Improved throughput by Interference Avoidance in co-located
Bluetooth networks
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Abstract
The Bluetooth channel is represented by a pseudo-random hopping sequence over 79 RF channels. When more than one Bluetooth piconet is operated in any given location, there will be mutual interference because each piconet selects its hop frequency independently. Packets will be lost whenever nodes hop to the same frequency. The larger the number of co-located piconets, the higher the probability that a packet will be lost due to co-channel interference. By co-ordinating the selection of hop frequency, mutual interference can be avoided. This represents an improvement in throughput with increasing number of co-located piconets. The emphasis in this paper is on minimising interference and consequent packet loss by eliminating co-channel interference when multiple clients access services via co-located access points.

1. Introduction
Usage models of Bluetooth enabled devices often involve nodes accessing services via an access point. For many scenarios envisaged, several client nodes will be used to access services via an access point. In order to provide a large number (>7) of clients to access services at a particular location, several access points will have to be co-located, as each access point can support a maximum of seven clients.

Bluetooth MAC is a Time Division Duplex Frequency Hopping Spread Spectrum. Parameters of the master node in a piconet formed determine the hopping sequence for all nodes in that piconet. The next hop frequency is evaluated based on the Bluetooth device address and the current value of the master node’s native free running clock. There are 79 hop frequencies over which co-located piconets will hop randomly.

Since each access point will, by default, create its own frequency hopping sequence independently, it is expected that there will be a significant measure of interference from these co-located piconets. This co-channel interference would degrade performance if piconets are co-located. A means to minimise or avoid the occurrence of co-channel interference by means of co-ordinating the hop frequency selection between co-located piconets is described in this paper. Related work that seeks to minimise interference is first referenced. Next the selection of hop frequencies is considered, together with a scheme to select mutually non-interfering frequencies when access points are co-located. Finally, a simulator for a co-ordinated piconet arrangement is described, along with a discussion of results obtained.

2. Related Work
Bluetooth devices acting as access points should perform well with only a few nodes accessing them. When the offered load is increased or the number of client devices is increased, access points must be capable of meeting the load, in order to provide acceptable levels of quality of service. One method proposed in [1] to permit a large number of client devices to access an Access Point is to make use of the HOLD and PARK modes [2], in order to support up to 255 devices. While this method increases the number of nodes that may be used at a particular location, it does not improve throughput per client. The method proposed here is to increase the number of access points. Each master will have a number of slaves connected to it in order to distribute the load between them (Figure 1). Collocated piconets may interfere with each other. Throughput will be further enhanced if there is little or no interference at all.

Figure 1 Co-located Piconets

Co-channel and adjacent channel interference is studied by Sousissi in [3]. Important observations are that (i) 20 independent co-located piconets provide maximal system capacity, and (ii) a time synchronisation of piconets (where packet transmissions begin at the same time) allows for a two fold increase in the maximum achievable throughput. Nevertheless, co-channel interference is not eliminated. Significant work has been done on methods of avoiding interference in Bluetooth Piconets especially in the IEEE802.15 task group 2 (TG2) on co-existence issues. [4] [5] [6] [7]. Most of the work addresses coexistence between Bluetooth and IEEE 802.11 technologies. However, the avoidance of interference within co-located Bluetooth piconets is not addressed. Capacity of co-located piconets in the presence of adjacent co-channel interference is discussed in [8].

3. Hop frequency selection
The hopping sequence is unique for a piconet and is determined by the Bluetooth device address (BD_ADDR) of the master; the Bluetooth clock of the master determines the phase in the hopping sequence (namely which portion of the unique sequence is used at
a particular instant). The clock has a resolution of 312.5 μs - a clock rate of 3.2kHz, and has a period of $2^{27}$. The master of a piconet transmits in the even numbered slots starting from 0. The hop frequency used in a multislots packet transmission is maintained during the transmission of the entire packet and the next value is determined by the new/current value of the Bluetooth clock.

The clock is implemented as a 28-bit counter. The input to the hop frequency selection kernel is the 27 or 28 MSBs of the clock (depending on the hopping sequence or substate of the Bluetooth device), and 28 Least significant bits of the 48-bit Bluetooth address. This is depicted in Figure 2.

![Figure 2. Block diagram of hop frequency selection.](image)

Figure 2. Block diagram of hop frequency selection.

Figure 3 shows the hop selection kernel for the 79 hop system. The inputs A...F, X,Y1 and Y2 are bit combinations of the clock as indicated in Table 1, and they take on different values depending on the state of the Bluetooth device. The $A_i$ values indicate the BD_ADDR address bit values. The CLK, and CLKN, are the master and natural clock bit values of the device respectively.

![Figure 3 Frequency hop selection kernel for 79-hop system](image)

Figure 3 Frequency hop selection kernel for 79-hop system

Choosing of hop frequency among co-located APs in order to avoid interference is proposed. One node is chosen as the ‘Lead’ master node from among a set of co-located master nodes, each acting as an access point. The parameters of the Lead Master Node, namely 48-bit Bluetooth address BD_ADDR and 28-bit clock value are passed on to all the other master nodes by a sequence of exchanges at setup time. The 48-bit BD_ADDR is an IEEE defined 48-bit extended unique identifier.[9] All the access points should thus generate the same hopping sequence (implies interference on each hop). A condition where no interference occurs can be obtained if the master nodes hop in tandem using the same hopping sequence, but separated in phase by a number of hop frequencies as in Figure 4.

![Figure 4 Same frequency hopping pattern with time difference](image)

Figure 4. Same frequency hopping pattern with time difference

A set of clock offsets can be determined such that throughout the Bluetooth clock cycle, no co-channel interference will be experienced by any two co-located piconets as illustrated in Figure 5 and Figure 6. All piconets ($P_1...P_n$) will generate the hop frequency using the same Master1 address value. However, different offsets will be added on to the Master1 clock value. This will result in different frequencies being generated for each piconet.

![Figure 5 Clock offsets used simultaneously produce mutually non-interfering frequencies](image)

Figure 5 Clock offsets used simultaneously produce mutually non-interfering frequencies

Thus for any piconet formed, a relationship between the Master Bluetooth address and clock offsets that give no interference is to be sought.

4. Determining suitable offsets

To determine the offsets that offer no co-channel interference to another node using the same Bluetooth address, but with different clocks, the frequency selection kernel has to be evaluated. The address and clock offsets used are noted. To determine that no interference will occur the Bluetooth FH block is evaluated for all possible clock offsets.

5. Observations

Results of the evaluation indicated that

1. For an arbitrary address, the number of offsets that will give no interference in a fixed interval of time is very variable.
2. For a given address, there is no pattern of recurrence of suitable offsets. It appears to be random.
3. Comparing the suitable offsets for two different addresses shows no pattern of recurrence, for example, a uniform ‘shift’ in time at which the offsets occur is not observed.
4. Data collected over an extended period showed no patterns between desirable clock offsets and individual BD_ADDR bit combinations.

5. It may be impractical to have to determine the suitable offsets for a Bluetooth device chosen as the lead node in a co-ordinated piconet arrangement every time one was elected. It takes too long to determine the desirable offsets. (potentially tens of years even with a Pentium processor) Furthermore, there may be too few of such offsets to be useful for certain Bluetooth addresses. In the case of fixed access point installations, these offsets would have to be evaluated once at installation time.

6. Although several offsets may be found which do not offer co-channel interference to the frequencies generated with the natural clock, they are not mutually non-interfering. Once an offset is selected, most of the other offsets become unusable because they were not mutually non-interfering offsets. If more than two picnets/access points have to be co-located, mutually non-interfering offsets are required. The lead node will use its own native clock, the next access point will use offset \( \delta_1 \) and so on as illustrated in Figure 6.

![Figure 6. Co-ordinated piconet use different clock offsets for hop frequency generation](image)

Instead of determining a method to obtain the suitable offsets given any arbitrary BD_ADDR, a universally available or unassigned BD_ADDRs [10] was selected for evaluation. This way, offsets will never need to be re-evaluated at run time whenever setting up a new co-ordinated piconet system. The results obtained would be a one-time solution, which could be standardised and reused for any co-ordinated co-located system. The all-zero addresses (0x00000000) is chosen for consideration. It is possible to set up a large cluster of \( n \) co-ordinated co-located picnets. The lead master node in the cluster is assigned to use the 0x00… address. All other master nodes also share this same address, each master node supporting up to seven client devices each.

For a shorter period of time \( T_{SHORT} \) (instead of the Bluetooth Clock period), a set of offsets \( \delta_i \) have been obtained such that there is no mutual interference. After each \( T_{SHORT} \) period of time has elapsed, the cycle is repeated so that the frequencies generated over this period would be such as not to cause any mutual interference. An arbitrary reduced time \( T_{SHORT} \) of 20 minutes has been chosen because of computational limitations, but could be much longer.

6. Simulator Description

It is desired to simulate a set of co-located access points each with a client terminal accessing it. It is to be determined how much mutual interference is generated and what percentage of packets are lost relative to the number of active access points present at this location, and also to the packet type selected. The number of packets lost per session has an impact on throughput of that session and on the combined throughput of the arrangement. First, an uncoordinated set of nodes using a random selection of BD_ADDRs, each node with its own native clock is set up and simulated. Next, a co-ordinated set where all devices share one BD_ADDR and a suitably allocated clock offset is simulated. The results are compared. Furthermore, a test is carried out to determine what combination of packet types may be used, particularly in the co-ordinated network that produces minimum or no interference.

Each piconet will consist of a master node and one slave. It is not necessary to have more than one slave in this section because the slave hop frequency is determined by the master parameters. Access points (master nodes) are uniformly distributed on a circle of radius 1m and client nodes are on a radius of 8m. All master frequency hops will be generated (for both master-to-slave and slave-to-master transmissions), thus covering all possible frequencies that can be used in any piconet, irrespective of the number of slave nodes. The simulation will cycle through all possible frequencies that will be visited in one (reduced) period (\( T_{SHORT} \)) of the Bluetooth clock.

At the start of the simulation, the topology/layout of the individual nodes is read from a file, along with start-up settings for example the clock offset \( \delta_i \) to be used by each node. Packet type to be used during the session is also specified. The pairing between master and slaves is also set at this time. For an uncoordinated co-located scenario, all nodes have their own unique, natural clock CLKN values and individual BD_ADDR values, also read from the file. On the other hand, in a co-ordinated scenario, all master nodes share the same BD_ADDR, which is assumed to have been passed to the other master nodes during initialisation. Also suitable offsets, which generate mutually non-interfering hop frequencies, are read from the file.

It is also assumed that nodes are in the connection state (a steady state). It is expected that during the initial setup of the co-ordinated system, there may well be interference as in any other uncoordinated system. However, a client would not notice this as there would be no session established yet with any clients at this stage. After the system has been setup, then clients may establish sessions.

For the simulated time, all clock values of all nodes are incremented on each iteration. All nodes whose next stage is to transmit send a packet, and all nodes, besides transmitters listen. In the transmit module, the correct frequency to be used by the current node is evaluated. A packets is generated which holds information about its source and intended destination, and other data to help the recipients filter out un-intended packets, and to evaluate interference. As a first approximation, adjacent channel interference is treated as an additional noise.
source [11]. Packets will be dropped if a certain CIR threshold is not exceeded. Forward Error Correction (FEC) and automatic repeat request (ARQ) are not incorporated. Packets accepted are assumed to be decoded correctly.

Subsequently, after all transmission and reception has taken place, the states of all nodes are adjusted and the cycle is repeated. Nodes that transmitted move into the receive state and vice-versa, unless a multislots packet is being transmitted, in which case the present state is maintained until the complete packet is processed.

Simulations are run with the following combinations of packet types in the co-ordinated system:

- All nodes use same length packets.
- All master nodes use one packet length and all slave nodes use another packet length.
- All master nodes use the same slot length, and most slaves use another length of packet. An increasing proportion of slaves are introduced that use a third packet type.
- An increasing number of master-slave pairs are introduced using an inverse assignment relative to the other pairs in the system. For example, if all master-slave pairs use a 5-slot and 3-slot assignment respectively, pairs are introduced using 3-slot and 5-slot packets respectively.

Starting from scenario 1 above, one slave is introduced with a different packet length. This packet type is changed for each repeat. Next, the number of slaves using this type of packet is also increased in number.

**Assumptions:**

- It is assumed that the access point is the master node.
- The 79-hop system is considered but the principle can be applied to the 23-hop system; the set of offsets used for the 23-hop system has to be determined separately.
- The path loss in dB is given by
  \[ 32.4 + 20 \log(2.4^8d) \text{ if } d < 8m \]
  \[ 58.3 + 33 \log(2.4/8) \text{ otherwise } \]
- There is perfect packet alignment between all transmitting sources, namely, all packet transmission starts at the same instant.
- The duty cycle of all links is 100%, all nodes transmit in every transmit time slot.
- For the purposes of comparison, paging and inquiry procedures are assumed to affect both co-ordinated and uncoordinated systems equally.
- Furthermore, Bluetooth devices are assumed to be in the CONNECTION state.
- The access point can regulate the choice of packet type a client node may use at connection time, to avoid interference.

**7. Results**

There are only 3 categories of packet types under consideration: 1-, 3- and 5-slot packets. It is observed that when all master-slave pairs use the same combinations of packet types, co-channel interference is completely avoided. The combinations that offer no interference at all are listed in Table 2.

When the packet types assignments used by the master and slave packet types are interchanged, namely

<table>
<thead>
<tr>
<th>Master Packet Length</th>
<th>1</th>
<th>3</th>
<th>5</th>
<th>3</th>
<th>5</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slave’s Packet Length</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Amount of interference</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 2 Amount of Interference for packet type used**

This represents all possible combinations of master-slave packet types. When at least one member of the co-ordinated piconet system uses a packet type different from what its peers are using, co-channel interference occurs. If all master nodes use 5-slot packets and all slaves use 1-slot packets, whenever any master switches to using 1-slot or 3-slot packets, a measure of co-channel interference is expected. This situation is avoided by co-ordinating what packet types are used in the system, in order to avoid interference. Thus scenarios 3 and 4 are to be avoided if interference is to be avoided. A switch to 1-slot packets may be due to the need to transmit signalling or control packets.

It has been shown in [3] that the throughput of a synchronous system (one in which packet transmission slot times are aligned) is given by

\[ \theta = N \left( \frac{C-1}{C} \right)^{N-1} Dv \]

where \( N \) is the number of master nodes, \( C \) is the number of hopping channels within the allocated spectrum, \( D \) is the effective channel data rate and \( v \) is the duty cycle of each Master Node. With \( C=79 \), and \( N \) taking values between 1 and 9, the theoretical limit for throughput is illustrated in Figure 7. On the same graph is illustrated the throughput for co-ordinated co-located piconets. Both ignore the impact of control signalling. This plot is for the case where both master and slave nodes use single slot packets.

**Figure 7 Throughput for co-ordinated master nodes (co-ord DH1, co-ord DM1) compared to theoretical limit (DH1 and DM1) in uncoordinated piconets**

As the number of co-located piconets is increased from 1 to 9, the percentage of throughput improvement increases from 0% to 10.73% for both packet types. As the number of Master Nodes is increased, the percentage improvement will increase. These values are identical for both 3- and 5-slot packets. Further, this
8. Implementation issues

To implement this system, the frequency selection kernel should have inputs from a programmatically accessible register that holds the current Bluetooth address. This will permit the BD_ADDR used to evaluate the hop frequencies to be changed to a value other than its native BD_ADDR. Secondly, a sequence of packet exchanges akin to that used by a slave/client node to obtain an estimate of the master clock, or as when setting up a new connection, can be used to set all secondary master clock values.

Only access points or other nodes that may be used in co-ordinated piconets need to be enhanced this way. All client nodes can maintain their current Bluetooth implementation. A physical implementation will require that middleware coordinate the formation of a coordinated network. When not in use in a co-ordinated network, it would act as a normal Bluetooth device, using its native BD_ADDR. There is a deliberate use of middleware to minimise or avoid interference. Further, middleware may be employed to distribute load between the access points and for packet type assignment.

9. Issues and Advantages of co-ordination

A shorter connection time and setup time can be achieved. In a public area, a client may choose to search for the reserved address of the access point and/or page it directly. This is very useful in hand off if the network of “co-located” co-ordinated piconets are actually spread out. Sign up time can be decreased, since only the new clock value should be updated.

Bluetooth devices can be configured to a ‘co-location state’ where they could be used in the formation of such co-ordinated networks, through the use of middleware. Client terminals do not require any modifications at all because the master of the piconet determines the hop pattern. The client terminal evaluates the next hop based on data passed to it about what BD_ADDR and CLK values to use at set up time.

When all access points use the same BD_ADDR, security becomes an issue. However, the security techniques inherent in the existing format may still be used, but not used with the “public address”. The seed value used in evaluating security algorithms can still depend on the native BD_ADDR value.

It is mandatory that all Bluetooth devices support DM1. Control messages are passed on DM1 packet formats. This may present a potential problem of decreased performance whenever there is control signalling. This is under investigation.

10. Conclusion

This paper has shown that it is possible to minimise or eliminate co-channel interference when a number of Bluetooth piconets are co-located, by co-coordinating the hop frequency selection. To determine the next hop frequency, all nodes use the same Bluetooth Device address, and clock values identical to the ‘Lead’ master node’s, but offset by suitable values. Under these conditions, in the CONNECTION state, no co-channel interference occurs when all master nodes use packets of the same length, and all slave nodes also use packets of the same length. The latter packet length may be different from the former. A significantly improved throughput is obtained from a larger number of co-located APs if the hop frequency selection is co-ordinated.

11. Acknowledgement

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12. References