An Asynchronous Time Division Multiplexing - Multiple Access Protocol for Indoor Wireless Multi-service Networks

Tim Farnham, Hewlett-Packard Laboratories, Bristol

Abstract : This paper describes an Asynchronous Time Division Multiplexing - Multiple Access (ATDM-MA) protocol which is designed to support different types of service on future wireless indoor local area networks. The proposed architecture does not follow the conventional cellular or ad-hoc approaches but still supports both peer-to-peer communication and infrastructure access. It is assumed that a high bit rate (20Mbits/s) radio solution is used to provide the physical connectivity with omni-directional antennae. The goal of the ATDM-MA protocol is to provide efficient channel utilisation and re-use and operates in conjunction with different Medium Access Control (MAC) protocols for different traffic types (i.e. polling and random access). The throughput and delay of the proposed scheme obtained from computer simulation shows that good performance can be achieved with modest complexity.

INTRODUCTION

The purpose of wireless networking is to provide tetherless communication service connections. This is attractive for applications in which mobility is an absolute necessity (such as in vehicles). However, in an indoor business or home environment mobility has not been a requirement of high importance (in general cables can be used at a lower cost). However, the benefits of wireless networking become increasingly attractive to domestic and business network users as performance improves and the size and cost of portable appliances reduces. Removing the constraints which cables impose on the way in which computers and other information appliances communicate with each other could provide enhanced flexibility and enable new applications to emerge. Portable multimedia terminals, such as those described in [1], will soon be used in the home and workplace to provide video on demand, banking, shopping, entertainment, web browsing and other services to mobile users. The wireless network must allow for this degree of flexibility.

Frequency re-use partitioning is conducted in wireless networks to provide efficient utilisation of the available bandwidth. Measurement-based Dynamic Channel Assignment (DCA) frequency re-use schemes, such as those described in [2], are generally more efficient for indoor systems than fixed assignment schemes because the indoor channel characteristics can not be easily predicted. However, it is simpler to implement fixed assignment schemes, particularly in cellular architectures with pre-planned base station positions. The most suitable channel assignment scheme for a particular wireless network depends not only on the architecture and types of configuration, but also on the traffic characteristics. Isochronous traffic is most suitably accommodated with dedicated channels for the duration of the call, but such a scheme would be inefficient for bursty asynchronous traffic. Therefore, channel sharing is necessary to provide statistical multiplexing gain when the traffic is bursty. The issues of channel sharing and channel re-use are often treated in isolation resulting in an optimised channel sharing solution with non-optimal channel re-use partitioning or vice-versa (e.g. DECT and IEEE 802.11). However, using a DCA mechanism with time slot re-assignment integrated with a MAC protocol, can enable both efficient channel sharing and re-use, providing that accurate synchronisation between network nodes is maintained. Time slot re-assignment can be performed as in [3], to maintain the grade of service provided by the network in the presence of time varying channel characteristics. This paper combines an ATDM-MA approach to re-use partitioning with both a fully gated limited polling MAC protocol similar to that described in [4], and a random access MAC. The aim is to provide efficient multi-service provisioning on an indoor wireless network. The time-slot assignment scheduling for the proposed ATDM-MA protocol is performed in a distributed manner and is based on a fixed priority discipline depending on the traffic type and on the MAC operating for that traffic type. Global optimisation of time-slot assignments is regarded as being less important than the ability to react to the dynamic channel and traffic characteristics. It is for this reason that small radio cells (logical groups of nodes) are used. Interference estimates are made by taking power level measurements at radio nodes, and distribution of assignment information between schedulers is performed to enable channel re-use with limited co-channel interference.

The research described in [4], [5] and [6] examines polling schemes in cellular architectures that exploit the use of sectored or adaptive antenna arrays. The use of antenna arrays is only practical in the base stations of cellular based wireless networks operating in the frequency bands up to an including 5GHz. At these frequencies the antenna structures are large, cumbersome and expensive and can not be placed on mobile nodes. Omni-directional antennae are to be used with this new ATDM-MA protocol.

NETWORK ARCHITECTURE

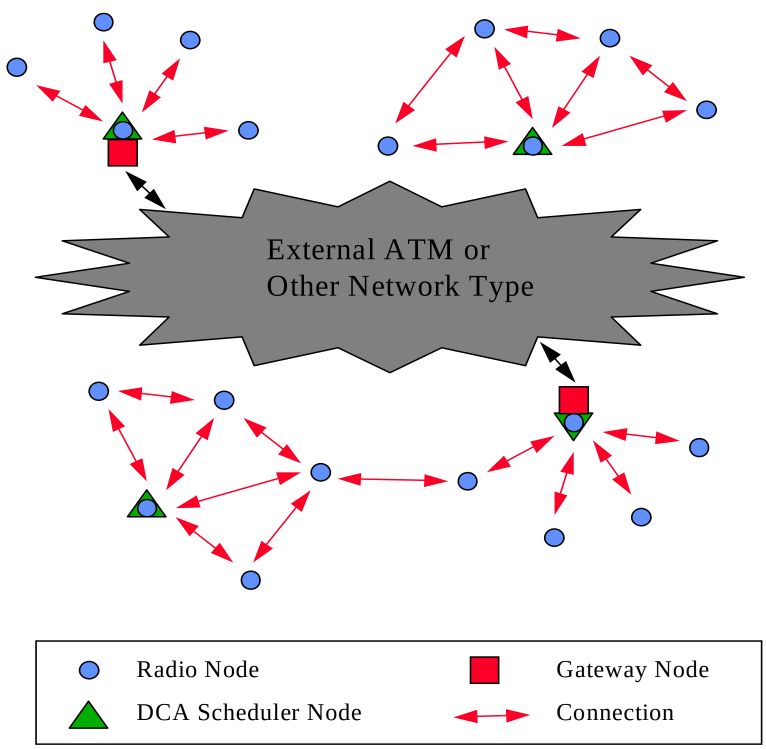

Figure 1 : Proposed Future Wireless Indoor Network Architecture

Future indoor wireless networks will need to be flexible enough to support applications of different characteristics and data rates, and allow both peer-to-peer (ad-hoc) communication and infrastructure access. Peer-to-peer communication is required for efficient provision of short range services (such as between portable computing platforms and other computing platforms or peripheral devices). Infrastructure access is required for retrieval or conversational services between a node and a server or another node in an external network. The architecture proposed for future indoor wireless networks is shown in figure 1. This general view of the architecture is shared by others researching future wireless networking requirements [7].

To be flexible enough to support both ad hoc and infrastructure communications, the proposed architecture consists of three basic functional blocks, a radio node, a gateway node and a DCA scheduling node. The functionality of these node types can be combined in a single node when necessary. The radio node function provides basic control and data communication in accordance with the DCA mechanism. It is also able to take power level measurements to enable the network connectivity to be assessed and to register with schedulers. The DCA scheduler node performs time-slot assignment and re-assignment for nodes registered with it. This node type must also support the registration of nodes and their handover to other schedulers. A distributed DCA approach using instantaneous signal power measurements is proposed because indoor propagation characteristics are difficult to predict. Time slot assignment information is distributed to other active schedulers in a localised area to constrain co-channel interference while attempting to allow maximum channel re-use. Finally, there is an interworking function which provides a gateway to external networks.

TRAFFIC CHARACTERISTICS

It is assumed that the network architecture must support four basic types of traffic:

- Type 0 = Real-time video, audio and data.
- Type 1 = Compressed Video traffic.
- Type 2 = High integrity unicast data.
- Type 3 = Multicast (and best effort) data.

It is proposed that type 0 traffic be supported with a constant bit rate service allocated at the peak bit rate. Types 1, 2 and 3 traffic, which comprise data units of varying sizes (although assumed to be taken from a negative-exponential distribution) will use an asynchronous service to allow statistical multiplexing and therefore an efficient utilisation of resources. These different services are accommodated in the ATDM-MA based protocol, by assigning variable size or a variable number of time-slots and re-assigning them on a periodic basis. To simplify the DCA process, it is proposed that only two sizes of time slot, referred to as slot bursts, be allowed. A short burst for type 0 traffic and a long one for the other traffic types. To accommodate these two burst sizes, a fixed length, basic time period, t, is defined. The burst lengths (short and long) comprise an integer multiple of t; a short busrt (for type 0 traffic) is 2t and a long burst (for all other traffic types) is 16t.

The data unit interarrival time for type 1 traffic is assumed to be constant (with period of 40ms) and exponentially distributed for type 2 and 3. Type 1 traffic is assumed to have a mean data unit size of 3.5kbytes, with a minimum of 2.5kbytes. Similarly for type 2 traffic the mean data units size is 1kbyte with a minimum of 50bytes. Type 2 traffic is error sensitive and requires error detection and retransmission mechanisms to ensure high integrity of data unit delivery. The delivery of type 0, 1 and 3 data units containing errors is assumed to be acceptable. The average data rate of a type 1 connection is 700kbits/s, which approximates to a half size PAL or NTSC video picture with MPEG-I compression ratios [8]. The encoding can be performed inexpensively in software if sufficient processing power is available in the portable terminal devices [9].

THE ATDM-MA PROTOCOL

The ability to re-use the channel at the earliest possible opportunity is the goal of re-use partitioning. The benefit of re-use is illustrated in figure 2, which indicates the channel data rate required for different re-use distances and capacity requirements. A 20Mbits/s channel with a re-use distance of around 60m could achieve an area capacity in the order of 2kbits/s per m^2, but for the same 20Mbits/s channel with a re-use distance of 100m would only achieve a capacity of 700bits/s per m^2 (about a third of the previous capacity).

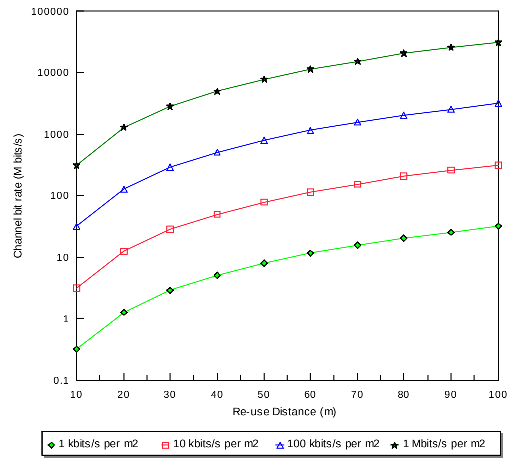

Figure 2 : Channel Data Rate Vs Re-use Distance (for various capacity requirements)

It is proposed that a combined ATDM-MA protocol based on DCA with time slot re-assignment and a fully gated limited polling MAC protocol can provide the asynchronous service required for type 1 and 2 traffic. The isochronous service required for type 0 traffic does not require a polling mechanism because a fixed number of time slots can be allocated and time slot re-assignments performed only when necessary. The asynchronous service required for type 3 traffic can be obtained by random access MAC (based on slotted aloha or slotted carrier sense multiple access) utilising the time slots not assigned to other traffic types.

The ATDM-MA protocol has a slotted frame structure with 20ms period. This period is selected so that it can be assumed that the channel (after multi-path countermeasures) is stationary over the frame duration (also assumed in [4]). Slow fading will occur due to shadowing effects caused by movement in the local area environment. It is assumed that Inter-Symbol Interference (ISI) and frequency selective fast fading are minimised by multicarrier modulation or channel equalisation techniques if necessary. The ISI problem could be less than other high bit rate radio systems (such as

HIPERLAN) if the maximum transmit power and therefore range is significantly lower.

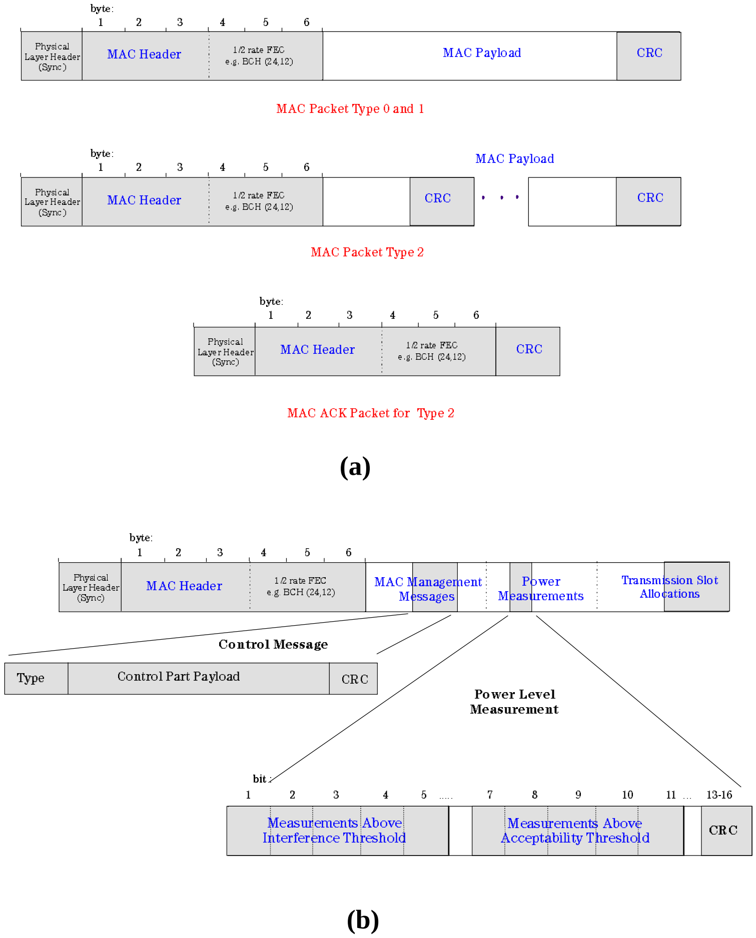

Figure 3 : (a) Data and (b) Control Packet format

The ATDM-MA frame is further divided into a fixed number of segments, each containing a fixed number of slots. Slots are grouped into slot bursts, some short, some long, and slot bursts are allocated by a scheduler node for transmission of one or more MAC packets. The format of the various types of MAC packet is shown in Figure 3. The purpose of the slot bursts is to provide a means of allocating capacity at a low level of granularity, but not so low that the overheads associated with assignment by the DCA mechanism become excessive. The optimal size of slot bursts depends on the traffic characteristics, frequency of re-assignment and transmission overheads. It is necessary that all schedulers in a localised area have knowledge of each others' assignments to limit co-channel interference to an acceptable level. The integrity of the distribution of control data, and particularly slot assignments, is important for achieving this. In a cellular architecture it could be achieved via the backbone infrastructure. However, in the proposed architecture the existence of a backbone can not be guaranteed. Therefore, distribution over the air is necessary. Two approaches are possible, one is to extend the range of control message transmissions (by spreading the signal bandwidth compared to the information bandwidth for example). Alternatively, a multi-hop forwarding technique can be used providing the connectivity of the radio network is sufficiently rich. The latter approach is proposed although it may not be appropriate in situations where the system consists of many fragmented islands of nodes.

The distribution overheads of the multi-hop approach can be constrained if a controlled broadcast flooding mechanism is used to distribute the slot assignment and other control information. This is possible because omni-directional antenna are used and the radio medium is intrinsically a shared medium. Therefore, most nodes within a re-use area can receive slot assignment data regardless of the scheduler node density if the connectivity between nodes has sufficient reliability.

The slot burst assignment is based on a DCA algorithm (an illustration of the assignment process is shown in figure 4). Polling of subordinate nodes by each scheduler is used to obtain up-to-date information regarding the type 1 and 2 traffic buffered within each node. The polling mechanism is also used to obtain the power measurement information to assess connectivity and interference susceptibility of node pairs. In order that this can be achieved, each scheduler node in a re-use area is assigned a unique segment number. The first *n* small slot bursts of the segment of an active scheduler are reserved for polling responses from the *n* nodes assigned to the active scheduler. A maximum of (3*n +1) additional small slot bursts may be used to distribute slot allocation information and other management messages to nodes within a re-use area. The format of these control packets is shown in Figure 3b. In an attempt to ensure unambiguous distribution of slot allocation statistics, control packets are broadcast over 4 hops using a controlled flooding technique.

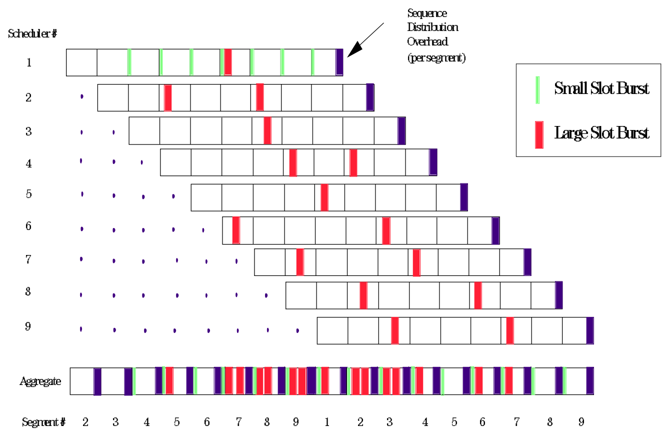

Figure 4 : Example of Slot Burst Assignment

The first hop involves the scheduler multicasting the packet to its neighbouring nodes within radio range. The next hop involves a repeat of this operation for each node assigned to that scheduler. The third hop involves the nodes not assigned to the initiating scheduler receiving the control packet on the second hop, and are not themselves schedulers. Finally, the last hop involves nodes receiving on the third hop and are not themselves schedulers combining the information in the polling response to the scheduler they are assigned to.

Note that this procedure does not guarantee accurate distribution of slot assignment information to the scheduler of all nodes with the potential to interfere with the transmissions. However, in an indoor propagation environment (with an attenuation index of approximately 3.8) it is assumed to be adequate in most circumstances. The worst case signal-to-interference ratio is 18dB in most cases. Note also that the assumption about indoor propagation will not be valid in large buildings with few obstructions. Therefore, the 4 hop distribution will not be sufficient and frequency separation of nodes in different re-use areas will be required. It is proposed that in this case peer-to-peer communication between nodes in different re-use areas is not supported.

The work in [10] examines the synchronisation requirements between nodes in a DCA mechanism. It considers the traditional cellular topology for radio access systems and therefore synchronisation is performed over the cable infrastructure. The synchronisation for the proposed ATDM-MA frame could be based on a narrow band beacon transmitted (by the first active scheduler node or subsequent elected stand-by schedulers in the event of scheduler discontinuing transmission) at the start of every frame. The beacon is transmitted on a carrier with a significantly lower frequency than the data channel. This enables the range to extend over the entire network coverage area with simple transceiver technology. The propagation delay across a network is assumed to be less than 2 microseconds to enable the accuracy of synchronisation to be much smaller than one slot duration without delay compensation.

Instantaneous power level measurements are made by all nodes, except when transmitting their own polling request or response. The first n small slot bursts within segments of active schedulers are reserved for these. These power measurements are compared with two threshold values, the interference and acceptable signal thresholds. This determines the likelihood of interference being caused by the node or the likelihood of a reliable connection being made between the two nodes. This information is passed to the scheduler in the polling response to enable it to form a view of the network connectivity and determine which (if any) simultaneous transmissions can occur.

Conventional frequency re-use schemes with fixed channel assignments in a cellular architecture can utilise 7 channels in a re-use area to provide a minimum signal to interference ratio of 19dB with an attenuation index of 3.8 and non-overlapping hexagonal coverage areas. In an indoor environment the coverage areas will not be hexagonal and there could be significant overlap. This is particularly the case if node positions are not pre-planned. For this reason, 9 schedulers per re-use area is considered to be more realistic for the same signal-to-interference ratio (further investigation is required to justify this choice). It is assumed that 9 segments, and therefore up to 9 schedulers per MAC frame, is sufficient for most scenarios. The slot duration is chosen to be 20 microseconds to correspond to the guard period required between segments. This is greater than the maximum transceiver turn-around time and also equal to the time required to take power level measurements. It also corresponds to the size of a standard ATM cell (with normal header replaced by a 2 byte CRC) if the channel rate is 20Mbits/s. There are 1000 slots per frame and 110 slots per segment (assuming 10 slots per frame are used as guard periods and synchronisation at the start of each segment and frame). The complexity of the scheduling function increases with *n*. However, if the channel utilisation of individual nodes is low and highly bursty, then a higher number of nodes per scheduler can enable a more efficient slot assignment.

Schedulers perform slot assignment for 9 segments (i.e. a frame period) at a time and distribute the slot assignment information in the segment corresponding to the scheduler identifier in the current frame. Each scheduler assigns the slot bursts for types of traffic (*i*) in such a way that the likelihood of allocations causing interference with those previously made within a re-use area is low (based on the power level measurements and an interference threshold). As the schedulers perform slot assignment sequentially, in segment order, there should be no conflict provided that the power level measurements are accurate and the allocations are successfully distributed within the re-use area. The number of slot bursts assigned to each node within a scheduler group *k* by the scheduler *j* (S_{ijk}) is determined by the polling MAC protocol for type 1 and 2 traffic. This is based on a fully gated limited polling mechanism which always attempts to transmit the next message (i.e. data unit) waiting in the queue. More slots are allocated to nodes provided that the scheduler quota (based on the average traffic) is not exceeded. This may be globally sub-optimal, but requires much less distribution of buffer loading information than an optimal solution. Type 0 traffic is allocated a fixed number of slots for the duration of a connection, the allocation being based on the peak data rate. Type 3 traffic is not assigned time slots, but utilises empty slots on a random access basis. Local optimisation of the time-slot assignments can be achieved by using a DCA algorithm which attempts to minimise interference rather than compare interference levels with a threshold (as discussed in [11]). Therefore, a DCA strategy which selects the slot bursts with lowest interference below an interference threshold is desirable, but its complexity is substantially increased.

SIMULATION MODEL

A simulation model was developed to examine the performance of the proposed ATDM-MA protocol and polling MAC scheme with type 1 and 2 traffic. A simple network configuration was used consisting of 5 nodes in a cluster (i.e. scheduler groups) with between 5 and 10m separating each node pair in each cluster, and between 10 and 15m separating the closest pairs of nodes from the different clusters. This could represent clusters of portable multimedia terminals or groups of distributed shared peripherals and computing platforms (as shown in figure 1). The coverage area of the network is approximately 5000m^2, and contains 40 active nodes. For simplicity, the nodes are assumed to be stationary with single hop connections carrying either type 1 or 2 traffic, but predominantly type 1. Each node is assumed to generate traffic having identical characteristics (with random destination nodes selected from those within radio range). The transmit power of the nodes is assumed to be 200mW, with omni-directional antennae and a data rate of 20Mbits/s. A propagation algorithm compatible with indoor operation in the 5GHz frequency band is used. this is expresed as,

$$Pathloss = 40.5 + 10.y.\log(separation)$$

where the separation is expressed in metres and *y* is the attenuation index (path exponent).

A uniformly distributed random error of between +3 and -3 dB is assumed in the power level measurements. Simple stop and wait Automatic Repeat reQuest (ARQ) is used on type 2 MAC data packets (the packet format is shown in figure 3a). To provide the integrity required in data unit delivery, a 16 bit CRC per slot interval is used to detect errors in the type 2 MAC packet. All MAC packet headers are protected by BCH (24,12) FEC which can correct up to 3 bit errors per codeword block and contains a parity checking mechanism.

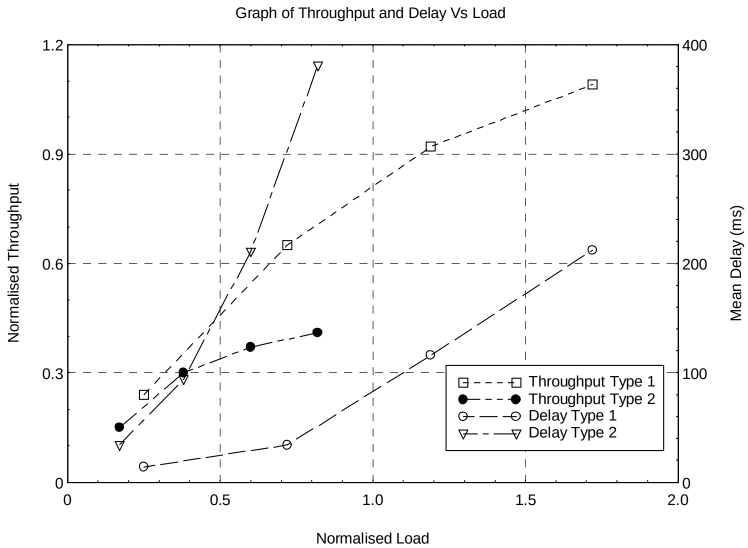

Figure 5 : Throughput and Delay Results for Type 1 and 2 Traffic (-85dBm interference and -60dBm acceptability thresholds)

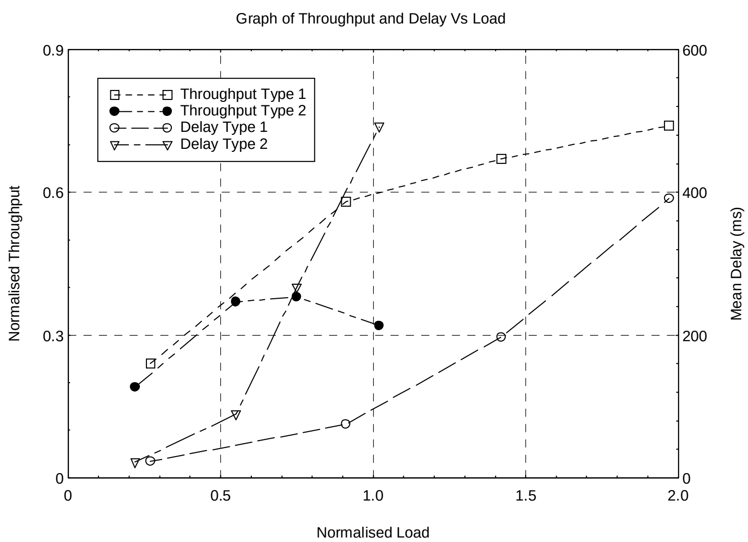

Figure 6 : Throughput and Delay Results for Type 1 and 2 Traffic (-85dBm interference and -65dBm acceptability thresholds)

The MAC packet overhead (including guard interval of approximately the transceiver turn around time) is taken as a slot duration per slot burst and the ACK packet (including transceiver turn around time) is taken as a slot duration per slot burst. The large slot burst size is taken as 16 slots (320 microseconds), therefore the MAC overhead is 1/15 for type 2 traffic and 1/16 for type 1. The polling responses, slot allocations and other management traffic can not utilise ARQ mechanisms because of their broadcast nature. To ensure successful delivery, Forward Error Correction (FEC) techniques are assumed to be used, but these are not included in the model.

RESULTS

The performance of the MAC protocol was obtained with 58% of slots allocated to type 1 and 2 traffic and 42% to combined type 0 traffic, MAC management and control traffic, frame and segment synchronisation and guard periods. The simulation results shown in Figure 5 utilise an acceptability threshold which results in fragmentation of the network into pairs of clusters of nodes. The maximum throughput obtained for type 1 and 2 traffic is high, approximately 100% and 40% of the channel data rate respectively with y=3.8 and only 58% of slots used for data traffic. This corresponds to 28 one-way 700kbits/s video connections and 8Mbits/s of data traffic. The delay performance of the two traffic classes indicate that reasonable delays can be achieved with relatively high traffic loads. However, only 32% of type 1 packets are received error free and 44% of type 2 packets are retransmitted, which is clearly unacceptable. The results in Figure 6 show the the performance of the network with the acceptability threshold reduced by 5dB to allow fragments to be joined. This results in the reduction in maximum throughput to 74% and 38% of the channel data rate for type 1 and 2 traffic respectively, corresponding to 22 one way video connections and 7.6Mbits/s of data traffic. This is equivalent to an area capacity of 4.5kbits/s per m^2. In this case only 8.6% of type 2 packets require retransmission and 84% of type 1 packets are received error free, which is a large improvement. However, the delays are larger for type 1 traffic.

The overhead in distributing slot assignment and channel measurement information depends largely on the number of nodes per scheduler n (if a maximum of 9 segments per frame is assumed). For n equal to 4, a maximum of approximately 17 small slot bursts per segment are required. This corresponds to 31% of all slots (with 50% efficiency this equates to 3Mbits/s). Further work is necessary to determine the full data distribution requirements of all management functions and the level of FEC protection required to ensure reliable delivery.

CONCLUSIONS

The results obtained indicate that the ATDM-MA implementation of wireless multi-service networks supporting peer-to-peer and infrastructure access connections is feasible and worth further consideration. The efficiency benefit of controlled re-use of the radio channel is only fully realised if the propagation attenuation index is high (3.8 is used in these simulations). This will not be the case in large buildings with few obstructions. the consequence will be a reduction in the re-use performance (i.e. reduced area capacity). In this case other channel re-use partitioning techniques could be required.

This paper only addresses the performance of the ATDM-MA mechanism with a polling MAC and not the random access MAC protocol required for type 3 traffic or a fixed number of slot bursts for type 0 traffic. Further work is also necessary to assess optimum slot burst sizes and number of nodes per scheduler for different traffic profiles and node ranges. The issues associated with handover between scheduler coverage areas also need to be addressed. The performance of the ATDM-MA protocol could potentially be improved by power control and optimisation of the interference and acceptability thresholds depending on the propagation environment (path exponent), network loading, traffic types and configuration. This would increase the complexity of such a scheme, but could have significant performance benefits.

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