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Modelling and performance analysis of an adaptive state-transition approach for power saving in Bluetooth

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ABSTRACT

In this paper, an approach is developed to improve the power efficiency of Bluetooth. The better efficiency is achieved by reducing the unnecessary polling operations in the Basic Rate/Enhanced Data Rate (BR/EDR) controllers. An analysis of the current low power modes in the Bluetooth BR/EDR controller indicates that their activation requires a critical and challenging parameter negotiation phase. These parameters have a wide range of choices and as a result the associated low power modes are typically ignored by the Bluetooth application developers. The new approach is based upon multiple polling intervals. It is shown that three different polling intervals: small, medium and large are sufficient for a broad range of data traffic scenarios. As the kernel idea, each controller runs a common algorithm to choose among the three polling intervals and adaptively switches link state between the active data transfer state and idle. The state-transition rules are derived, and a system model is established based on the Hidden Markov Model (HMM), which is used to analyze and design the new Bluetooth link state-transition algorithm. The simulation and analysis demonstrates significant power saving and relatively low average end-to-end packet delay for this state-transition based approach, in comparison to the conventional polling system and the low power sniff mode. Moreover, the state-transition approach enables easier parameter setting that can be further optimized for a specific Bluetooth scenario.

1. Introduction

Bluetooth [1] is a popular short-range wireless communications system, operating in the unlicensed 2.4 GHz ISM (Industrial Scientific Medical) band and its key features are robustness, low power, and low cost. The Bluetooth core system consists of a host and one or more controllers. A host is defined as all of the layers below the usage profiles and above the Host Controller Interface (HCI). A controller is defined as all of the layers below the HCI. As the Bluetooth protocol stack in Fig. 1 shows, the Bluetooth controller part includes a Basic Rate/Enhanced Data Rate (BR/EDR) controller, an optional Alternate MAC/PHY (AMP) controller and the recently specified Low Energy (LE) controller. The Link Manager (LM) controls how the Bluetooth networks are established and maintained. The HCI provides a uniform set of commands to access the controller capabilities. The Bluetooth host includes a comprehensive set of protocols and profiles to support a broad range of applications.

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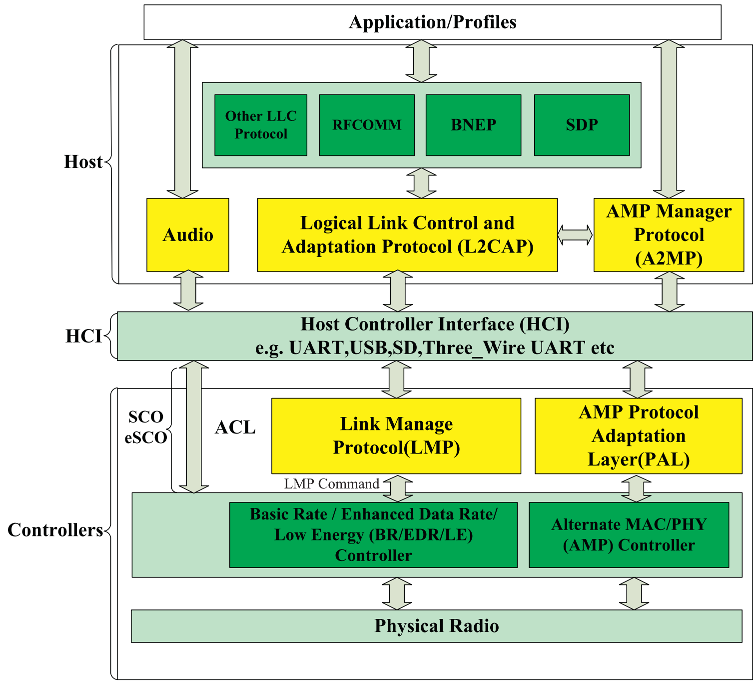

Fig. 1. The Bluetooth stack architecture.

The Bluetooth system employs a frequency hop transceiver to combat interference and fading. For full duplex transmission, the Bluetooth BR/EDR adopts a Time Division Duplex (TDD) scheme. The slot time for transmitted/received data is fixed at 625 μs and the BR/EDR controller can select 1, 3 or 5 slots to transmit/receive data with different packet types and flexible packet payload. Bluetooth transports real-time audio signals by Synchronous Connection-oriented [logical transport] (SCO) links and transports packet-switched, data traffic by Asynchronous Connection-oriented [logical transport] (ACL) links. Currently, Bluetooth is being applied to more and more ACL applications requiring variable data rates, for example Wireless Personal Area Networks (WPAN), Wireless Sensor Networks (WSN) for factory and industrial use, and Wireless Application Protocol (WAP) devices.

The problem of high power consumption caused by the Bluetooth polling system has been highlighted for a broad range of ACL based applications. In the core specification, the Bluetooth Special Interest Group (SIG) provides three low power modes for the BR/EDR controllers. However, there are difficulties in using the current low power modes, in particular related to the setting of parameters. Recently, to address high power consumption and to maintain competitiveness, the Bluetooth SIG has defined the Bluetooth Low Energy (LE) controller to cater for sensor network based applications, which often require very low data rates. However, it is necessary to integrate a new wireless chipset to support the targeted low data rate applications.

The Bluetooth standard defines three major states for the link controller operation in a BR/EDR controller: STANDBY, CONNECTION and PARK [1]. In the CONNECTION state, the active connection link has been established and both control and data packets can be exchanged. The sub-states of the CONNECTION state for an active ACL link are the active state, the idle state and the sleep state. The data packets and polling operations (i.e. POLL–NULL packets) are transmitted and received in the active state. The challenge addressed in the various polling operations and the low power mode scheduling schemes is to reduce the time in this active state, thereby allowing the device to enter an idle or sleep state. In particular, the BR/EDR controller may switch to an idle state (while the master is waiting to poll) or to a sleep state (while the master or slave is in the sniff mode). The sleep state allows for more aggressive power saving. Therefore, to reduce the time in the active state, a new approach to reduce the unnecessary polling operations is proposed in this paper, which can significantly improve power efficiency.

The rest of this paper is organized as follows: Section 2 reviews the related work on alternative Bluetooth polling schemes and Section 3 gives a short summary about the current Bluetooth low power operations; Section 4 presents the new approach and presents its state machine and state-transition rules; Section 5 establishes the system model of this approach based on the Hidden Markov Model (HMM), which can be used to analyze the state-transitions in Bluetooth; Sections 6 and 7 describe the model parameter estimates and the model utilization; Section 8 presents the performance analysis of the proposed approach and the simulation based evaluation is discussed in Section 9. Finally, Section 10 presents the conclusion.