Scatternet Formation of Bluetooth Ad Hoc Networks

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Abstract

Scatternet formation must be addressed before any ad hoc network protocol can be run over Bluetooth. This is due to the frequency hop nature and piconet unit of Bluetooth. In this paper, a protocol stack of Bluetooth group ad hoc network and a "blue-star island" network formation algorithm are proposed. The network formation locates within Bluetooth Network Encapsulation Protocol (BNEP) layer and is beneath the routing protocol. The main task of network formation is to establish and maintain Bluetooth network topology with better performance and in a fast and economic way. The routing protocol is mainly to find the best routes among the existing network topology. The network formation communicates with routing protocol and management entity using "Routing Trigger" mechanism. The "blue-star island" algorithm is a distributed 2-stages scheme. First, a group of neighbor nodes are self-organized into "blue-star island", where the joint node is slave in scatternet. Then, initiated by "Routing Trigger" from routing protocol, blue-star islands are bridged together. The "Routing trigger" can be "Route REQuest" message or "HELLO" message. The design has no assumption on number, distribution and mobility of nodes. We present discussion and simulation results that show the proposed algorithm has lower formation latency, maintain consume and generates an efficient and good quality of topology for forwarding packet.

1 Introduction

Wireless ad hoc network consisted of set of self-organizing mobile nodes. The ad hoc network provides communication between without fixed infrastructure. Bluetooth is a low-cost and low-power short range technology that will equip cell phone, laptops, digital cameral, cordless headset and so on to interconnect these devices easily and quickly without cable. Bluetooth ad hoc network enables effortless wireless connection between devices and other peripherals.

However, some Bluetooth characteristics place fundamental constraints on Bluetooth ad hoc network.[1] A slow Frequency Hop Spread Spectrum (FHSS) scheme is used at physical level and the hopping frequency covers 79 channels. The nominal hop dwell time is equal to 625μs, which is termed slot. Because no public broadcast channel of Bluetooth is defined, two Bluetooth devices cannot communicate with each other even when they are in radio range. They must be synchronization in a piconet first. The synchronization procedure, inquiry and page, is lengthy and resource waste. The basic architecture unit of Bluetooth system is piconet. The piconet is composed of a master and up to seven active slaves. The time slot is centrally allocated by master and alternatively used by master and slave. A slave can only directly communicate with its master.

Any Bluetooth device in ad hoc network has to decide whether to be a slave or a master. In addition, most Bluetooth can only support communication in limited range, i.e. 10m. When the area of Bluetooth ad hoc network is greater than 10m, a scatternet is defined in Bluetooth specification. In scatternet, a joint device is a member of at least two piconets. A slave can be slave or master in another piconet, while a master can only be slave in another piconet. The masters in a scatternet choose different hopping sequences to minimize the interference between piconets. A Bluetooth ad hoc network (scatternet) must be formed in advance. Then, the routing protocols can be run over the scatternet.

In Bluetooth Special Interest Group (SIG), the Personal Area Network (PAN) working group define group ad hoc network (GN) ability of Bluetooth.[15] The network formation algorithm is being developed. BSalonidis *et al* present Bluetooth Topology Construction Protocol (BTCP) for scatternet formation.[2] BTCP has three phases: first, a coordinator is elected with a complete knowledge of all nodes by using state alteration technique for symmetric link formation; second, the coordinator determinates the roles of each node; and third is actual connection establishment. The BTCP assumes all nodes are in radio range of each other. With the same assumption and known total nodes, Aggarwal *et al* clusters network into independent piconets.[3] After a "super-master" knowing about all nodes is elected, a re-organization process interconnects all the piconets. Inspired by research on resources discovery in general network, Law *et al* present a scatternet formation algorithm and prove its time complexity and message complexity.[4] All the nodes are partitioned into components with only one leader. A component is a set of interconnected nodes. The leader enters seek and scan state alternatively to connect, merge, mitigate or move a

Proceedings of the 36th Hawaii International Conference on System Sciences (HICSS'03)
0-7695-1874-5/03 $17.00 © 2002 IEEE

device. However, Law *et al* assume all nodes are in communication range of each other. Bluetree protocol organizes all nodes into a rooted tree where a master in a piconet is slave of another piconet.[5] In bluetree algorithm, a node must know whether it is a root node and its one hop neighbor. Tan *et al* propose Tree Scatternet Formation (TSF) with only one root and loop free path to simplified packet routing and schedule.[6] Bhagwat and Segall use routing vector method to rout traffic packet over the formed scatternet.[7] Raman *et al* argue for cross-layer optimization in scatternet.[8]

In this paper, we present a protocol stack of Bluetooth GN and a 2-stages scatternet formation algorithm. Section 2 presents Bluetooth GN scenarios and protocol stack. In section 3, the proposed "blue-star island" protocol is described in detail. The simulation is given in section 4. Finally section 5 offers the conclusions.

2 Bluetooth protocol stack

2.1 Bluetooth ad hoc network scenarios

The Bluetooth GN can be used as an extension of fixed network or network without any fixed infrastructure. The next lists several typical scenarios:

a) File share system: In a conference room without size limitation, all the attendees can view the presentation files of lecturer. The attendees can join, move and leave randomly.
b) File transfer: A node wants to forward file to one or several receivers. The locations of receiver are unknown and may be in multi-hops range.
c) Service discovery: A cell phone wants to forward file to a color printer, or a cell phone wants to send email through Access Point (AP). The two nodes are not in direct radio range of each other. Some relay nodes are needed. The former case does not need infrastructure network. The latter case connects a cell phone with the Internet.
d) Mouse+notebook+AP: The Bluetooth equipped mouse and notebook are in a piconet where the mouse is slave. The notebook and AP are in another piconet where the notebook is slave. In this case, the two piconets have no packet exchange.

Case a) denotes a node to join and leave an existing GN. Case b) and c) denotes a node initiate a multi-hop network service. Case b) includes both unicast case and multicast case. In case c), an extra service discovery is needed to find the destination node. Maybe, there are several potential destination nodes. The source nodes will select among them. Case d) shows two piconet without any data exchange.

The common things among the above Bluetooth GN scenarios are:

- No limitation on node distribution area and density.
- No limitation on the movement of nodes
- No priory knowledge on node number and distribution
- All nodes are independent and are not aware each other before connection

2.2 Some questions

In some Bluetooth profiles, not all nodes are equal. Some nodes may prefer to be either a master or a slave. For example, in Bluetooth Local Positioning, the server should be a master so as to serve more clients.[9] Here goes a question, what is the relation between upper layer profile and network formation? A Bluetooth profile is defined to provide services between source node and destination node, without or with a little consideration on performance of underplayed network.

Currently, IEEE 802.11b is widely used in the study of ad hoc network. In IEEE 802.11b ad hoc mode, any node can communicate with another as long as they are in radio range of each other because synchronization is frame by frame and there is no link setup procedure.[16] This means the network is always available. For multi-hops case, networking can be implemented by routing algorithm. There is no network formation issue. However, a Bluetooth node must join or create a piconet before any packet forwarding. Then, the question is what is the relation between network routing and network formation? The MANET routing protocols are designed for any MAC layer to forward packet from a node to another.[10] They mainly consider how many hops there are between source node and destination node. Generally, the routing protocols can be classified into two kinds: table driven routing and on demand routing. Among them, the on-demand kind of protocols establish network only when traffic comes, while the table-driven protocols monitor every movement of every node. Both of them consider the connection between any two nodes is always available whenever needed. However, a Bluetooth node must join a piconet to be either a master or a slave. The routing protocols do not say your guy should be a master and your guy should be a slave.

For example, Fig. 1 shows the scenario c), where a cell phone wants to print a mail where the printer is out of its direct radio range. For routing protocol, Fig. 1(a) and Fig. 1(b) are the same. Both of them define a 4 nodes route. But, for network formation, they are different. There are 3 piconets in Fig. 1(a), while there are only 2 piconets after node roles are changed in Fig 1(b). Generally, less number of piconet is expected for less neighbour piconet overlap, and more intra-piconet schedule.

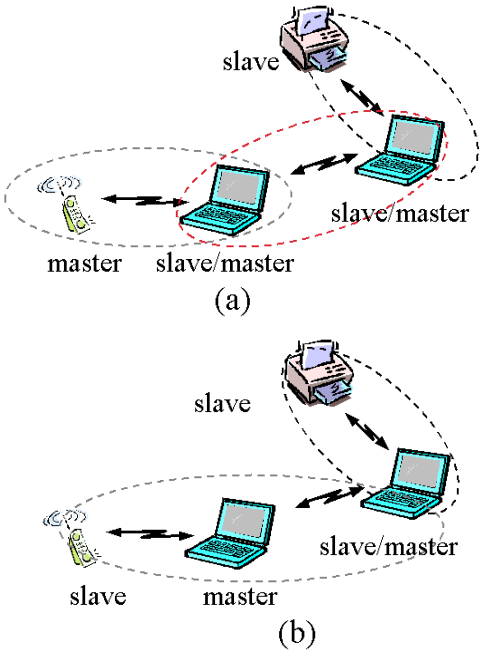

Fig. 1 Example of different Bluetooth ad hoc network configurations. (a) 3 piconets and (b) 2 piconets

For simple, the network formation is in charge of providing and maintaining not only a route, but also a 'better' route from the view point of data link layer and physical between source node and destination node. (The requirements on 'better' route are discussed in Section 4.) That is to decide when and which node is a master, a slave or which kind of joint node along the route. Maybe, there are multiple paths between two nodes, it is routing protocols' task to select a route among them.[1] The node identity (IP address allocation), route optimization, multicast, QoS guarantee etc. are done in routing protocols, too. Of course, the routing algorithms may help to establish a network.[10] This is known as "route discovery". Then, it is the network formation's job to re-organize all nodes along the selected route to make it better for Bluetooth packet forward. The routing protocol can guide the network formation.

2.3 Bluetooth protocol stack

Fig. 2(a) lists the protocol stack of 802.11, there is no network formation entity or sub-layer in 802.11 protocol stack. In the Bluetooth SIG PAN group, Bluetooth Network Encapsulation Protocol (BNEP) is being developed to provide an Ethernet like interface to IP layer.[11,12] The BNEP provides a broadcast segment across a scatternet, consisting of multiple piconets, which enables ordinary IP hosts to be interconnected in a Bluetooth scatternet. Therefore, as shown in Fig. 1(b), the network formation entity locates within the BNEP layer and is beneath the routing protocol. The solid double arrow line denotes signaling pipe which make the network formation exchange message with routing protocols and management entity. The network formation provides utility to form a network, possible multi-hops network, under the guide of routing protocol. The crucial issue is a network with "better performance" from the viewpoint of data link layer and physical layer.

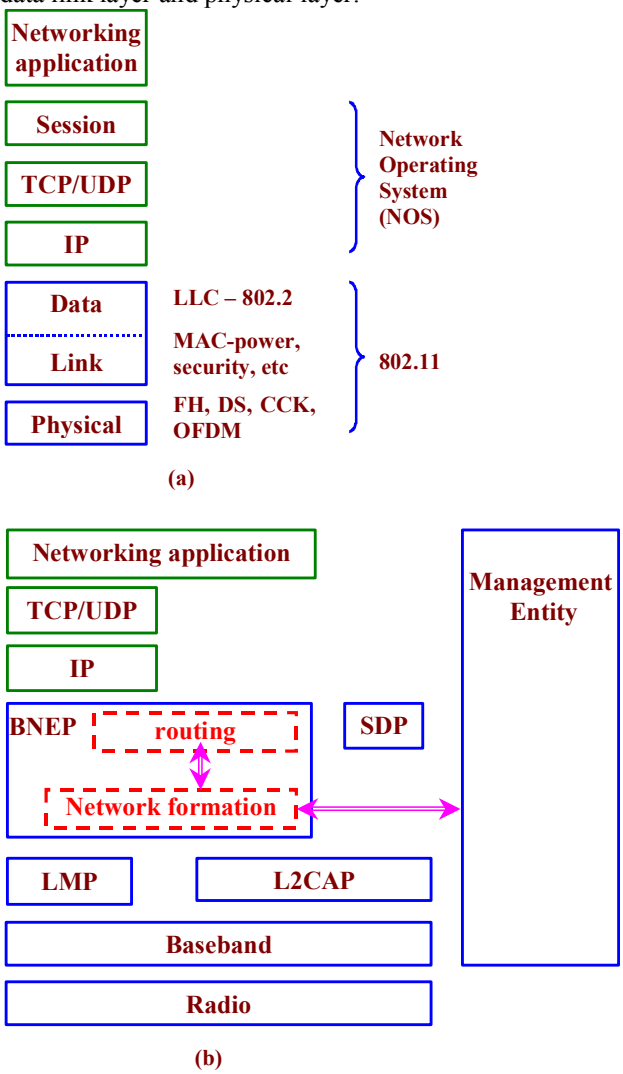

Fig. 2 (a) 802.11 and (b) Bluetooth group ad hoc network protocol stack.

Fig. 3 (see the end of paper) presents a simplified protocol stack in Bluetooth GN environment. In the case of routing protocol knows route to destination node, the data packet can be directly forwarded to the destination. In the case of routing protocol does not know route to destination node, the routing protocol inquire the below network formation

[1] Here we use different words "path" and "route". The "path" denotes all the network connections between any two nodes. The "route" denotes one of path selected by routing protocol for packet forward and acknowledgement.

layer if path to the destination node is available.[2] If the paths between source and destination are available in network formation layer, all of them are reported to routing protocol. The routing protocol selects a route among them. If the network formation protocol does not have path to destination node, it launches inquiry and page procedure through HCI message to establish a connection with new neighbour nodes. Then, the network topology information or destination node request is exchanged in the network formation layer between two new neighbour nodes. If routing protocol of the new connected node finds it is not the destination node, it becomes an intermediate node. The inquiry and page procedure is launched to find the next neighbour node. The process is repeated until the destination node is found or any other conditions stop it.

3 blue-star island network formation

In this paper, we assume the Bluetooth nodes are of SCATTER mode ability and all of them are equal and independent.[13] (Battery power, traffic load, security *et. al.* are not counted in. All of them can be considered as extra constraint conditions on the general solution.) The node preferences are as follow:

- Joint node can interconnect *M* piconets at most: this is to balance node capacity and simplify network topology.
- Node prefers to be a slave rather than a master: the reason is that there are more slaves than master in Bluetooth piconet. Also, this can help to minimize piconet number and reduce power consumption of node.
- All the node want to be connected to others.

The "blue-star island" network formation is a two-phases algorithm: "blue-star island" formation and "blue-star island" bridging. In the first phase, all nodes are self-organized into different "blue-star islands" where the joint node is slave in both piconet. Then the isolated "blue-star islands" are bridged by "Routing Trigger" to form a fully connected network.

3.1 "Blue-star island"

Without considering idle state, any Bluetooth node runs the same state machine, which transits between inquiry-scan state, inquiry state and connection state. This is shown in Fig. 4. The initial state after power on is inquiry-scan state, which the node wants to be a potential slave with probability of *Ps*. The potential slave opens inquiry scan window and waits to be connected periodically. On the contrary, a node enters inquiry state to connect another node as master with a probability of *Pm*. Note that *Ps* should be smaller than *Pm* because there are more slaves than masters. The node alternates between inquiry state and inquiry scan state to discover another node or be discovered by another node until a connection setup. The interval between two state transits is *Ti*. When a node receives an inquiry response from another node, the two nodes are connected by page procedure immediately. After joining or creating a piconet, the node transits to connection state. *Tc* describes the time a node dwell in connection state, which in turn describes traffic capacity of a node. For example, the *Tc* of a free node is 0 because it cannot be involved in any communication. The *Tc* of a master decides the throughput of a piconet.

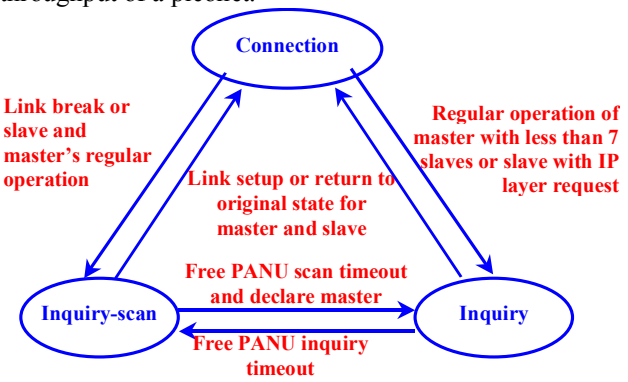

Fig. 4 Bluetooth node state transition

Each node can act four roles in scatternet. As shown in Fig. 5, they are free node, slave node, master node and joint node, respectively. In the beginning, all isolated nodes are free nodes, without any connection to others. After the first connection setup, a free node becomes either master node or slave node in a piconet. After joining a piconet, a slave node periodically enter inquiry-scan state so as to be discovered by another master node and join it to be a joint node until *M* piconet have been joined. The two piconets with a joint slave node becomes a "blue-star island". A master node enters inquiry state periodically until *Ns* slaves are connected. Besides, the master node enters inquiry-scan state periodically. This prevents two masters from being in radio range of each other. If a master node is scanned by another master node, it breaks all current links and joins the piconet as slave. All slave nodes in broken piconet become free nodes. They will join the existed piconet or create a new piconet if joining fails. None of the slaves becomes master automatically by master-slave switch. Should this become a rule, the new master can happen to be in radio range of another master. Then, a new master-slave switch has to be performed again. In this way, a local role switch may spread to the whole network. As a result, network maintenance will be dramatically increased.

[2] Because of different strategies and considerations, the network formation knows more about the network topology than the routing protocol.

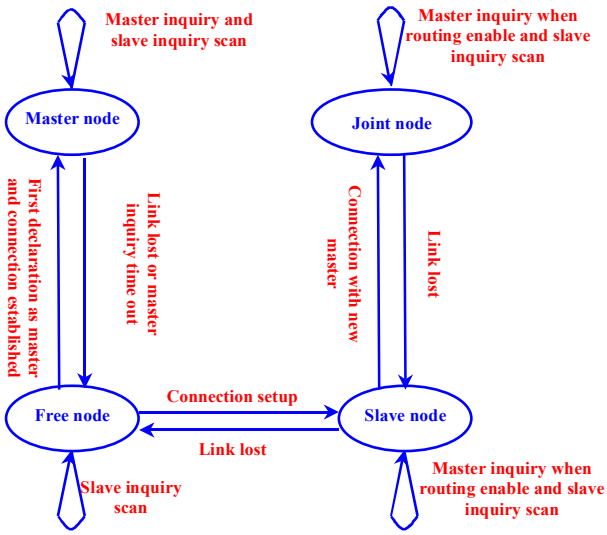

Fig.5 Bluetooth node role transition

3.2 Bridge "blue-star islands" by "Routing Trigger"

Because all Bluetooth nodes are self-organized, multiple isolated "blue-star islands" maybe formed. For example, there are 6 nodes in Fig. 6. The two nodes at left belong to a piconet, and the four nodes at right belong to another "blue-star island". However, the two neighbor "blue-star islands" cannot communicate because they are cannot be connected according to the above rules. A slave node is only to be discovered, while the discovery enabled masters are out of its radio range.

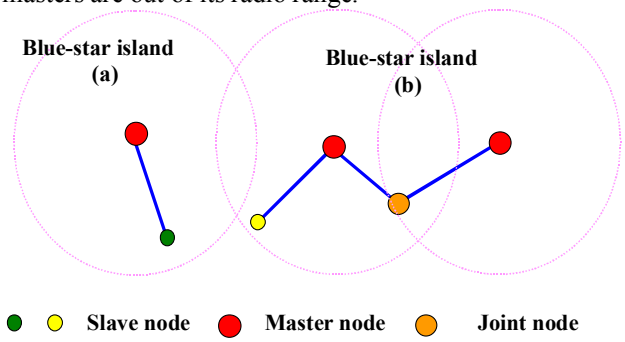

Fig. 6 two isolated "blue-star islands"

The bridging of isolated "blue-star islands" can be driven by message from routing protocol titled "Routing Trigger". The term "Routing Trigger" is borrowed from "L2 trigger" in IETF. The "L2 trigger" is "an abstraction of the notification from L2 (potentially including parameter information) that a certain event has happened or is about to happen. The trigger can be implemented in a variety of ways." Upon receiving a "Routing Trigger", the slave node performs inquiry actively to find if there are any other slave nodes in its radio range. If a new slave node is found, a new piconet will be established. Therefore, two isolated "blue-star islands" are connected. In this case, the joint node is master in a piconet and slave in another piconet.

The table driven routing protocols maintain consistent state information from each node to every other node. Each node updates its route table to other nodes periodically by flooding message. While, the on demand protocols create routes with finite lifetime only when desired by route discovery message. The "Route REQuest" (RREQ) message in on-demand protocols or "HELLO" message in both table-driven and on-demand protocols can be mapped to Bluetooth BNEP as "Routing Trigger" to initiate bridging "blue-star islands" operation. However, there are some differences between the "RREQ" message and "HELLO" message. "RREQ" message is used to find a node labeled by IP address, while "HELLO" message is used to sense if neighbour node is still available. Upon receiving a "RREQ" message from another nodes, the slave node first checks if the destination is in its reachable range. This is done by routing protocol.

- If it is yes, a "Route REPly" message from routing protocol will be generated by routing algorithm. The node sends RREP message along the backward path to source;
- If it is not, the node generates "Routing Trigger" to inform all reachable slave nodes to perform inquiry to seek the neighbour "blue-star island". [3]
- If no node response to inquiry, the node stops inquiry.
- If a node response inquiry, "RREQ" message is forwarded to the node after a BNEP connection is established between them.
- The procedure is repeated until the destination is found or the maximal hop number is reached.

In this way, the "RREQ" message is relayed by the intermediate "blue-star islands". On the country, "HELLO" message are only used to sense the neighbour nodes. No destination node is defined. Therefore, "HELLO" message can launch trigger only in source "blue-star island" without relay.

The "Routing Trigger" can also come from management entity, e.g. "service discovery" message. What is needed in many cases of ad hoc network is a service attribute. For example, in scenario c) of the first section, the node wants to access a "color printer". When a node cannot provide the specified service, it will relay the "service request" to its neighbor nodes. The node may initiate discovery process after boot-up or before it wants to communicate with others.

[3] The schedule of Slave Node inquiry should be carefully arranged, e.g. randomly. When all slave nodes perform inquiry concurrently, there may be severe ID packet collision. This makes worse performance of inquiry operation, i.e. long connection setup and waste of bandwidth.

Because of the possibility of multiple paths to a same node, the routing protocol or management entity must check if the received "Routing Trigger" is a duplicated "Routing Trigger". A duplicated "Routing Trigger" will be ignored by network formation.

3.3 Mobility consideration

The above algorithm enables Bluetooth nodes to join, move or leave the network arbitrarily. When a master node leaves a piconet or moves into radio range of another master node, all slave nodes in the broken piconet become free nodes. This localizes the role switch only in affected area. When a slave node leaves a piconet, it becomes a free node. When a joint node leaves, a "blue-star island" is divided into two "blue-star islands". The isolated "blue-star islands" will be connected until "Routing Trigger" is received.

4 Simulation

4.1 Measurement metrics

In Bluetooth ad hoc network, network formation must be run in a distributed fashion. Generally, the evaluation of a network formation algorithm includes two aspects: connectivity and communication efficiency. The metrics of connectivity measure the procedure of network establishment and maintenance, which includes

- Time complexity: The time of network convergence to a steady state where all necessary nodes for traffic are connected. It also denotes network recovery time due to the possible node movement.
- Message complexity: the number of packets sent between nodes in network establishment, maintenance and recovery. It is the power and bandwidth spent on network formation.
- Network robustness: the impact of local topology change to the total network. Any node may join and leave the network randomly. Loop free network is easy routing, however it is sensitive to movement of some key points.

A scatternet must be formed and updated as fast as possible. Slow response to network topology change will introduce extra latency of traffics packet. The proposed method makes all nodes working independently, so a fast network formation is possible. Increasing the probability of *Pm* will accelerate network convergence at expensive of more smaller "blue-star island" being formed and more node battery power is consumed. A small probability of *Tc* makes a fast response to network topology change at expensive of less network throughput. Therefore, it is also crucial to have scatternet with good quality, e.g., throughput, goodput and latency. The metrics of communication efficiency includes

- Packet latency and latency variance: This is a complex metric which is related with almost all underlying factors, including routing algorithm, intro-piconet and inter-piconet schedule algorithm, as well as the network topology.
- Network diameter: number of hops between nodes. Basically, this is also a routing metric. One of the criteria in routing algorithm is to minimize number of hops between source and destination. Generally, loop free network makes more hops between nodes because of the existence of key node.[6,10]
- Number of piconet: interference among piconets. As all piconets share the same ISM band in a local area, the less the number of piconet is, the less the packet collision probability is. Besides, the intra-piconet packet scheduling is more efficient than the inter-piconet packet scheduling.

A good balance between quality measures and complexity measures is desirable.

4.2 Simulation results

Simulation based on "Bluehoc" and "Bluescat" from IBM in ns2 network simulator is developed.[14] The simulation room size is 30m*40m. All the nodes are randomly positioned in the simulation area. Here, we only report the simulation results after the network converges to a steady state. The dynamic process of network formation to optimize parameters set, i.e. *Ns*, *Ps*, *Pm*, and *Ti* is being developed. We compare the proposed algorithm with the TSF algorithm from Tan *et. al.*. We measure the average distance (hop counts) between two nodes normalized by the optimal distance that would be possible if logical links are established to all the neighbors, the ratio of reachable nodes to all the nodes, as well as the number of links per each node.

Fig. 7 shows the average distance normalized by the optimal distance for varying number of nodes. The figure shows that TSF is more sensitive to the number of nodes. The reason is that there is only one route between any pair of nodes in TSF. Packet transmission between any nodes must reach the root node first. Fig. 8 shows the ratio of reachable nodes to all the nodes. Unreachable nodes may occur when a group of nodes is isolated beyond the radio range of any other nodes or a path is broken due to disappearance of a node. The results indicate that "blue-star island" achieves more nodes because of more paths are available. Fig. 9 shows the average number of links per node. The "blue-star island" connects more links compared to the TSF because of possible multiple routes from source node to destination node. This increases the robustness of the network.

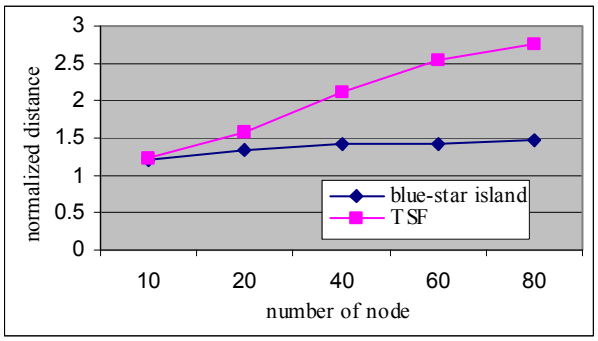

Fig. 7 Normalized distance between nodes

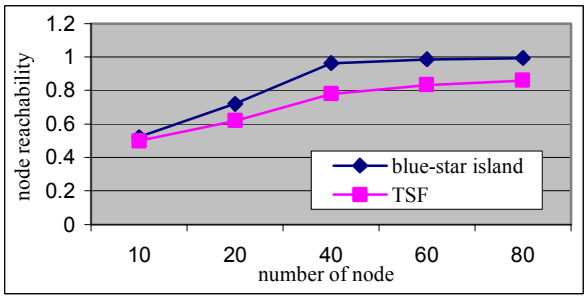

Fig. 8 Average ratio of reachable node

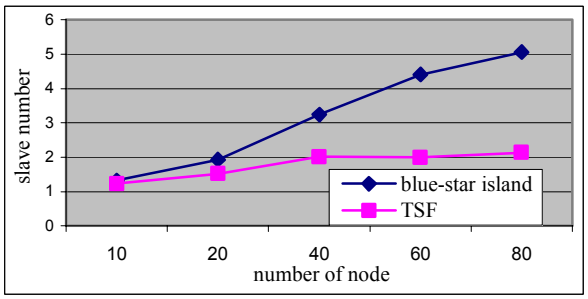

Fig. 9 Average number of slave in a piconet

5 Discussions and conclusion

The motivation of this protocol is to provide an always-ready Bluetooth GN with consideration on piconet number, batter power and network maintenance cost. The "blue-star island" network formation maintains up-to-date connection of every node in the network. The design does not need any prior information like number of node, nor does it require that all nodes be within radio range of each other. Furthermore, it updates the network topology dynamically, which enable the nodes to leave and join at arbitrary time.

Currently, most network formation algorithms are based on some kind of assumption, e.g. all nodes number and undefined symmetric link formation protocol, which is inconvenience or impossible for practical application.[2-5,7] Some algorithms even require all nodes be in radio range of each other which can only used in limited scenarios. Although TSF is not based on any prior information, a loop free tree style network structure is formed. The joint node can only be master in a piconet and slave in another piconet. The tree style structure suffers from key nodes, e.g. root nodes of the tree. All the packets have to reached root nodes in different layer first. The root nodes become bottleneck of the route. If the connection to root breaks because of movement, the entire branch has to be re-constructed. This leads to a long network convergence time. Another question is why the network should be loop free. The Internet requires the route to be loop free instead of the connection loop free. The loop free network is easier to be attacked. Beside, as shown in simulation, loop free results in larger network diameter. The third drawback is power consumption. Both the master and slave have to enter inquiry state to find new neighbours. More battery power is used.

The same as TSF algorithm, the proposed protocol has no prior assumption on node distribution. It separates routing functions from network formation function into different layers as much as possible and makes them communicate with a simple mechanism. This simplifies network formation and enables the protocol to accommodate different routing protocols and profiles. The functionalities are shared without overlap and the interface is simple.

All the slave nodes dwell in "inquiry scan" state except upon receiving "Routing Trigger" from routing protocol. This help to save the battery power of slave node.

The introduction of "blue-star island" is to minimize the piconet number. Less piconet number make less interference among piconet in a common area and more intra-piconet packet scheduling. It also provides good communication efficiency because the intra-piconet packet scheduling is more efficient than inter-piconet packet scheduling. All the nodes are self-clustered to "blue-star island" in a random way. For the same node distribution, there may be different node topologies for difference tries. The worst case is that all the "blue-star islands" are piconets. A tree style scatternet has to be formed. The best case is that all nodes aggregate in a single "blue-star island".

There is no network optimization even when all the "blue-star islands" are simple piconets. The reason is that each node only knows the local topology information without global topology information. Another reason is that network optimization may spread the local change to global change. As a result, network is fragile and lots of radio resource and capacity have to be spent on network maintenance.

The further research will focus on more simulation to verify the performance of the algorithm. The node mobility model and traffic mode should be considered to optimize the parameter set. Like the routing protocol, the network formation can also works in on-demand or reaction way. Furthermore, the "Routing Trigger" concept can also be used in the ad hoc mode of HyperLAN2 network that is connection oriented also.

In conclusion, this paper separates network formation from routing and describes a distributed 2-stages Bluetooth scatternet formation algorithm. First, a group neighbor nodes are self-organized into "blue-star island" by switching between inquiry and inquiry scan state. Then, bridging "blue-star islands" is initiated by "Routing Triggers" from routing protocol. The slave nodes perform inquiry to find slave node of neighbor "blue-star islands".

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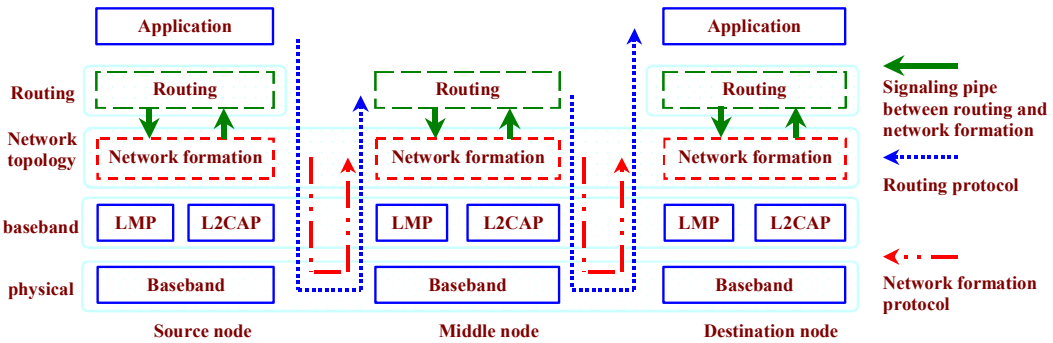

Fig. 3 A simplified Bluetooth GN protocol stack