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Predictive scheduling approach in Inter-piconet Communications

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Abstract

Recent researches in wireless communications have gained extraordinary interests, especially in short range wireless communications like Bluetooth, the scientific interests have been followed up in industry. Bluetooth is a new method for wireless low cost, short range communicating between mobile devices. Originally it was developed as cable replacement. For the time being, it has been used as a mobile ad hoc network, which is intended for both voice and data communications, e.g. voice traffics, TCP/IP data traffics.. . Knowledge on mobile ad hoc network will be in need of studying and applying to Bluetooth. The communication in Bluetooth is based on a frequency hopping physical layer and is organized in piconet with a master and a number of slaves. Two and more piconets can overlap coverage areas to form a true mobile ad hoc network, scatternet.

The end-to-end Quality of Service delivered to end users in Bluetooth networks depends on large number of parameters at different levels, e.g. link capacity, packet delays.., which require various control and optimization methods. In this paper, an important part of inter-connected communications, inter-piconet scheduling, is mentioned, an approach for the inter-piconet predictive scheduling is highlighted and analyzed and a simulation with bursty traffic sources, IBP, is carried out. The simulation results show that the performance of the Bluetooth network is improved when using the predictive scheduling.

1. Introduction

Wireless ad-hoc networks, or mobile distributed multi-hop wireless networks, have gained a lot of attention during the last couple of years [1]. The mobile nodes may rapidly move around and all communication is carried over the wireless channel. The main difference between ad-hoc networks and conventional cellular technology is the lack of any centralized entity within ad-hoc networks. Ad-hoc networks can be deployed quickly since no fixed infrastructure is needed. These networks can be fault tolerant because no central entity is used.

Bluetooth is a wireless communication technology using the unlicensed Industrial-Scientific-Medical (ISM) frequency band, supporting synchronous voice traffic and asynchronous IP-based data traffic [2, 3]. Bluetooth is a de facto standard, and a specification for low cost, short range radio links between electronic devices, such as cordless phones, laptops and wireless headsets. The communication is organized in piconet with a master and a number of slaves. Each piconet uses a unique frequency hopping sequence, and several piconets can be created with overlapping coverage areas to form a scatternet. Scatternets are important because they extend the rather limited coverage of piconets, and provide a flexible network structure required by some applications. Furthermore, the overall capacity of Bluetooth networks is increased when several frequency hopping sequences are used simultaneously. However, the new concepts introduced in Bluetooth systems, like piconets and scatternets, need to be understood to efficiently use the new technology.

The performance of Bluetooth networks depends on a large number of parameters at different levels [4]. The mobility of the nodes and the limited power available makes them even more difficult to handle efficiently compared to fixed networks. Network capacity should be efficiently managed to guarantee Quality of Service. An appropriate resource allocation of Bluetooth networks is needed to satisfy Quality of Service requirements.

In this paper, we explore the possibility to reallocate capacity of Bluetooth networks through inter-piconet scheduling. The inter-piconet scheduling handles traffic within and between inter-connected piconets. It is supposed to run in “thin clients” and should be adaptively controlled according to traffic variations. To address theses requirements, a predictive approach of inter-piconet scheduling is highlighted and analyzed through simulations. Data traffic sources are modeled by Interrupted Bernoulli Process (IBP) processes to investigate the impact of bursty sources, both for homogeneous and heterogeneous load scenarios. The piconets use Fair Exhaustive Polling (FEP) scheme, but other polling schemes are extensible. Neither are any assumptions needed about the internal details of the simulation model. The results obtained show that the performance of Bluetooth inter-piconet communications could be improved with the predictive approach.

2. Bluetooth technology

Bluetooth, a new wireless communication technology, operates at 2.4 GHz in globally available, license-free ISM (Industrial, Scientific and Medical) band. The operating band is divided into 1 MHz-spaced channels with the chosen modulation scheme of GFSK (Guasian Frequency Shift Keying), this equates to 1 Mb/s. The channel is divided into consecutive time slots, each time slot lasts 0.625 ms. Every Bluetooth device has a unique Bluetooth device address. All Slaves use the Master’s clock and address to synchronize to the Master’s frequency hop sequence. The Master allows Slaves to transmit by allocating slots for voice or data traffic.

A collection of Slave devices operating together with one common Master is referred as a piconet. All devices on a piconet follow the frequency hopping sequence and timing of the Master. A piconet can have up to 7 active slaves, with each slave only communicating with the shared master. A packet can be exchanged between master and slave device in each slot. Each

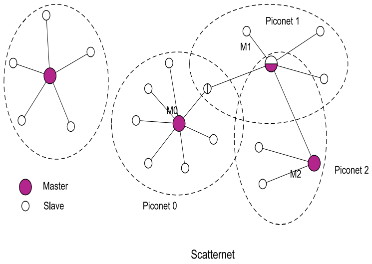

Figure 1: Bluetooth piconet and scatternet

Bluetooth have a fixed defined format, which consists of 72-bit access code, 54-bit header and up to 2745 bit payload. A packet is sent in one slot, three slot, or five slots on single hop channel. The master may begin to send a packet in even numbered slots only. The slave addressed by this packet is the only device allowed to send in the odd numbered slots following the master's packets. Between master-slave pairs, both Synchronous Connection Oriented (SCO) links and Asynchronous Connectionless link (ACL) are supported. The masters allocate capacity for SCO links by reserving slots and for ACL links by using a polling scheme. This central polling scheme is to prevent collisions between slave transmissions. A collection of multiple piconets can be linked into an ad hoc larger network, which called scatternet, where some devices are member of more than one piconet, which called bridge node. Figure 1 shows an example of a piconet and a scatternet, which includes three piconets. The bridge node can be roled as master in a piconet and slave in another or slave in both. It requires carefully packet scheduling for the node participating in multiple piconets. Bluetooth also supports power-saving techniques. A slave in a piconet may be in active, parked, sniff or hold mode.

3. Inter-piconet predictive scheduling

3.1. Inter-piconet scheduler

As stated above, Bluetooth is a frequency hopping system which uses multiple channels for communications. In piconet, the common channel is shared using a slotted time scheme (TDD), where a master uses a polling style protocol to allocate time-slots to slave nodes.

Multiple piconets can overlap at least partially in time and space to create scatternet. The bridge node can be a master in one piconet and slave in another or a slave in all poconets. The bridge node uses time sharing between piconets to communicate. When the bridge nodes want to communicate, is referred as inter-piconet communication and the main issue becomes how to schedule the bridge node in different piconets in order to have an efficient controlling of traffic flows between piconets.

As shown on figure 2 [8], the scatternet scheduler is built on two parts : Master-Slave scheduler and Inter-piconet scheduler. The Master-Slave scheduler uses a polling scheme to control traffic flow within each piconet. Several polling schemes have been proposed, such as FEP, PFP, which provide an fair and efficient bandwidth distribution to the nodes inside the piconet. The inter-piconet scheduling uses time-sharing to schedule the active interval of bridge node in a piconet. During the time that a bridge node is not active in the piconet, it should be switched to power save mode, e.g. SNIFF or HOLD modes. Updating active, sniff or hold intervals can be carried out through message exchanging in Link Manager Protocol (LMP).

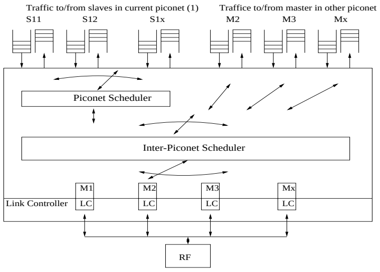

Figure 2: Scatternet scheduler sub-layer in a master node

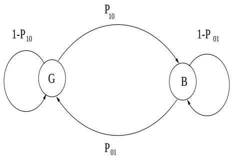

Figure 3: Transition structure of the Markov Loss Model

3.2. An approach for inter-piconet scheduling

Bluetooth baseband link can be modeled as a discrete two-state Markov chain as in figure 3. Each master-slave connection is associated with independent Markov channel model. The states are termed G (good) and B (bad). Channel state transitions are assumed to occur on a slotted basis with probability P_{01} (P_{10}) from the B (G) state to the G (B) state. The probabilities that channel being at the B state and the G state (steady state conditions) are P_0 and P_1, respectively. Hence, we have:

$$P_1 = \frac{P_{01}}{P_{01} + P_{10}} \tag{1}$$

$$P_0 = \frac{P_{10}}{P_{01} + P_{10}} \tag{2}$$

The average time between state transition can be expressed by $T_G = 1/P_{10}$ and $T_B = 1/P_{01}$.

Under the assumption of independent channel conditions and when taking into account that the transmission time statistic of the packet at the head of device buffer is different from that of the following packets, the first transmission attempt of packet at the head of the polled device may be successful with probability P_{01} or unsuccessful with probability $1 - P_{01}$. Conversely, the first transmission attempt of any packet in a lower queue position may be successful (unsuccessful) with probability $1 - P_{10}$ (P_{10}), since channel must be in the G state whenever a new packet reaches the head of the transmission buffer (i.e. the transmission attempt of the packet ahead has had success).

We define the number of nodes communicating with the master during nth polling cycle of piconet is $A_n^{(i)}$, the length of the nth piconet polling cycle, with respect to node i expressed in slots is $L_{n,i}$, the number of packets buffered at node i when this node is polled during the nth cycle is $Z_n^{(i)}$, and $N_{n,k}^{(i)}$ is the number of packets arriving during the kth slot of the nth cycle at node i (equal or less than 1 from the connected source when packet arrivals are set aligned with time slots).

Define $N_i(Y_n^i)$ as the total number of packets served at node i during the $(n+1)$st polling cycle, given Y_n^i, represented as Markov chain vector; and $W_i(Y_n^i)$ as the sum of the waiting-time components of all packets served at node i, in the $(n+1)$st polling cycle. These definitions give us [10]:

$$N_i(Y_n^i) = Z_{n+1}^{(i)} \tag{3}$$

$$\begin{aligned} W_i(Y_n^i) = \; & \Big\{ N_{n,1}^{(i)} \cdot (L_{n,i} - 1) + N_{n,2}^{(i)} \cdot (L_{n,i} - 2) + \cdots \\ & + N_{n,L_{n,i-1}}^{(i)} \Big\} + \sum_{l=1}^{Z_{n+1}^{(i)}} W_{n,l}^i \cdot I(Z_{n+1}^{(i)} \geq 1) \end{aligned} \tag{4}$$

where the terms $W_{n,l}^i$ are defined as

$$W_{n,l}^i = \left[\left(\sum_{k=1}^{l-1} w_{n,k}^i \right) + (l-1) \right] \cdot I(l2) + w_{n,l}^i \tag{5}$$

with

$W_{n,l}^i$ waiting time of packet l at node i in the polling cycle n, $w_{n,l}^i$ delay for packet l at node i in the polling cycle n due to its retransmission (if any), I indicator function.

In figure 4, an approach for inter-piconet scheduling is presented. The background of this approach is to allocate just enough capacity to meet Quality of Service requirements (QoS) in the bridge node's time sharing. The demanded QoSs can be buffer sizes, packet delays, number of packet queueing at the nodes in the Bluetooth scatternet network.

Initially, the inter-connected communication is established and the bridge node is set with pre-determined active and sniff or hold intervals to the piconets, which it is present on. Traffic information is periodically sent, through Link Manager, to the masters of the piconets, which take part in the inter-piconet communication. The traffic information can be current traffic loads, utilization, traffic flows within and between the piconets. The offered traffic is estimated and predicted from a record of the collected information. It is also possible to be fed with traffic demand for the piconets. The predicted traffic is compared with the allocated capacity and the inter-piconet scheduler will decide whether it is satisfied the QoS criteria and changes according to the requirements. These decisions are done at regular intervals of length T_S in time slots or after a number of active/sniff or hold intervals. The process of calculation is quite complicated, hence it is suggested to use precalculated tables to achieve real-time applicability. The next step is to use the predicted traffic and offered capacity to decide fair-share fractions of the active, sniff or hold intervals in next period for the bridge node in the piconets, which contain the bridge node. The fair-share fractions, the allocated capacity and the priority class can be used for window size decisions of active/sniff periods at the bridge node.

4. Simulation results

The system in consideration was a Bluetooth network, as depicted in figure 5, which consisted of two inter-connected piconets. The piconet provides full-duplex transmission using time slots, where each slot is 0.625 ms long. Polling in Bluetooth piconets can be done in many different ways. The difference between the polling mechanisms is related to the order in which slaves are polled and the service disciplines used to serve a slave. In this simulation, we use the Fair Exhaustive Polling (FEP) [6] as the polling scheme in the piconet. The FEP gives a high bandwidth efficiency with a fair allocation and still being simplistic. The piconet has a master and N slaves, $0 \leq N \leq 7$ and its traffic can be modeled as in [7]. The inter-piconet data packets are transfered through a bridge node ($S07/S17$, fig. 5). It is possible to send packets in multiple slots, which may be either 3 or 5 slots long. This study considers only single slot data packet transmission between nodes in the network. As we study Bluetooth performance in terms of queueing, it may be assumed there is no packet loss due to transmission errors and buffer sizes of the devices are infinite. Moreover, as mentioned in [9], the piconets were assumed being synchronized, which means there is no guard frames when nodes switched between piconets.

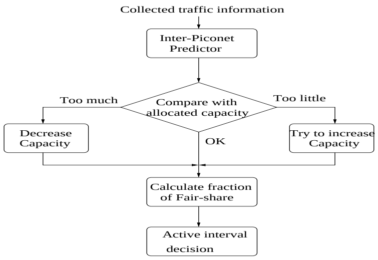

Figure 4: Predictive scheduling approach

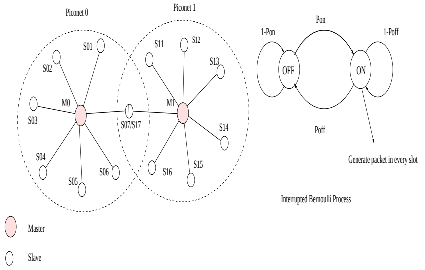

Figure 5: Modeled scatternet with two inter-connected piconets

For homogeneous load scenario, the packet arrivals can be modeled by an Interrupted Bernoulli Process (IBP). Incoming and outgoing traffics between nodes are equally distributed. The probabilities of transitions between ON and OFF states could be characterized by P_{ON} and P_{OFF}. The probability for a packet arrival in one slot is υ and it is set to zero in the OFF state and one in the ON state. The packet arrival is aligned with the time slots for the modeled piconets. In the equations 6 and 7, the probability that a job arrives from one source, ρ and the squared coefficient of variation, C^2, for packet arrival times are used to express the burstiness of the traffic sources, e.g. internet traffic:

$$\rho = \frac{p_{ON}}{p_{ON} + p_{OFF}} \tag{6}$$

$$C^2 = \frac{p_{OFF}(2 - p_{OFF} - p_{ON})}{(p_{OFF} + p_{ON})^2} \tag{7}$$

At initialization, the scheduled inter-connected window period T_S of the bridge node is set to 400 time slots and is fairly

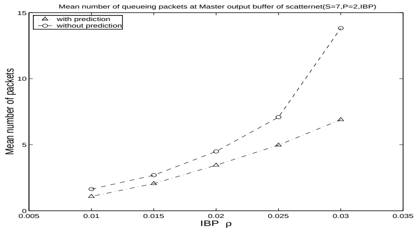

Figure 6: Mean number of data packets in master output buffer, with and without inter-piconet prediction scheduling, piconet FEP polling scheme, homogeneous balanced traffic loads

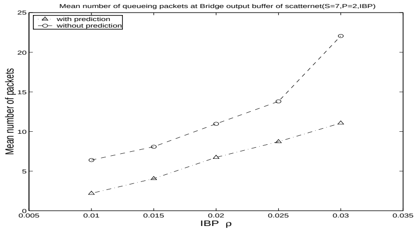

Figure 7: Mean number of data packets in bridge node output buffer, with and without inter-piconet prediction scheduling, piconet FEP polling scheme, homogeneous balanced traffic loads

allocated to the piconets, $P0$ and $P1$, which the bridge node is connected to. The simulation length is 10^6 time slots for all simulations. When applying the inter-piconet predictive scheduling, the scheduled inter-connected window T_S is adaptively updated and changed in accordance with the predicted traffic and queueing packets at output buffers in the network nodes. The allocated active intervals of the bridge node on each piconet, which it belongs to, are dynamically varied depended on inter-piconet traffics and to/from the bridge node.

Figures 6, 7 and 8 show the mean queue lengths at the output buffers of a master, the bridge node and a slave in case of balance traffic. In the balance mode, the traffic to and from a node in the network is assumed to be symmetric and packets from a node are equally destinated to other nodes. It illustrates the mean queue lengths varying according to the changes of traffic loads, which depend on the p_{ON} and p_{OFF} of the IBP traffic sources that connected to the nodes in the network. As can be seen, the mean queue lengths were significantly reduced when applying the inter-piconet predictive scheduling for the bridge node, which was suffered higher inter-connected traffics, masters as well as slaves in the modeled Bluetooth network. It seems that the mean queue lengths were more severely increased when the predictive scheduling was not used in comparison with the case when it was.

In the imbalanced traffic load scenario, the traffic sources in the piconet 0 generated packets with destinating to the nodes in the piconet less than to the outside piconet nodes. This scenario was to determine the working abilities of the predictive scheduling when the traffics were highly imbalanced. The figures 9 and 10 show the results of the imbalanced traffic scenario. The imbalanced rate R_o, which is the probability that the generated packet is destinated to a node within the piconet, which the node belongs to, was set to 0.35 to the piconet 0. It means that there were very high rates of packets from the nodes in the piconet 0 addressed to the nodes in the piconet 1. The destinations for the packets generated from the nodes in the piconet 1 were still kept in symmetric as the previous experiment. The similar results as the balanced traffic scenario can be seen: the mean queue lengths at output buffers at heavy traffic nodes, the master and the bridge node, when applying the predictive scheduling , were lower than when not applying the predictive scheduling. When the imbalanced rates R_o were set equally for both the piconets, 0 and 1, the performance of the bridge node, which is highly sensitive with high external traffic, is shown on the figure 11 for different IBP traffic loads (ρ) and with the predictive scheduling application. It should be noted that when R_o is small, i.e. high inter-piconet traffics.

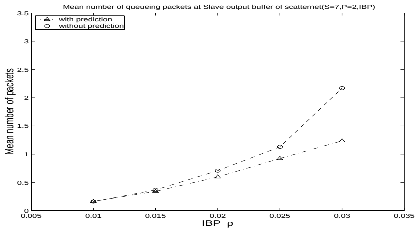

Figure 8: Mean number of data packets in slave node output buffer, with and without inter-piconet prediction scheduling, piconet FEP polling scheme, homogeneous balanced traffic loads

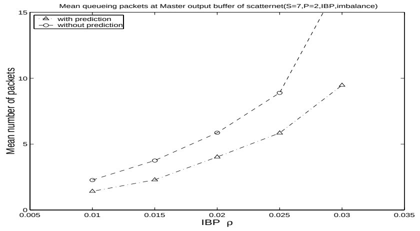

Figure 9: Mean number of data packets in master output buffer, with and without inter-piconet prediction scheduling, piconet FEP polling scheme, imbalanced loads, imbalanced rate $R_o = 0.35$

5. Conclusions and future development

In this paper, the predictive scheduling approach for inter-piconet communications of the Bluetooth network has been highlighted and analyzed. The queueing model in the network has been mentioned. The simulations of the behaviors of the Bluetooth network with and without using the predictive scheduling has been set up. The traffic sources were modeled

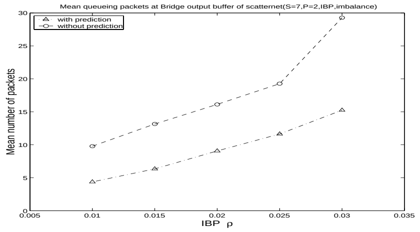

Figure 10: Mean number of data packets in bridge node output buffer, with and without inter-piconet prediction scheduling, piconet FEP polling scheme, imbalanced loads, imbalanced rate $R_o = 0.35$

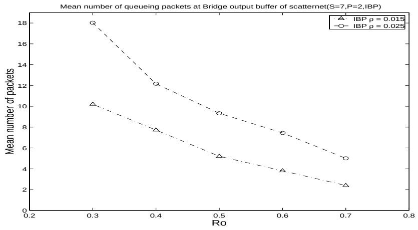

Figure 11: Mean number of data packets in bridge output buffer, with same imbalanced rates R_o for both piconets, with inter-piconet prediction, piconet FEP polling scheme

for bursty traffics (IBP) with considering cases of balanced and highly imbalanced traffics.

The simulation results show that the inter-connected traffics have significantly affected the working ability of the Bluetooth networks and the necessity to control the bridge nodes in the inter-piconet environment. It also shows that by applying the inter-piconet predictive scheduling approach, the performance of the network could have some performance improvements to meet QoS requirements, such as the queue lengths and packet delays.

By defining QoS criteria and constructing appropriate QoS-based predictive scheduler for inter-piconet communications, the working ability of Bluetooth networks will be improved in terms of satisfying the QoS requirements.

We will construct better methods for estimating and predicting traffics, especially Internet traffic. The method will take in to account of different dynamic traffic patterns.

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