Energy Efficient Network Mobility under Scatternet/WLAN Coexistence

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Abstract—Nowadays, it is common that people carry several kinds of portable devices such as cellular phone, MP3 player, and PDA etc. If we assume that these devices build a WPAN (Wireless Personal Area Network) via Bluetooth Piconet, the master node of the Piconet plays a role of MR (Mobile Router) with maintaining connection to Internet via WLAN (Wireless LAN). Thus WPAN with Bluetooth is quite suitable for realizing NEMO (Network Mobility). Furthermore, if it is assumed that two or more Piconets are connected with one another through Scatternet, the nested mobility is achieved easily. In this situation, each slave device will connect to Internet via the mobile router. Then the mobile router can use the path via WLAN or make a new path through Scatternet, i.e., via a master node in other Piconet, in order to forward the connection of each slave device.

In this paper, we show that the path through Scatternet is more energy efficient, especially in terms of the lifetime of mobile routers. For this purpose, we present an energy consumption model of WLAN and Bluetooth, which is based on payload size and transmission/receiving duration. In addition, we show that making a new path through Scatternet built on two or more Piconets is more beneficial to prolonging the lifetime. We prove the energy efficiency of our proposal through ns-2 simulations.

Index Terms—Energy Efficiency, Network Mobility, Piconet and Scatternet, Wireless LAN

I. INTRODUCTION

Recently, it is usual that people carry several different kinds of Bluetooth-enabled portable devices (e.g., cellular phone, MP3 player, PDA, etc.). Therefore it is possible to build a Piconet-based WPAN (Wireless Personal Area Network), and which becomes quite suitable for realizing NEMO (Network Mobility).

In NEMO, MR (Mobile Router) connects to fixed infrastructure or other MR, and provides portable devices in mobile network with connectivity to Internet. Thus unlike the terminal mobility, each device does not need to concern with the changes of its point of attachment to the fixed infrastructure [15].

Piconet builds up polling-based network with one master device and one or more slave nodes. Thus, if we provide the master node with connectivity to Internet, and impose the role of MR on it, the Piconet can support NEMO [3, 4]. Furthermore, a Scatternet that connects two or more Piconets can realize nested mobility with less effort.

Usually, portable devices in Piconet are battery-operated. Therefore, it is essential to consider finite energy consumption.

Fig. 1. An example topology. M2 can use the path via M1 instead of WLAN in order to save energy consumption.

Consider a simple example topology shown in Fig. 1 where M1 and M2 are master devices and play a role of MR. We also assume that each master node is connected to Internet via WLAN (Wireless LAN). M2 can build the path to Internet with direct connection through WLAN, or by traversing M1, i.e.,
through Scatternet.

In this paper, we show that the path via $M_1$ is more beneficial to saving transmission energy of $M_2$ than the path through WLAN. Therefore, if a device that has shorter battery lifetime uses the path that traverses other MR that has longer lifetime, the lifetime of whole network can be improved\footnote{In Piconet or Scatternet, the lifetime of master nodes comes to an end the lifetime of whole network.}. For this goal, we establish an energy consumption model that reflects payload size and transmission/receiving duration. By implementing this model in ns-2 simulator\[10], we show that reduced energy consumption is achieved by building up a new path through nested mobility and Scatternet. Moreover, we measure the amount of throughput degraded, especially in terms of delivery delay, when Scatternet is used instead of WLAN.

The rest of this paper is organized as follows: In Section II, we present the energy consumption models of WLAN and Bluetooth. In Section III, we express the difference in the amount of energy consumed in two different paths formally. In Section IV, we show the simulation results. Finally, concluding remarks are given in Section V.

II. ENERGY CONSUMPTION MODELS

In this section, we give the energy consumption models of both WLAN and Bluetooth. For WLAN, we apply the parameters given in\[5, 6], and for Bluetooth, apply those given in\[7, 8]. The energy consumption model of a device that is in idle state is presented in Section III.

A. Energy consumption model for WLAN

We assume that the transmission and receiving processes are composed of set of operations (denoted as $A$). We denote the amount of power required on each operation $a \in A$ as $P_a$, and duration of each operation for handling $D$ bytes of packet as $T_a(D)$. Then, the total amount of energy consumption for transmission or reception of $D$ bytes is

$$ E_{\text{trans}}(D) = \sum_{a \in A} T_a(D) \times P_a. \quad (1) $$

In WLAN, each device is in one of the following four states: sleep, idle, receive, and transmit. The amount of power consumed in each state is listed in Tables I and II. We observe that the device consumes the highest power in transmit state, and on the other hand, it only consumes within a range of 47~75mJ in sleep state.

The frame size of IEEE 802.11b is 2384 bytes. Header size is 38 bytes, and the header of each frame is transmitted at the rate of 1Mbps. Thus the maximum payload size is 2346 bytes, and it is transmitted at a rate of 1Mbps, 2Mbps, 5.5Mbps, or 11Mbps. If the payload size is bigger than 2346 bytes, upper layer, i.e., IP, will fragment it. Thus the time for transmitting or receiving payload of $D$ bytes with considering the fragmentation is expressed as follows:

$$ T(D) = \frac{D \times 8}{\text{Transmission Rate}} + \frac{\text{Header Size} \times 8}{\text{Basic Rate}} \times \left\lfloor \frac{D}{\text{MTU}} \right\rfloor. \quad (2) $$

Consequently, the amounts of energy consumed in transmitting and receiving payload of $D$ bytes are

$$ E_{\text{trans}}(D) = T(D) \times P_{tx}. \quad (3) $$

We do not consider the change of the transmission rate by ARF (Automatic Rate Fallback), packet loss, and access control.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Meaning</th>
<th>Symbol</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STANDBY</td>
<td>Consumed in standby state</td>
<td>$P_{\text{sb}}$</td>
<td>50.90</td>
</tr>
<tr>
<td>TX</td>
<td>Consumed in transmission state</td>
<td>$P_{tx}$</td>
<td>277.20</td>
</tr>
<tr>
<td>RX</td>
<td>Consumed in receiving state</td>
<td>$P_{rx}$</td>
<td>181.58</td>
</tr>
<tr>
<td>MAS</td>
<td>Consumed for the operation of master node</td>
<td>$P_{\text{mas}}$</td>
<td>32.02</td>
</tr>
<tr>
<td>SLV</td>
<td>Consumed for the operation of slave node</td>
<td>$P_{\text{slv}}$</td>
<td>58.46</td>
</tr>
<tr>
<td>TRM</td>
<td>Consumed additionally for transmission or receiving in master mode</td>
<td>$P_{\text{trm}}$</td>
<td>45.74</td>
</tr>
<tr>
<td>TRS</td>
<td>Consumed additionally for transmission or receiving in slave mode</td>
<td>$P_{\text{trs}}$</td>
<td>19.34</td>
</tr>
</tbody>
</table>

Our Bluetooth energy consumption model is based on the power model in\[7] where the Bluetooth operations are modeled into a finite state machine with providing each state with logical activity. The amount of power required in each state (activity) is listed in Table III. By estimating the duration on each activity, we can estimate the amount of energy consumed.
in transmission or receiving as illustrated in Fig. 2.

In Bluetooth, transmission and receiving occur every 625 μs. Since all data in a slave node are transmitted or received in response to polling from a master node, the transmission duration $T_{tx}$ at the master node is same as the receiving duration $T_{rx}$ at the slave node, and also $T_{tx}$ at the slave node is same as $T_{rx}$ at the master node. When there is no data to be transmitted or received in the slave node, the slave node sends a NULL packet in response to a POLL packet from the master node. Therefore the minimum time for transmitting data is same as the duration for transmitting a POLL or NULL packet.

![Power Flow Diagram](image1)

**Fig. 2. Illustration of amount of energy consumed in transmission and receiving**

In Bluetooth, there are two major types of packet, which are SCO (Synchronous Connection-Oriented) and ACL (Asynchronous Connectionless). In this paper, only ACL type is considered. The ACL type supports various payload size and odd number of multiple time slots.

Since the transmission delay is proportional to the number of time slots, the number of time slots required for transmitting data of $D$ bytes is expressed as

$$N(D) = \left\lfloor \frac{D}{\text{max}_\text{payload}} \right\rfloor \times (1 + n) \quad (4)$$

where $n$ is the number of time slots. The type of packet determines max_payload. Then, the duration for transmitting data of $D$ bytes is

$$T(D) = 625 \mu s \times N(D). \quad (5)$$

Due to the feature of frequency hopping in Bluetooth, only max_payload bytes. Then we can formulate the amounts of energy consumed in sender and receiver respectively as follows:

$$E_{bttx}(D) = N(D) \times \left\{ \begin{array}{l} T_{slot} \times P_{tx} \\
\frac{1}{n+1} \times T_{ll} \times P_{ll} \end{array} \right\} \quad \text{and} \quad (6)$$

$$E_{bttx}(D) = N(D) \times \left\{ \begin{array}{l} T_{slot} \times P_{tx} \\
\frac{1}{n+1} \times T_{ll} \times P_{ll} \end{array} \right\} \quad (7)$$

where $T_{ll}$ is the time required for transmitting a POLL or NULL packet. Since both POLL and NULL packets do not have any payload, their size are fixed to 126 bits, and thus $T_{ll} = 126 \mu s$.

![Example Topology](image2)

**Fig. 3. An example topology for the comparison of the amount of energy consumed in two different paths.**

In this section, we compare the amount of energy consumptions on two different paths, i.e., via WLAN and via Scatter-net, using the models described in Section II. We use the simple example topology shown in Fig. 3, where $M_2$ tries to connect to Internet, and it can select a path between path 1 → 5 and path 1 → 2 → 3 → 4.
\[ E_{\text{diff}}(D) = \left\{ \begin{array}{ll} E_{\text{wlanTx}}(D)_{M_1} + E_{\text{wlanRx}}(D)_{B} & \text{if } D_{\text{idle}} = 1 \\ E_{\text{bttx}}(D)_{B} + E_{\text{btRx}}(D)_{M_1} & \text{if } D_{\text{idle}} = 0 \end{array} \right. \] \quad (8)

If it is sure that there will be no further communication using WLAN, it can save a lot of energy by changing the mode idle into sleep \([5, 13, 14]\). In this example topology, if the node \(M_2\) selects the path \(1 \rightarrow 2 \rightarrow 3 \rightarrow 4\), it can save more energy by setting its WLAN into sleep state. With reflecting this state change, the difference of the amount of energy consumed in the two paths is as follows:

\[ E_{\text{diffidle}}(D) = \left\{ \begin{array}{ll} P_{\text{wlanidle}} E_{\text{bttx}}(D)_{B} + E_{\text{btRx}}(D)_{M_1} & \text{if } D_{\text{idle}} = 1 \\ P_{\text{wlanidle}} E_{\text{bttx}}(D)_{B} + E_{\text{btRx}}(D)_{M_1} & \text{if } D_{\text{idle}} = 0 \end{array} \right. \] \quad (9)

IV. SIMULATION

We give some simulation results of our proposal. We implemented our energy consumption models in UCBT (Bluetooth extension for ns-2) \([9]\) that supports most of Bluetooth specifications, such as baseband, LMP, L2CAP, BNEP etc. There are another Bluetooth extensions for ns-2, for instance, Bluehoc \([11]\) and Blueware \([12]\). Bluehoc supports simulations on a single Piconet only, and Blueware implements only partial set of Bluetooth operations.

A. Simulation scenario and environments

![Simulation topology](image)

We generate a Scatternet of two Piconets as shown in Fig. 4. We assume that both the bridge nodes in Piconet-1 and Piconet-2 are in the mode of slave/slave. We let the bridge node be activated by being polled by the master nodes in every 256 timeslots, and let the duration of each activation be 128 timeslots. We also assume that there is no additional activation, and the polling processes are scheduled in round robin fashion.

We measure the amount of energy consumption and delivery delay on the path \(M_0 - B_3 - M_4\) with various packet types provided by the Bluetooth specification, which are DH1, DH3, DH5, 2-DH5, and 3-DH5 \([1, 2]\). It is assumed that both \(M_4\) and \(M_0\) have connectivity with Internet through WLAN, and the bridge node is a unique slave node in each Piconet.

B. Simulation results

Fig. 5 compares the amount of energy consumed by the transmission via the path \(M_0 - B_3 - M_4\) with the amount of energy consumed when the WLAN is in idle state. It is observed that the WLAN device, even though it is in idle state, consumes more energy than a Bluetooth device that is in transmission mode. Moreover, if we allow the WLAN state in \(M_0\) to be in sleep state during the transmission via the Scatternet, it can save its own energy, and the network lifetime is prolonged\(^2\).

![Energy Consumption](image)

Fig. 5. Comparison of amount of energy consumption(traffic type: TCP).

Fig. 6 compares the delivery delay on the path \(M_0 - B_3 - M_4\) and in WLAN. It is observed that it takes longer time to transmit the data through Scatternet. However, in the case of transmitting the packet type of 3-DH5, the difference is quite small.

![Delivery Delay](image)

Fig. 6. Comparison of delivery delay.

In Fig. 7, the amount of energy consumed in traversing two or more consecutive Piconets is shown. Even the total amount of energy consumed in five consecutive Piconets is smaller than the energy consumed by WLAN in idle mode. Thus it is certain that, as several numbers of Piconets are traversed, it is highly beneficial to prolong the network lifetime. It is desirable for the master and bridge node at the last Piconet to have larger quantity of battery power than others.

\(^2\) We assume that \(M_4\) has longer battery lifetime than \(M_0\).
However, the delivery delay is penalized in Scatternet, especially, in case of traversing two or more consecutive Piconets. As the number of traversed Piconets increases, the delivery delay also increases as shown in Fig. 8.

![Fig. 7. Comparison of the amount of energy consumption in case of traversing two or more consecutive Piconets.](image)

![Fig. 8. Comparison of delivery delay in case of traversing two or more consecutive Piconets.](image)

V. CONCLUSION

In this paper, we illustrate that the amount of energy consumption can be reduced and network lifetime can be prolonged by building up a new path through constructing Scatternet and nested mobility under the Scatternet/WLAN coexistence. We compared the amount of energy consumption and delivery delay by implementing our energy model to the ns-2 UCBT simulator. Also we show that the performance depends on the depth of nested mobility and path selection.

In our energy model, transmission error in wireless channel, packet losses by overflow, and access control are not considered. Since the values applied to our energy model were obtained from the previous research literatures, it is needed to establish more precise practical model in order to produce better realistic results. In addition, we should consider that the performance of Bluetooth is strongly affected by the number of slave nodes, the topology characteristics of Scatternet, and the intra and inter-Piconet scheduling. These issues need further investigations, and will be our main future challenges.

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REFERENCES