Evaluation and Accelerating Bluetooth Device Discovery

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Abstract— As a promising short-range wireless communication technology with the characteristics of interference resilience and power efficiency, Bluetooth is a ubiquitous candidate for wireless sensor network. The device discovery time of Bluetooth is the key for fast connection establishment, and hence successful scatternet formation and maintenance, which are required for wireless sensor networks. The frequency hopping technique used in Bluetooth and the asymmetric device discovery in Inquiry procedure result in undiscovered devices even within radio range. In this paper, we address the problem of device discovery in the context of scatternet formation. We evaluate the factors that affect device discovery process when multiple Bluetooth devices exist within radio range and wish to form a scatternet. Then we introduce a modified Inquiry scheme using extended ID packet to accelerate the device discovery process. Simulation results show that our scheme leads to better performance for Bluetooth device discovery.

Index Terms—Frequency hop communication, computer network performance, personal communication networks.

I. INTRODUCTION

Bluetooth is initially designed to replace a physical cable connecting portable or fixed electronic devices. The recent confluence of advanced micro–sensing technology and enormous novel sensor network applications have opened a new prospect for Bluetooth as a sensor network radio and MAC layer protocol candidate because of its ubiquity, interference resilience, and power efficiency. As an example, the Intel Mote [1] has been developed based on Bluetooth as an enhanced generation of sensor mote platform.

The Bluetooth specification [2] defines a network with a *Master/Slave* structure. One *Master* and up to 7 active *Slaves* form a piconet. Multiple piconets can be linked together to form a scatternet within which multi-hop communication is realized.

The first step for Bluetooth devices to be grouped into piconets and form scatternet thereafter is to be aware of their neighbors. Bluetooth's *Master/Slave* architecture requires both time synchronization and frequency synchronization during its device discovery. Two devices are time synchronization when they are in opposite states (*Inquiry* for *Master* and *Inquiry Scan* for *Slave*) and synchronize in the transmission/reception schedule. The frequency synchronization means two devices hop to the same frequency at the same time. When both of these synchronizations occur, a communication link can be established. The synchronization requirements imply that Bluetooth devices that are in each other's radio range may not even know about the others' existence if they are unsynchronized. In this case, physical proximity does not mean the existence of communication links. In [3], the connection establishment of two Bluetooth devices is evaluated. However, this process becomes complicated when multiple devices exist and interfere with each other, which we will evaluate in the following sections.

Another problem for Bluetooth device discovery is the discovery duration, and hence fast scatternet formation. Most of the existing schemes rely on timeout such as [4]. A recent study on the number of neighbors needed to form a connected wireless network is presented in [5]. It is proved that the network is asymptotically connected if each node is connected to a set of neighbors and the number of neighbors is larger than a value related to the total number of nodes in the network. In the Bluetooth specification, when more than 7 slaves exist within a piconet, some of them have to be parked, which is complicated and time consuming. [6] shows through extensive simulations that in Bluetooth scatternet, 6 and 7 neighbors can guarantee the topology connectivity with high probability. Therefore, the device discovery can be terminated when the specific number of neighbors have been detected. Exiting device discovery by exploiting the limit on the discovered neighbors, rather than waiting for a timeout, has twofold benefits. First, the duration for device discovery is reduced without waiting for timeouts. Secondly, the number of *Slaves* within a piconet is never more than 7. As a result, no device parking is needed in the scatternet formation.

In this paper, we evaluate the performance of Bluetooth device discovery when more than two devices exist within communication range. We discuss the selection of parameters such as mean state residence time and the probability of *Master/Slave* role assignment to optimize the device discovery. The number of neighbors is limited to 7 as stated before to speedup the discovery phase and avoid parking *Slaves*. Based on the properties of Bluetooth device discovery and the performance evaluation, a modified *Inquiry* with Extended ID (EID) packet is then proposed to accelerate the Bluetooth device discovery process for scatternet formation. The performance gain compared to the traditional *Inquiry* is shown through simulations. The modified *Inquiry* scheme can be cooperated into any scatternet formation mechanisms to accelerate the process of device discovery.

The remainder of this paper is organized as follows. Section II introduces the asymmetric property of Bluetooth device discovery and the improvement of symmetric protocol with state alternating. Section III evaluates various factors that affect the performance of Bluetooth *Inquiry* process. Section IV describes our proposed *Inquiry* scheme to accelerate the connection establishment and compares its performance with the traditional *Inquiry* scheme. Finally, the conclusions and future work are discussed in section V.

II. BLUETOOTH DEVICE DISCOVERY

In Bluetooth system, an *Inquiry* procedure is defined for neighbor discovery. The *Master* get the device address and clock value of the discovered *Slave* through the FHS packet whereas the *Slave* has no knowledge of the *Master*. This is the so-called Bluetooth asymmetric device discovery.

The connection establishment delay (D) for two Bluetooth devices with preassigned *Master/Slave* roles is: $D = 2FSD + BD$, where FSD is the frequency synchronization delay, and BD is the delay due to random backoff.

When Bluetooth devices want to establish a communication link without preassigned *Master/Slave* roles, state switching must be in effect in order for devices to be in opposite *Inquiry* states. A symmetric link formation protocol is presented in [7]. In this symmetric protocol, a Bluetooth device alternates independently between *Inquiry* and *Inquiry Scan* states. The state alternation mechanism is depicted in Figure 1. With the state alternating, the factors affecting the promptness of device discovery, especially when multiple devices exist within radio range, are more than the frequency synchronization delay and the backoff delay discussed earlier in this section. We will discuss the effects of two major elements: the initial state a device enters and the residence time in each state in the next section.
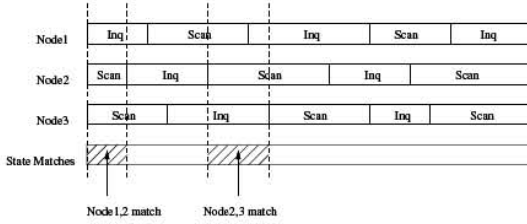

Fig. 1. Symmetric device discovery with state alternation

III. FACTORS AFFECTING BLUETOOTH DEVICE DISCOVERY

In order to measure the speed of device discovery when multiple Bluetooth devices coexist, we limited the number of neighbors to no more than 7 as it is shown in [6] that 7 discovered neighbors can guarantee the connectivity of the topology with high probability. The average node degree was used to indicate the effect of device discovery. The closer the average node degree to the discovered neighbor limit, the higher the probability that the discovered topology is connected. At the same time, the 7 discovered neighbor limit also guarantees that no more than 7 *Slaves* can exist within one piconet. The scatternet formation and communication is simplified thereafter without parking *Slaves*.

To evaluate the effects of various parameters' on device discovery latency, we ran simulation experiments using *GT-NetS* [8], a packet level simulator for large scale network simulation. In our previous work [9], we have designed and implemented a detailed Bluetooth model for *GTNetS*, including a frequency hopping kernel which generates pseudo-random hopping sequences. In order to investigate the properties of device discovery for multiple Bluetooth devices to form a scatternet, we enhanced the simulator with mechanisms for each node to

assume a *Master* or *Slave* role with dynamic probability. In addition, the state alternation between *Inquiry* and *Inquiry Scan* was implemented for the symmetric device discovery.

We ran the simulations following the specification of Class 3 Bluetooth devices with a radio range of 10 meters. The Bluetooth nodes were randomly and uniformly distributed in a geographic square area with sides of 30 meters. The number of Bluetooth nodes was set at 50 to evaluate the performance under moderate node density. The number of neighbors was limited to 7. The effects of the residence time and the probability for a node to assume *Master* role initially are discussed next.

A. Effect of Residence Time

In order for Bluetooth devices without preassigned roles to discover each other, alternation between *Inquiry* and *Inquiry Scan* is needed. Due to the frequency synchronization delay, the residence time at each state of the alternation has an effect on the device discovery delay. It has been shown that fixed state residence time results in arbitrarily large connection establishment time [10]. So we chose random residence time with uniform distribution and varied its mean value. A node was assumed to be a *Master* or a *Slave* role initially with equal probability. We ran the device discovery for 10 seconds and 20 seconds respectively and collected the average node agree. The simulation results are shown in Figure 2.
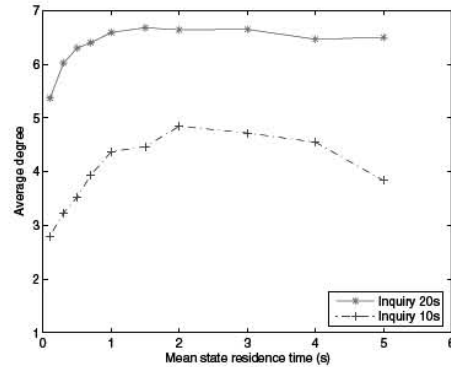

Fig. 2. Effect of mean residence time

Figure 2 shows that the average node degree is relatively stable for the 20 seconds device discovery period as long as the mean residence time is larger than 1 second. This indicates that 20 seconds is sufficient time for device discovery. The average node degree is very close to 7, which means the discovered neighbors can guarantee excellent connectivity of the topology. When the device discovery period is reduced to 10 seconds, the average node degree decreases when the mean residence time is less than 1 second and larger than 4 seconds. This is because when the residence time is too small, it takes several state switches in order to finish the *Inquiry* process, which includes the frequency synchronization, backoff, and frequency synchronization again as illustrated in Figure 4. Therefore, the number of detected neighbors is lower within a specific time duration. The reason for the decreased average node degree with large residence time is waiting in vain for a state switch when devices

are at the same states instead of the opposite *Inquiry* and *Inquiry Scan* states. Figure 2 shows that the optimal mean residence time is around 2 seconds. Thus, the device discovery time can be improved by appropriately choosing mean residence time.

B. Effect of Initial State

The speed at which Bluetooth devices without preassigned roles can discover their neighbors depends on the state switch frequency of each device as discussed in section III-A. Does it also depend on the initial roles that the devices enter? In order to answer this question, we varied the probability that a device is initially assigned as *Master*, and measured the average node degree. The mean state residence time was chosen to be 2 seconds as an optimal value resulting from the experiments in section III-A. The simulation results are shown in Figure 3.
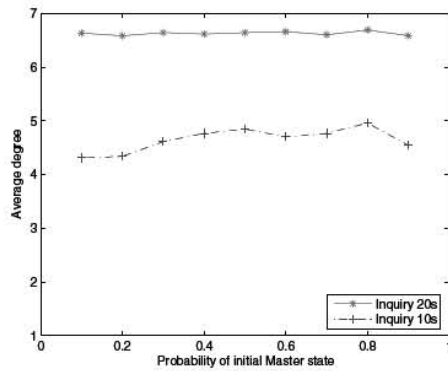

Fig. 3. Effect of probability of initial Master state

From Figure 3 we can see that the probability of a device being initially assigned as *Master* doesn't affect the performance of device discovery too much for the *Inquiry* period of 20 seconds. When the device discovery period is 10 seconds, the average node degree is a little higher with medium probability of assuming *Master* role initially. However, the differences are very small. This is different from our intuition that lower probability of being assigned as *Master* will result in fast device discovery because of the *Master/Slave* ratio within a piconet. The constant performance for various probability indicates that the possibility of discovering neighbors with initial state settings is very small. Most of the device discovery actions require state switches. So the residence time plays a much more important role in Bluetooth device discovery.
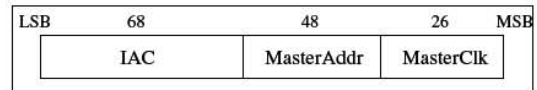
IV. ACCELERATING BLUETOOTH DEVICE DISCOVERY

In section III, we evaluated the effect of residence time and probability of dynamic role assignment on the performance of Bluetooth device discovery. Although the Bluetooth devices alternate between the states of *Inquiry* and *Inquiry Scan*, the knowledge exchanged in *Inquiry* process is still not reciprocal. Devices in *Inquiry* states have knowledge of devices in *Inquiry Scan* states, but not vice versa. For the multi-hop scatternet formation, it is essential to attain mutual knowledge and accelerate the Bluetooth device discovery. Therefore, we propose a modified *Inquiry* with Extended ID (EID) packets as described next.
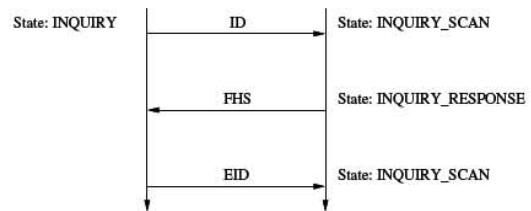
A. EID and Modified Inquiry

The original ID packet in Bluetooth consists of only 68 bits for the *inquiry access code* (IAC). It is used to probe neighbors and to facilitate synchronization. The short *Inquiry* message design is to save energy since the number of ID packet transmissions is very large. The Extended ID packets (EID) structure in our scheme are used in the modified *Inquiry* rather than replacing the original ID packets in order to save energy. Each field and their corresponding length in EID packet are shown in Figure 4(a). The *MasterAddr* is the Bluetooth device address of the *Master* node and the field of *MasterClk* denotes the native clock of the *Master*. They are useful for gaining mutual knowledge in *Inquiry* process.

The *Inquiry* process is modified to accommodate the introduction of the EID packet. The modified *Inquiry* process is illustrated in Figure 4(b). An EID packet is sent by the *Master* after receiving the FHS packet in the normal *Inquiry* process. Since the *Master* attains the device address and clock information of the discovered device (*Slave*) from the FHS packet, it can anticipate the hopping frequency the *Slave* is scanning at and sends the EID packet to the *Slave* at that frequency. In this case, the *Slave* can get the device address and clock information of the *Master* in *Inquiry* process while small size ID packets are still used for the large number of neighbor and synchronization probes.

(a) EID packet format

(b) Modified inquiry process

Fig. 4. Modified inquiry with EID packet

One other work trying to get mutual knowledge for both *Master* and *Slave* is presented in [11]. In this work, a temporary piconet is set up once a new neighbor is discovered. This piconet is transient, lasting only long enough for the exchange of device address, clock value, and other relevant information to achieve mutual knowledge. Although mutual knowledge is attained by this scheme, both *Master* and *Slave* need to leave *Inquiry* and *Inquiry Scan* states in order to set up a temporary piconet by *Page* process. During this period of piconet setup, *Master* cannot discover new neighbors and *Slave* cannot be discovered by other *Masters*. In addition, frequent state switching is needed for temporary piconet setup. On the contrary, our scheme does not need

set up a temporary piconet and switch between *Inquiry* and *Page* regularly. Moreover, without leaving *Inquiry* or *Inquiry Scan* states, the Bluetooth device discovery process is accelerated.

B. Performance Comparison

To evaluate the performance of our modified *Inquiry* with EID packets with respect to the speed of device discovery, we implemented it in *GTNetS* [8] and compared its performance to the traditional *Inquiry* process.

We ran the simulations with the parameters described in section III. The number of Bluetooth nodes uniformly distributed in the area was 30, 50, 70, 90, and 110 respectively to evaluate the performance under different node density from sparse networks to dense networks. The probability of initial role as *Master* was 0.5, and the mean residence time was 2 seconds as the optimal selection from the evaluation in section III. Figure 5 illustrates the simulation results from these experiments.
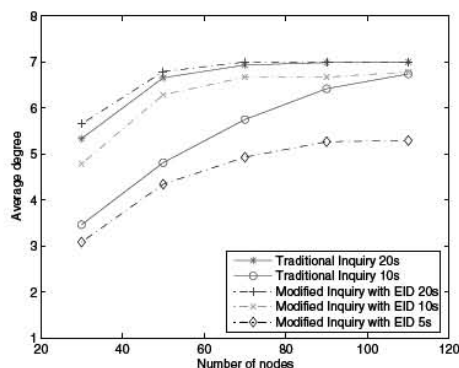

Fig. 5. Comparison of device discovery speed

It is shown in Figure 5 that the average node degree increases for the same device discovery period as the node density increases. This is obvious since more neighbors exist in dense networks, leading to more chances for frequency matching. When the device discovery period is 20 seconds, the average node degree difference between the traditional *Inquiry* and our modified *Inquiry* with EID packet is small. This is because 20 seconds discovery period gives more than enough time for neighbor detection even for the traditional *Inquiry*. In order to distinguish the promptness of device discovery, the discovery period was reduced to 10 seconds. In this case, our modified *Inquiry* scheme shows great advantage over the traditional *Inquiry*, especially for sparse network without high node density. The performance of our modified *Inquiry* scheme with 10 seconds discovery period is comparable to the traditional *Inquiry* scheme with 20 seconds discovery period. This is due to the mutual knowledge exchange we introduce in the EID packets. In addition, although the average node degree decreases with low node density, our modified *Inquiry* scheme achieves much flatter curve as the node density decreases. Even with 30 nodes case, the average node degree for the modified *Inquiry* is still 4.79 whereas it is only 3.46 for the traditional *Inquiry* when the discovery period is 10 seconds. As the discovery period further reduces to 5 seconds, the average degree of the modified *Inquiry* for highly dense net-

work (110 nodes) is only 5.29. Therefore, 10 seconds is a good point for the balance of quick device discovery and topology connectivity guarantee.

V. CONCLUSION

We discussed the issue of Bluetooth asymmetric device discovery and frequency synchronization which contribute to the significant connection establish delay. After that, we evaluated the effect of the residence time and the initial state on the performance of Bluetooth device discovery when multiple Bluetooth devices exist within communication range. The measurement of average node degree was used as the metric for the promptness of device discovery when multiple Bluetooth devices exist and wish to form a scatternet. This is based on the theory of the number of neighbors needed for topology connectivity. The neighbor number limitation will also benefit the scatternet formation after device discovery since no parking is needed for more than 7 *Slaves* within a piconet. Simulation results show an optimal range for the mean residence time selection and the minor effect of initial state on the discovery performance.

In order to accelerate the Bluetooth device discovery process, we proposed a modified *Inquiry* scheme with extended ID (EID) packet for mutual knowledge acquirement. Performance comparison demonstrates the superior of our scheme to the traditional *Inquiry* process in terms of higher average node degree within short discovery period. Our modified *Inquiry* scheme can be used in any scatternet formation mechanisms as the neighbor discovery process.

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