Interference due to Link Management Signalling in Co-ordinated Co-located Bluetooth Networks

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***Abstract*— In the normal mode of operation of co-located Bluetooth piconets, nodes in different piconets transmit independently of each other, and thus inband co-channel interference is certain to occur from time to time. Co-ordinated co-located access points (CCAP) however offer significantly higher throughput than both the uncoordinated synchronous and asynchronous cases because an interference avoidance scheme is employed when in the Bluetooth CONNECTION state. However with a CCAP system, some interference is observed to occur when Link Management Signalling (LMP) takes place. The varying amount of interference generated due to Link Management signalling, the conditions under which it occurs and how this may be avoided or minimised is examined in this paper. It is shown that under certain conditions the CCAP scheme still outperforms normal Bluetooth systems even with the inclusion of LMP signalling.**

Keywords-Bluetooth; coordianted; colocated; signalling; LMP; interference;

I. INTRODUCTION

Bluetooth [1] transmitters use a frequency hopping spread spectrum scheme. The choice of hop frequency for any time slot is selected independently within each piconet by its master node. Thus when several Bluetooth nodes are operated in the vicinity of each other, interference is expected to occur from time to time, randomly. Co-located Bluetooth piconets are generally neither co-ordinated nor synchronised. In analysing interference and throughput of co-located piconets however, a simplifying assumption is often made, that the transmit and receive time slots of all piconets are aligned. This is described in literature [3][4][5][6] as a “synchronous” system. The starts of transmit-receive slot times are aligned across all participating nodes. A synchronous system gives better throughput results than an asynchronous case, nevertheless, the CCAP scheme does better.

The hop frequency is determined by two variables: the Bluetooth address and clock of the master node. It has been shown that by fixing one of these variables, the Bluetooth address, and by suitable choice of clock offset values for all participating access points, interference can be mutually avoided between all co-located piconets[2]. In this Co-ordinated Co-located Access Point scheme (CCAP), all master nodes transmit one packet type, and all slave/client nodes negotiate for a packet type at session startup. This synchronised co-ordinated selection of hop frequencies offers a significantly improved throughput over the uncoordinated case. For example, when single slot packets are in use, a 12.67%, 32.75% and 54.09% improvement over the unsynchronised, asynchronous case when 9, 20 and 30 Access Points (AP) are co-located is achieved. These results are however obtained under “steady state” CONNECTION state conditions and ignore the impact of LMP signalling. LMP defaults to using single slot packets irrespective of what packet type has been chosen in the CCAP scheme. With no Link Management Protocol (LMP) signalling, no interference occurs and hence no subsequent retransmissions are required, aggregate throughput is the maximum that can be expected -baring interference and noise from other sources, or other radio propagation effects.

The focus of this paper is to evaluate the impact of LMP signalling on sessions in a CCAP system. The conditions under which the impact of LMP signalling is minimal or maximal are identified. CCAP, synchronous and asynchronous piconets, with single and multi-slot packets, identical and mixed packet type transmissions between AP and client, and between piconets are explored. The expression CCAP is used to distinguish this co-ordinated scheme from a “synchronous” or “synchronised” arrangement (also described) that lacks the “co-ordination” between participating nodes.

II. THEORETICAL LIMITS

The theoretical limits on throughput are obtained analytically, and are compared to results from simulation based on the co-ordinated co-located access point (CCAP) scheme under various conditions. The CONNECTION state in Bluetooth is examined and this is limited to single slot packet interferers, for the purpose of comparison with the CCAP system undergoing LMP signalling. Worst case conditions where nodes always have packets to transmit is considered. It is assumed that nodes are co-located, thus all packets transmitted on the same frequency are lost; neither path loss nor adjacent channel interference is considered. Interference is the result of time overlap and frequency coincidence of transmitted packets.

A. *Synchronous case*

This assumes all packet transmissions begin and end at time slot boundaries.

Single Slot and Identical Muli-slot packet types: The probability of a successful transmission P_s between two nodes within a piconet, in the vicinity of another piconet is (1-1/f), where f is the number of hop frequencies. 1/f is the probability that the transmission fails because the two piconets choose the same frequency. With n-1 possible interferers in a piconet, assuming the maximum achievable throughput in a piconet is φ, the combined throughput for n such piconets is $\vartheta(n) = n\varphi(1-1/f)^{n-1}$. This represents a higher throughput that the unsynchronised case. Nevertheless, it has been shown that the CCAP outperforms even the synchronised Bluetooth system (e.g. at n=30, the percentage improvement is 44.69%) [2]

Mixed packet types: In the CCAP scheme, single slot interferers will occur as a result of LMP signalling, although all other sessions may be using a longer packet type. Longer packets may be affected by more than one short packet. Figure 1 illustrates a 3-slot packet that receives interference from 3 other piconets at different times.

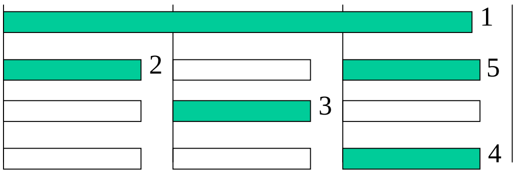

Figure 1. A packet may have more than one potential interferer over its duration

With *m* nodes signalling and transmitting single slot packets in a set of *n* co-located piconets, the probability of successful transmission is the probability that neither a *t*-slot packet nor a 1-slot signalling packet causes the interference. Probability of successfully transmitting a *t*-slot packet is $P_{st}=(1-1/f)^{(n-1-m)}.(1-1/f)^{t(m)}$ where *t* is either 3 or 5, depending on which packet type is in use. This expression is valid if the number of interferers is more than one.

B. *Unsynchronised case:*

This scenario represents the real world deployment of co-located access points. Neither synchronisation nor co-ordination exists between nodes.

Single slot packets: For an unsynchronised system, where transmission time slots in piconets are not aligned, packets transmitted in other piconets may overlap the desired packet to varying extents. More than one packet may interfere with a desired packet as illustrated in Figure2. The slot occupancy of packets are also taken into consideration- packets do not occupy an entire slot. Let t_d be the duration of a packet transmission, and t_s the slot length. The length of 1, 3 and 5 slot packets are presented in Table I.

TABLE I. PACKET DURATIONS

Packet type	Slot occupancy (µs)
1-slot	366
3-slot	1622
5-slot	2870

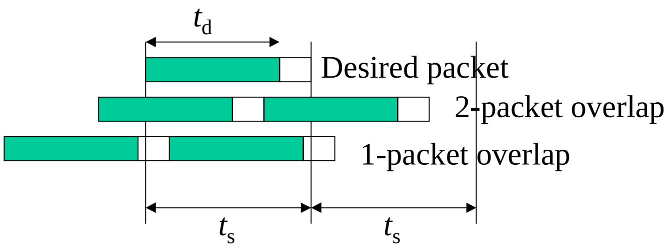

Figure 2. Asynchronous piconets, showing packet possible positions (identical packet length types)

For n co-located piconets (n-1 interferers), the probability of successfully transmitting a one-slot packet in the presence of unsynchronised 1-slot packet interferers (taking account of the mean of the distribution of interferers) is evaluated in [3] as

$$P_s = \left(\left(\frac{2(t_s - t_d)}{t_s} \right) \left(1 - \frac{1}{f} \right) + \left(\frac{2t_d - t_s}{t_s} \right) \left(1 - \frac{1}{f} \right)^2 \right)^{n-1}$$

Multi-Slot packets: In co-located systems employing a *t*-slot packet type, a second interfering piconet also employing t-slot packet will be such that over an entire session, either *t* packets will always overlap the desired packet or *t*+1 of them will. In general, the number of packets that overlap, (assuming the worst case where the interferer always has a packet to transmit) will remain constant. This will vary from piconet to piconet, but stay the same for one piconet.

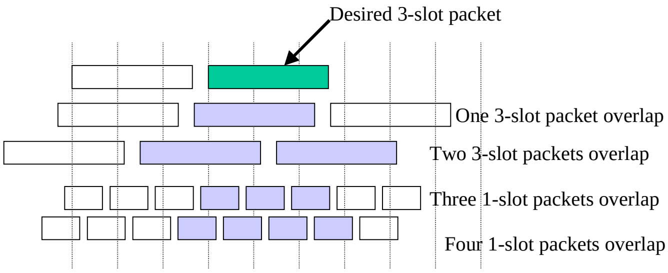

Figure 3. Interference from 3-slot and 1-slot packets

Let $t_{p_1}, t_{p_3}, t_{p_5}$ represent the packet duration of 1-, 3- and 5-slots respectively. For a 3-slot packet affected by single slots, one 3-slot packet may be affected by three or four single slots, depending on the extent of overlap in the offending piconet. The time over which four packets cause interference is $(2t_{p3}-3t_s)$ and the time over which the packet is subject to interference from exactly three packets is $2(3t_s - t_{p3})$. Where there are also 3-slot packet interferers, a single 3-slot packet is affected by one or two 3-slot packet interferers. The period over which the desired packet is exposed to a single packet is $2(3t_s-t_{p3})$ and $(t_{p3}-3t_s)$ to double interferers. The probability of correctly receiving a 3 slot packet in the presence of single slot packets is

$$P_s = \left(\left(\frac{2(3t_s - t_{p_3})}{3t_s} \right) \left(1 - \frac{1}{f} \right)^3 + \left(\frac{(2t_{p_3} - 3t_s)}{3t_s} \right) \left(1 - \frac{1}{f} \right)^4 \right)^{n-1}$$

If the interferers are 3-slot packets only, the probability of success is then

$$P_s = \left(\left(\frac{2(3t_s - t_{p_3})}{3t_s} \right) \left(1 - \frac{1}{f} \right) + \left(\frac{2t_{p_3} - 3t_s}{3t_s} \right) \left(1 - \frac{1}{f} \right)^2 \right)^{n-1}$$

For successful transmission in an environment where piconets transmit 3-slot packets but with n_1 engaged in signalling using single slot packets, the probability of successful 3-slot packet transmission will then be

$$P_s = \left(\left(\frac{2(3t_s - t_{p_3})}{3t_s} \right) \left(1 - \frac{1}{f} \right)^3 + \left(\frac{(2t_{p_3} - 3t_s)}{3t_s} \right) \left(1 - \frac{1}{f} \right)^4 \right)^{n_1} \times$$
$$\left(\left(\frac{2(3t_s - t_{p_3})}{3t_s} \right) \left(1 - \frac{1}{f} \right) + \left(\frac{2t_{p_3} - 3t_s}{3t_s} \right) \left(1 - \frac{1}{f} \right)^2 \right)^{n-1-n_1}$$

Similar expressions can be obtained for the probability of correctly receiving single slot LMP signalling packets in the presence of 3-slot packet "interferers", as well as for use of 5-slot packets. Figure 4 represents the plots of probability of packet loss based on these functions where the co-located piconets employ single-slot (1-1), 3-slot (3-3) or 5-slot packets (5-5) between master and slave nodes. From the legend, an *x*-*y* curve represents the case where the master transmits *x*-slot packets and the slave transmits *y*-slot packets in the reverse direction.

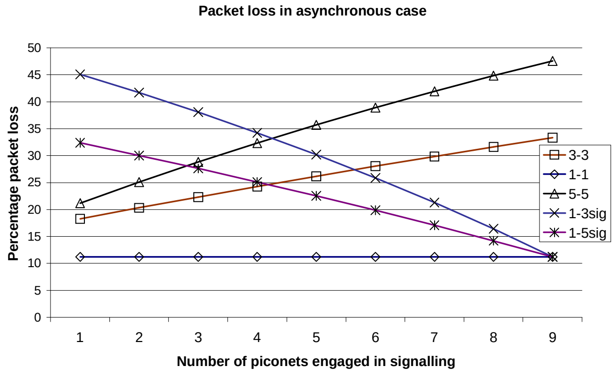

Figure 4. Analytical evaluation of packet loss in asynchronous environment

In all cases, there is an increasing number of nodes introduced that are signalling, acting as sources of interference. The probability of failure to receive a signalling packet is also indicated (1-3sig), (1-5sig) which respectively represent the probability of incorrectly receiving the LMP signalling packets in the presence of 3-slot and 5-slot packet "interferers". The longer packet types interfere with the correct reception of the signalling packets. The 1-1 case shows no variation because both the data packets and signalling packets are single slot packets. The probability of failed LMP packets decreases as the number of nodes using 1slot packet increases, and approaches the case where all nodes use 1slot packets. On the other hand, the probability of loss for *t*-slot packets increases as the number of LMP packets increase. The net probability of successful transmission is the probability both the desired packet and the signalling packet are correctly received.

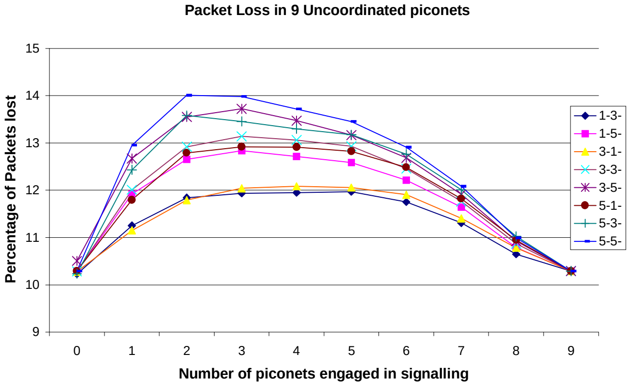

Figure 5. Probability of packet loss in synchronous system

Similar curves based on analysis can be drawn for the synchronous case. Figure 5 represents curves obtained from a simulation of such a system. (excludes case for 1-1 packets). As before, the number of piconets engaged is signalling is increased from 0 to 9. The interference that occurs when all piconets are engaged in signalling (abscissa =9) is the value expected when all nodes are transmitting single slot packets.

III. CO-LOCATED CO-ORDINATED ACCESS POINTS:

Single and multi-slots packets: It has been shown in the CCAP scheme proposed[2] that there is a higher throughput because no interference occurs in the steady state connection state. Some interference however occurs when link management signalling takes place because the LMP packets will default to using single slot packets. This has been simulated to determine the extent of packet loss that occurs.

The simulation makes use of sets of co-located APs, each consisting of one master-slave pair, making use of all available frequencies in each piconet. In each piconet, a pair of packet types is selected to be used by the master and slave nodes in their transmissions (they may be identical sometimes). All nodes in the CCAP system will use the selected types of packets. All nodes are in the CONNECTION state. When using the packet types assigned in each piconet while in the CONNECTION state, no interference occurs. An access point and its corresponding client node is then introduced that performs LMP signalling continuously during the entire session of simulated time. This is implemented by a continuous transmission of single slot packets by both the master and slave node involved in the LMP signalling. This is a worst case scenario. The effect of this signalling on all the other piconets is determined and graphed. The values presented represent the ratio of the total number of packets lost due to co-channel interference in the entire CCAP system, to the total number of packets actually transmitted. There are a total of nine (9) co-located piconets in the CCAP simulated.

IV. RESULTS AND OBSERVATIONS

Two sets of simulations results have been carried out (a) with clock offsets used in the CCAP closely spaced (less than the slot duration of a 3 packet slot) and (b) with wide separation between the clock offsets.

1) *Case A:*

Figure 6 represents the average percentage loss in a CCAP system with nine co-located piconets. This is the average taken from results of 28 runs. As the number of nodes that are involved in signalling is increased, the percentage packet loss increases untill the number of APs involved in signalling is almost equal to half the number of APs using the prescribed piconet packet type. The decline in interference is because as more than half the APs are involved in signalling, more than half of the number will be using the same packet type (single slot packets), which in itself does not cause interference. Thus, the prescribed packet type will then be the source of interference, and not the signalling packets themselves. At the point where all APs are signalling, no interference would be observed.

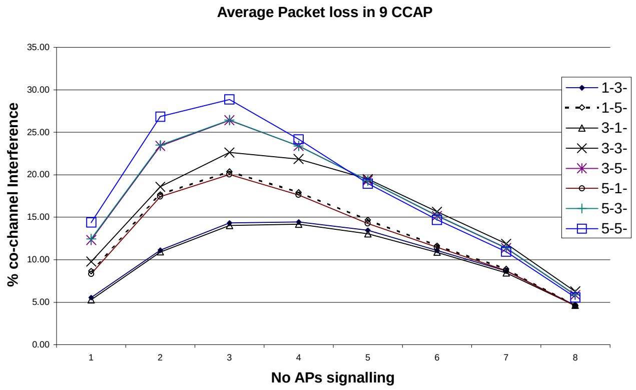

Figure 6. Percentage Packet Loss in CCAP Scheme

When there are no nodes involved in signalling, or when ALL nodes are involved in signalling, the percentage loss is zero. (not indicated on this graph). From the legend, an *x*-*y* curve represents the case where the master transmits *x*-slot packets and the slave transmits *y*-slot packets in the reverse direction. The curve for the case when a master transmits an *n*-slot packet and the slave returns an *m*-slot type packet is almost identical to the case when the master and slave now use *m*- and *n*-slot types respectively (interchanged assignment). Comparing Figure 5 to Figure 6, it is evident that depending on packet type, the packet loss can be higher, comparable or lower in the CCAP than in the uncoordinated case.

The graph in Figure 6 does not tell the entire story. It only represents the average percentage packet loss in each piconet. When the source data is examined, although an arrangement may appear to have a high percentage of packets loss, in most cases, almost all piconets have successful undisturbed transmission, often 100% of the time. However, a small number (e.g. 2) of access points may have most of their transmissions interfered with by signalling packets. Losses can be of the order of 50%-100% in such a piconet, although all other APs in the same CCAP system would be received without error.

This feature of high packet loss in some piconets and none in others is related to the clock offsets used in the CCAP, and to which master-slave pair is involved in signalling. Most of the clock offsets that have been used in this simulation are related. There is only a difference of 4 between many of the consecutive clock offsets that have been employed. This difference of four actually represents a two hop frequency difference between two piconets. The implication is that when piconet A uses a hop frequency f1, two hop frequencies later (two slots later), piconet B will also use the same hop frequency f1. This presents no problem as long as all nodes use the same packet types in transmitting and receiving, even if they are multi-slot packets. However, with one node engaged in signalling and transmitting single slot packets, it would make use of every hop frequency available (as in the worst case scenario described in the simulation). Figure 7 illustrates a CCAP scheme with master nodes transmitting 3-slot packets and client nodes transmitting single slot packets. Piconet B is engaged LMP in signalling. Piconet A operates trouble free, whereas all master transmissions in Piconet C receive interference from Piconet B. In this particular case, every other master transmission in piconet B will be lost. This combined behaviour results in a higher packet loss than in a synchronous system as shown in Figure 6. The result of this will be that it will take a slightly longer time to complete the signalling -up to two times the normal length of time; ignoring capture, path loss and channel conditions. It is noteworthy however that not all the signalling packets are lost, and will thus be successfully completed after a while, after which the CCAP will resume its state where no transmissions receive mutual interference from another piconet.

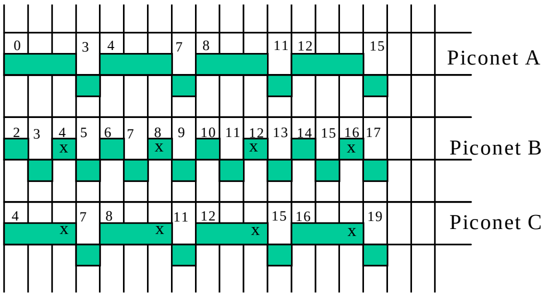

Figure 7. CCAP with piconet B signalling

2) *Case B:*

Using a wider separation between clock offsets, a much lower packet loss is obtained, and the rate at which such mutual interference will occurs (if at all) during signalling is reduced to a random event. This is illustrated in Figure 8. The percentage of packet loss is now reduced to less than 2.5%. Figure 8 and 9 represent the results from using 6 co-located piconets. 1 to 6 piconets are engaged in signalling. The result for no piconets engaged in signalling has been omitted, -that case has no interference reported.

For the sake of comparison, the results for a CCAP with 6 co-located piconets is presented in Figure 9. It is evident that this has a similar characteristic to that that in Figure 6. There is clearly a very significant decrease in interference when the clock offsets are separated sufficiently. The results indicate a decrease from a range of 8.14-28% down to a range of 0.69-2.26%.

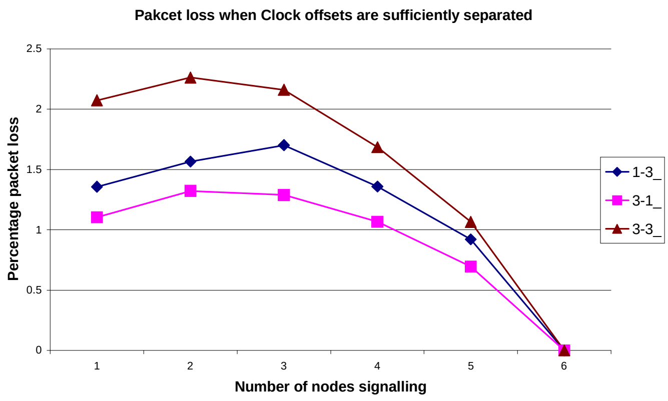

Figure 8. Packet loss when clock offsets are widely separated

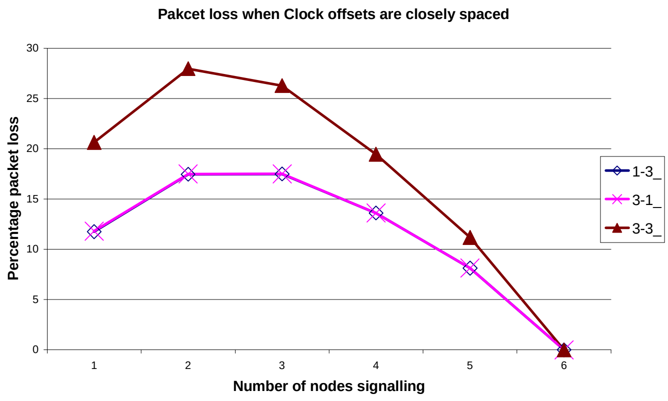

Figure 9. Packet loss when clock offsets are closely spaced

It is also observed that the curve for the case when a master transmits an *n*-slot packet and the slave returns an *m*-slot type packet is almost identical to the case when the master and slave now use *m*- and *n*-slot types respectively (interchanged assignment) as in Figure 5.

Based on the curves in Figures 6 and 9, it is evident that interference increases with increased numbers of co-located piconets when closely space offsets are used in the CCAP. Nevertheless, this is also true of uncoordinated, unsynchronised systems. A similar conclusion cannot yet be made for the case where piconets use offsets that are widely spaced. This is pending further investigation.

V. CONCLUSIONS

Packet loss due to LMP signalling in CCAP schemes is significantly lower than in the synchronised (and consequently less than in the asynchronous case) if the clock offsets used are sufficiently spaced. On the other hand, if the offsets used are closely spaced, a higher packet loss occurs during signalling. For the master and slave transmitting single slot packets in the CCAP, no interference is noticed at all during LMP signalling.

The scenario investigated represents the worst case when there is a continuous presence of at least one master slave pair using engaged in LMP signalling. Typically, in a session LMP commands will only constitute a small percentage of the number of packets transmitted during an entire session. Thus most sessions will operate error free, until there is the need to make a change to the state of a session, to establish or to tear down one. The assumptions typify the worst case- any incidence of co-channel interference results in packet loss, irrespective of signal strength received; and that some nodes are constantly signalling. Thus, in practice, less interference would be expected as a result of co-channel interference.

Though some interference may result from LMP messaging while in the CONNECTION state, the net effect is negligible compared to the huge gains due to synchronisation. LMP signalling occurs over short time intervals, and thus this coordination approach is still a much better result than with uncoordinated co-located piconets.

VI. ACKNOWLEDGEMENT

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