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Semi-Distributed Scatternet Re-formation for Improving Bluetooth Network Availability

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Abstract: ***Since most of Bluetooth devices are portable and battery-driven, the mobility and residual battery energy of the devices dominate the network availability of Bluetooth scatternet. In this paper, a Semi-Distributed Scatternet Re-formation (SDSR) approach is proposed to re-construct Bluetooth scatternet to cope with device mobility and low battery energy. Firstly, a super node is responsible for collecting, in a centralized manner, the mobility and residual lifetime of each device in the Bluetooth network, and then figures out the highly available scatternet. Thereafter, the super node broadcasts the designated roles for all devices and the devices, according to their designated roles, re-form the scatternet in a distributed way to improve the network availability. The simulation study was conducted to evaluate the proposed approach. The simulation results show that the proposed approach can effectively improve the network availability of a Bluetooth scatternet with additional control overhead.***

Keywords: Bluetooth, scatternet formation, network availability, mobility.

1. Introduction

Bluetooth [1] is a short-range, low-power, wireless communication technology that can replace the cables for connecting electronic devices, such as cellular phones, laptop computers, and personal digital assistants (PADs), etc. Bluetooth devices operate in the Industrial, Scientific and Medical (ISM) band, which is globally available and unlicensed, at 2.45 GHz and use a frequency-hopping (FH) scheme to provide wireless communications among the electronic devices.

An elementary Bluetooth network called piconet consists of a master device and up to 7 active slave devices. Within a piconet, the master is responsible for scheduling the packet transmissions between the master and slaves. Most noticeably, there is no direct slave-to-slave communication, but a slave can indirectly send a packet to another slave via the master. Furthermore, several piconets can interconnect by employing the bridge devices to form a scatternet. The bridge should interchangeably play two roles, which are either master/slave or slave/slave, in the two piconets. Figure 1 illustrates a Bluetooth scatternet.

In the literature, many formation approaches for Bluetooth scatternets were proposed [2-10]. These approaches can be classified into either the centralized approach or the distributed approach. The distributed formation approach is more flexible and can construct the scatternet quickly with less control overhead. However, the centralized formation approach requires much time to form a scatternet and incur much control overhead. In contrast, the centralized formation approach could construct a scatternet with higher availability rather than the distributed approach does since the scatternet-wide device information can be gathered for constructing the scatternet.

Few existing formation approaches take the residual energy of the device's battery into account. Moreover, the masters and bridges in a scatternet would consume much power due to forwarding others' packets. Thus, when a master or a bridge uses up its battery energy, the scatternet would be partitioned and the network availability is then degraded seriously. Besides, since the device mobility is hard to be estimated before constructing the scatternet, most of the existing formation approaches do not consider device mobility [11-12], which would strongly affect the network availability [13-14].

In this study, we assume that a scatternet was formed by using any one of the existing formation approaches and each device in the scatternet has recorded its movement behavior and residual lifetime for a predefined time interval. Based on the real mobility and residual lifetime of the device, the proposed semi-distributed scatternet re-formation (SDSR) approach can adapt the scatternet to improve its network availability.

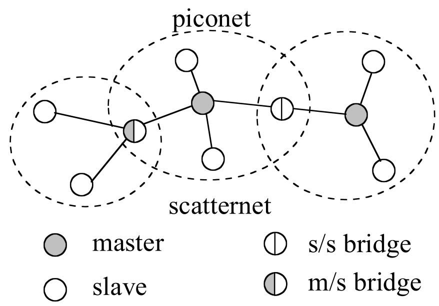

Fig. 1. Bluetooth scatternet.

The rest of this paper is organized as follows. In Section 2, we briefly discuss the related work. In Section 3, we present the proposed SDSR approach. Then, Section 4 presents the simulation study and discusses the simulation results. Finally, Section 5 concludes this paper.

2. Related Work

In this section we discuss the existing scatternet formation approaches proposed in the literature. We classified these approaches into three categories: (i) conventional scatternet formation [2-10] (ii) dynamic scatternet formation [15-17], and (iii) scatternet re-formation [18-19].

The conventional scatternet formation adopts either distributed or centralized manner to form the scatternet with the topology that is similar to the conventional network has, such as star, tree, mesh, ring, etc. Persson *et al.* addressed the criteria for scatternet formation and proposed general models of scatternet topologies in [2]. These criteria (e.g., complete scatternet connectivity, maximized aggregate bandwidth, minimized bridge switching overhead, etc.) are usually employed by researchers on developing their scatternet formation approaches, which are almost distributed. These distributed approaches include the MIT approach [4], the Bluetrees [5], Bluenet [6], MTSF [9], etc. Moreover, Salonidis, *et al.* had proposed an asynchronous distributed approach [8] that can begin with no knowledge of node's surroundings. And, Cuomo *et al.* had proposed a distributed algorithm [10] to construct the scatternet that can support QoS and variable topology. Moreover, the SF-Devil [7] is also a distributed approach that considers the device and link characteristics on forming the scatternet. In contrast, there are few centralized approaches addressed in the literature. Hodge *et al.* introduced a centralized meta-heuristic framework and genetic algorithms for forming the optimal scatternet in [3].

For the dynamic scatternet formation, nodes may arrive and leave arbitrarily, so some new issues, such as loop-free scatternet topology etc., must be dealt with on constructing the scatternet. Jayanna, *et al.* had proposed a dynamic and distributed scatternet formation protocol [15], which does not restrict the arrival and departure times of nodes and works within Bluetooth specification. And, He *et al.* presented a formation protocol [16], which works in a complete distributed fashion to build a scatternet with tree topology in a dynamic environment. Moreover, Yang *et al.* proposed a formation algorithm [17], which can deal with the single-device movement. And, they claimed that the algorithm can be easily extended to cope with the group mobility issue. In the literature, there are few works addressed the mobility of Bluetooth device. Albrecht *et al.* first addressed the mobility issue for Bluetooth in [11] and Yang *et al.* proposed a mobility model for Bluetooth devices in [12].

Though a large number of scatternet formation approaches have been proposed in the literature, a new idea about the scatternet performance was pointed out in [18-21]. The idea is that instead of constructing a scatternet to meet high performance requirements at the initialization phase, re-forming an existing scatternet to achieve the goal of high performance is more effective and realistic[18, 19]. Chang *at al.* proposed a protocol [20], which makes use of adaptive role switching to improve scatternet performance. And, Yu proposed a two-stage approach [21] to form a mesh topology for Bluetooth ad hoc networks. In this paper, we propose a SDSR approach to reconstruct an existing scatternet in a dynamic environment to improve the network availability.

3. PROPOSED SDSR APPROACH

In this section, we present the proposed semi-distributed scatternet re-formation (SDSR) approach. The operations in the proposed SDSR approach can be divided into two stages as shown in Fig. 2. The first stage is to make use of a centralized approach to gather the required information of the scatternet, which had been constructed by executing any existing scatternet formation algorithm. The required information includes network topology, node mobility and node residual lifetime. The second stage is to re-form the scatternet in a distributed manner on basis of the gathered information to improve its network availability.

First, we summarize the notations that are used in this study as follows.

S : the original scatternet
$\bar{S}$: the scatternet that is re-formed by using SDSR
k : the total number of nodes in S
SN : the super node in S
n_i : the i -th node in S
p_i : normalized residual power of n_i
m_i : mobility of n_i
t_{eval} : time interval for gathering information of S
Δt_p : factor for distinguishing the finite and the infinite lifetime
Δt_m : time tick for measuring mobility during t_{eval}
$\mathbf{TP}(S)$: topology information of S
$\mathbf{QM}(S)$: quality measurement of S
$\mathbf{T}_p$: table of normalized residual power for S
$\mathbf{T}_m$: table of mobility for S
m_{UB} : upper bound of mobility
m_{LB} : lower bound of mobility

3.1 Gathering Scatternet Information

First, we make the following assumptions for this study. (i) There exists a scatternet, which was constructed by making use of a certain scatternet formation approach. We denote this original scatternet as S. For generality, the topology of the scatternet can be irregular or regular. (ii) Suppose there is a super node (SN), which is a stationary device (e.g., the desktop workstation or PC) equipped with uninterruptable power, in the scatternet. (iii) After the scatternet S being constructed, the scatternet S has to work for a time period t_{eval}, so that the SN can collect the required information of the nodes in the scatternet. The required information includes scatternet topology, residual lifetime, and mobility of each node. The procedure of the SN collecting the required information is discussed in the below.

During the time period t_{eval}, the SN broadcasts, at every time click Δt_m, a control packet, GetPiconetState (GPS), to all masters in the scatternet. For each master receiving the GPS packet, it sends a control packet, GetNodeState (GNS), to the slaves and bridges that it connects to. Then, each of the slaves and bridges replies to the master with a control packet, ReplyNodeState (RNS), which carries its Bluetooth address, residual lifetime in minutes and connection status to the piconet. After a master collecting the topology (i.e., Bluetooth addresses and roles), residual lifetime, and connection status of each node in the piconet, the master replies a control packet, ReplyPiconetState (RPS), to the SN. The RPS packet carries the collected information of all the nodes in the piconet. Furthermore, when the SN has collected piconet states from all piconets in the scatternet, the SN can process the collected information to update $\mathbf{TP}(S)$, $\mathbf{T}_p$, and $\mathbf{T}_m$ periodically. After the last time of gathering the required information during the time period t_{eval}, the SN would finalize $\mathbf{TP}(S)$, $\mathbf{T}_p$, and $\mathbf{T}_m$. Then, based on $\mathbf{T}_p$ and $\mathbf{T}_m$, the SN can obtain the quality measurement $\mathbf{QM}(S)$, which records the quality measurement of each node in the scatternet. With $\mathbf{TP}(S)$ and $\mathbf{QM}(S)$, the SN can proceed to execute the second-phase operations. We present how the super node figures out the required information as follows.

3.1.1 Normalized Residual Power

Suppose that each node in the scatternet has a measurement of its residual lifetime. Let t_i denote the residual lifetime in minutes of node i in the scatternet. If a node i is equipped with the uninterruptable power, the value of t_i for this node is set to be infinite. Thus, the SN can calculate the normalized residual power of each node j in S according to the following Equation.

$$p_j = \begin{cases} 1, & \text{if } t_j = \infty \\ \dfrac{t_j}{\max\limits_{i \in S \wedge t_i \neq \infty}(t_i) + \Delta t_p}, & \text{otherwise} \end{cases} \quad (1)$$

where Δt_p is a factor for distinguishing the finite lifetime and infinite lifetime. So, the SN can obtain the normalized residual power $\mathbf{T}_p$ of the nodes in S, and the larger the value of p_j the much residual power the node has.

3.1.2 Complete Scatternet Topology

Since SN has received the piconet states from all masters in the scatternet. Each piconet state contains the Bluetooth addresses and the roles of the nodes in the piconet. Thus, the SN can obtain the complete scatternet topology $\mathbf{TP}(S)$ from these piconet states.

3.1.3 Mobility

Unlike the residual lifetime of a node, the mobility of a node in the scatternet is hard to be obtained instantly from the node itself. Thus, we make use of the following approach to measure the mobility of a node during the time interval t_{eval}. Initially, after receiving the first RPSs from all master nodes, the SN builds a mobility table $\mathbf{T}_m$ for all nodes in the scatternet, and the initial value of the mobility of each node is set to the upper bound m_{UB}. During the time interval of t_{eval}, each master node in the scatternet would receive a GPS from SN for each time tick. Then, the master replies a RPS to SN for each GPS received and the RPS carries the connection states of all nodes in the piconet. Thus, the SN can figure out the mobility of the nodes as follows. If the node keeps connected to the master, the SN will decrease the node's mobility by δ for each RPS. If a stationary node always connects to the scatternet, such as the desktop PC, the value of its mobility will be decreased until the lower bound m_{LB}. On the other hand, if a node i that has

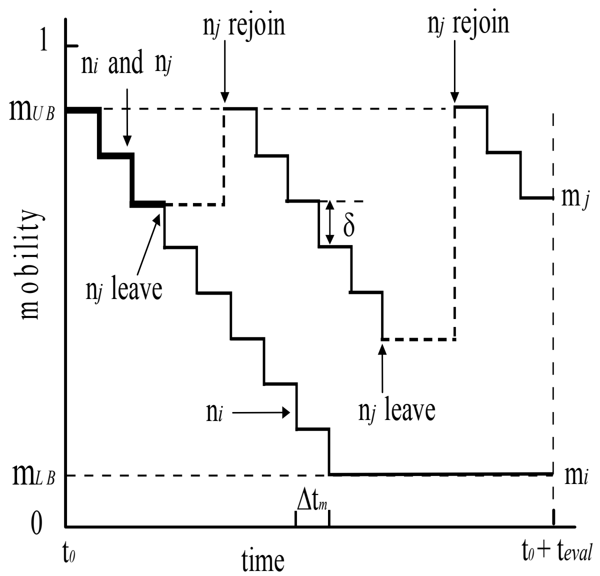

Fig. 3. Mobility measurement approach.

moved during the time period of t_{eval}, the value of its mobility (m_i) will be reset to m_{UB} when it re-joins to the scatternet. Thus, after processing the last RPSs from the masters, the mobility of the nodes $\mathbf{T}_m$ in the scatternet can be obtained. Note that the values of the m_{LB} and m_{UB} must satisfy the following Equation.

$$0 < m_{LB} < m_{UB} < 1 \quad (2)$$

And we summarize the approach of obtaining the mobility of each node in the scatternet as Equation (3). Note that $m_i(k)$ represents the mobility of n_i at the k-th time tick during the time period of t_{eval}.

$$m_i(k)=\begin{cases} m_{UB}, & \text{if } k=0 \text{ or } n_i \text{ moved out and rejoins to S} \\ \max\{m_i(k-1)-\delta,\, m_{LB}\}, & \text{if } n_i \text{ connects to } S \end{cases} \quad (3)$$

Thus, the mobility of each node in the scatternet can be obtained and the value of the mobility of any node i would satisfy $m_{LB} \le m_i \le m_{UB}$. Note that the value of δ represents the granularity of measuring the mobility of the node. To set the δ to a proper value is important for accurately distinguishing the different mobility of the nodes in the scatternet. Figure 3 illustrates the mobility measurement approach.

3.1.4 Quality Measurement of a Node

Since both the mobility and the normalized residual power of a node in the scatternet can affect the network availability, the proposed SDSR approach re-forms an existing scatternet based on a quality measurement that considers both the mobility and the normalized residual power. We define the quality measurement q_i for a node i in the scatternet as follows.

$$q_i=\sqrt{p_i\times(1-m_i)} \quad (4)$$

Thus, the quality measurement of a node represents its contribution to the network availability. In other words, a node with the larger quality measurement means that the node has much residual power for operating in a longer lifetime and the node can keep stationary with higher probability. Thus, the scatternet that includes this node to act as a master or bridge could increase its network availability.

3.2 Scatternet Re-formation

After the SN gathers the required information of the nodes in the scatternet, it will initiate a distributed scatternet re-formation to construct a highly available network. There are three phases in re-forming the scatternet. We address the operations in the three phases as follows.

3.2.1 Phase-One Operations

In the first phase SN would sort the quality measurements of the nodes in the scatternet to classify each node into either a high-quality node or a low-quality node. Suppose there are k nodes in the scatternet. SN would select $\lfloor \rho \cdot k \rfloor$ nodes that have higher quality measurements from all nodes. In general, the value of ρ is used to trade off the improved availability and the reduced connectivity. Moreover, we denote the set of high-quality nodes as N_{HQ} and the set of the low-quality nodes as N_{LQ}. Figure 4(a) illustrates an original scatternet, which is to be re-formed later. For this example, some master nodes in the original scatternet are not high-quality nodes. Thus, the scatternet availability will degrade seriously if the master node uses up its battery energy to cause network partitioned and unavailable.

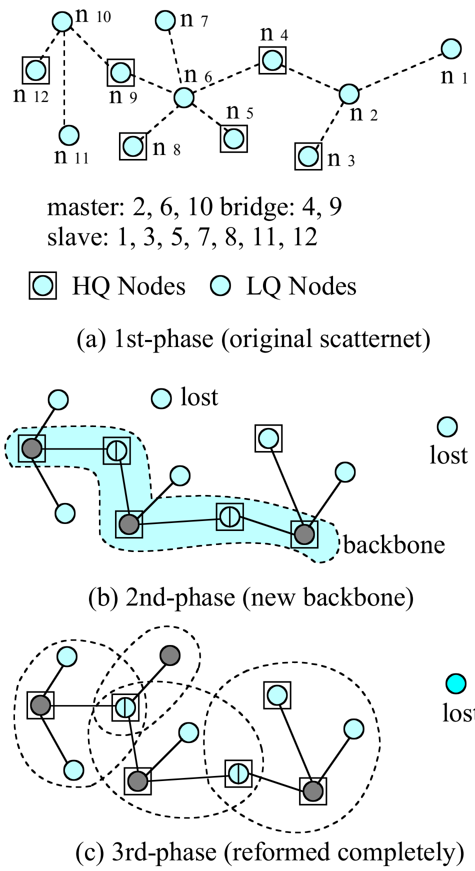

Fig. 4. Illustration of scatternet re-formation.

3.2.2 Phase-Two Operations

After classifying the nodes into N_{HQ} or N_{LQ}, SN broadcasts a control packet, Quality Measurement Notification (QMN), which indicates each node's quality measurement as either N_{HQ} or N_{LQ}. When a node that belongs to N_{HQ} receives the QMN packet, it has to reply an ACK to SN. As the SN gets the ACKs from all nodes of N_{HQ}, the SN broadcasts a ReForm Scatternet (RFS) control packet to all the nodes in the scatternet. Then, the nodes in N_{HQ} would act as either master or bridge during the re-formation, so that the backbone of the scatternet would consist of only the high-quality nodes. On the other hand, the low-quality nodes can just be invited to connect to the piconet as being a slave only. The second-phase operations are done after both the backbone is built and most of the low-quality nodes are connected to the backbone.

Note that the differences between the proposed re-formation protocol and the existing scatternet formation protocols such as [4] are to force the high-quality nodes to act as masters or bridges and to force the low-quality nodes to act as slaves. In other words, the high-quality nodes should inquire its neighbor nodes to be its bridge during the first step of the re-formation. If there are two or more high-quality nodes resided in a piconet, one of the high-quality nodes would finally be the master and the other is to be the bridge. After the high-quality nodes construct the backbone, the master nodes start inquiring the low-quality nodes, which are deferred for a while to inquiry scan their master nodes. When a high-quality master inquires and the low-quality node inquiry scans concurrently, they will match to form a master-slave pair. Thus, the scatternet can be re-formed. In Fig. 4(b), we depict the possible backbone with most of the slaves. Note that there are two slaves that cannot connect to the backbone. We address this issue in the third-phase operations.

3.2.3 Phase-Three Operations

Unfortunately, after the first- and second-phase operations, some nodes may possibly lose their connection to the newly re-formed scatternet because it is far away from the new master. Thus, the third-phase operations are required. After a time period, the lost low-quality node finally would detect that it cannot connect to the newly re-formed scatternet. So, the lost low-quality node should try to inquire its neighbor nodes, which is either a low-quality node that acts as a slave in the new scatternet or a high-quality node that acts as a bridge. In order to maintain high availability, the lost low-quality node should only play a master role and connect to the high-quality bridge node that is included in the re-formed scatternet. However, in some worse case, some node may not connect to the newly re-formed scatternet after the re-formation. This is the cost of the scatternet re-formation for achieving high network availability. Figure 4(c) illustrates the re-formed scatternet, which has a high-quality backbone to improve network availability, and one low-quality node is lost after the re-formation.

4. Simulation Study

4.1 Simulation Model

We conducted simulation experiments to elementarily evaluate the performance as well as the cost of SDSR approach. The simulation model is described as follows. (i) Suppose that all of the nodes are randomly dispersed in a square area (50x50 m^2). And the radio range of each node is a circle with the radius of 10 meters. (ii) For simplicity, the quality measure, q, of each node is randomly selected from 0.1 to 0.9. (iii) The value of ρ is set to 0.25. (iv) The value of $t_{eval}/\Delta t_m$ is assumed to be 10 for evaluating the control overhead.

The performance of SDSR approach is evaluated with respect to the following metrics: (1) r_{bn} : ratio of the number of the high quality nodes in the backbone to the number of all nodes in the backbone, (2) r_{cn} : ratio of the number of connected nodes after re-formation to the number of all nodes in the original scatternet, (3) n_{oh}, the average number of control packets incurred by the re-formation for each node in the scatternet. Moreover, the total number of the nodes, N, in the scatternet varies from 100 to 500.

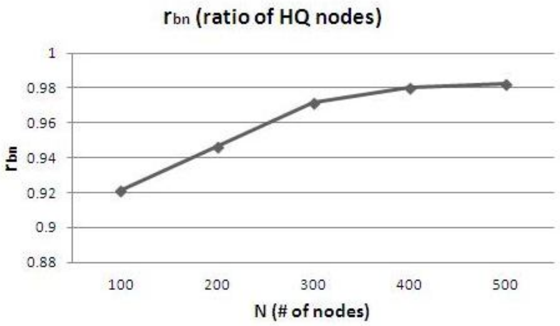

Fig. 5. The ratio of HQ nodes versus N.

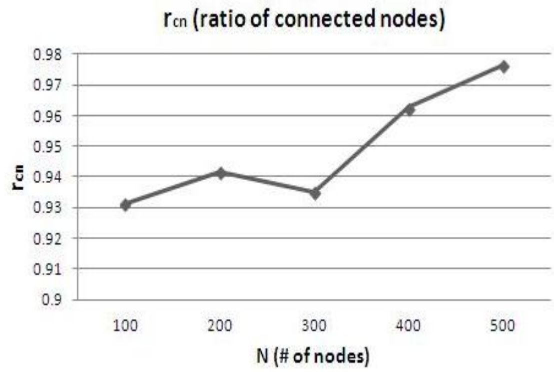

Fig. 6. The ratio of connected nodes versus N.

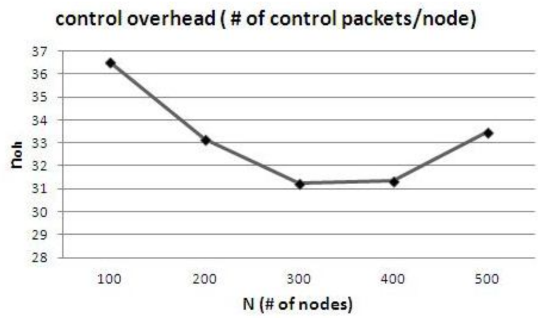

Fig. 7. The control overhead.

4.2 Simulation Results

Figure 5 shows the values of r_{bn} versus the value of N. As the total number of nodes in the scatternet increases, the value of r_{bn} increases accordingly. Though the above simulation result is obvious, the value of r_{bn} is crucial to SDSR approach and may be studied from the point of view of node density. For the two cases of low node density (i.e., $N = 100$ or 200) the values of r_{bn} are under 0.95. In other words, there are almost five percent of high quality nodes not connected to the backbone due to the topology irregularity. On the other hand, the scatternet with high node density (i.e., $N = 400$ or 500) could be re-formed by using SDSR approach to re-construct a backbone with high quality nodes (i.e., $r_{bn} \cong 0.98$). So the network availability could be improved effectively by using SDSR approach for the scatternet with high node density.

Moreover, the performance of SDSR approach can be evaluated with respect to the value of r_{cn}. As shown in

Fig. 6, the scatternet with lower node density may connect to about 94% of all nodes in the scatternet after re-formation. On the other hand, for high node density cases, the scatternet can connect to more than 96% of nodes after re-formation. Some nodes may not be connected to the newly re-formed scatternet due to the irregularity of scatternet topology. To achieve complete re-connection to the nodes in the scatternet could be studied in ongoing research, but its cost may be high. Thus the trade-off between the performance and cost of the SDSR approach is an interesting topic for further study.

The cost of SDSR approach can be evaluated with respect to another factor, control overhead (n_{oh}). Figure 7 shows the values of n_{oh} versus the values of N. The simulation result is very interesting since the value of n_{oh} decreases as the value of N increases from 100 to 300. However, the value of n_{oh} increases as the value of N increases from 400 to 500. The above result can be explained as follows. For a scatternet with low node density (i.e., N = 100 or 200) more control packets were incurred by SDSR approach, since the average distance between two nodes is larger and the broadcasting of control packets such as GPS and GNS may be lost/corrupted. Thus, more control packets are incurred by SDSR approach. On the other hand, for a scatternet with high node density (i.e., N = 500) the control packets incurred by SDSR approach are more than the case of N = 300 or 400, since the average distance between two nodes is short and the transmission of control packets such as RPS and RNS may be collided with the transmission of RPS and RNS sent from neighbor piconet. Fortunately, such transmission collision is less than the re-broadcasting of the GPS and GNS, so that the control overhead of SDSR approach for the high node-density case is less than that of the low node-density case.

5. Conclusions

In this paper a semi-distributed scatternet re-formation (SDSR) approach was proposed and evaluated. The operations of SDSR approach is divided into two stages. For the first stage, it makes use of a centralized approach to gather the required information, i.e., network topology, node mobility and node residual lifetime, of a scatternet, which had been constructed by using any one of the existing scatternet formation approaches. During the second stage, the scatternet is re-formed in a distributed manner on basis of the gathered information, so that the network availability can be improved effectively. The methods to obtain and normalize the residual power of each node as well as to measure the mobility of a node were proposed, and then the quality measurement of each node in the scatternet can be further derived from the normalized residual power and the mobility. Finally, with some proposed control packets the scatternet can be re-formed through three-phase operations. To evaluate the performance and cost of the proposed approach, some simulation experiments were conducted, and the simulation results show that: (i) Network availability could be improved effectively by using SDSR approach for the scatternet with high node density. (ii) For the high and low node-density cases, the scatternet can connect to more than 94% of nodes after re-formation. (3) For a scatternet with low node density more control packets were incurred due to the lost/corrupted control packets. On the other hand, for a scatternet with high node density more control packets are required due to transmission collision. Finally, the trade-off between performance and cost of the SDSR approach is an interesting topic for further study.

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