MATR: A Mobility-Aware Topology Restructuring Scheme for Bluetooth Body Area Networks

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Abstract

Bluetooth low energy technology has gradually penetrated into people's daily life. Nowadays, a number of wearable devices which are embedded with tiny sensors and Bluetooth radio can create a Bluetooth body area networks (BANs). Because of human mobility, the signal strength of Bluetooth links might be decreased with the link distance, increasing the transmission delay and hence dropping the network throughputs. Considering the mobility issue, this paper presents a mobility-aware topology restructuring scheme, called *MATR*, for Bluetooth body area networks. The proposed *MATR* mechanism changes the piconet topology for redirecting the traffic flow to the links with better quality. In addition, the proposed mechanism is also extended to restructure the topology of a scatternet, further reducing the transmission delay of link connecting different Piconets. Performance study reveals that the proposed *MATR* approaches further reduce the transmission delay and the energy consumption for Bluetooth BANs, decrease the network overheads raised by packet retransmissions, and improve the network throughput of Bluetooth radio area networks.

Keywords: Mobility, Transmission delay, Wearable, BANs

1 Introduction

Bluetooth is a wireless communication technology, characterized by short-range, low-cost, low power, and operated on 2.4 GHz industrial scientific medical band. Bluetooth Low Energy (BLE) has been an example of the current trend to portability, and is described in the Bluetooth 4.0 standard [1], which enables communication at dramatically lower energy consumption than the classic Bluetooth. With the published Bluetooth 4.0 standard, Bluetooth low energy technology has gradually penetrated into people's daily life. Recently, Bluetooth 4.0 has been supported by more and more released tablets and smartphones. The released tablets and smartphones are prepared for communication with BLE devices, and also known as Bluetooth SMART READY devices [2].

A number of devices, including bracelets, glasses, shoes as well as watch, have been embedded with sensor and Bluetooth radio, becoming smart wearable devices as found in commercial products. The tiny sensors collect behavior or physiology data and then transmit them to Internet using Bluetooth low energy consumption technology, aiming to improve the throughput or conserve energy of the batteries (also known as Bluetooth SMART) [3-6]. In Bluetooth radio networks, a piconet is the basic networking unit within a distance of approximately 10 meters where contains one master and the other devices are slaves. Two or more piconets may form a larger Bluetooth network, called scatternet. A connecting common device which is responsible to adjacent piconets in a scatternet is called as gateway or bridge [7-9]. These Bluetooth devices are possible moved from one place to another place. Since the signal strength is decreased with the distance between two Bluetooth devices which have constructed a link in piconet, the decreasing of link quality can drop the link throughput and hence increase the transmission delay. To maintain the link quality and a good piconet topology has become a big challenge when considering the mobility in Bluetooth personal area networks.

In literature, many studies have addressed the problems of adjacent channel and co-channel interference in Bluetooth network [10]. However, more efforts are still needed for reducing interference or even elimination when considering Bluetooth body area network mobility.

A well-structured scatternet has several good properties, such as the proper number of gateways, the appropriate number of piconets, and each device playing its suitable role. Recently, much work is aiming at [11-17] proposing the scatternet formation protocols for constructing a connected scatternet. Most scatternet formation protocols have sought to reduce

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the scatternet formation time or increase the probability of constructing a connected scatternet and adaptive role switching protocol for improving scatternet performance. However, most of them don't consider how to restructure a piconet dynamically when the Bluetooth mobility is introduced. Since most wearable devices are embedded with Bluetooth chips and they can form a Bluetooth body network, the mobility caused by human can occur frequently, raising the requirement of dynamically reconstructing the piconet structure.

A novel Bluetooth topology restructuring mechanism that changes the piconet and scatternet topologies for improving the transmission delay by considering the mobility of Bluetooth body area networks is presented in this paper. The contributions of the paper are itemized as follows:

Reducing the transmission delay for Bluetooth networks. By evaluating the link quality, the proposed mechanism restructures the piconet and scatternet topologies, aiming to eliminate the weak links. Hence the transmission delay can be reduced.

Reducing the network overheads raised by packet transmissions. This paper proposes a Mobility Aware Topology Restructuring mechanism (*MATR*), which uses the role switching operations following Bluetooth standard to restructure the piconet and scatternet topology. The reconstructed Bluetooth network reduces the phenomenon of packet retransmission and hence substantially reduces the network overheads.

Reducing the energy consumption for Bluetooth networks. The time and energy costs of packet retransmissions are improved because of the improvement of success rate of packet transmission. Consequently, the energy consumptions of Bluetooth devices will be saved.

The remainder part of this paper is organized as follows. Section II gives the notation list and network environment, and formulates the problem investigated in this paper while Section III elaborates the proposed *MATR* mechanism. Section IV presents the simulation experiments results of the proposed mechanism. Finally, Section V offers a conclusion.

2 Network Environment and Problem Statement

To achieve the readability, a set of notations which are used in this paper are listed in Table 1.

2.1 Network Environment

This section presents the assumptions and the problem formulations of the investigate issue. Let H denote the set of Bluetooth channels. Let $A=\{a_1,a_2,...,a_{|A|}\}$ denote a set of Bluetooth devices which are existing in the considered network environment. Every device a_1 is embedded with a single half-duplex antenna, which allows either sending or receiving data at the same time. In addition, every device has a unique 48-bit MAC address. After executing the connection process, the master device is aware of the MAC addresses of all slave devices, and each slave device is also aware of the MAC address of the master device.

Let $C_{i,j}$ denote the achievable channel capacity between devices a_i and a_j. Based on the Shannon theorem, Eq. (1) presents the channel capacity, where B, $\rho_{i,j}$ and $\varphi_{i,j}$ represent the link bandwidth, average received signal strength, and average noise strength between devices a_i and a_j, respectively.

$$C_{i,j}=B\times\log\left(1+\frac{\rho_{i,j}}{\varphi_{i,j}}\right),\forall a_i,a_j\in A. \quad \textbf{(1)}$$

Let l_{data} denote the average size of each Bluetooth packet. The propagation delay of the packet transmitted from device a_i to a_j, denoted by $\beta_{i,j}$, is calculated using Eq. (2).

$$\beta_{i,j}=\frac{l_{data}}{C_{i,j}},\forall a_i,a_j\in A. \quad \textbf{(2)}$$

2.2 Problem Formulation

This paper aims to dynamically reconstruct the scatternet topology. Let T denote a time period, and T consists of q time segments $T=\{T_1, T_2, \ldots, T_q\}$. Let $S(t)$ denote the scatternet topology in time segment T_t. The expected number of retransmission times for device a_i successfully to transmit one packet to its master a_j, denoted by $k_{i,j}^{S(t)}$, is depending on the bit error rate $e_{i,j}^{S(t)}$ under $S(t)$. The value of $k_{i,j}^{S(t)}$ can be calculated using Eq. (3).

$$k_{i,j}^{S(t)}=\frac{1}{1-(1-e_{i,j}^{S(t)})^{l_{data}}},\forall a_i,a_j\in A. \quad \textbf{(3)}$$

Let $d_{i,j}^{S(t)}$ denote the delay time of device a_i successfully transmitting one packet to its master a_j. Let t_{re} denote the time duration between the time where the packet is failed to transmission and the time where it starts the retransmitted. The value of $d_{i,j}^{S(t)}$ can be calculated using Eq. (4).

$$d_{i,j}^{S(t)}=k_{i,j}^{S(t)}(\beta_{i,j}+t_{re}),\forall a_i,a_j\in A. \quad \textbf{(4)}$$

Let $H_i^{S(t)}$ denote the routing path from a_i to the gateway. The delay time of device a_i successfully

Table 1. Notation list

Notation	Definition
H	The set of Bluetooth channels
A	A set of Bluetooth devices, $A=\{a_1, a_2, ..., a_{\lvert A \rvert}\}$
$C_{i,j}$	The achievable channel capacity between devices a_i and a_j
B, $\rho_{i,j}$, $\varphi_{i,j}$	The link bandwidth, average received signal strength, and average noise strength between devices a_i and a_j, respectively
l_{data}	The average size of each Bluetooth packet
$\beta_{i,j}$	The propagation delay of the packet transmitted from device a_i to a_j
T	The q time segments $\{T_1, T_2, \ldots, T_q\}$
$S(t)$	The scatternet topology in time segment T_t
$k_{i,j}^{S(t)}$	The expected number of retransmission times for device a_i successfully to transmit one packet to its master a_j
$e_{i,j}^{S(t)}$	The bit error rate under $S(t)$
$d_{i,j}^{S(t)}$	The delay time of device a_i successfully transmitting one packet to its master a_j
$H_i^{S(t)}$	The routing path from a_i to the gateway
t_{re}	The time duration between the time where the packet is failed to transmission and the time where it starts the retransmitted
$\delta_i^{S(t)}$	The delay time of device a_i successfully transmitting one packet to the gateway via multi-hop communication
$\gamma_i^{t,x}$	The Boolean variable indicating whether device a_i stays on channel x at time t
$i_{sending}^t$	The Boolean variable indicating whether device a_i is sending data at time t
$i_{receiving}^t$	The Boolean variable indicating whether device a_i is receiving data at time t
$i_{idlelistenging}^t$	The Boolean variable indicating whether device a_i is idle listening data at time t
$i_{Master}^{S(t)}$	A Boolean variable indicating whether device a_j is master in $S(t)$
$i_{slave}^{S(t)}$	A Boolean variable indicating whether device a_j is slave in $S(t)$
$i_{Bridge}^{S(t)}$	A Boolean variable indicating whether device a_j is master/slave bridge in $S(t)$
i_{even}^t	A Boolean variable indicating whether device a_j send packet initially at even time t
i_{odd}^t	A Boolean variable indicating whether device a_i send packet initially at odd time t
ρ_θ	The threshold of Bluetooth signal strength
$T_{i,j}^k$	The transmission delay time of a packet from device a_i to device a_j where a_k plays a master role
$l_{i,j}$, $\lvert l_{i,j} \rvert$	A path from device a_i to device a_j with the length $\lvert l_{i,j} \rvert$
$SNR_{i,j}$	Signal-noise radio
$f_{i,j}^1$, $f_{i,j}^2$	Two flow data volumes from slave a_i to master a_k and from master a_k to slave a_j, respectively
T_k	The total transmission delay time of master a_k
γ_k	Piconet restructuring benefit of master a_k
a_{net}^g	The gateway that supports Internet access
N_k	A set of Bluetooth devices neighboring to the master a_k, $N_k=\{a_{k,1}, a_{k,2}, ..., a_{k,q}\}$
$A_{k,i}$	The set of routers from neighboring device $a_{k,i}$ to the Internet gateway $a_{Internet}^g$, $A_{k,i}=\{a_{k,i,1}, a_{k,i,2}, ..., a_{k,i,h}\}$
$T_{k,i,net}$	Total transmission delay of the packets transmitted from device a_k to the neighboring device $a_{k,i}$ and then from $a_{k,i}$ to the Internet gateway a_{net}^g

transmitting one packet to the gateway via multi-hop communication, denoted by $\delta_i^{S(t)}$, is calculated using Eq. (5).

$$\delta_i^{S(t)} = d_{ij}^{S(t)} \sum_{a_u \in H_i^{S(t)}} d_{uv}^{S(t)}), \forall a_i, a_j, a_u, a_v \in A. \quad \textbf{(5)}$$

The following expresses the purposes and constraints for completing an efficient Bluetooth scatternet reconstruction method.

Objective Function

$$Minimize \sum_{t=1}^{q} \max_{a_i \in A} \delta_i^{S(t)} \quad \textbf{(6)}$$

Subject to:

Channel Constraint.

$$\sum_{x \in H} \gamma_i^{t,x} = 1, \forall a_i \in A, \text{ where}$$

$$\gamma_i^{t,x} = \begin{cases} 1, \text{if device } a_i \text{ stays on channel } \chi \text{ at time } t \\ 0 \qquad\qquad\qquad\qquad , \text{otherwise} \end{cases}. \quad \textbf{(7)}$$

Antenna Constraint.

$$i_{senging}^{t} + i_{receiving}^{t} + i_{idle_{listening}}^{t} = 1, \forall a_i \in A, \text{where}$$

$$i_{sending}^{t} = \begin{cases} 1, \text{if device } a_i \text{ is sending data at time } t \\ 0 \qquad\qquad\qquad , \text{otherwise} \end{cases},$$

$$i_{receiving}^{t} = \begin{cases} 1, \text{if device } a_i \text{ is receiving data at time } t \\ 0 \qquad\qquad\qquad , \text{otherwise} \end{cases}, \quad \textbf{(8)}$$

$$i_{idle\_listening}^{t} = \begin{cases} 1, \text{if device } a_i \text{ is idle listening at time } t \\ 0 \qquad\qquad\qquad , \text{otherwise} \end{cases}.$$

Role Constraint.

$$i_{Master}^{S(t)} + i_{Slave}^{S(t)} + i_{Bridge}^{S(t)} = 1, \forall a_i \in A, \text{where}$$

$$i_{Master}^{S(t)} = \begin{cases} 1, \text{if device } a_i \text{ is master in } S(t) \\ 0 \qquad\qquad\qquad , \text{otherwise} \end{cases},$$

$$i_{Slave}^{S(t)} = \begin{cases} 1, \text{if device } a_i \text{ is master in } S(t) \\ 0 \qquad\qquad\qquad , \text{otherwise} \end{cases}, \quad \textbf{(9)}$$

$$i_{Bridge}^{S(t)} = \begin{cases} 1, \text{if device } a_i \text{ is master/slave bridge in } S(t) \\ 0 \qquad\qquad\qquad , \text{otherwise} \end{cases}.$$

Direction Constraint.

$$i_{MtoS}^{t} + i_{MtoM}^{t} = 1, \forall a_i \in A, \text{where}$$

$$i_{MtoS}^{t} = \left(i_{Master}^{S(t)} \wedge i_{even}^{t}\right) \vee \left(i_{Master}^{S(t)} \wedge i_{idle_{listening}}^{t}\right),$$

$$i_{StoM}^{t} = \left(i_{Slave}^{S(t)} \wedge i_{odd}^{t}\right) \vee \left(i_{Slave}^{S(t)} \wedge i_{idle_{listening}}^{t}\right), \quad \textbf{(10)}$$

$$i_{even}^{t} = \begin{cases} 1, \text{if device } a_i \text{ send packet initially at even time } t \\ 0 \qquad\qquad\qquad , \text{otherwise} \end{cases},$$

$$i_{odd}^{t} = \begin{cases} 1, \text{if device } a_i \text{ send packet initially at odd time } t \\ 0 \qquad\qquad\qquad , \text{otherwise} \end{cases},$$

The objective of this paper is presented in Exp. (6), which aims to minimize the maximum end-to-end delay for improving Bluetooth scatternet efficiency.

According to abovementioned, each device is embedded with a single half-duplex antenna, Exp. (7) presents the *channel constraint*, which constrains that each device can only stay on one of the C channels at time point t. Based on radio characteristics, Exp. (8) presents the *antenna constraint*, which further constrains that each device can only *send*, *receive*, or *idle listen* packet at time point t.

The role constraint is identified in Exp. (9) that each device can only be *master*, *slave*, or *bridge* in any scatternet topology $S(t)$. Exp. (10) presents the *direction constraint*, which allows the *master* and slave can only transmitting packet in even and odd slots, respectively.

This section presents the proposed Bluetooth scatternet reconstruction protocol which aims to achieve the objective given in Exp. (6) while satisfying constraints (7)-(10).

3 Mobility Aware Topology Restructuring (*MATR*) Mechanism

In Bluetooth network, before data transmitting, the Bluetooth devices need to establish a piconet network which consists of a master and several active slaves. As shown in Figure 1, there are four piconets, represented by p_1, p_2, p_3 and p_4, respectively. A person wear Smart Shoes, bracelets, leather belt and smartphone and these Bluetooth devices have constructed piconet p_1. The piconet p_2 contains gloves, watch and smartphone. Another set of Bluetooth devices, including Smart glasses, ECG sensor, Smart Shoes and smartphone have also constructed p_3. In piconets p_1, p_2 and p_3, the smartphone plays a master role. In addition, piconet p_4 consists of the smartphones of p_1 and p_2, sphygmomanometer, fat scale as well as gateway. The gateway plays a master role and supports the Internet access for all Bluetooth devices in the four piconets. The four piconets have established a Bluetooth scatternet.

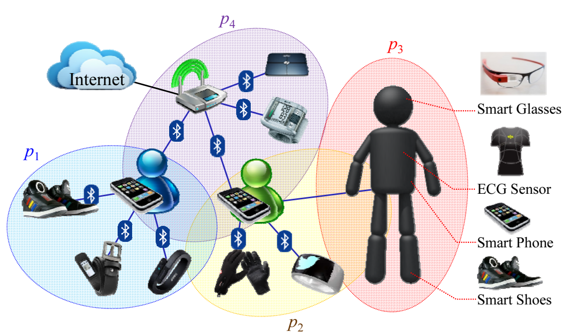


Figure 1. The considered scenario of Bluetooth body area networks

Figure 2 represents the same scatternet as shown in Figure 1. As shown in Figure 2, notations a_i $(1 \le i \le 14)$, denote the Bluetooth devices. The gateway is responsible for getting Bluetooth devices' data, passing and storing the data to the Internet.

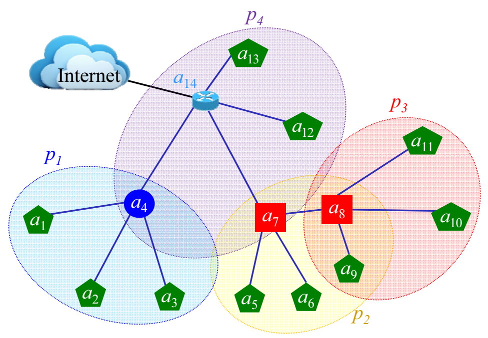


Figure 2. An example of the considered Bluetooth scatternets

3.1 Piconet Topology Restructuring

Since piconet p_1 is a body network constructed by four Bluetooth devices, the human mobility can lead to the situation that the body area network p_1 moves along south direction. And the master a_4 is far away from the gateway a_{14} as shown in Figure 3. Consequently, the quality of link connecting device a_4 and gateway becomes weak, which increase the transmission delay of each packet. As a result, all the other Bluetooth devices in piconet p_1 will spend more time to transmit data to gateway. To improve the transmission delay of a piconet, this paper aims to reorganize the piconet dynamically, choosing a proper device playing the master role. To achieve this, the master should collect the signal strengths of all links to which it connects and the traffic demands of the corresponding Bluetooth devices.

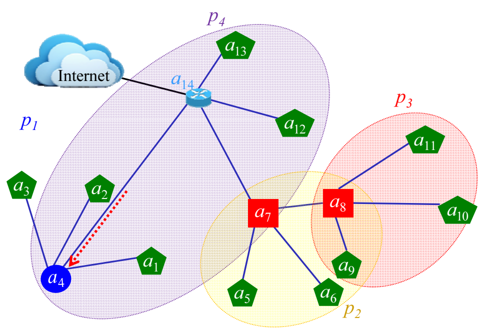


Figure 3. The body area network p_1 moves along south direction

If the master moves far away from the gateway, the transmission rate will be decreased, and hence the delay time will be increased. To handle this situation, master might change the piconet topology to improve the network performance. The following describes the operations designed in this paper. Assume that the considered piconet P consists of n Bluetooth devices, represented by $P=(a_1, a_2, ..., a_n)$, where the device a_k plays the master role and the gateway is denoted as $a_g = (g \notin \{1, 2, ..., n\})$. Let $\rho_{i,j}$ denote the Bluetooth signal strength of device a_i received from device a_j. The value of $\rho_{i,i}$ should be zero where the signal strength RSSI is strongest, because the Bluetooth signal strength is negative. Let ρ_θ denote the threshold of Bluetooth signal strength. If the master a_k moved, it should exam if the condition $\rho_{k,g} \le \rho_\theta$ holds. If it is the case, master a_k will initiate the evaluation phase. On the contrary, the master a_k will not be replaced.

The evaluation phase is responsible for choosing a proper slave to play the master role. The selection of slave for playing the new master role must consider two factors, the total transmission delay and the Bluetooth signal strength between the selected slave in piconet P and the gateway. First, according to the Bluetooth Spec. [1], a slave can only transmit packets to the master and not allow to establish a direct communication link between slaves. As a result, the source slave should firstly transmit the packets to master, and then the master subsequently relays the packets to the destination slave. As a result, the change of master might cause that the change of the total transmission delay time in the piconet. In addition to the Bluetooth signal strength factor, the benefit of the master will be weak dramatically when the master moves away from the gateway. The old master should be replaced by the slave who has a stronger Bluetooth signal strength from the gateway.

According to the abovementioned two factors, the evaluation phase aims to choose a proper slave playing a new master to reconstruct an optimal topology. To achieve this, the master should evaluate the best benefit of piconet restructuring and determine the best slave to play a new master. Consequently, if the evaluation benefit of the new master is better than the old one, the role switching phase will be started. On the contrary, the master will not be changed. The calculation procedure of the benefit is presented as follows.

Let $T^k_{i,j}$ denote the transmission delay time of a packet from device a_i to device a_j in piconet P, where a_k plays a master role. The value of $T^k_{i,j}$ is zero. Let $l_{i,j}$ denote the path from device a_i to device a_j in piconet P and $|l_{i,j}|$ denote its path length. If a_i and a_j are slaves, we have $|l_{i,j}|=2$ since the packets should be relayed by the master a_k. Otherwise, if one of a_i or a_j is a master, we have $|l_{i,j}|=1$. Let $C_{i,j}$ denote the channel capacity from device a_i to device a_j. The value of $C_{i,i}$ is zero. Let B denote the bandwidth.

According to the Shannon Theorem

$$C_{i,j} = B * \log_2(1+(S/N)_{i,j}) \quad \textbf{(11)}$$

Let $SNR_{i,j}$ denote signal-noise radio. The value of

$(S/N)_{i,j}$ can be obtained by Exp. (12) [18]

$$(S/N)_{i,j} = 10^{SNR_{i,j}/10} \quad \textbf{(12)}$$

Let $f_{i,j}^1$ and $f_{i,j}^2$ denote the flow data volume from a_i to a_k and then from a_k to a_j, respectively. Let $C_{i,j}^1$ and $C_{i,j}^2$ denote the channel capacity from a_i to a_k and from a_k to a_j, respectively. The value of $f_{i,i}^k$ should be zero. The transmission delay time $T_{i,j}^k$ can be obtained by applying Exp. (13),

$$T_{i,j}^k = f_{i,j}^1 / C_{i,j}^1 + \xi\, f_{i,j}^2 / C_{i,j}^2 \quad \textbf{(13)}$$

where ξ denotes a Boolean available, representing whether or not the Bluetooth device a_i or a_j is a master. That is

$$\xi = \begin{cases} 0, \text{if one of } a_i \text{ and } a_j \text{ is a master} \\ 1, \qquad\qquad\qquad\quad \text{,otherwise} \end{cases}. \quad \textbf{(14)}$$

Let T_k denote the total transmission delay time of master a_k. We have

$$T_k = \sum_{\forall l_{i,j}} T_{i,j}^k \quad \textbf{(15)}$$

Therefore, the restructuring benefit γ^k can be calculated by Exp. (15).

$$\gamma^k = 1 - \frac{T_k}{T_{old_{master}}}. \quad \textbf{(16)}$$

According to Exp. (16), the best restructuring benefit of the new master in piconet *P* should be

$$a_{new_{master}} = arg \max_{1 \le k \le n} \gamma^k \quad \textbf{(17)}$$

If $a_{new_{master}}$ is as same as the old master, the evaluation phase will be finished and the master will not be changed. On the contrary, the role switching phase will be started.

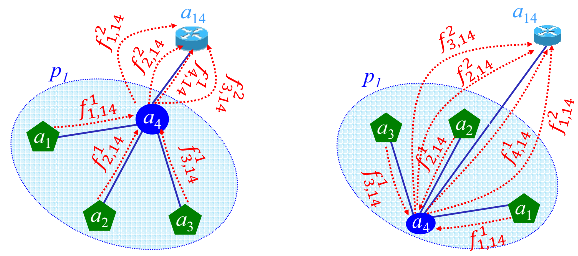
To facilitate the details of abovementioned operations, an example shown in Figure 4 is used throughout this section. We assume that device a_4 plays the master role, bridging all packets exchanges among slaves a_1, a_2 and a_3, and collecting all packets to/from gateway a_{14} as shown in Figure 4(a). As shown in Figure 4(b), the master a_4 moves far away from gateway a_{14}. Suppose there are four flows:

Flow 1(from a_1 to a_{14}): $l_{1,14}$ contains ${f_{1,14}}^1$ and ${f_{1,14}}^2$.

Flow 2(from a_2 to a_{14}): $l_{2,14}$ contains ${f_{2,14}}^1$ and ${f_{2,14}}^2$.

Flow 3(from a_3 to a_{14}): $l_{3,14}$ contains ${f_{3,14}}^1$ and ${f_{3,14}}^2$.

Flow 1(from a_4 to a_{14}): $l_{4,14}$ contains ${f_{4,14}}^1$.



(a) Before the master a_4 moving (b) After the master a_4 moving

Figure 4. Example of the evaluation phase

The four flows are with the flow data volume 12, 13, 10 and 15, respectively, as shown in Table 2.

Table 2. Flow data volume

Flow path	$l_{1,14}$	$l_{2,14}$	$l_{3,14}$	$l_{4,14}$
Flow data volume	12	13	10	15

Assume that the value of $SNR_{i,j}$ is given in Table 3. According Exp. (11), the channel capacity of $C_{i,j}$ is calculated in Table 4.

Table 3. Signal-noise ratio

$SNR_{i,j}$	a_1	a_2	a_3	a_4	a_{14}
a_1	—	45	47	21	31
a_2	45	—	48	19	36
a_3	47	48	—	20	30
a_4	21	19	20	—	10
a_{14}	31	36	30	10	—

Table 4. The value of Channel capacity

$C_{i,j}$	a_1	a_2	a_3	a_4	a_{14}
a_1	—	14.9	15.6	7	10.3
a_2	14.9	—	15.9	6.3	12
a_3	15.6	15.9	—	6.6	10
a_4	7	6.3	6.6	—	3.5
a_{14}	10.3	12	10	3.5	—

According to Exp. (15), the total transmission delay times of all devices in piconet p_1 are calculated as follows.

$T_1 = 8.51$
$T_2 = 7.98$
$T_3 = 8.85$
$T_4 = 19.58$

According to Exp. (16), the restructuring benefit of devices in piconet p_1 are calculated as follows.

$\gamma^1 = 1 - T_1/T_4 = 1 - 8.51/19.58 = 0.57$

$\gamma^2 = 1 - T_2/T_4 = 1 - 7.98/19.58 = 0.59$

$\gamma^3 = 1 - T_3/T_4 = 1 - 8.85/19.58 = 0.55$

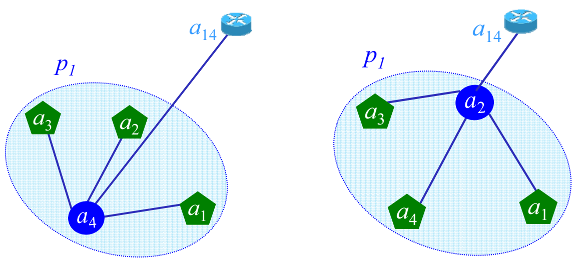
$\gamma^4 = 1 - T_4/T_4 = 1 - 19.58/19.58 = 0$

As a result, according to Exp. (17), the new master can be derived by

$$a_{new_{master}} = arg \max_{1 \le k \le 4} \gamma^k = a_2$$

Since device a_2 has the largest benefit, the old master a_4 executes the following role switching phase.

This section uses Figure 5 as an example to illustrate the operations designed in the role switching phase. As shown in Figure 5(a), device a_4 plays the master role and bridges all packet exchanges among slaves a_1, a_2 and a_3. According to the evaluation phase, device a_2 has the maximal restructuring benefit in piconet p_1. Therefore, it will be selected to play the master role in the new piconet. The old master a_4 initiates the execution of role switching phase. The process of role switching phase is presented as following.



(a) Before executing role switching (b) After executing role switching

Figur 5. Example of the role switching phase

Firstly, the old master a_4 broadcasts a control message (*CTL_MSG*) to slaves a_1, a_2 and a_3, aiming to reserve sufficient time slots for executing role switching operations. Then the old master a_4 notifies the new master a_2. Upon receiving *CTL_MSG*, each slave which isn't the new master a_2 responses an acknowledgement message to the old master a_4. Then the new master a_2 initiates a role switching request to the old master a_4. After that, the old master a_4 replies the role switching response back to the new mater a_2. Using the old hopping sequence, new master a_2 sends the time alignment *LMP* (Link Manager Protocol) message to each slave, asking a_1, a_3 and a_4 to synchronize their times with a_2. Afterward, device a_2 uses even slot to send a *FHS* packet to slave a_1. Then slave a_1 responses with the *FHS* acknowledgement to device a_2. The *FHS* packet contains the 48-bit BT_ADDR and clock information. Based on the information, slave a_1 can derive a new hopping sequence, which is generated by applying the 48-bit BT_ADDR and clock information of the new master a_2. Similarly, a_2 will send FHS packet to slaves a_3 and a_4. As a result, all slaves, including a_1, a_3 and a_4, in the new piconet can derive the new hopping sequence. Hence the new master a_2 and all slaves can apply the new hopping sequence. After that, the new master a_2 sends devices a_1 and a_3 a *POLL* packet that is similar to the *NULL* packet but requires a confirmation from the recipient to verify the switch. As shown in Figure 5(b), device a_2 takes over all resources of master a_4, playing a master role in the restructured piconet.

The formal algorithm of the proposed *MATR* mechanism is shown in Figure 6. In Lines 1 to 4, the old master perceives signal strength of device a_k received from the gateway and makes the decision whether or not to initiate the *Evaluation Phase*. In Lines 5 to 15, the old master calculates the restructuring benefit of every device a_k. Lines 16 to 20 present the procedure of *Role Switching Phase.*

A new piconet will be constructed according to execution of the proposed *MATR* scheme. It is expected to have more benefits than the old piconet in terms of network throughput and total transmission delay.

3.2 Scatternets Topology Restructuring

The last section mainly handles the restructuring of piconet topology. In Bluetooth radio networks, two or more piconets can be connected by gateways to form a larger network, called scatternet. This section considers the topology change of scatternets when the mobility causes unreliable links. Consider Figure 7. The body network p_3 consists of four Bluetooth devices, including a_8, a_9, a_{10} and a_{11}. And device a_8 plays a master role. The gateway a_7 connects two piconets p_2 and p_3. When the body network p_3 moves along north direction as shown in Figure 8, the quality of the link connecting the masters a_8 and a_7 becomes weak, resulting in high retransmission rate. Consequently, the transmission delays of all the Bluetooth devices in p_3 are increased. To improve this problem, it is necessary to choose a proper gateway in the scatternet to redirect the flow from link connecting devices a_7 and a_8 to other link. To achieve this, the master a_8 should collect signal strength from the surrounding Bluetooth

Algorithm: *Mobility Aware Topology Restructuring (MATR)*

Inputs: (1) An old piconet P;
(2) The traffic of each flow in P
(3) The Bluetooth signal strength threshold ρ_θ;
(4) Bluetooth signal strength $\rho_{k,g}$ of master a_k received from the gateway a_g
(5) The signal-noise ratio of each flow $SNR_{i,j}$.

Output: The new master $a_{new_{master}}$ of new piconet.

Perceiving Phase:
if ($\rho_{k,g} \leq \rho_\theta$) {
enter the *Evaluation phase*.
}
Evaluation Phase:
for each device a_k {
calculate the total transmission delay time of piconet by
$T_k = \sum_{\forall l_{i,j}} T_{i,j}^k$, where $T_{i,j}^k = f_{i,j}^1 / C_{i,j}^1 + \xi\, f_{i,j}^2 / C_{i,j}^2$
where
$C_{i,j} = B * \log_2(1 + (S/N)_{i,j})$
calculate the benefit of device γ^k, where
$$\gamma^k = 1 - T_K / T_{old\_master}$$
}
find the new master $a_{new_{master}}$ by applying
$$a_{new_{master}} = \arg\max_{1 \leq k \leq n} \gamma^k$$
if ($a_{new_{master}} = a_{old_{master}}$)
exit MATR
Role Switching Phase:
$a_{old_{master}}$ sends *CTL_MSG* to all slaves.
$a_{new_{master}}$ initiates role switch request.
$a_{new_{master}}$ sends *LMP* and *FHS* packets.
$a_{new_{master}}$ sends *POLL* packet.

Figure 6. The algorithm of MATR

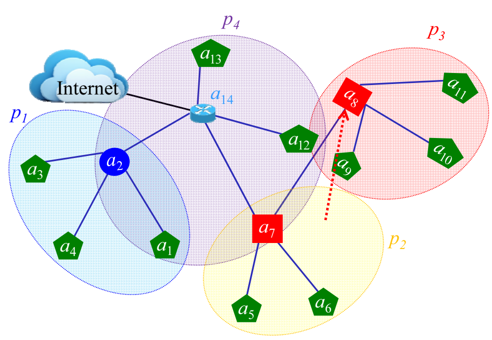


Figure 7. The body network p_3 moves along north direction

devices and find a proper relay Bluetooth device with the maximal benefit. The procedure for evaluating the benefit of each device is presented as follows.

Assume that the considered mobile piconet P consists of n Bluetooth devices, represented by $P = \{a_1, a_2, ..., a_n\}$, where device a_k plays the master role. Let a_{net}^g denote the gateway that supports Internet access. Assume that there are q Bluetooth devices neighboring to the master a_k, represented by $N_k = \{a_{k,1}, a_{k,2}, ..., a_{k,q}\}$.

Let $A_{k,i} = \{a_{k,i,1}, a_{k,i,2}, ..., a_{k,i,h}\}$ denote the set of routers from neighboring device $a_{k,i} \in N_k$ to the Internet gateway $a_{Internet}^g$. Let $f_{k,j}$ denote the flow data volume from device a_k to a_j. The $f_{k,k}$ should be zero. Let $T_{k,i,net}$ denote the total transmission delay of the packets transmitted from device a_k to the neighboring device $a_{k,i}$ and then from $a_{k,i}$ to the Internet gateway a_{net}^g. Let f_{a_i,a_j} denote the flow data volume from a_i to a_j. Let C_{a_i,a_j} denote the channel capacity from device a_i to a_j. The channel capacity C_{a_i,a_j} can be calculated by applying Exps. (11) and (12). The $T_{k,i,net}$ can be obtained by Exp. (18).

$$T_{k,i,net} = f_{a_k,ai} / C_{a_k,ai} + f_{a_k,i,h,_{net}^g} / C_{a_k,i,h,_{net}^g} + \sum_{j=1}^{h-1} f_{a_k,i,j,a_k,i,j+1} / C_{a_k,i,j,a_k,i,j+1} \quad (18)$$

According to Exp. (18), the minimal transmission delay time of the new relay device should be

$$a_{new_{relay}} = \arg\min_{1 \leq i \leq q} T_{k,i,net} \quad (19)$$

If $a_{new_{relay}}$ is the same as the old one, the evaluation phase will be finished and the relay device will not be changed. On the contrary, the role switching phase will be started.

To facilitate the details of this mechanism, an example shown in Figure 8 is used. When device a_8 moves along north direction, the signal strength of link connecting a_8 and a_7 becomes weak. As a result, the transmission delay of this link will be increased. Device a_8 should change its bridge device a_7 for transmitting data to gateway a_{14}. According to Exps. (18) and (19), device a_8 will evaluate the best benefit of surrounding Bluetooth device. Suppose device a_{12} has the minimal total transmission delay, a_8 will choose a_{12} as a new relay device. Finally, the packets of device a_8 will be transmitted to the gateway a_{14} through device a_{12}.

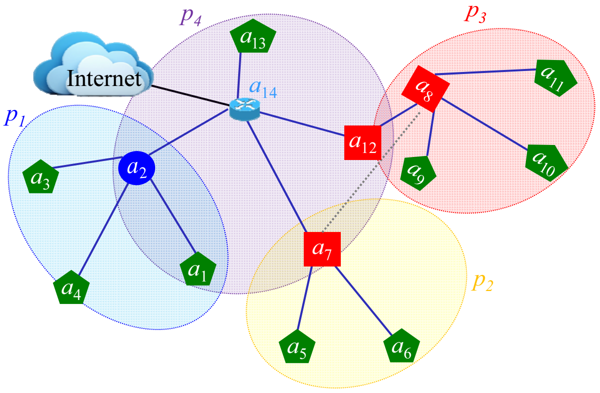


Figure 8. The body network p_3 changes the relay device

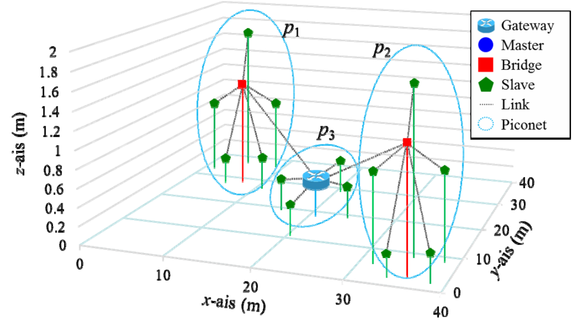


Figure 9. The topologies of Piconet and Scatternet considered in the experiments

4 Performance Evaluation

This section compares the performances of the proposed *MATR* mechanism and the Bluetooth standard [1]. To simulate a realistic situation, we employ MATLAB Simulink, which has been widely used in simulating realistic and expandable networks. Table 5 summarizes the simulation environment.

Table 5. Simulation parameters

Parameter	Value
Simulation Tool	MATLAB Simulink
Wireless Technology	Bluetooth Low Energy
Transmit Power	0 dBm
Receiver Sensitivity	-90 dBm
2.4 GHz Noise Floor	-102 dBm
Frequency Band	ISM 2400-2500 MHz
Modulation	GMSK
Data Rate	1 Mbps
Dimension of the Topography	40m × 40m
Moving Speed	1.5 m/s
Moving Direction	North/South/Random
Simulation Time	100 seconds
Simulation Repetitions	1500 times

Figure 9 gives the constructed scatternet in our experiments. The size of service region is set by 40 meter × 40 meter. The z-axis presents the height of each Bluetooth device. A gateway is placed at the center of the service region. It connects four Bluetooth devices and two piconets (p_1 and p_2). The piconets p_1 and p_2 are mobile and initially located at south-east and north-west side of the service region.

Each performance result is the average of 1500 independent runs. In our experiments, 95% confidence interval is always smaller than 5% for all reported values.

The following discusses the performance comparisons of Bluetooth Standard and the proposed *MATR* approaches in terms of minimum RSSI. The RSSI is an indication of the power level being received by the receiver's radio. Therefore, the higher the RSSI value, the stronger the signal received by receiver. A smaller RSSI value can cause unreliability and transmissions failed, as a device might require many retransmissions. This indicates that the interference sources will cause packet retransmission and hence raise the traffic overheads. A good piconet restructuring algorithm should maintain the good RSSI and hence generate low traffic overheads.

In Figure 10, the RSSI values of Bluetooth standard and the proposed *MATR* are compared. The initial moving direction of piconets p_1 and p_2 are south-to-north and north-to-south, respectively. When the piconet encountered the boundaries, the moving direction will change to the opposite direction. The values of avg.distance_ p_1 and avg.distance_ p_2 represent the average distance between the Bluetooth device in piconet p_1 and p_2 and the Gateway, respectively. As shown in Figure 10, *MATR* maintains higher RSSI value, as compared with the Bluetooth standard, because the proposed *MATR* mechanism changes the piconet and scatternet topologies for redirecting the traffic flow to the links with better quality.

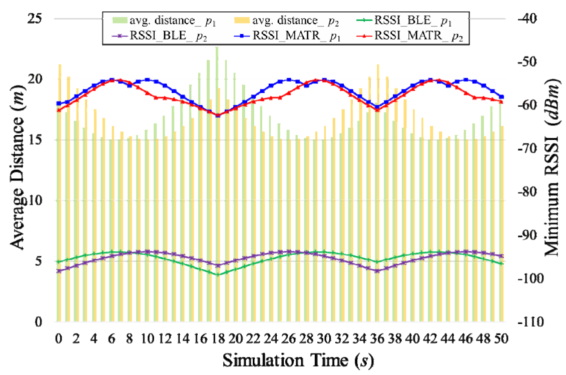
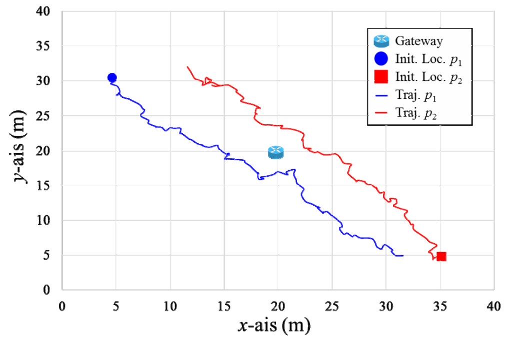
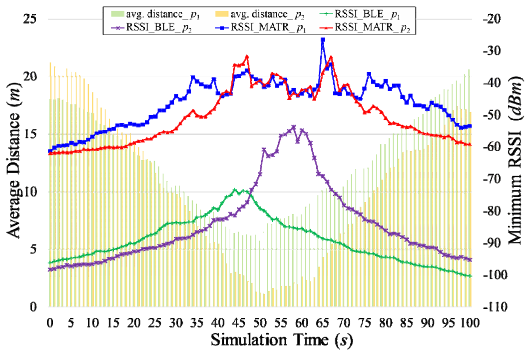


Figure 10. The RSSI values of the proposed MATR and the Bluetooth standard

Figure 11 further simulates the environment that the piconets are randomly moving in the service region. Figure 11(a) presents the moving trajectory of the piconet p_1 and p_2 . As shown in the Figure 11(b), *MATR* maintains highest RSSI value, as compared with the Bluetooth standard. This occurs because that the proposed *MATR* mechanism efficiently reconstructs the piconet and scatternet topologies for improving the link quality.



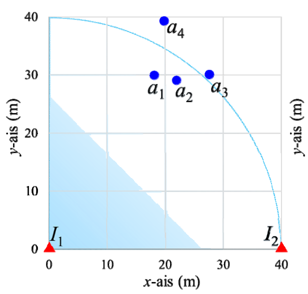
(a) The moving trajectory of piconet p_1 and p_2



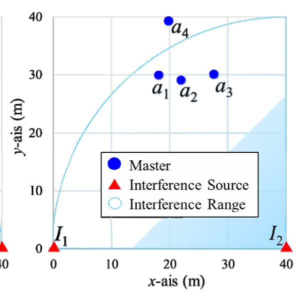
(b) RSSI values of the proposed *MATR* and the Bluetooth standard

Figure 11. The RSSI values when the piconet moving randomly

Furthermore, the interference from other wireless networks can affect the network throughput. Figure 12 considers the interferences in our experiments. Two locations of the interference sources, as marked by I_1 and I_2 were set in the service region. Figure 12 represents the two experimental scenarios. The first and second scenarios set up the interference locations.



(a) 1st Scenario: Interference source is set at I_1



(b) 2nd Scenario: Interference source is set at I_2

Figure 12. The interference sources considered in the experiments

Figure 13 compares the Bluetooth standard and the proposed *MATR* in terms of traffic overheads. In Figure 13, the interference source at location I_1 is considered and hence only a_1 and a_2 suffer the interference. The traffic overheads of devices a_3 and a_4 are ignored because that devices a_3 and a_4 are not affected by the interference in the second scenario. The sums of traffic overheads of curves "*BLE_* a_1" and "*BLE_a*$_2$" are closed to that of the curve "*BLE_Piconet*". Therefore, the traffic overheads of the whole "Piconet" are similar to the sum of traffic overheads of devices a_1 and a_2. Similarly, the sum of traffic overheads of curves "*MATR_a*$_1$" and "*MATR_a*$_2$" is closed to that of the curve "*MATR_Piconet*". In general, the proposed *MATR* mechanism outperforms the existing Bluetooth standard in terms of traffic overheads of a_1, a_2 and piconet.

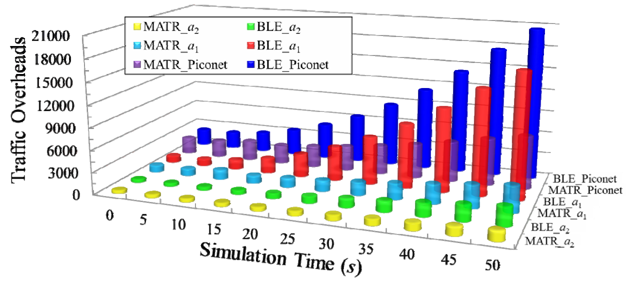


Figure 13. Traffic overheads raised due to interference source I_1

Similarly, Figure 14 compares the traffic overheads of devices a_1, a_2, a_3 and Piconet in the third scenario. The interference source is set at location I_2. The created interference only impacts on the traffic overheads of devices a_1, a_2 and a_3. Since device a_4 does not be affected by the interference, this experiment does not consider a_4. In general, the proposed *MATR* mechanism outperforms the existing Bluetooth standard in terms of traffic overheads.

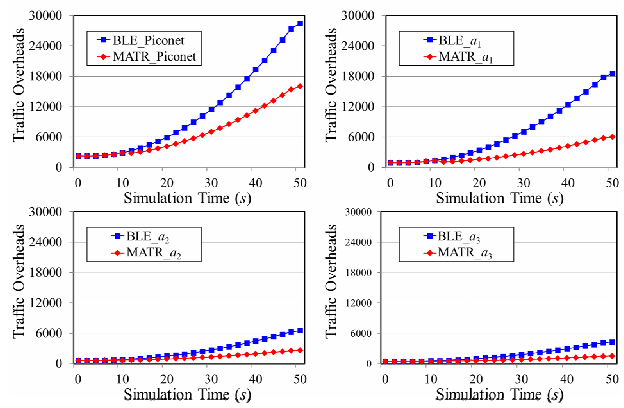
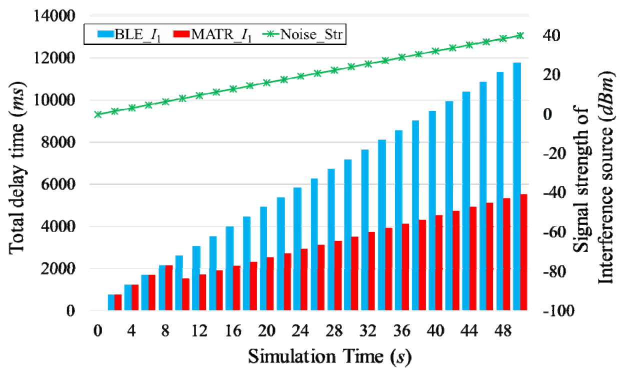
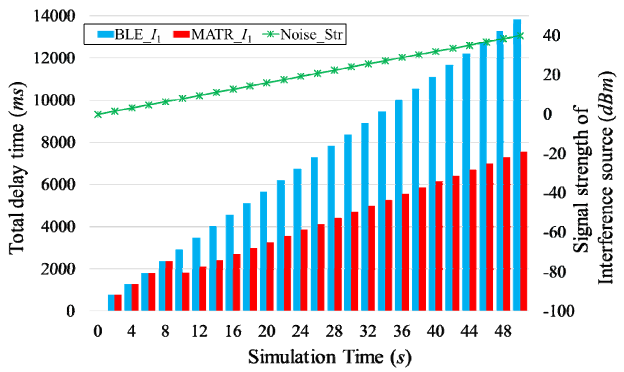


Figure 14. Traffic overheads raised due to interference source I_2

Figure 15 compares Bluetooth standard and the proposed *MATR* in terms of total delay time of the scatternet. The green curve represents the signal strength of the interference source. The packet arrival time for every device is 2.91ms. Figure 15(a) and 15(b) applies the first and second scenarios as the experiment environments, respectively. The blue and red columns depict the total delay time of the scatternet by applying the Bluetooth standard and the proposed *MATR* algorithms, respectively. As shown in the Figure 15, *MATR* maintains lower delay time, as compared with the Bluetooth standard. This occurs because the proposed *MATR* mechanism efficiently reconstructs the piconet and scatternet topologies for improving the link quality.



(a) Interference source is set at I_1



(b) Interference source is set at I_2

Figure 15. Total delay time of the scatternet with different interference scenario

5 Conclusion

This paper presents Mobility-Aware Topology Restructuring scheme for Bluetooth body area networks, called *MATR*. The proposed *MATR* mechanism restructures the topology of piconet and scatternets by applying role switching operations. As a result, the new Bluetooth topology can reduce the transmission delay and the energy consumption for Bluetooth BANs, reduce the network overheads raised by packet retransmissions, and improve the network throughput of Bluetooth radio networks. Experiment results show that the proposed mechanisms outperform the traditional Bluetooth protocol in terms of transmission delay and energy consumption.

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References

[1] Bluetooth Special Interest Group, *Bluetooth Core Specification v.4.0*, https://www.bluetooth. org/en-us/specification/ado-pted-specifications

[2] C. Bryant, H. Sjoland, A 0.55 mW SAW-Less Receiver Front-End for Bluetooth Low Energy Applications, *Emerging and Selected Topics in Circuits and Systems*, Vol. 4, No. 3, pp. 262-272, September, 2014.

[3] D. Contreras, M. Castro, Adaptive Polling Enhances Quality and Energy Saving for Multimedia over Bluetooth, *Communications Letters*, Vol. 15, No. 5, pp. 521-523, May, 2011.

[4] M. Collotta, G. Pau, A Novel Energy Management Approach for Smart Homes Using Bluetooth Low Energy, *Selected Areas in Communications*, Vol. 33, No. 12, pp. 2988-2996, December, 2015.

[5] J. R. Lin, T. Talty, O. Tonguz, On the Potential of Bluetooth Low Energy Technology for Vehicular Applications, *Communications Magazine*, Vol. 53, No. 1, pp. 267-275, January, 2015.

[6] J. Nieminen, C. Gomez, M. Isomaki, T. Savolainen, B. Patil, Z. Shelby, M. Xi, J. Oller, Networking Solutions for Connecting Bluetooth Low Energy Enabled Machines to the Internet of Things, *Network*, Vol. 28, No. 6, pp. 83-90, November-December, 2014.

[7] S. Ravi, A. Raghunathan, P. Kocher, Security in Embedded Systems: Design Challenges, *Embedded Computing Systems*, Vol. 3, No. 3, pp. 461-491, August, 2004.

[8] K. Saravanan, D. Yuvaraj, An New Secure Mechanism for Bluetooth Network, *Computer and Automation Engineering*

(ICCAE) of Conference, Singapore, 2010, pp. 202-205.

[9] J. Dunlop, N. Amanquah, High Capacity Hotspots Based on Bluetooth Technology, *Communications*, Vol. 152, No. 5, pp. 521-527, October, 2005.

[10] S. Souissi, E. F. Meihofer, Performance Evaluation of a Bluetooth Network in the Presence of Adjacent and CO-channel Interference, *Emerging Technologies Symposium: Broadband, Wireless Internet Access of Conference*, Richardson, TX, 2000, pp. 6-11.

[11] C. M. Yu, J. H. Lin, Enhanced Bluetree: A Mesh Topology Approach Forming Bluetooth Scatternet, *Wireless Sensor Systems*, Vol. 2, No. 4, pp. 409-415, December, 2012.

[12] K. Morsi, Q. Gao, H. G. Xiong, Interference Impact on Throughput Performance of Bluetooth Scatternets Under Different Traffic Loads, C*ommunications and Networking in China (CHINACOM) of Conference*, Beijing, China, 2010, pp. 1-5.

[13] R. Roy, M. Kumar, N. K. Sharma, S. Sural, Bottom-up Construction of Bluetooth Topology under a Traffic-aware Scheduling Scheme, *Mobile Computing*, Vol. 6, No. 1, pp. 72-86, January, 2007.

[14] C. Y. Chang, H. R. Chang, Adaptive Role Switching Protocol for Improving Scatternet Performance in Bluetooth Radio Networks, *Consumer Electronics*, Vol. 52, No.4, pp. 1229-1238, January, 2007.

[15] Y. S. Chen, T. H. Lin, A Time-slot Leasing-based QoS Routing Protocol over Bluetooth WPANs, *International Journal of Ad Hoc and Ubiquitous Computing*, Vol. 2, No. 1-2, pp. 92-108, January, 2006.

[16] W.-Z. Song, Y. Wang, C.-H. Wu, X.-Y. Li, Multihop Scatternet Formation and Routing for Large Scale Bluetooth Networks, *International Journal of Ad Hoc and Ubiquitous Computing*, Vol. 4, No. 5, pp. 251-268, July, 2009.

[17] W. El-Hajj, H. Safa, M. Guizani, Survey of Security Issues in Cognitive Radio Networks, *Journal of Internet Technology*, Vol. 12, No. 2, pp. 181-198, March, 2011.

[18] A. J. Goldsmith, P. P. Varaiya, Capacity of Fading Channels with Channel Side Information, *Information Theory*, Vol. 43, No. 6, pp. 1986-1992, November, 1997.

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