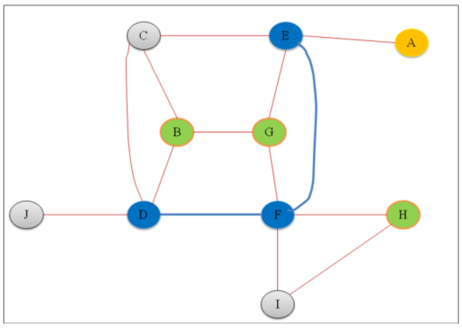



**Figure 7** Constructed MCDS Network

Thus, as shown in Figure 7 constructed MCDS is {E, D, F} from CDS of {C, E, G, F, D}.

### 2.2 Multicast routing protocol for WSN

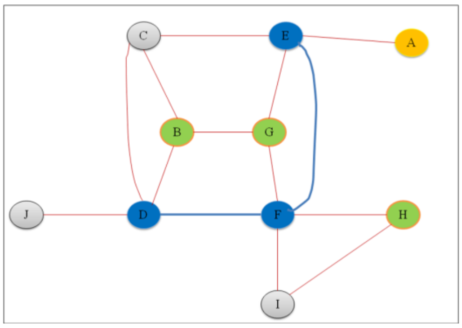
In this work, the selected reactive or on-demand routing protocol is ODMRP. Because, most of the researchers show that reactive method is better than the proactive method in many aspects such as nodes movement, network life time, self-organizing network model also states that the major strength of ODMRP are its simplicity and scalability [4].

#### 2.2.1. On-Demand Multicast Routing Protocol

ODMRP is a state-of-art on-demand multicast routing protocol [4]. It is a mesh based and a source initiated protocol. Forwarding Group (FG) concept is used to establish a mesh structure in a given network also "soft state" approach is followed to maintain a mesh.

#### 2.2.2. Minimum Connected Dominating Set based Multicast

MCDS is popularly used for constructing virtual backbones for multicast operation in many wireless networks. MCDS based multicast routing is not only applied for proactive routing, it can also be applied to reactive routing, where routes are computed in on-demand. In this paper, reactive multicast routing protocol, ODMRP is considered. Figure 8 shows MCDS network with ODMRP. In the MCDS network, each dominating node keeps following information: Dominating node's membership list, routing table and forwarding node table. Dominating node's membership list is a list of non-MCDS node which are adjacent to its dominating node. Routing table includes one entry with membership list of dominating node. Each entry also contains the next-hop information of a shortest path and the distance to the specified MCDS destination. This work extends the ODMRP algorithm by adding further routing information as shown in Figure 8 (b) to be sent between MCDS nodes to a quite selective multicast process.




(a)

Sender= 1

Receiver= 3, 11,12,16,20

Forwarding Group= 4,7,8,9

Gateway Domain member list of node 4: 2, 5

Gateway routing table of node 4:

| Destination | Member list | Next Hop | Distance |
|---|---|---|---|
| 7 | 6,10,11,12 | 7 | 1 |
| 8 | 13,14,15,16 | 8 | 1 |
| 9 | 17,18,19,20 | 7 | 2 |

(b)

**Figure 8** (a) Multicast data transmission through MCDS (b) Multicast routing information

## 2.3. Random Linear Network Coding

Recently, RLNC is emerged promising technique for various applications in wireless networks, which has been applied in multicast routing to increase the capacity of a network for maximum multicast flows and reduce the multicast traffic.

### 2.3.1. Random Linear Network Coding for Unicast

In RLNC, the output data of a given node is obtained as a linear combination of its input data. The coefficients selected for this linear combination are completely random in nature, hence named Random Linear Network Coding. The forwarding node combines a number of packets it has received or created into one or several outgoing coded packets. Typically, RLNC performs three different operations [43], they are 1. Encoding, 2. Re-encoding, 3. Decoding

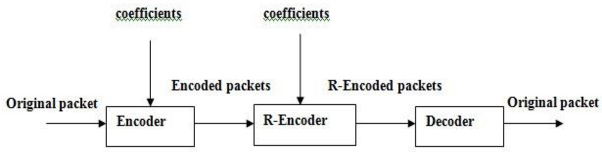



**Figure 11** RLNC Process

From the Figure 11, the encoding process can be done at source node of the network. Re-encoding process can be done at forwarding node, which is almost similar to encoding process but the coefficients are completely newly generated. Finally, decoding process can be done at destination nodes. The encoding, re-encoding and decoding operations are implemented via matrix operations. First consider the unicast network, when there is a single-source single-destination capacity (max-flow) is achievable by Min-cut Max-Flow, in other words, the maximum amount of flow is equal to the capacity of a minimum cut [21].The basic idea of RLNC for unicast communication can be illustrated in the Figure 12-15.

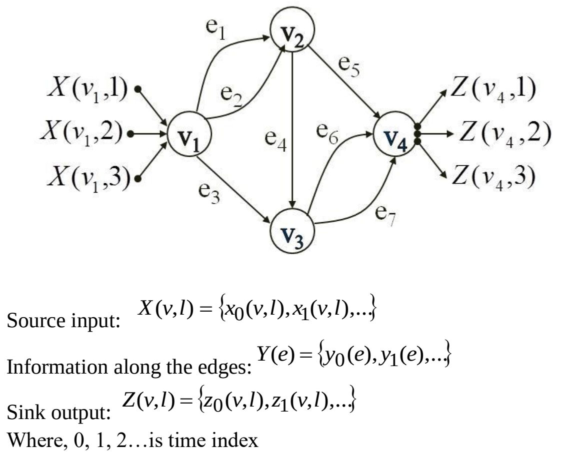



**Figure 12** A simple example of RLNC for unicast in WSN

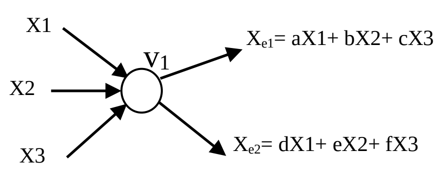



**Figure 13** Encoder at Source node

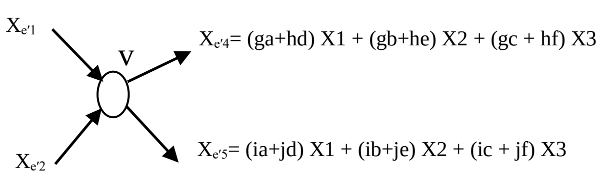



**Figure 14** Re-encoder at intermediate node

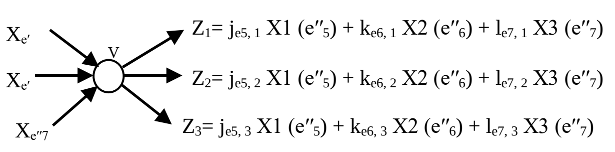



**Figure 15** Decoder

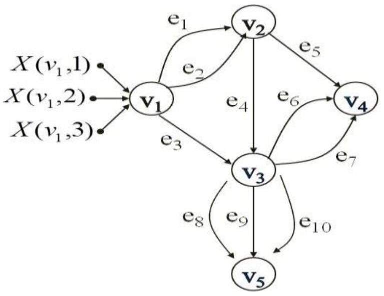
The data X1, X2 and X3 are given to node $V_1$ as input then node ($V_2$) received two coded packets: aX1+ bX2+ cX3 and dX1+ eX2+ fX3 as output of node $V_1$. In order to perform the re-encoding operation on the two received coded packets, the node ($V_2$) generates two random coefficients (g, h) for the two coded packets to be re-encoded. The coding vector of the new re-encoded packet can be calculated as following:

g (aX1+ bX2+ cX3) + h (dX1+ eX2+ fX3) = (ga+ hd) X1 + (gb+he) X2 + (gc + hf) X3

where, (ga+ hd), (gb+he) and (gc +hf) are the new coefficients of the re-encoded packet. The decoding operation is performed at the node $V_4$ by collecting the coded packets. The coded packets are decoded by forming a matrix from linear coefficients. The matrix is referred to as decoding matrix or transfer matrix [43].

### 2.3.2. Random Linear Network Coding for Multicast

In this section, multicast network is considered with multiple independent messages, when a source node wants to send multi message to a set of destination nodes, cutset bound is tight and is achieved error-free using random linear network coding [21]. Distributed RLNC has been applied to multicast routing in WSN, in which destination nodes decode the output data by taking random linear combinations of input data. RLNC process for multicast is depicted in the Figure 16. The basic idea of RLNC for multicast communication can be illustrated in the Figure 17 [44, 45].




Source input: $X(v,l) = \{x_0(v,l), x_1(v,l), \ldots\}$

Information along the edges: $Y(e) = \{y_0(e), y_1(e), \ldots\}$

Sink output: $Z(v,l) = \{z_0(v,l), z_1(v,l), \ldots\}$

Where, 0, 1, 2…is time index

**Figure 16** RLNC in single source multicasting

Consider a multicast network G= (V, E) as depicted in the above Figure 16. Where, V is the set of nodes and E is the set of edges. The source node $V_1$ wants to send packets to receivers $V_4$ and $V_5$ with the help of forwarding nodes $V_2$ and $V_3$, the source node $V_1$ observing three source packets $X_1$, $X_2$ and $X_3$ also called native packets and randomly chosen coefficients α, β, and γ from finite field for encoding, there are three paths from $V_1$ to $V_4$ and another three paths from $V_1$ to $V_5$. Forwarding nodes $V_2$ and $V_3$ performs the re-encoding operation on the two received coded packets with the random coefficients, the coding vector of the new re-encoded packet can be given as input to the node $V_4$ and $V_5$. Decoding operation is performed at the node $V_4$ and $V_5$ by collecting the coded packets. These packets form linear equations and can be solved by forming a matrix which is referred as decoding matrix or transfer matrix.

RLNC operations for multicasting is illustrated through the following equations, the information through the edges i.e $e_1$, $e_2$, $e_3$ can be calculated by equation (1).

$$Y(e) = \sum_{l=1}^{\mu(v)} \alpha_{l,e} X(v,l) + \sum_{e':head(e')=tail(e)} \beta_{e',e} Y(e') \qquad (1)$$

Where Y(e) is coded packets on the outgoing edges from node $V_1$, which are linear combination of the sources X(v,1), X(v,2), X(v,3). The information at the destination nodes can be calculated by equation (2), which is received from forwarding nodes,

$$Z(v,j) = \sum_{e':head(e')=v} \varepsilon_{e',j} Y(e') \qquad (2)$$

Where Z(v, j) is re-encoded packet at destination nodes, which are received from forwarding nodes. Linear combinations of coded packets y ($e_1$), y ($e_2$), y ($e_3$) on the edges $e_1$, $e_2$, and $e_3$ can be expressed as

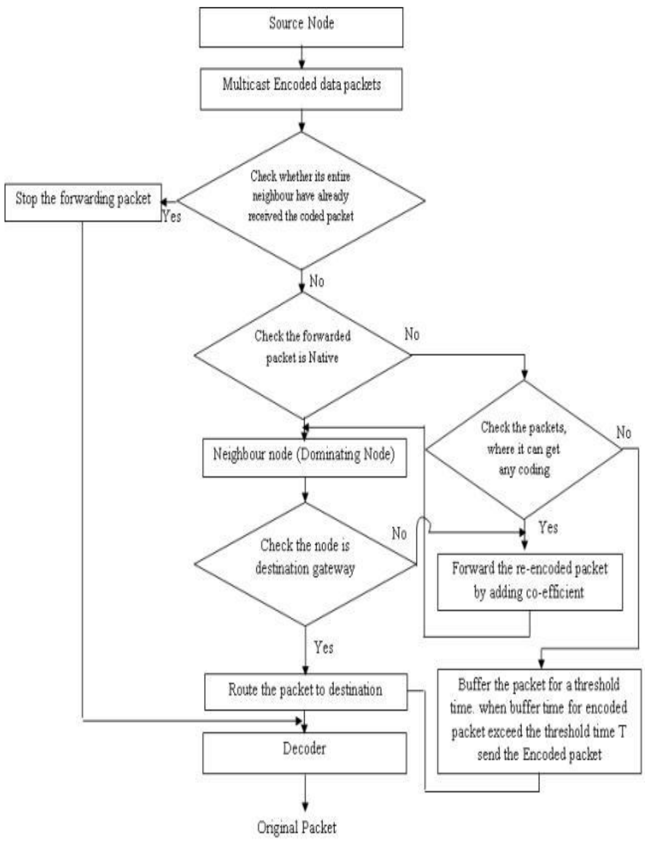



**Figure 17** Flowchart for RLNC for multicast

$$Y(e_1) = \alpha_{1,e_1} X(v,1) + \alpha_{2,e_1} X(v,2) + \alpha_{3,e_1} X(v,3) \quad (3)$$

$$Y(e_2) = \alpha_{1,e_2} X(v,1) + \alpha_{2,e_2} X(v,2) + \alpha_{3,e_2} X(v,3) \quad (4)$$

$$Y(e_3) = \alpha_{1,e_3} X(v,1) + \alpha_{2,e_3} X(v,2) + \alpha_{3,e_3} X(v,3) \quad (5)$$

Let α denote the 3 × 3 matrix. The above equations (3-5) can be written as matrix form as

$$\begin{bmatrix} Y(e_1) \\ Y(e_2) \\ Y(e_3) \end{bmatrix} = \alpha \begin{bmatrix} x(v,1) \\ x(v,2) \\ x(v,3) \end{bmatrix} \text{ Where, } \alpha = \begin{bmatrix} \alpha_{1,e_1} & \alpha_{2,e_1} & \alpha_{3,e_1} \\ \alpha_{1,e_2} & \alpha_{2,e_2} & \alpha_{3,e_2} \\ \alpha_{1,e_3} & \alpha_{2,e_3} & \alpha_{3,e_3} \end{bmatrix}$$

Linear combinations of re-encoded packets $y(e_4)$, $y(e_5)$, $y(e_6)$, $y(e_7)$ on the edges $e_4$, $e_5$, $e_6$ and $e_7$ can be expressed as

$$Y(e_4) = \beta_{e_1,e_4} Y(e_1) + \beta_{e_2,e_4} Y(e_2) \quad (6)$$

$$Y(e_5) = \beta_{e_1,e_5} Y(e_1) + \beta_{e_2,e_5} Y(e_2) \quad (7)$$

$$Y(e_6) = \beta_{e_3,e_6} Y(e_3) + \beta_{e_4,e_6} Y(e_4) \quad (8)$$

$$Y(e_7) = \beta_{e_3,e_7} Y(e_3) + \beta_{e_4,e_7} Y(e_4) \quad (9)$$

Let $\beta$ denote the 3 × 3 matrix. The above equations (6-9) can be written as matrix form as

$$\begin{bmatrix} Y(e_5) \\ Y(e_6) \\ Y(e_7) \end{bmatrix} = \beta'.\alpha \begin{bmatrix} x(v,1) \\ x(v,2) \\ x(v,3) \end{bmatrix}$$

where β and α are given by

$$\beta = \begin{bmatrix} \beta_{e_1,e_5} & \beta_{e_1,e_4}\beta_{e_4,e_6} & \beta_{e_1,e_4}\beta_{e_4,e_7} \\ \beta_{e_2,e_5} & \beta_{e_2,e_4}\beta_{e_4,e_6} & \beta_{e_2,e_4}\beta_{e_4,e_7} \\ 0 & \beta_{e_3,e_6} & \beta_{e_3,e_7} \end{bmatrix} \text{ and}$$

$$\alpha = \begin{bmatrix} \alpha_{1,e_1} & \alpha_{2,e_1} & \alpha_{3,e_1} \\ \alpha_{1,e_2} & \alpha_{2,e_2} & \alpha_{3,e_2} \\ \alpha_{1,e_3} & \alpha_{2,e_3} & \alpha_{3,e_3} \end{bmatrix}$$

Destination node $V_4$ recover the original packets from the received re-encoded packets $[y(e_5), y(e_6), y(e_7)]^T$ and obtain,

$$Z(v_4,1) = \varepsilon_{e_5,1} Y(e_5) + \varepsilon_{e_6,1} Y(e_6) + \varepsilon_{e_7,1} Y(e_7) \quad (10)$$

$$Z(v_4,2) = \varepsilon_{e_5,2} Y(e_5) + \varepsilon_{e_6,2} Y(e_6) + \varepsilon_{e_7,2} Y(e_7) \quad (11)$$

$$Z(v_4,3) = \varepsilon_{e_5,3} Y(e_5) + \varepsilon_{e_6,3} Y(e_6) + \varepsilon_{e_7,3} Y(e_7) \quad (12)$$

For the destination node $V_5$, Re-encoded data on edges $e_8$, $e_9$ and $e_{10}$ denoted by $Y(e_8)$, $Y(e_9)$ and $Y(e_{10})$. They are linear combinations of $Y(e_3)$ and $Y(e_4)$ and can be expressed as,

$$\begin{bmatrix} Z(e_8) \\ Z(e_9) \\ Z(e_{10}) \end{bmatrix} = \begin{bmatrix} \gamma_{e_3 e_8} & \gamma_{e_4 e_8} \\ \gamma_{e_3 e_9} & \gamma_{e_4 e_9} \\ \gamma_{e_3 e_{10}} & \gamma_{e_4 e_{10}} \end{bmatrix} \begin{bmatrix} Y(e_3) \\ Y(e_4) \end{bmatrix}$$

By applying equation (6) in above expression and obtain the following, because, both coded packets $y(e_1)$ and $y(e_2)$ pass through edge $e_4$, therefore, disjoint paths are not enough for $V_5$ from $V_1$.

$$\begin{bmatrix} Z(e_8) \\ Z(e_9) \\ Z(e_{10}) \end{bmatrix} = \begin{bmatrix} \gamma_{e_4 e_8}\beta_{e_1 e_4} & \gamma_{e_4 e_8}\beta_{e_2 e_4} & \gamma_{e_3 e_8} \\ \gamma_{e_4 e_9}\beta_{e_1 e_4} & \gamma_{e_4 e_9}\beta_{e_2 e_4} & \gamma_{e_3 e_9} \\ \gamma_{e_4 e_{10}}\beta_{e_1 e_4} & \gamma_{e_4 e_{10}}\beta_{e_2 e_4} & \gamma_{e_3 e_{10}} \end{bmatrix} \begin{bmatrix} Y(e_1) \\ Y(e_2) \\ Y(e_3) \end{bmatrix}$$

Further, $[Y(e_1)\ Y(e_2)\ Y(e_3)]^T$ can be represented in terms of $[X(v,1)\ X(v,2)\ X(v,3)]^T$ and denote the above matrix by κ , which share the common coefficients of $y(e_1)$ and $y(e_2)$. Then,

$$\begin{bmatrix} Z(e_8) \\ Z(e_9) \\ Z(e_{10}) \end{bmatrix} = \kappa.\ \alpha.\ \begin{bmatrix} x(v,1) \\ x(v,2) \\ x(v,3) \end{bmatrix}$$

Destination node $V_5$ recover the original packets from the received re-encoded packets $[y(e_8), y(e_9), y(e_{10})]^T$ and obtain,

$$Z(v_5,1) = \gamma_{e_8,1} Y(e_8) + \gamma_{e_9,1} Y(e_9) + \gamma_{e_{10},1} Y(e_{10}) \quad (13)$$

$$Z(v_5,2) = \gamma_{e_8,2} Y(e_8) + \gamma_{e_9,2} Y(e_9) + \gamma_{e_{10},2} Y(e_{10}) \quad (14)$$

$$Z(v_5,3) = \gamma_{e_8,3} Y(e_8) + \gamma_{e_9,3} Y(e_9) + \gamma_{e_{10},3} Y(e_{10}) \quad (15)$$

Now, the original multicast data at destination node $V_4$ is decoded from equations (10) – (12), similarly, destination node V5 is decoded from equations (13)-(15), by solving the relation between $\bar{x}$ and $\bar{z}$ ,

$$\bar{z} = \bar{x} \cdot M \qquad (16)$$

where $\bar{x}$ is the vector of input processes, $\bar{z}$ is the vector of output processes and M is the transfer matrix, which is obtained from solving the following matrix,

$$M = A \cdot \begin{bmatrix} \beta_{e_1,e_5} & \beta_{e_1,e_4}\beta_{e_4,e_6} & \beta_{e_1,e_4}\beta_{e_4,e_7} \\ \beta_{e_2,e_5} & \beta_{e_2,e_4}\beta_{e_4,e_6} & \beta_{e_2,e_4}\beta_{e_4,e_7} \\ 0 & \beta_{e_3,e_6} & \beta_{e_3,e_7} \end{bmatrix} \cdot B \qquad (17)$$

where $A = \begin{bmatrix} \alpha_{1,e_1} & \alpha_{1,e_2} & \alpha_{1,e_3} \\ \alpha_{2,e_1} & \alpha_{2,e_2} & \alpha_{2,e_3} \\ \alpha_{3,e_1} & \alpha_{3,e_2} & \alpha_{3,e_3} \end{bmatrix}$ and $B = \begin{bmatrix} \varepsilon_{e_5,1} & \varepsilon_{e_5,2} & \varepsilon_{e_5,3} \\ \varepsilon_{e_6,1} & \varepsilon_{e_6,2} & \varepsilon_{e_6,3} \\ \varepsilon_{e_7,1} & \varepsilon_{e_7,2} & \varepsilon_{e_7,3} \end{bmatrix}$

The square matrices β′.α and κ. α are invertible and unicoding is possible. Each destination node wants to decode the vector data $\bar{z}$. This implies that det(β.α) ≠ 0 and det(κ. α) ≠ 0 det($M_i$) ≠ 0 ∀ i , therefore the product of determinant is non-zero. Determinant is non-zero means that it has some data for the particular destination node.

## 2.4. Operation Of Proposed Protocol RLNMCDS-ODMRP

The main contributions of this work can be summarized as follows: 1) RLNMCDS-ODMRP brings RLNC into multicast only with a few minor changes to the protocol packet formats of ODMRP and is compatible with ODMRP. 2) A network prototype system uses MCDS for RLNC in ODMRP to multicast data to show the practicality of RLNMCDS-ODMRP. Implementation of the proposed protocol has two phases as shown in Figure 19 and Figure 20. In the first phase, the source node discovers the route and constructs the MCDS using convex hull, in the second phase, the source node transmitting the data by applying RLNC through the constructed MCDS in ODMRP to its receivers.

As shown in Figure 19, in the first phase, the source node initiates the route construction process by broadcasting the join request packet JOIN_REQUEST, the source node check whether it is a source gateway host, if so, source gateway act as new source to route the packet and check the node belong to network or adjacent to source node, if yes, mark the selected node as dominating node, otherwise select the another routing path to find dominating node as above steps, then the dominating node collect neighbor information of its neighbor node and member list. Based on the neighborhood information and member list, the dominating node rebroadcast the JOIN_REQUEST packet to its neighbor, then the neighbor node checks the above condition to find dominating node, finally check whether the selected node is destination gateway, if so , it construct join reply packet JOIN_REPLY and forward to the source node through the dominating node. In the second phase as shown in Figure 20, RLNC is applied to multicast the packets from a source node to multiple receivers. The source node multicast encoded data packets to its receivers through the dominating node (forwarding node) of MCDS, based on the neighborhood information it checks whether it's entire neighbor already have received the coded packet, if yes, it simply stops the forwarding packet, otherwise it checks whether coded packet is a native one. If so, it sends the coded packet to its neighboring dominating node directly. Otherwise, dominating node forward the re-encoded packet by adding co-efficient to its adjacent dominating node.

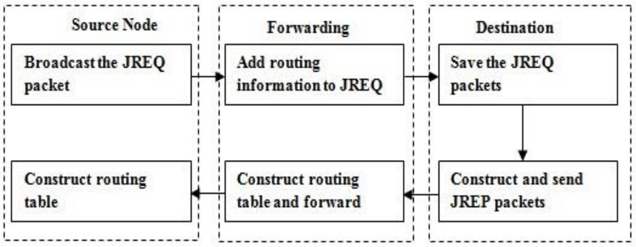



**Figure 18** Route Discovery and Route reply through MCDS

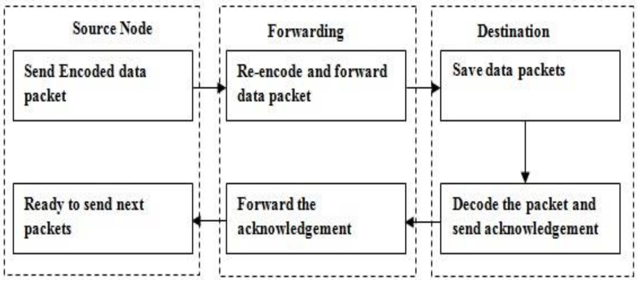



**Figure 19** Multicast Data Transmission by applying RLNC

When dominating node receiving a native packet, it checks whether any coding opportunities to encode the packet with the remaining packets in the output queue that it needs to forward, if yes dominating node forward the re-encoded packet. If not, the dominating node buffers the packets for a threshold time T and transmit it later. When buffer time for the encoded packet exceeds the threshold time T send the encoded packet to its destination node. The dominating node check whether it is a destination node, if so, destination node save and decodes the original multicast packet and send acknowledgement to the source node through the connected dominating nodes. Otherwise, forward the re-encoded packet to its neighbour node until the re-encoded packet reached to its destination node, now the source node is ready to multicast next packet to its receivers.

## 3. SIMULATION ENVIRONMENT AND PERFORMANCE EVALUATION

### 3.1. Experimental setup

In the simulation experiment, nodes were placed uniformly at random locations in an area of 500 m × 500 m. The multicast traffic is Constant Bit Rate (CBR) with 250 bytes data packet.The simulation scenarios are created by the setdest tool of ns-2. The simulation time is 200 seconds. Mobility model uses a random waypoint model in a rectangular field. Here, 1-to-many multicast concept has been taken, i.e., Sender is fixed as one and only the receivers are varied from 9 to 99. The minimum and maximum speed were set from 0 to 20 m/s, respectively while pause time duration is 1 simulation seconds, which corresponds to constant motion and transmission rate is 128 Kbps, transmission range is 50 m for all nodes. The simulation parameters such as simulator, routing protocol, number of nodes, simulation time, sender, receiver, CBR packet size, arrival rate, mobility speed, traffic load are summarized in Table 1.

**Table 1** Simulation parameters

| S.No | Parameters | Particulars |
|---|---|---|
| 1. | Simulator | Network Simulator-2 |
| 2. | Routing protocol | ODMRP |
| 3. | No.of nodes | 100 |
| 4. | Simulation time | 200 secs |
| 5. | Simulation area | 500 m × 500 m to 1200 m × 1200 m |
| 6. | Node movement | Random way point |
| 7. | Sender & Receiver | Sender-1 Recevier-09-99 |
| 8. | Pause time | 1 sec |
| 9. | Traffic | CBR |
| 10. | CBR Packet size | 250 bytes |
| 11. | Traffic Load | 5 pkts/sec |
| 12. | Arrival Rate | 10 kbps-100 kbps |
| 13. | Routing Metric | Success Probability Product (SPP) |
| 14. | Transmission rate | 128 Kbps |
| 15. | Mobility speed | 0,5,10,15,20 m/s |
| 16. | Transmission range | 50 m |
| 17. | Topology | Multi-hop |
| 18. | Methods | MCDS and RLNC |

### 3.2. Performance metrics

#### 3.2.1. Reliability

Reliability is defined as the successful end-to-end data delivery ratio [46, 47].

$$\text{Reliabilit } y(r_0, r_1 \ldots\ldots r_{h-1}, r_h) = \exp\left(-\sum_{i=1}^{h} \frac{d^k_{ri-1ri}}{snr_{ri-1ri}}\right) \quad (18)$$

Where $(r_0, r_1 \ldots\ldots r_{h-1}, r_h)$ is route

$d^k_{ri-1ri}$ is distance between the nodes

$snr_{ri-1ri}$ is the transmitted signal-to-noise power

### 3.3. Experimental results and analysis

In this section, simulation results of the proposed approach (RLNMCDS-ODMRP) for the performance metric of reliability are elaborated. The proposed protocol is simulated and analyzed by the following four scenarios: a) By varying the terrain size, b) By varying the arrival rate, c) By varying the number of nodes and d) By varying the mobility speed. The following graph shows that performance comparison between proposed RLNMCDS-ODMRP multicast routing protocol, ODMRP with RLNC, ODMRP with MCDS and normal ODMRP separately after filtering the data from trace files generated after simulation.

#### 3.3.1. Scenario-I – By varying the Terrain Size

In the scenario-I, the performance of proposed protocol is measured for the reliability considered in this paper by varying the terrain size from 500 m × 500 m to 1200 m × 1200 m for fixed minimum speed of 0 m/s (static) and for the fixed 20 nodes network coverage area, selected routing metric is SPP, arrival rate is set to 10 kbps and traffic load is fixed as 5 pkts/sec and equally distributed among all senders.The transmission radius (radio range) of sensor nodes is fixed at 50 m.

Sensor nodes are static and uniformly deployed in the given terrain. After node deployment, maintenance of node is difficult process. For this reason, all nodes have to adapt their behaviours to the environmental changes also sensor nodes are aware of their own location coordinates. Since sensor nodes are static, assigning location coordinates to sensor nodes is a one-time task and is part of the initial setup of WSN. In this method nodes are deployed in Unit Disk (UD) model.

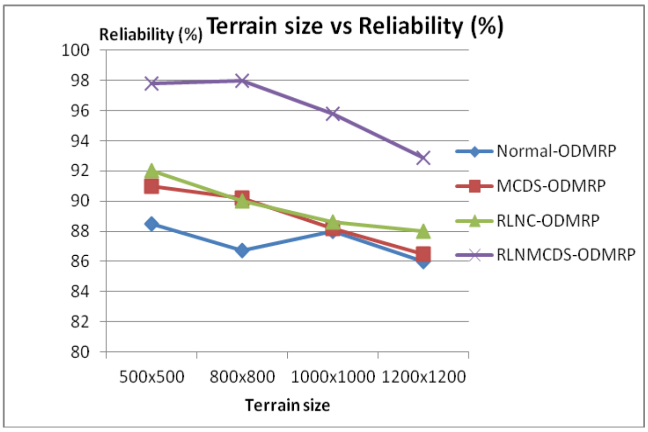



**Figure 21** Terrain size(m) vs Reliability

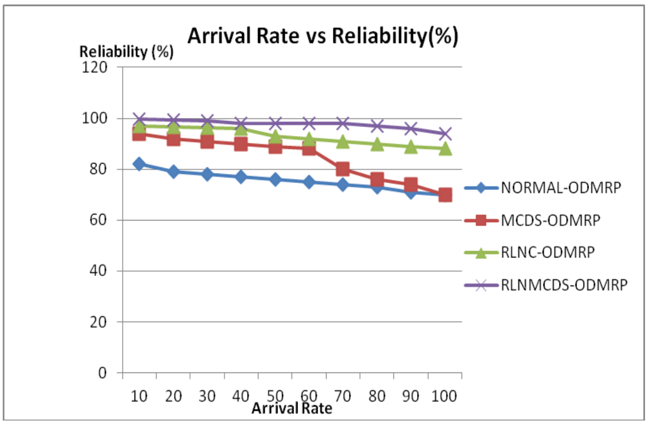



**Figure 22** Arrival rate(Kbps) vs Reliability

Figure 21 shows the terrain size versus number of nodes with low load. From the figure, it is observed that reliability of the proposed protocol (RLNMCDS-ODMRP) is high at the small terrain area (500 m × 500 m), the proposed protocol performed well as compared to other protocol in different terrain size (800 m × 800 m, 1000 m × 1000 m and 1200 m × 1200 m).Similarly, reliability is decreasing, when increasing the terrain size for other multicast routing protocol. The overall results says that when we implement sensor nodes in small terrain areas give better performance rather than Large and very large terrain areas.

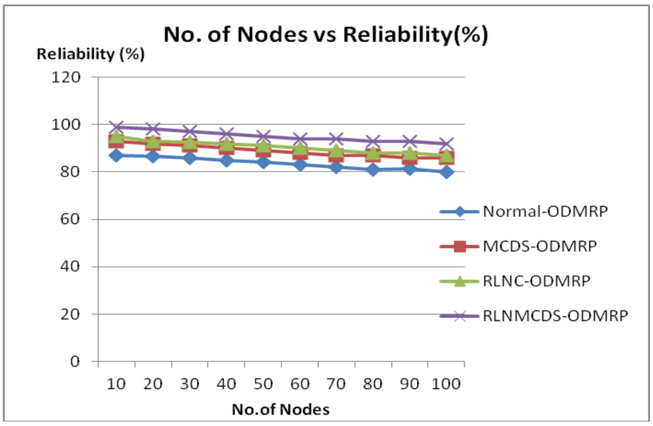



**Figure 23** No. of nodes vs Reliability

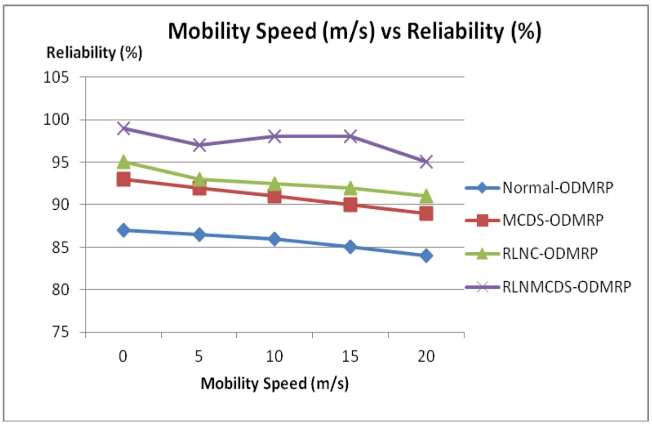



**Figure 24** Mobility speed (m/s) vs Reliability

### 3.3.2.Scenario-II – By varying the Arrival Rate

In the scenario-II, the performance of proposed protocol is measured for the reliability considered in this work by varying the arrival rate from 10 kbps to 100 kbps for fixed minimum speed of 0 m/s (static) and for the fixed 20 nodes network coverage area, selected routing metric is SPP, terrain size is fixed as 500 m × 500 m, traffic load is fixed as 5 pkts/sec and equally distributed among all senders.

Message arrival rate is the rate at which messages are multicast in the group. The message arrival rate is a combined rate of the number of messages multicast by all group members that multicast messages. Reliability is the percentage of multicast messages received by a group member for a given arrival rate. In this work, message arrival rate is varied from 10-100 kbps. In particular, message arrival rates significantly affect a protocol performance. By one-active arrival pattern, the single sender generated multicast traffic based on a deterministic model. Members started multicasting messages 0.5 s after joining the group using a given arrival rate. They continued to multicast messages for a period of 10 s.

Figure 22 shows the reliability as a function of message arrival rate (kbps). First, the proposed protocol RLNMCDS-ODMRP exhibit high reliability (close to 100%) at low arrival rates. This indicates that proposed protocol is able to recover from almost all message losses when the arrival rate is low. In general, RLNC-ODMRP provides a (very) slightly higher reliability than MCDS-ODMRP under low arrival rate. Hence, as far as reliability is concerned, there is little to choose between the two protocols when the arrival rate is low. The second observation is that the reliability starts decreasing significantly with increase in arrival rate after a certain value of arrival rate in other three protocols. The reason for this is increase in network congestion. For lower arrival rate, RLNMCDS-ODMRP and RLNC-ODMRP are able to recover from almost all message losses. However, as network starts getting congested with increase in arrival rate, these protocols start losing more messages. An important observation here is that the rate of decrease in reliability is significantly higher in Normal-ODMRP than in RLNMCDS-ODMRP. The main reason for this is the technique used to recover from message losses. A message loss in Normal-ODMRP results in more control messages being transmitted per unit time than RLNMCDS-ODMRP. As a result, a message loss further congests the network in Normal-ODMRP, and hence, worsens the protocol reliability. The main reason for poor performance of MCDS-ODMRP and Normal- ODMRP is at larger group sizes or a higher arrival rate is that it consumes significantly larger bandwidth. As the message arrival rate becomes larger, the number of overhead messages increases significantly.

### 3.3.3. Scenario-III – By varying the number of nodes

In the third scenario, the performance of proposed protocol is measured for the reliability considered in this work by increasing number of nodes from 09 to 99 nodes for fixed minimum speed of 0 m/s (static) in network coverage area and selected routing metric is SPP. Arrival rate is set to 10 kbps, terrain size is fixed as 500 m × 500 m, traffic load is fixed as 5 pkts/sec and equally distributed among all senders.

Reliability should be high for better performance of the network. Reliable protocol consumes less bandwidth by reducing the retransmission and acknowledgement of participating nodes in a network. As described in the Figure 23, efficient techniques can be used to improve the reliability. To achieve certain reliability, limited number of transmission, neighbourhood nodes estimation and channel quality link between source and destination node is important.

Figure 23 shows the reliability versus number of nodes with low load. In the single source multicasting, collisions between multicast packets are very rare under low load therefore, reliability increases for all protocol. Nevertheless, it is observed that, on increasing the number of nodes, the proposed protocol RLNMCDS-ODMRP provides better reliability (received messages) than other multicast routing protocol because, it reduces packet error rate in end-to-end in dynamic environment. ODMRP with RLNC offers average reliability because of communication overhead. As nodes are strongly connected in ODMRP with MCDS, the reliability is improved than Normal_ODMRP.

### 3.3.4. Scenario-IV – By varying the speed of the nodes

In the Scenario-IV, the performance of proposed protocol is measured for the reliability considered in this work by increasing the speed of the nodes from 0 to 20 m/s for the fixed 20 nodes in network coverage area and selected routing metric is SPP. Arrival rate is set to 10 kbps, terrain size is fixed as 500 m × 500 m, traffic load is fixed as 5 pkts/sec and equally distributed among all senders.

When nodes are moving in a coverage area at different speed, it constructs multiple independent paths from source to destinations dynamically. This ensures that reliability of a network. Non-acknowledged virtual backbone multicasting is improving the reliability of network. Figure 24 shows that the reliability versus mobility speed (m/s).

It is observed that, on increasing the speed of nodes, the proposed protocol RLNCDS-ODMRP provides better reliability than other multicast routing protocol because it has less delay for transmission of message and also each node moves within a speed of 0 –20 m/s. The message load is low and the message size is low. On the other hand, ODMRP with RLNC, ODMRP with MCDS and normal ODMRP has less reliability, because it has higher delay where every message is delayed for further transmission.

## 4. CONCLUSION

In this paper, Random Linear Network Coding over Minimum Connected Dominating Set in ODMRP is proposed to improve the performance of multicast routing protocol for WSN. Based on the experiments, it is concluded that the proposed protocol RLNMCDS-ODMRP has following advantages, (1) consumes less time to construct multicast topology than normal ODMRP, (2) reliability is enhanced 12 times of its conventional ODMRP, (3) achieves 95% of the theoretical maximum multicast capacity which is several times of ODMRP's, meanwhile only with about 15% extra bandwidth consumption compared with ODMRP. As future work, to face the key challenges of sensor nodes such as limited energy, limited bandwidth, short memory, limited processing ability and security, the proposed protocol will be modified suitably.

## REFERENCES

1. I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, A Survey on Sensor Networks, IEEE Comm. Magazine, vol. 40, no. 8, pp. 102-114, Aug. 2002.
2. Jing Dong, Reza Curtmola, Cristina Nita-Rotaru, Secure High-Throughput Multicast Routing in Wireless Mesh Networks, IEEE Transactions on mobile computing, Vol.10, No.5, May 2011.
3. Md.Arafatur Rahman and Farhat Anwar, A Simulation based performance comparison of routing protocol on Mobile Ad-hoc Network (Proactive, Reactive and Hybrid) Proc. of the IEEE ICCCE, 2010.
4. S.J. Lee, W. Su, and M. Gerla, On-demand multicast routing protocol in multihop wireless mobile networks, ACM/Kluwer Mobile Networks and Applications, vol. 7, no. 6, December 2002, pp. 441–452.
5. Javad Akbari Torkestani, Mohammad Reza Meybodi, Weighted Steiner Connected Dominating Set and its Application to Multicast Routing in Wireless MANETs, Wireless Pers. Commun., Springer, Feb. 2010.
6. Haynes,T.W., et al.., (1998).Funcamentals of domination in graphs. Marcel Dekker, Inc., A Sireis of Monographs and Text books.
7. Javad Akbari Torkestani, Mohammad Reza Meybodi Mobility-based multicast routing algorithm for wireless mobile Ad-hoc networks: A learning automata approach Computer Communications, Volume 33, Issue 6, 15 April 2010, Pages 721–735.
8. Du, H., Wu, W., Shan, S., Kim, D., & Lee, W. Constructing weakly connected dominating set for secure clustering in distributed sensor network. Journal of combinatorial optimization 23.2 (2012): 301-307.
9. Guha, Sudipto, and Samir Khuller. Approximation algorithms for connected dominating sets Algorithmica 20.4 (1998): 374-387.

10. Purohit, G. N., and Usha Sharma. Constructing minimum connected dominating set: algorithmic approach International journal on applications of graph theory in wireless ad hoc networks and sensor networks 2 (2010).
11. R. Ahlswede, N. Cai, S.-Y. R. Li, and R. W. Yeung, Network information flow, IEEE Trans. Inform. Theory, vol. 46, pp. 1204-1216, July 2000.
12. P. Ostovari, J. Wu, and A. Khreishah, Network coding techniques for wireless and sensor networks, in The Art of Wireless Sensor Networks, H. M. Ammari, Ed. Springer, 2013.
13. Najla Al-Nabhan, Bowu Zhang, Mznah Al-Rodhaan, Abdullah Al-Dhelaan, Two Connected Dominating Set al.gorithms for Wireless Sensor Networks, Wireless Algorithms, Systems, and Applications, Lecture Notes in Computer Science, Volume 7405, 2012, pp 705-713.
14. Blum, J., Ding, M., Thaeler, A., Cheng, X.: Connected Dominating Set in Sensor Networks and MANETs. In: Handbook of Combinatorial Optimization, vol. 5, pp. 329–369. Kluwer Academic Publishers (2005).
15. Rai, M., Verma, S., Tapaswi, H. A Power Aware Minimum Connected Dominating Set for Wireless Sensor Networks. Journal of Networks 4(6), 511–519 (2009).
16. Liang, O, Multipoint Relay and Connected Dominating Set Based Broadcast Algorithms for Wireless Ad Hoc Networks. Monash University, Melbourne (2007).
17. Shuai Wang, Chonggang Wang, Kai Peng, Guang Tan, Hongbo Jiang, and Yan Dong. Network coding over connected dominating set: energy minimal broadcasting in wireless ad hoc networks. Springer. Wirel. Netw. Vol.20, No. 5 (July 2014).
18. Zhang, Z., Gao, X., Wu, W., & Du, D. Z. A PTAS for minimum connected dominating set in 3-dimensional wireless sensor networks. Journal of Global Optimization 45.3 (2009): 451-458.
19. Hongwei Du, Qiang Ye, Jioafei Zhong, Yuexuan Wang, Wonjun Lee,and Haesun Park, PTAS for Minimum Connected Dominating Set with Routing Cost Constraint in Wireless Sensor Networks, International Journal of Distributed Sensor Networks, 2013
20. Kui, X., Sheng, Y., Du, H., & Liang, J., Constructing a CDS-based network backbone for data collection in wireless sensor networks. International Journal of Distributed Sensor Networks (2013).
21. Abbas El Gamal and Young-Han Kim. 2012. Network Information Theory. Cambridge University Press, New York, USA.
22. Swapna, B. T., Atilla Eryilmaz, and Ness B. Shroff. Throughput-delay analysis of random linear network coding for wireless broadcasting. Information Theory, IEEE Transactions on 59.10 (2013): 6328-6341.
23. Zeng, Deze, et al.. On the throughput of two-way relay networks using network coding. Parallel and Distributed Systems, IEEE Transactions on 25.1 (2014): 191-199.

24. Keshavarz-Haddad, Alireza, and Rudolf H. Riedi. Bounds on the benefit of network coding for wireless multicast and unicast. Mobile Computing, IEEE Transactions on 13.1 (2014): 102-115.
25. Lien, Ching-Min, Cheng-Shang Chang, and Duan-Shin Lee. A Universal Stabilization Algorithm for Multicast Flows with Network Coding. Communications, IEEE Transactions on 61.2 (2013): 712-721.
26. Tran, Tuan T., et al.. Secure Wireless Multicast for Delay-Sensitive Data via Network Coding. Wireless Communications, IEEE Transactions on 12.7 (2013): 3372-3387.
27. Lin, KC-J., and De-Nian Yang. Multicast With Intraflow Network Coding in Multirate Multichannel Wireless Mesh Networks. Vehicular Technology, IEEE Transactions on 62.8 (2013): 3913-3927.
28. Arash.Ghafouri, Ahmad Ghasemi. A Power-based Method for Improving the ODMRP protocol Performance in Mobile Ad-hoc Networks, International Journal of Wireless and Microwave Technologies. 8 (2): 27-36 (2018).
29. Mallapur, S.V., Patil, S.R. & Agarkhed, J.V. Multi-constraints reliable multicast routing protocol for group communications in MANETs. International Journal of Information Technology. (2018) 10:147.
30. Keller, Lorenzo, et al.. SenseCode: Network coding for reliable sensor networks. ACM Transactions on Sensor Networks (TOSN) 9.2 (2013).
31. Han, Zhi-jie, Ru-chuan Wang, and Fu Xiao. A Multicast Algorithm for Wireless Sensor Networks Based on Network Coding. International Journal of Distributed Sensor Networks (2014).
32. Rout, Rashmi Ranjan, and Soumya K. Ghosh. Enhancement of lifetime using duty cycle and network coding in wireless sensor networks. Wireless Communications, IEEE Transactions on 12.2 (2013): 656-667.
33. X.M. Wang, J.P. Wang, Y.L. Xu, Data dissemination in wireless sensor networks with network coding, EURASIP Jouranl on Wireless Communications and Networking, Volume 2010, Artical Id 465915, 14 pages, 2010.
34. Liu, Wang, et al.. On the throughput capacity of wireless sensor networks with mobile relays. Vehicular Technology, IEEE Transactions on 61.4 (2012): 1801-1809.
35. Jennings, Michael Michael Vincent. The application of network coding to multicast routing in wireless networks Diss. Massachusetts Institute of Technology, 2007.
36. S. Katti, H. Rahul, W. Hu, D. Katabi, M. Médard and J. Crowcroft, XORs in the Air: Practical Wireless Network Coding, IEEE/ACM Transactions on Networking, pages 497-510, Jun. 2008.
37. Tracey Ho, Muriel Médard, Ralf Koetter, David R. Karger, Michelle Effros, Jun Shi, and Ben Leong, A Random Linear Network

Coding Approach to Multicast, IEEE Transactions on information theory, vol. 52, no. 10, october 2006.

38. Y. Zhu, B. Li, and J. Guo. Multicast with network coding in application layer overlay networks. IEEE J. Sel. Areas Commun., 22(1):107–120, 2004.
39. S. Dumitrescu, M. Shao, and X. Wu, Layered multicast with interlayer network coding, in The 28th IEEE Conference on Computer Communications (INFOCOM'09), April 2009.
40. S. Jaggi, P. Sanders, P.A. Chou, M. Effros, S. Egner, K. Jain, and L.M.G.M. Tolhuizen. Polynomial time algorithms for multicast network code construction. IEEE Trans. Inf. Theory, 51(6):1973–1982, 2005.
41. D. B. West, Introduction to Graph Theory, 2nd ed. Upper Saddle River, NJ:Prentice Hall, 2001.
42. A. Schumacher, Dominating set based Routing, Algorithms for ad-hoc networking, Seminar talk, 2003.
43. Mahmood, Kashif, Thomas Kunz, and Ashraf Matrawy. Adaptive Random Linear Network Coding with Controlled Forwarding for wireless broadcast. Wireless Days. 2010.
44. S. R. Li, R. W. Yeung, and N. Cai, Linear Network Coding, IEEE Transactions on Information Theory, pages 371-381, Feb. 2003.
45. Ramamoorthy Aditya, Jun Shi, and Richard D. Wesel. On the capacity of network coding for random networks. Information Theory, IEEE Transactions on 51.8 (2005): 2878-2885.
46. A. Khandani, E. Modiano, J. Abounadi and L. Zheng, Reliability and route diversity in wireless networks, Proc. Conf. on Inform. Science and System, 2005.
47. Mohammad Hossein Anisi, Abdul Hanan Abdullah, Shukor Abd Razak, Energy-efficient and reliable data delivery in wireless sensor networks, Springer, Wireless Networks, Volume 19, Issue 4, pp 495-505, May 2013.