# A Self-organizing Location and Mobility-Aware Route Optimization Protocol for Bluetooth Wireless

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***Abstract*—Bluetooth allows multi-hop ad-hoc networks that contain multiple interconnected piconets in a common area to form a scatternet. Routing is one of the technical issues in a scatternet because nodes can arrive and leave at arbitrary times; hence node mobility has a serious impact on network performance. Bluetooth network is built in an ad-hoc fashion, therefore, a fully connected network does not guarantee. Moreover, a partially connected network may not find the shortest route between source and destination. In this paper, a new Self-organizing Location and Mobility-aware Route Optimization (LMRO) protocol is proposed for Bluetooth scatternet, which is based on node mobility and location. The proposed protocol considered the shortest route ahead of the source and destination nodes through nodes location information. In addition, proposed protocol guarantees network connectivity through executing Self-organizing procedure for the damaged route by considering signal strength. The proposed LMRO protocol predicts node mobility through the signal strength and activates an alternate link before the main link breaks. Simulation results show that the LMRO protocol has reduced the average hop count by 20%-50% and increased network throughput by 30%-40% compared to existing protocols.**

***Keywords—Bluetooth; Hop count; Mobility; Routing; Resource optimization; Scatternet; Self-healings***

## I. INTRODUCTION

In recent years, wireless technology has facilitated consumers in terms of conventional cable independence and has provided facilities to connect multiple devices for short-range connectivity [1]. Among various appliances of the wireless technology, Bluetooth is one of the most popular because of its low cost and low power applications [2]. Initially, Bluetooth was only launched as a wireless cable replacement but later it became an emerging wireless technology. According to Bluetooth specifications [3], devices can communicate through a basic network unit at called a piconet. A piconet consists of one master device and most seven active slave devices at the same time. Since Bluetooth allows synchronous transmission, all slaves are synchronized with the clock of the piconet master. The master controls the entire communication in a piconet; it allocates channel and schedules data transmission for its slaves. All the slaves listen to the master and reply to the master when the master explicitly addresses any slave. The master has a unique queue for each slave, while each slave maintains a queue of packets that have to be sent to the master. If there is no data for the slave, the master sends zero payload POLL packets to the slave, and in response, if the slave also has no data for the master; it sends a NULL packet to the master.

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Bluetooth devices connected with different master cannot directly communicate with each other even if their distance is shorter than the radio communication range [4]. The reason is that their channel hopping sequences are different [5]. However, two devices at different piconets are allowed to communicate through an overlapping device called a relay/bridge node. The relay/bridge node can be Slave-Slave (SS) or Master-Slave (MS) in its status. An SS relay device concurrently participates in more than one piconet, and alternatively plays the role of slave. An MS relay device plays a master role in one piconet and a slave role in other piconets [6]. A relay can be a slave in multiple piconets but it can act as master in only one piconet because if multiple piconets have the same master, their frequency hopping would be the same and cause interference. Therefore, a relay provides multi-hop communication among different piconets, and it shares its time among different piconets through the Time Division Multiplexing technique. When different piconet devices intend to communicate, they form a scatternet, which is a bigger network based on multiple piconets being connected through a relay; this is called a scatternet. Communication in a scatternet is possible through a master and relay, where a master uses the services of a relay to forward packets from one piconet to another [7]. Bluetooth specifications however, do not define a protocol for inter-piconet communication; it is achieved through higher layers that significantly affect the network performance.

Bluetooth implements centralized control, where normal ad-hoc network protocols cannot be used for inter-piconet communication [8-14]. Bluetooth specifications do not provide any solution for inter-piconet communication, therefore, different protocols exist in literature. In this context, most of the research is focused on reducing the intermediate hop count that could improve the system performance. Few research contributions in the area of Bluetooth inter-piconet communication are highlighted in [15-18]. The type of scatternet topology has a significant impact on network performance [19]. The inter-piconet communication in a scatternet is still an open research issue, as it is not defined in Bluetooth [20]. Bluetooth's link formation time is too long;

therefore dynamic source routing is preferred for scatternet communication. Furthermore, location-aware protocols have been proposed using different technologies; however, these technologies cannot measure node location [21, 22] accurately. In [23], the authors proposed "Indoor positioning in Bluetooth networks using fingerprinting and lateration approach (IPFT)". IPFT has significantly reduced error between node estimation and actual position, where node information is transmitted without user participation.

The rest of the paper is organized as follows. Literature review is done in Section 2. To create the shortest path using the IPFT, Self-organizing Location and Mobility-aware Route Optimization is proposed in Section 3. Simulation results containing the performance analysis of the proposed routing protocol and its comparison with similar routing protocols are presented in Section 4 by using the NS-2 and UCBT. Finally, Section 5 concludes the whole paper along with some possible future work.

## II. Background and Related Works

Bluetooth specifications do not provide any solution for inter-piconet scheduling, i.e. scatternet communication. Therefore, different approaches are in practice for inter-piconet communication based on the six feasible scatternet topologies as elaborated in [24]. All these configurations have their own benefits and drawbacks. A complex management algorithm is required for mesh topologies but their strength is that if a link fails, communication is still possible [25, 26]. Ring and tree configurations are easy for routing but result in inefficient utilization of bandwidth. Literature review reveals that several routing protocols have been proposed to construct an efficient route in a scatternet. Based on this observation, the development of a routing protocol in a scatternet of a Bluetooth network shall consider. Relay Reduction and Disjoint Routes Construction (RRDR) [27], Location Aware Routing Protocol (LARP) [28], and Scatternet Formation Algorithm for Bluetooth Networks (SFBN) [29] as the reference models since these protocols have significant similarities with the proposed routing protocol. As RRDR does not demand for location information, while LARP and SFBN are based on location information to reduce number of hops for inter-piconet communication.

### A. *Relay Reduction and disjoint route construction protocol (RRDR)*

RRDR [27] was proposed to reduce unnecessary relays and reduce route length. RRDR performs relay reduction and disjoint route construction for a scatternet over a Bluetooth radio system in a distributed manner. RRDR reduces the hop count between a source and its destination, based on relay. An example of RRDR route reduction is shown in Fig. 1, where the source node $S_3$ broadcasts a route RSP packet to the destination $S_6$ node, ($S_3 \rightarrow M_2 \rightarrow R_2 \rightarrow M_3 \rightarrow R_3 \rightarrow M_4 \rightarrow R_4 \rightarrow M_5 \rightarrow S_6$). When $S_6$ receives the RSP, it appends its BD_Addr and $k_{\text{offset}}$ value between $S_6$ and $M_5$ and transmits the RRP packet to $M_4$. All the intermediate devices perform the same operation as $S_6$. Finally, $S_3$ receives the BD_Addr and $k_{\text{offset}}$ information of all the devices from source to destination. For reducing the intermediate hops, $S_3$ start paging procedure and tries to construct the shortest path, but there is no node available, therefore, it simply forwards the packet. On receiving the packet $R_2$ also tries to reduce the route as $R_2$ is in its range, so it creates a new connection with $R_3$ and acts as a master in the new piconet. Thus, RRDR constructs a final route between $S_1$ and $S_5$, which is ($S_2 \rightarrow M_2 \rightarrow R_2 \rightarrow R_3 \rightarrow R_4 \rightarrow M_5 \rightarrow S_6$). It can be observed that RRDR needs 6 hops to create a route from the source to the destination. In this scenario, RRDR has not completely optimized the route length because it only considers relay and master nodes for route length optimization.

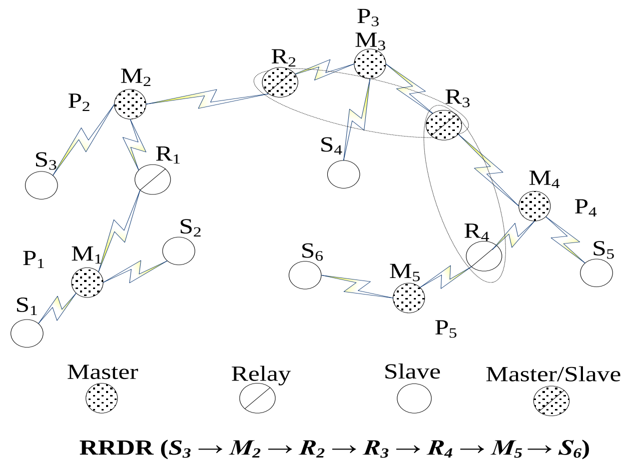
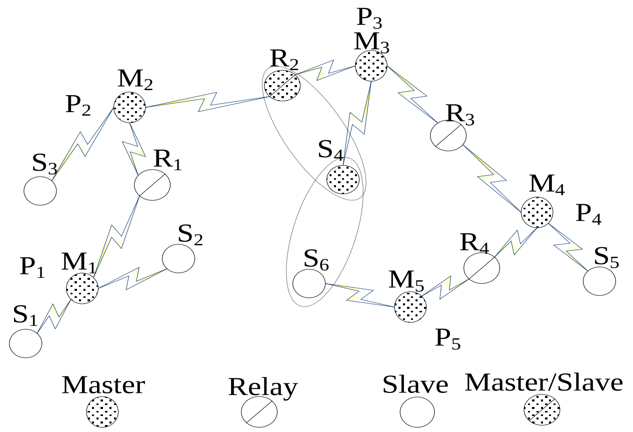



Fig. 1. Route construction through RRDR

### B. *Location Aware Routing Protocol (LARP)*

LARP [28] was proposed for a Bluetooth scatternet, which also considers slave nodes for hop count reduction between source and destination. A source node appends its ID and location (LOC) and transmits a RSP to a master node, the RSP contains the destination ID, but the LOC field is empty as it is unknown. On receiving the RSP, each master node performs route reduction and appends its ID and LOC, and forwards the RSP to all the connected relay nodes. On receiving the RSP, each relay node appends its ID and LOC, and forwards to the connected masters. Finally, destination node receives RRP and replies RRP in reverse order to the master. Since each master knows its slaves ID and location, a master node checks for hop count reduction and replaces the intermediate hops with any node that can reduce the hop counts. This process is continued until the RRP does not reach the source node. Thus, the source node gets the shortest path to the destination node, and it starts the route construction process.

As an example, $S_3$ forwards a RSP for $S_6$ through ($S_3 \rightarrow M_2 \rightarrow R_2 \rightarrow M_3 \rightarrow R_3 \rightarrow M_4 \rightarrow R_4 \rightarrow M_5 \rightarrow S_6$). After applying all the route reduction procedures, according to LARP, the source node gets the RRP, which contains the final shortest path ($S_3 \rightarrow M_2 \rightarrow R_2 \rightarrow S_4 \rightarrow S_6$). In the route construction phase, $R_2$ goes to the Page state where it acts as the master, and $S_4$ goes to the Page Scan state to become a slave; thus, both the devices build a new connection. The same procedure is followed by $S_4$ and $S_6$, where LARP reduces the hop counts to four, as shown in Fig. 2. Although, LARP considers slave nodes for hop count reduction, it depends heavily on RSP, and therefore, it is analyzed that LARP has not completely reduced the route length.




**LARP ($S_3 \rightarrow M_2 \rightarrow R_2 \rightarrow S_4 \rightarrow S_6$)**

Fig. 2. Route construction through LARP

### C. Scatternet Formation Algorithm for Bluetooth Networks (SFBN)

The authors in SFBN [29] used efficient location-based routing protocol for Bluetooth scatternet. In SFBN when a node receives RSP, if destination address matches its Bluetooth Device Address (BD_Add), it sends packet to upper layer, otherwise the received packet is forwarded to next MS bridge. On receiving RSP, MS finds destination information, if it is in its routing table it forwards the packet to downstream. Otherwise, the packet is forwarded to SS bridge for upstream master. This process continues until packet is received by the destination. A source node S3 sends a RSP to the destination node S6. Since SFBN constructs the route through a relay and a master, the RSP is forwarded through (*S3 → M2 → R2 → M3 → R3 → M4 → R4 → M5 → S6*), which is the final routing path between S3 and S6. SFBN route mainly based on scatternet formation, in the above example it follows (*S3 → M2 → R2 → S4 → S6*).

### D. Hybrid indoor position estimation technique

Bluetooth device can obtain location information via GPS [30], or advanced antenna techniques [31]. But these techniques are not suitable for indoor environments due to accuracy limitation. A Hybrid Indoor Position Estimation [32] technique is proposed to find node location in Bluetooth network. In this technique, inquiry-based Received Signal Strength Indicator (RSSI) is obtained and passed to Kalman filter to estimate position of the target node. A mobile node position is estimated through RSSI and filtered by Gradient predictor and filter. The estimated position is denoted by Target(x; y). In the offline stage of fingerprinting-based approach, the whole area is divided into equal size grids. The RSSI samples are collected at each grid several times. The average of measured RSSI values is calculated and stored in a lookup of table with their corresponding coordinates. The RSS measurements are observed and the mean RSSI value for each location is calculated and stored in a database. Euclidian distance formula is used to calculate the distance between these points. When the distances are given, then trilateration approach can be used to calculate the coordinates of the target location.

Based on a review of these analyses, it is observed that every new protocol has tried to reduce the hop count, but none of them has completely succeeded in the scatternet. It has been analyzed that RRDR follows the longest route, while SFBN and LARP have reduced the route length. Moreover, LARP obtains node location through Bluetooth Location Network (BLN) [31] that can support only static environment. The main drawback with all these techniques is that they do not consider the case when a device suddenly goes out from the radio range. Once a link breaks between a connected source and destination, new connection procedure is starts from inquiry and inquiry scan that it will take more time to find another way for connecting the broken links. It is analyzed due to node mobility routing path may be disturbed and increasing the routing overheads.

The proposed LMRO contains two basic procedures for route optimization. First, the final piconet master tries to find the shortest route ahead of destination host piconet. Second, on receiving an RRP, the source host master tries to reduce intermediate hosts based on destination location. In addition, the proposed protocol repaired the damaged routing path by considering the location information and mobility of the nodes, if routing path is disturbed due to nodes mobility in existing scatternet. Thus, proposed protocol overcomes frequent link disconnection setback.

## III. The Proposed Self-Organizing Location and Mobility-Aware Route Optimization Protocol

In this section, the LMRO protocol is proposed for a Bluetooth scatternet. The proposed LMRO requires the location information of mobile nodes to reduce route length between a source and destination in the scatternet topology. In addition, a role-switching operation is performed to dynamically construct a link during the route construction and repairing procedure. In the proposed LMRO each master maintains a node information table, where node location, BD_Addr, and $k_{\text{offset}}$ are stored. LMRO finds the node location through IPFT technique and not only constructs the shortest routing path between source and destination but also guarantees network connectivity.

### A. The proposed LMRO system model

Assume a Bluetooth scatternet is constructed. There are $N$ numbers of randomly distributed nodes, where each node $i \in N = \{1,2,\ldots,N\}$ is selected to be either a slave, relay, or master in the scatternet. A Bluetooth node has a unique 48-bit BD_Addr, which is used for synchronization. The set of master is denoted by $M$, set of slaves is denoted by $S$, and set of relays is denoted by $R$ such that $M \cup S \cup R = N$. A piconet is defined as follows:

**Piconet:**

$$P_i\left(S_{ij} \in M_i\right) = \begin{cases} 1 & S_{ij} \text{ connects } M_i \\ 0 & S_{ij} \text{ does not connect } M_i \end{cases} \qquad (1)$$

Subject to $S_{ij} \leq 7, \forall i$ (2)

Distance $ED\left(S_{ij} \wedge M_i\right) < 10m$ (3)

where $P_i$ represents the $i^{th}$ piconet and $M_i$ corresponds to the piconet master, $S_{ij}$ is the $j^{th}$ slave node in $i^{th}$ piconet. $S_{ij}$ is set to

1 if there is a master-slave relationship between node $i$ and node $j$, otherwise it is set to 0. Constraint (2) determines each piconet has one master and a maximum of up to seven active slaves, where constraint (3) limits each slave within the range of 10 m from the master. Coordinates (x, y) of a mobile node are obtained using IPFT technique in a scatternet topology over a 2-D plane without user participation. The distance between two points (devices) is calculated through equation 4.

$$ED = \sqrt{(x_1 - x_2)^2 - (y_1 - y_2)^2} \quad (4)$$

where $ED$ denotes Euclidian distance, and (x, y) are the coordinates of $i^{th}$ and $j^{th}$ node in scatternet respectively.

In the proposed protocol, each master maintains a Node Information Table ($NIT$), $S_{ij} \in M_i = NIT \sum_{j=1}^{k} (ID, NCLK, LOC)$, which contains the node's $ID$, $k_{offset}$, and $LOC$, where $k$ is total number of devices connected with $i^{th}$ master.

$$Src_{HM} = Src(S_{ij}) \in P_i \quad (5)$$

where $Src_{HM}$ denotes source host master and $S_{ij}$ is one of the connected slaves with the master.

A master device is called source host master ($Src_{HM}$) if the route request is initiated one of its connected slave. A master is called Destination host master ($Dst_{HM}$), if the destination belongs the same piconet mentioned in equation (6). A $Src_{HM}$ and $Dst_{HM}$ unicast route search packet and route reply packet respectively to optimize route length. A potential candidate (node) in the network is called Auxiliary host (AH), if it can reduce the route length. The $Src_{HM}$ and $Dst_{HM}$ nodes find $ED$ between each node in RSP and RRP respectively in the NIT, and if any nearest relay is found by the source or destination, it forwards the packet to find the shortest route.

$$Dst_{HM} = Dst(S_{ij}) \in P_i \quad (6)$$

In the proposed protocol, each master also gets to know the location information of the intermediate nodes between a source and destination through IPFT. According to Bluetooth, master and slave have periodic communication. In the proposed protocol each master obtains nodes information through RSSI and it takes a constant $O(1)$ time. The proposed route optimization protocol consists of three main steps (Route search, Route reply, Route construction). In addition, mobility of mobile node is also monitored during transmission phase through RSSI.

### B. Route optimization procedure

This sub-section describes the proposed route optimization procedure that is divided into three phases: route search, route reply, and route construction. The proposed LMRO constructs the shortest routing path by using the ID, $k_{\text{offset}}$, and location information of the nodes.

#### 1) Route Search Phase

Before starting an inter-piconet communication, each source initiates a route request. When a source initiates a route request and transmits a RSP to the $Src_{HM}$ node in order to find a route to the destination that exists in a different piconet. The RSP payload is used to store the nodes' information as shown in Fig. 4. Initially, the RSP contains the source ID and LOC, while it is assumed that the source knows the destination node ID, however the location is unknown. On receiving the RSP, the $Src_{HM}$ appends its ID and LOC and forwards the packet to all the attached relays. On receiving the RSP, the relay also includes its ID and LOC, and forwards the RSP to all connected masters. All the receiving masters then search for any node that can reduce hop count, and append its information in the RSP. If the next selected host is a relay, the master will not include its information; it simply forwards the RSP, and removes the unnecessary nodes' information from the RSP, since the relay itself includes the required information in the RSP. Ultimately, several RSPs are received by the destination, but it only considers the least number of hops. The destination appends required information in the RSP and forwards to $Dst_{HM}$. Where $Dst_{HM}$ searches for an Auxiliary Host, if $Dst_{HM}$ finds any AH, it forwards the RSP to the AH, and all the intermediate nodes include their information in the RSP. The final AH master performs route optimization and returns the RSP to $Dst_{HM}$.

The RSP format is shown in Fig. 3. Source $S_3$ initiated a route request and transmitted a RSP to destination $S_6$, where next hop and Auxiliary host field are NULL. The RSP is forwarded through ($S_3 \rightarrow M_2 \rightarrow R_2 \rightarrow M_3 \rightarrow R_3 \rightarrow M_4 \rightarrow R_4 \rightarrow M_5 \rightarrow S_6$). Initially, $S_3$ added its ID and LOC in the RSP and forwarded the RSP to $M_2$, where $M_2$ became the $Src_{HM}$, and appended its ID and LOC information in the next hop field and forwarded the received packet to $R_2$. As $R_2$ was a relay it simply appended its information and forwarded to $M_3$, where $M_3$ performed route optimization and did not include its information in the RSP. As the next hop $R_3$ is in the range of $R_2$ and it has reduced the roué length. Finally, $S_6$ received RSP with optimized route ($M_2 \rightarrow R_2 \rightarrow R_3 \rightarrow R_4 \rightarrow M_5$) information. It has been observed, that in end of route search the route length is 6 hops which is the same path as RRDR.

| Route Search Packet (RSP) | | | | |
|---|---|---|---|---|
| **Sender** | **Source** | **Next Hop** | **Destination** | **AH** |
| $S_3$ | $S_{3(ID,LOC)}$ | NULL | $S_{6(ID, NULL)}$ | NULL |
| $M_2$ | $S_{3(ID,LOC)}$ | $M_{2(ID, LOC)}$ | $S_{6(ID, NULL)}$ | NULL |
| $R_2$ | $S_{3(ID,LOC)}$ | $M_{2(ID, LOC)} \rightarrow R_{2(ID, LOC)}$ | $S_{6(ID, NULL)}$ | NULL |
| $M_3$ | $S_{3(ID,LOC)}$ | $M_{2(ID, LOC)} \rightarrow R_{2(ID, LOC)}$ | $S_{6(ID, NULL)}$ | NULL |
| $R_3$ | $S_{3(ID,LOC)}$ | $M_{2(ID, LOC)} \rightarrow R_{2(ID, LOC)} \rightarrow R_{3(ID, LOC)}$ | $S_{6(ID, NULL)}$ | NULL |
| $M_4$ | $S_{3(ID,LOC)}$ | $M_{2(ID, LOC)} \rightarrow R_{3(ID, LOC)} \rightarrow R_{3(ID, LOC)}$ | $S_{6(ID, NULL)}$ | NULL |
| $R_4$ | $S_{3(ID,LOC)}$ | $M_{2(ID, LOC)} \rightarrow R_{2(ID, LOC)} \rightarrow R_{3(ID, LOC)} \rightarrow R_{4(ID, LOC)}$ | $S_{6(ID, NULL)}$ | NULL |
| $M_5$ | $S_{3(ID,LOC)}$ | $M_{2(ID, LOC)} \rightarrow R_{2(ID, LOC)} \rightarrow R_{3(ID, LOC)} \rightarrow R_{4(ID, LOC)} \rightarrow$ | $S_{6(ID, NULL)}$ | NULL |

| | | | | |
|---|---|---|---|---|
| | | $M_{5(ID, LOC)}$ | | |
| $S_6$ | $S_{3(ID,LOC)}$ | $M_{2(ID, LOC)} \rightarrow R_{2(ID, LOC)} \rightarrow R_{3(ID, LOC)} \rightarrow R_{4(ID, LOC)} \rightarrow M_{5(ID, LOC)}$ | $S_{6(ID, LOC, k_{offset})}$ | NULL |

Fig. 3. Route search packet through different nodes in the scatternet

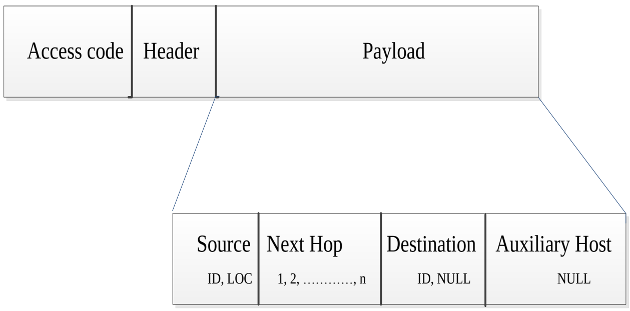



Fig. 4. Route Search Packet format

*2) Route Reply Phase*

Once route search process finished, the destination sends a unicast reply to the source host. During the route reply, the destination acts as a source and sends a RRP along the selected shortest path, that is created during the route search phase. It is important to note that RRP is sent in the reverse order of RSP. Each master knows the location and BD_Addr of its slaves. When a master receives the RRP, it again performs route optimization based on updated nodes information. If any of its slave is selected to reduce hop count for the new route. The master appends the selected node information, i.e. ID, LOC and Native Bluetooth $k_{\text{offset}}$ and forwards the RRP to the next hop. Ultimately, the RRP is received by $Src_{HM}$, if the $Src_{HM}$ finds any AH it forwards the RRP to AH and waits for reply. All the intermediate nodes append their information in the RRP, until it is received by the AH master. On receiving the RRP AH master verifies if any node can reduce the hop count. The AH master forwards the received RRP to AH, where selected AH appends required information in the RRP, and sends a unicast RRP to the source. In the next step, AH enters into page scan mode to create a new connection.

Using the example of Fig. 1. the RRP format is given in Fig. 5. Route optimization through RRP is explained, where $S_3$ forwards the RSP through ($S_3 \rightarrow M_2 \rightarrow R_2 \rightarrow M_3 \rightarrow R_3 \rightarrow M_4 \rightarrow R_4 \rightarrow M_5 \rightarrow S_6$) to $S_6$. All intermediate masters run the optimization algorithm, but only $M_3$ found a node ($S_4$) that replaced ($R_3$, $R_4$, $M_5$) and reduced 2 hops. Finally, $Src_{HM}$ $M_2$ received the RRP, it checked in NIT for AH, and forwarded the RRP to AH $R_1$. On receiving RRP $R_1$ added required information in AH field and forwarded RRP to $M_1$. It can be observed that the distance can be reduced through $S_2$, therefore, $M_1$ forwarded RRP to $S_2$. On receiving the RRP, $S_2$ appended its BD_Addr and $k_{\text{offset}}$ value between $S_2$ and $M_1$ and transmits the RRP packet back to $M_1$. Finally, $S_3$ received the RRP, where ($M_2$ , $R_2$, $S_4$) *are replaced with* $S_2$. Thus, numbers of intermediate host are decreased to one, which is the best shortest path in the present scatternet.

| **Route Reply Packet (RRP)** | | | | |
|---|---|---|---|---|
| **Sender** | **Source** | **Next Hop** | **Destination** | **AH** |
| $S_6$ | $S_{3(ID,LOC)}$ | $M_{2(ID, LOC)} \rightarrow R_{2(ID, LOC)} \rightarrow R_{3(ID, LOC)} \rightarrow R_{4(ID, LOC)} \rightarrow M_{5(ID, LOC)}$ | $S_{6(ID, Loc, k_{offset})}$ | NULL |
| $M_5$ | $S_{3(ID,LOC)}$ | $M_{2(ID, LOC)} \rightarrow R_{2(ID, LOC)} \rightarrow R_{3(ID, LOC)} \rightarrow R_{4(ID, LOC)} \rightarrow M_{5\ (ID, LOC, k_{offset})}$ | $S_{6(ID, Loc, k_{offset})}$ | NULL |
| $R_4$ | $S_{3(ID,LOC)}$ | $M_{2(ID, LOC)} \rightarrow R_{2(ID, LOC)} \rightarrow R_{3(ID, LOC)} \rightarrow R_{4(ID, LOC, k_{offset})} \rightarrow M_{5(ID, LOC, k_{offset})}$ | $S_{6(ID, Loc, k_{offset})}$ | NULL |
| $M_4$ | $S_{3(ID,LOC)}$ | $M_{2(ID, LOC)} \rightarrow R_{2(ID, LOC)} \rightarrow R_{3(ID, LOC)} \rightarrow R_{4(ID, LOC, k_{offset})} \rightarrow M_{5(ID, LOC, k_{offset})}$ | $S_{6(ID, Loc, k_{offset})}$ | NULL |
| $R_3$ | $S_{3(ID,LOC)}$ | $M_{2(ID, LOC)} \rightarrow R_{2(ID, LOC)} \rightarrow R_{3(ID, LOC, k_{offset})} \rightarrow R_{4(ID, LOC, k_{offset})} \rightarrow M_{5(ID, LOC, k_{offset})}$ | $S_{6(ID, Loc, k_{offset})}$ | NULL |
| $M_3$ | $S_{3(ID,LOC)}$ | $M_{2(ID, LOC)} \rightarrow R_{2(ID, LOC)} \rightarrow S_{4(ID, LOC, k_{offset})}$ | $S_{6(ID, Loc, k_{offset})}$ | NULL |
| $R_2$ | $S_{3(ID,LOC)}$ | $M_{2(ID, LOC)} \rightarrow R_{2(ID, LOC, k_{offset})} \rightarrow S_{4(ID, LOC, )}$ | $S_{6(ID, Loc, k_{offset})}$ | NULL |
| $M_2$ | $S_{3(ID,LOC)}$ | $M_{2(ID, LOC, k_{offset})} \rightarrow R_{2(ID, LOC, k_{offset})} \rightarrow S_{4(ID, LOC, k_{offset})}$ | $S_{6(ID, Loc, k_{offset})}$ | $R_{1(ID, LOC)}$ |
| $R_1$ | $S_{3(ID,LOC)}$ | $M_{2(ID, LOC, k_{offset})} \rightarrow R_{2(ID, LOC, k_{offset})} \rightarrow S_{4(ID, LOC, k_{offset})}$ | $S_{6(ID, Loc, k_{offset})}$ | $R_{1(ID, LOC, k_{offset})}$ |
| $M_1$ | $S_{3(ID,LOC)}$ | $S_{2(ID, LOC)}$ | $S_{6(ID, Loc, k_{offset})}$ | NULL |
| $S_2$ | $S_{3(ID,LOC)}$ | $S_{2(ID, LOC, k_{offset})}$ | $S_{6(ID, Loc, k_{offset})}$ | NULL |

Fig. 5. Format of RRP through different nodes in the scatternet

*3) Route Construction Phase*

Finally, the route construction phase is executed after the completion of the route search and route reply phases. Ultimately, the source receives all the possible intermediate nodes information that can be used to construct the shortest path between a source and a destination. The source checks the next hop if it is not $Src_{HM}$, it goes to the Page mode and tries to connect the next hop. There are 32 page frequencies with 1.28s interval. Frequencies are divided into two trains (train A and train B) mentioned in equation 7 and 8.

$$A - train\{ f(k-8) ... f(k) ... f(k+7)\} \quad (7)$$

$$B - train\{ f(k+8) ... f(k+15), f(k-16), ..., f(k-9)\} \quad (8)$$

where f(k) is receiver frequency of paged device, the key k indicates the input functions.

If the sequence selection is set to page state then the paging device use the $A - train\{ f(k-8) ... f(k) ... f(k+7)\}$. There exist 32 paging frequencies including a page hopping sequence which is obtained by the BD_Addr of the paged device. Bluetooth devices change their listening frequencies after 1.28s [33]. The master page response Xprm hopping sequence can be gained by the equation 9 for X input:

$$X_{prm} = [CLKE^{*}_{16-12+koffset^{*}} + (CLKE^{*}_{4-2,0} - CLKE^{*}_{16-12}) \bmod 16 + N] \bmod 32 \quad (9)$$

The master device freezes its predictable slave clock to the value that triggered a reply from the paged device. It is equal to using the clock values estimation when receiving the slave response. The frozen clock value is used at the content where the recipient’s access code is identified. Let $N$ be a counter that starts from zero and increases by one for each time when CLKN is set zero that matches to the start of a master TX slot. Once the connection is established, it forwards the selected route packet to the next hop. The route construction process continues until the packet does not reach the destination. Once the connection is established, both the nodes start transmission, and when transmission, all nodes return to the original state, and re-apply the role-switching operation.

Consider an example of first route from ($S_3$ to $S_6$). Once $S_2$ replied it entered into the HOLD (low power) mode in $P_1$, and started the Page-Scan procedure to construct a new piconet to reduce the hop count. Finally, $S_3$ received the BD_Addr and $k_{offset}$ information of all the devices from source to destination. For reducing the intermediate hops, $S_3$ entered into the HOLD mode in $P_2$ and tried to construct the shortest path, i.e. ($S_{3\ (ID,\ LOC)} \rightarrow S_{2\ (ID,\ LOC,\ k_{offset})} \rightarrow S_{6(D,\ LOC,\ k_{offset})}$). $S_3$ entered to the Page mode and connected $S_2$ as its slave. After connecting to $S_2$, it forwarded the packet to $S_2$, which has only $S_6$ information. Hence, $S_2$ entered the Page mode and connected $S_6$ as its slave. Thus, the proposed LMRO final route construction is shown in Fig. 6.

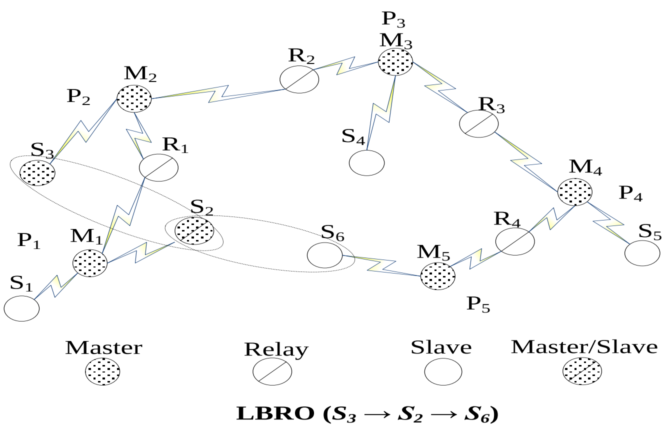



Fig. 6. Route optimization through LMRO

### C. Self-organizing Procedure

A node is called routing master if the master itself or any of its node is involved in the selected route between the source and the destination. The main object of Self-organizing procedure is healing between the source and the destination, if a link is disturbed due to node mobility. As each routing master stores the route information that includes node *ID*, $k_{offset}$, and *LOC* of the members participating in the routing. Node $M_1$ is the routing masters of the piconet, since $S_2$ is its member which is participating in the shortest routing path. A piconet contains a routing master ($M_i$) called routing piconet (*Pi*). If any slave joins any of the routing piconet, BD_Addr, $k_{offset}$, and LOC of that new node is forwarded to the routing master of the corresponding routing piconet. A sub-route selection procedure is executed if Signal-to-Noise Ratio (SNR) threshold is below $\rho$. Where $\rho$ = -45*db* is fixed for all routing nodes as below:

$$SNR = \frac{Received\ power}{Interferience\ power} \geq \rho \qquad (10)$$

A link is marked as weak link if SNR is greater than ρ, and the receiver node notifies to sender about weak link status. As shown in Fig. 7(a). a link is created between node $S_2$ and $S_4$ due to node mobility the distance has been increased. Thus, the link between $S_2$ and $S_4$ become weak which is notified by $S_4$, shown in Fig. 7(b). On receiving weak link information $S_2$ sent BD_Addr, LOC, and $k_{offset}$ of $S_1$ and $S_4$ to routing master $M_1$ and requested for its replacement. Once the request is sent $S_2$ left hold mode and entered into its original mode in $P_1$ as a pure slave node.

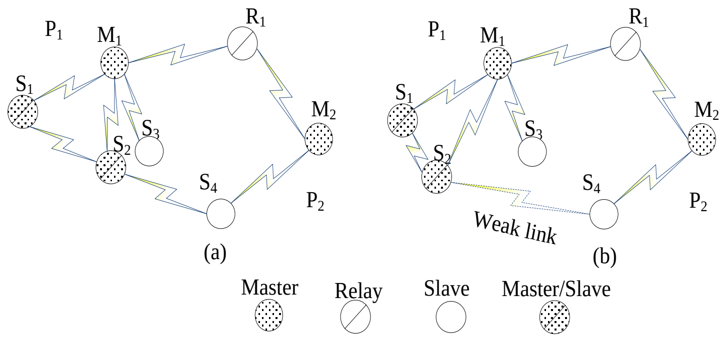



Fig. 7. (a) Original link (b) Weak link

Bluetooth is an ad hoc network, therefore, new nodes may join an existing scatternet. When $M_1$ received weak link information in the routing path of a Bluetooth scatternet, it verified from NIT which device can be a replacement of the requested device. For the device verification, $M_1$ executed the device selection procedure. $M_1$ verified $S_3$ distance from $S_1$ and $S_4$. Meanwhile, $S_2$ also transmitted weak link information to $S_1$ and $S_4$, where $S_3$ and $S_4$ entered page and page scan mode respectively to establish the new links. After waiting for a random backoff time, $M_1$ executed node replacement procedure, and transmitted a member collection packet to $S_3$ which contains $S_1$ and $S_4$ BD_Addr, LOC, and $k_{offset}$. Upon receiving a member collection information packet, $S_3$ entered to page scan mode and established the first link with $S_1$ as a slave. Once the first link is established $S_3$ executed role switch operation and entered page scan mode and established the second link with $S_4$, where $S_4$ played slave role and $S_2$ played master role as shown in Fig. 7(c).

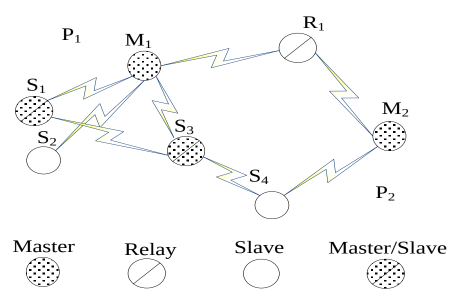



Fig. 7. (c). After replacement procedure

## IV. PERFORMANCE ANALYSIS

This section discusses the simulation environment that is used for evaluating the proposed LMRO protocol and presents the simulation results. Importantly, the performance of the LMRO protocol is analyzed to see whether its objective for efficient inter-piconet communication has been achieved or not. The performance is compared against the standard Bluetooth routing protocols such as the, RRDR [27], LARP [28], and SFBN [29] in terms of route optimization parameters, such as hop count, control packets, delay, guard time, and throughput.

*A. Simulation setup*

To evaluate the performance, the LMRO protocol is implemented in the UCBT [34], which is an NS-2 based Bluetooth simulator [35]. The UCBT is the only open source Bluetooth simulator that is freely available and supports mesh-shaped scatternets. In addition, the UCBT supports SS and MS bridge role. The UCBT implements the majority of the protocols in the Bluetooth protocol stack. Bluetooth unlicensed Industrial-Scientific-Medical (ISM) band at about 2.4 GHz is used. The Radio Frequency (RF) range of Bluetooth devices is ten meters. Bluetooth 79 RF frequencies are used, where a different frequency is used through the Frequency Hopping Spread Spectrum (FHSS) in each time slot to avoid channel interference. Bluetooth devices use a different frequency in each time slot for communication. The frequency remains the same during the transmission of a packet before transmitting the next packet. Bluetooth devices access medium through the Time Division Duplex (TDD) scheme, which is controlled by the master. Each channel is divided into time slots of $T = 625$ $\mu s$ which is synchronized to the clock of the piconet master.

TABLE I. SIMULATION PARAMETERS

| Parameter | Value |
|---|---|
| The number of nodes | 10 – 90 |
| Network size | 80 x 80 $m^2$ |
| Communication range | 10 m |
| Power class | B |
| Traffic model | Constant Bit Rate (CBR) |
| Node deployment | Random Deployment |
| Number of pairs | 45 pairs |
| Energy consumption | 0.0763 x $10^{-6}$ J/bit |
| Packet type | DH3, DH5 |
| Mobility Model | Random waypoint model |
| Mobility speed | 0.5 – 3.0 m/s |
| Polling algorithm | Round Robin |
| Bridge scheduling algorithm | MDRP |
| Packet size | 349 Bytes |
| Inquiry time | 10.24 s |
| Page time | 128 – 256 s |
| Packet interval | 0.15 s |
| Queue length | 50 packets |
| Simulation time | 1000 s |

The parameters used in the simulation are listed in Table 1. [10, 36]. The confidence interval of simulation was 0.05%. The number of nodes is varied from 10 to 90, and randomly deployed in a simulation area of 80 x 80 $m^2$. The radio range for a mobile node is 10 meters. Transmitting or receiving energy consumption is set to 0.0763 x $10^{-6}$ J/bit and the queue length on each link is 50 packets. The Priority-based Round Robin (PRR) algorithm is used for polling, while Inter-piconet communication is achieved through Maximum Distance Rendezvous Point (MDRP) [37]. The Constant Bit Rate (CBR) is used to send 349 byte packets randomly selected sources and destinations. Each node can participate in multiple connections. The Random waypoint mobility model is used for the simulation. Total simulation time is 1000 seconds, where the first 99 seconds are used for scatternet construction, and CBR traffic is started at the $100^{th}$ second. The simulation is performed 10 times, and results are taken by averaging the obtained results.

*B. Simulation results and discussion*

From the series of simulation results as described below, it can be concluded that the proposed LMRO routing protocol has outperformed the four contemporary protocols of RRDR, LARP, and SFBN for inter-piconet communication in a scatternet of a Bluetooth network. The LMRO performs route optimization beyond the source and destination. In addition, the LMRO considered the node mobility, hop count reduction, and link repairing. It is analyzed that the RRDR, and LARP route optimization is based on an route search that increases route length in the scatternet. On the other hand, SFBN route construction depends on scatternet efficiency. The simulation results that are presented in the following sub-section are a set of evidence to support the superiority of the LMRO routing protocol. In ad-hoc networks, lifetime is considered the key challenging issue because all the nodes are battery powered and have limited battery. Thus, prolonging network life is important to carry out all the primitive functions of nodes such as: sensing, receiving, transmitting, processing etc. In Bluetooth, multiple slaves wait to utilize a common medium, due to inherited nature of wireless technology. Bluetooth does not allow node contention for simultaneous transmission. The proposed protocol reduced intermediate nodes, therefore, disconnection probability has been reduced and ultimately, overall less system resources consumed.

Hop count refers to the number of intermediate hosts between a source and a destination. Average hop count is calculated through total number of intermediate links between source and destination nodes. Fig. 8. shows the average hop count for all four protocols; it can be observed that LMRO reduces hop count as compared to RRDR, LARP, and SFBN. RRDR does not efficiently reduce route length, as it only considers relay nodes for hop reduction, which increases the path length. Further, LARP depends on a RSP, where it has been found that RSP does not always follow the shortest route. It is analyzed that SFBN protocols is straightforward and easy to implement, but its topology affects scatternet performance by network partitioning. SFBN topology follows Master-slave (MS) bridge policy for inter-piconet communication which stops intra-piconet communication due to master node unavailability. With the LMRO protocol, the shortest route can be found beyond the source and destination nodes in the scatternet. It is observed that LARP and SFBN reduce the number of hops compared to RRDR because it does not consider slave nodes for hop reduction. It can be analyzed that LARP and SFBN has almost similar average hop count for inter-piconet communication. The proposed LMRO considers slave nodes beyond source and destination during route searches and route replies, which gives significant improvement in terms of hop count reduction. The simulation results showed that the proposed LMRO l has reduced hop count between 20% - 50%.

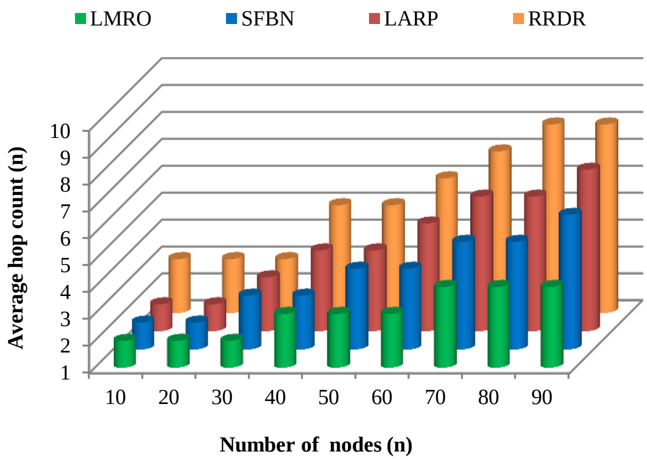



Fig. 8. Average hop count vs. number of nodes

Bluetooth uses different types of control packets for connection activation and information exchange. Total size of information that is used for communication is known as control overhead. Control message overhead is calculated as the sum of bytes in MAC, base-band, NULL, and POLL packets. Every time a message is forward through the network, intermediate devices need to synchronize and exchange control messages. It is observed that a longer route needs more control messages due to the Bluetooth devices' synchronization process. RRDR uses distributed relay reduction with heavy control packets that creates a huge amount of overhead for different mobile nodes. LARP reduces the hop count, but creates an extra amount of message overhead due to longer route selection. In SFBN, master also performs bridge functionality and exchanges more control messages for slot reservation and network maintenance. It is observed more route links break by increasing mobility speed, thus, all four existing protocols start establish new link from Inquiry and Inquiry Scan which consume large number of control packets. In contrast, the proposed LMRO protocol selected the shortest route and repaired damaged links without flooding, therefore, it reduced the control overhead. From Fig. 9. it is observed that the LMRO protocol performs better as compared to all three protocols of RRDR, LARP, and SFBN in terms of control packets.

Throughput is defined as the successful data bytes received by a destination per unit time. Throughput is calculated as total number of bytes received by destination nodes divided by simulation time. As discussed above, all the protocols of RRDR, LARP, and SFBN have neglected the routing link condition. RRDR has tried to reduce the route, but it is only based on relay nodes, and therefore, RRDR did not really optimize the route length. On the other hand, the LARP route depends on RSP, and it has not completely optimized the route length between a source and a destination. LMRO is more efficient than RRDR, LARP, and SFBN in terms of throughput by reducing the guard time, as the guard time affects the throughput on all the existing protocols. There are many chances for the traffic to follow the same link for multiple connections, once a link breaks, it starts heavy flooding problems as that of RRDR, LARP, and SFBN. SFBN has reduced path lengths, however, it suffers from bottleneck nodes which reduces network throughput and partitions network due to the tree hierarchy. As shown in Fig. 10. with passing time all three existing protocols reducing throughput due to link breakage. On the other hand, the proposed LMRO protocol has maintained throughput by performing network maintenance, therefore, the proposed LMRO has 30% to 40% higher throughput as compared to the existing protocols.

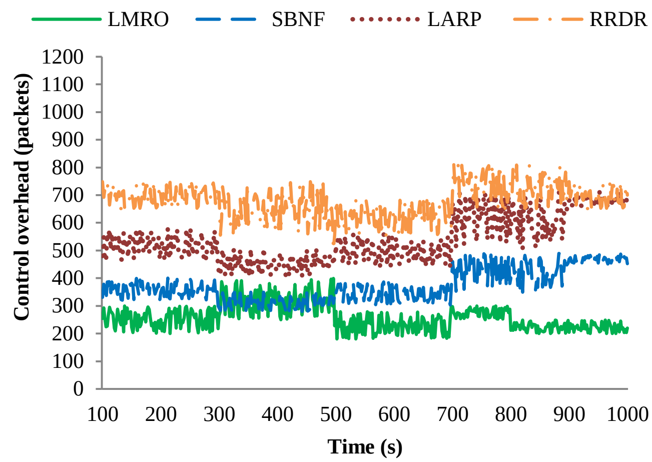



Fig. 9. Control packets vs. simulation time

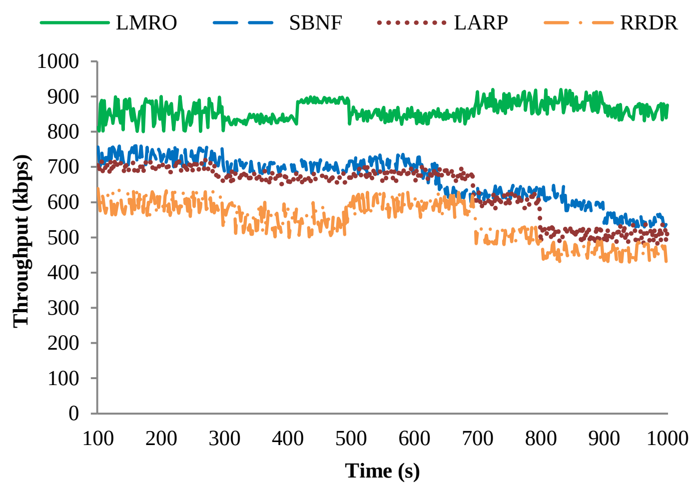



Fig. 10. Average network throughput vs. simulation time

The time required for a bit to be forwarded from a source to a destination is called delay. Average End-to-end delay is the sum of each (packet received time – packet transmitted time) divided by time. If a node leaves its position during transmission, all transmission is aborted. Therefore, a new route connection procedure starts from an inquiry and the inquiry scan which increases transmission delay. Delay in a scatternet highly depends on the number of connections passing through a node (master/relay). A node activation time depends on synchronization time and service time. In the proposed protocol, the master checks the traffic load of each AH in the piconet. If multiple AHs exist, the first priority is given to slave or a lower degree node is selected for new route connection to avoid bottleneck problem. It is analyzed that the average delay of LMRO is less than that of RRDR, LARP, and SFBN. When mobility increases, the delay also increases; this is because frequent node mobility has increased the polling time of the masters. It is observed that a large number of intermediate devices increase delay and link disconnection probability. In addition, large number of devices also increases route length of the randomly selected source and destination. Due to mobility and frequent link breakage, the average end-to-end delay of RRDR LARP, and SFBN is high. Fig. 11. shows the end-to-end delay of different protocols against simulation time. It is observed that the proposed protocol outperforms RRDR, LARP, and SFBN in terms of delay. Generally, a short route length has reduced delay in a network, where LMRO has selected the shortest route in the scatternet and reduced sub-route construction time.

The time required by a node to wait for synchronization with a master/relay is called guard time. During the guard time, a transmission is blocked due to the synchronization process. When the number of nodes increases, the guard time also increases; this is because greater number of nodes increases the polling time of the masters. Since large number of intermediate devices increase guard time, and increase link disconnection probability. Increasing numbers of nodes also increase route length of randomly selected source and destination. As a relay needs 3Δ time for synchronization, it means a message that passes through relay needs 2(3Δ) because a relay synchronizes with two masters. A piconet contains a maximum of eight active devices, and all of the devices need separate slots for uplink (slave to master) and downlink (master to slave) transmissions. It can be analyzed that guard time increases when mobility speed increases. The reason is that a node has to share its time among all the connected masters.

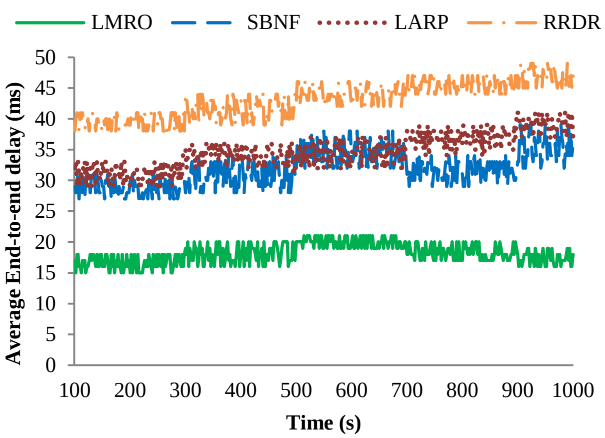



Fig. 11. Total end-to-end delay vs. simulation time

As RRDR, LARP, and SFBN protocols do not consider network maintenance, there are many chances that one node participates in multiple links, and subsequently increases the guard time. The proposed protocol of LMRO tries to find the shortest route, this effort reduces the chances of a single node participating in a large number of links. Fig. 12. shows the effect of the guard time and improves the overall network performance. As mobility increases, the guard time also gradually increases, but it can be observed that LMRO has less guard time as compared to RRDR, LARP, and SFBN.

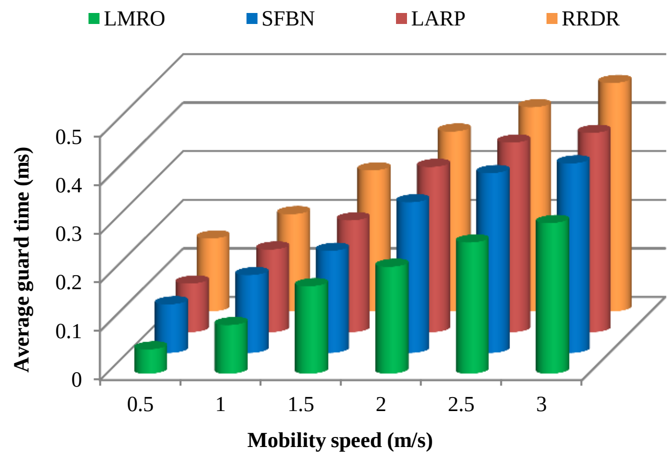



Fig. 12. Guard time vs. average speed

## V. Conclusion and Future Work

Bluetooth devices are becoming more popular as modern technology is transferring data onto wireless mediums for access flexibility and user mobility. Specifically, Bluetooth is one of the technologies that is capable enough to provide the last-meter connectivity. However, the inefficient inter-piconet communication in the scatternet topology has led to the overall inefficiency of the Bluetooth communications. This inefficiency is mainly contributed to the delay and control overhead in the inter-piconet scheduling policy. It is analyzed, that existing routing protocols construct a route that is based on a master and relay nodes that increases the number of hops. Furthermore, the existing protocols perform route optimization, but route optimization is based only on the RSP. Therefore, the existing protocols do not reduce an optimum number of hops. This motivates towards the development of a new routing protocol that would reduce the number of hops and repair weak link that ultimately improve the overall system performance. The proposed LMRO protocol finds the best shortest route between a source and a destination. Analytically, the LMRO has reduced the hop count and successfully repaired damaged link between a source and a destination. Empirically, through simulation, the performance of the proposed LMRO protocol is compared against the performance of the RRDR, LARP, and SFBN protocols based on several performance metrics. It was found that the LMRO protocol has outperformed all four protocols in terms of hop count, message overhead, delay, and throughput. Interestingly, the LMRO's throughput has improved in the range of 30% - 40%, and this was achieved by reducing hop count in the inter-piconet routing.

There is still room for future study and development. In the future, more research issues would be addressed based on the proposed study. A more realistic approach would be adopted to adjust a node in a piconet to which it is frequently communicated in order to reduce the scheduling overhead. In addition, the proposed LMRO protocol will be extended to overcome frequent link disconnection problems due to node mobility, which is based on a stable node selection.

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