SCHEDULING IN PACKET RADIO NETWORKS - A NEW APPROACH

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Abstract

In the broadcast schedule construction problem in a radio network, a frame of minimum length provides every transceiver an opportunity for transmission after least amount delay. However, such a frame does not necessarily maximize the network throughput. The network throughput can be increased by choosing a frame of suboptimal length, although in this situation the throughput of some of the individual transceivers might decrease. In this paper we present a schedule construction scheme that takes into account the interests of the network as well as the individual transceivers and finds a balance between the two conflicting interests. The objective of this scheme is to maximize the network throughput without a significant adverse impact on the performance of individual transceivers. This scheme guarantees a network throughput that is at least as large as in the traditional scheduling schemes using the minimum length frame.

1 Introduction

A packet radio network is a collection of radio transmitters and receivers (transceivers) located in a geographical region. Associated with each transceiver is a transmission range, which depends on its transmission power. A transceiver T_j located within the transmission range of another transceiver T_i can receive the messages from T_i. The transceivers of the network share the communication medium for message transfer. This gives rise to conflict situations where two or more of the transceivers may want to use the same shared medium simultaneously. Such conflicts result in garbling and eventual loss of messages. Communication protocols are used to avoid such events. The protocols may be divided into two broad classes, *static* and *dynamic*. In case of a *static* protocol an a priori assignment of the communication resources, such as time, frequency or code, is made among the transceivers to avoid contention. Dynamic protocols have no a priori resource allocation, instead resource requests are met on demand. *Time Division*, *Frequency Division* and *Code Division* multiple access (referred to as TDMA, FDMA and CDMA respectively) are examples of the a priori assignment of resources. ALOHA and CSMA are examples of dynamic protocols. Static allocation is well suited for a steady stream of traffic while dynamic allocation is well suited for a bursty traffic .

In this paper we restrict our attention to static allocation in general and TDMA in particular. However, it may be noted that the results presented in this paper are also valid for other static allocation schemes. In a packet radio network operating under a TDMA scheme, some of the transceivers are allowed to transmit simultaneously. However, the geographic locations and the transmitting powers of these transceivers should be such that not only do they not cause interference to each other but also do not cause interference at any other transceiver which may be within their transmission ranges. In case of a TDMA system, time is divided into fixed length slots and a set of non-interfering transceivers are allowed to transmit in each slot. A *frame* is a sequence of fixed length time slots where a slot is assigned to a set of non-interfering transceivers for transmission of messages and every transceivers appears at least once in a slot. *Frame length* is measured by the number of time slots in a frame. A *schedule* is a assignment of transceivers to the slots. Traditionally, a schedule is said to be *optimal* if it uses the minimum length frames.

The problems associated with the construction of an optimal schedule have been studied extensively by researchers [1, 2, 3, 4]. Most of these studies dealt with the construction of two different types of schedules,*broadcast schedules* and *link schedules*, under two different types of interference, *primary interference* and *secondary interference* [2]. In a broadcast schedule each

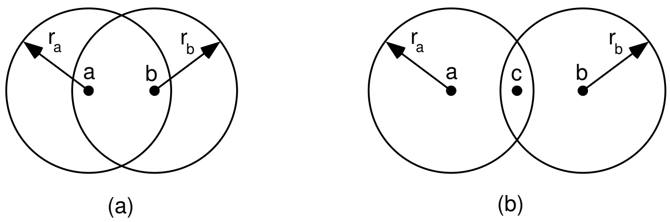

Figure 1: Type 1 and Type 2 Interferences

transceiver is scheduled to ensure collision free transmission of messages to all transceivers within its range. In link scheduling, the transmission of a station is intended for only one specific transceiver within its range and the schedule needs to ensure that there are no collisions. Primary interference is said to occur when a transceiver is expected to perform more than one operation at the same time, such as receiving from two different transmitters at the same time or transmitting and receiving at the same time. Secondary interference occurs when a transmission from a neighboring transmitter unwittingly interferes at the receiving end of a communication between a transmitter and a receiver. Primary interference can be of two types. In fig. 1(a) the transceivers a and b are within the transmission range of one another. In this case if a and b start transmission at the same time, then both the transceivers will be expected to transmit and receive simultaneously. We refer to this as type 1 primary interference. In fig. 1(b) the transceivers a and b are not within the transmission range of one another, but there is a third transceiver c which is within the transmission range of both a and b. In this case if a and b start simultaneous transmissions then c will be expected to receive from both a and b at the same time. We refer to this as type 2 primary interference.

For the purpose of constructing an optimal schedule all prior research [1, 2, 3, 4] modeled a packet radio network as a graph, where a node in the graph represents a transceiver and there is a directed edge from the node v_i to the node v_j if the transceiver j is within the transmission range of the transceiver i. It may be noted that the resulting graph is a directed graph in which the existence of an edge from v_i to v_j does not necessarily imply the existence of an edge from v_j to v_i. However, in a network where the transmission range of all the transceivers are equal, existence of an edge from v_i to v_j will imply the existence of an edge from v_j to v_i.

2 Network Model

We assume that all transmitters are omnidirectional. We draw a circle with the transmitter position at the center and radius equal to the transmission range of the transmitter. This circle represents the area covered by the transmitter. We refer to this circle as the *transmission circle.*

Point graphs were introduced in [3, 4] for the purpose of modeling packet radio networks. Given a set of points $P = (p_1, ..., p_n)$ in an m-dimensional space, each specified by an m vector $(x_1, ..., x_m)$ and a range r_i associated with each p_i, the *point graph* constructed from this set of points is a graph $G = (V, E)$, where each node v_i represents a point p_i and there is a directed edge from node v_i to v_j if $d(p_i, p_j) \leq r_i$, where $d(p_i, p_j)$ is the Euclidean distance between the points p_i and p_j. *Planar point graphs* are point graphs constructed from the points on a two dimensional plane (m = 2).

Optimal Broadcast Schedule Construction (OBSC) Problem

INSTANCE: Given a planar point graph G=(V, E) and an integer constant k.

QUESTION: Is there a partition V=$V_1 \cup ... \cup V_k$ such that if u and v are distinct nodes of some set V_i in the partition then (i) there is no edge from u to v, (ii) there is no edge from v to u and (iii) there is no node w in the graph G such that there is an edge from u to w and from v to w?

The OBSC problem is also known as the *distance-2 k-colorability of planar point graphs* and *distance-2 coloring of planar point graphs.* In [3, 4] it was shown that the OBSC problem is NP-complete. An approximation algorithm for the problem with a constant performance bound was given in [5].

3 Limitations of the Traditional Approach

It is clear form the discussion in the previous section that the traditional approach to the scheduling problem is to construct a *minimum frame length* schedule that is free of type 1 and 2 interference. The *throughput* of a network over a period of time is the number of packets delivered to the destinations during that period. The traditional approach constructs the schedule with the smallest frame length with the objective of maximum utilization of the network resources. However, we show in this paper that dividing the network transceivers into the smallest number of mutually non-interfering groups does not necessarily maximize the throughput.

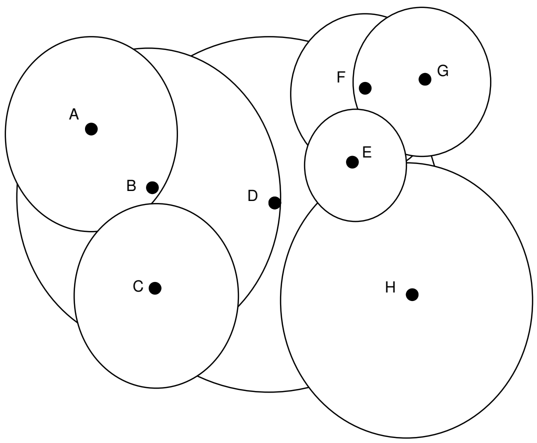

Figure 2: Locations of the Transceivers and their transmission ranges

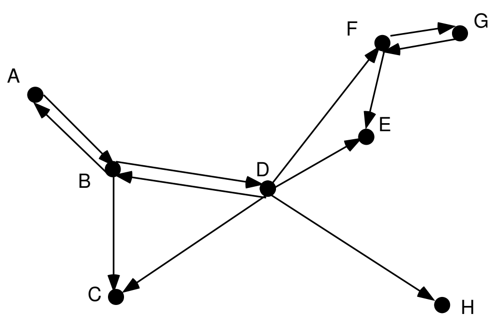

Figure 3: Graph modeling the packet radio network

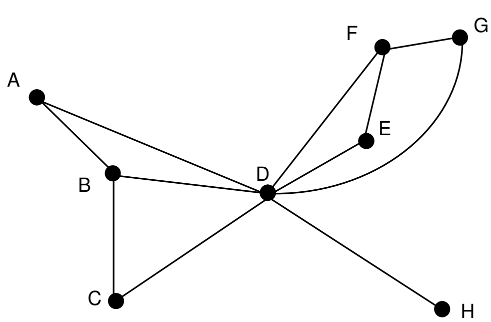

Figure 4: Derived graph of packet radio network

We demonstrate this pheonomenon with the help of an example. Figure 2 shows the locations of a set of transceivers on a plane and their transmission ranges. From the set of locations of the transceivers on the plane and their transmission ranges, we construct a graph $G = (V, E)$ as follows: Corresponding to every transceiver we have a node in the graph G, and their is a directed edge from node u to node v in the graph if the transmission from the transceiver corresponding to node u can reach the transceiver corresponding to the node v. Figure 3 shows the graph model of the radio network of figure 2. In this example the transceivers like B and C should not be scheduled to transmit in the same slot to avoid type 1 interference and the transceivers like A and D should not be scheduled to transmit in the same slot to avoid type 2 interference. From the directed graph G we construct an undirected graph G' as follows: The node set of G' is the same as G. The edge of G' is constructed using the following rules: (i) There is an edge between the nodes u and v in G', if there is an edge from u to v or from v to u in G, and (ii) There is an edge between the nodes u and v in G', if for any node w, there is an edge from u to w and from v to w in G. We will refer to the graph G' as the *derived graph*. The derived graph for the problem instance shown in figure 2 is shown in figure 4. The *chromatic number* of a graph is the minimum number of colors necessary to color the nodes of the graph in such a way that no two adjacent nodes have the same color. It is clear from the discussion that the chromatic number of the derived graph G' gives the minimum frame length schedule for the radio network that avoids both type 1 and type 2 interference.

In our example, the minimum length schedule comprises of three slots with transceivers A, C, E, G, H transmitting in slot 1, transceivers B, F transmitting in slot 2 and transceiver D transmitting in slot 3. If the number of packets transmitted during each slot is x, then the total number of packets transmitted over the duration of a frame will be $8x$. However, it may be observed that if in addition to transceivers B and F, the transceiver H is allowed to transmit in slot 2, it will not introduce any type 1 or type 2 interference but at the same time enhance the throughput per frame to $9x$. Suppose, T, the period of time over which the network throughput is measured (in terms of number of slots) is a multiple of three slots. For our discussion we assume $T = 12y$, for some integer y. During time T, the traditional schedule will transmit $32xy$ packets whereas the modified schedule will transmit $36xy$ packets. Thus it is clear that the traditional approach to scheduling does not necessarily maximize the throughput.

4 A New Approach to Optimal Schedule Construction

It is clear from the discussion in the previous section that throughput can be further enhanced by allowing multiple transmissions by some transceivers within the same frame. For example, we can construct a four slot frame where the transmitters A, C, E, G, H transmit in slots 1 and 2, transceivers B, F, H transmit in slot 3 and transceiver D transmits in slot 4. In this case the number of packets that will be transmitted per frame is $14x$ and the number of transmitted packets in time $T = 12y$ will be $42xy$.

The drawback of this schedule is that transmitters like B, F and D do not get an opportunity for transmission in every three slot any more. In this schedule, they get to transmit in every four slots. As such the throughput for these transceivers will decrease whereas the throughput for the entire network increases. This situation clearly calls for a trade-off between the interest of the individual transceivers and the interest of the overall network. Next we suggest two different schemes that are compromises between the interests of the individual transceiver and the interest of the entire network. Both the schemes try to *maximize* the network throughput without being unduly unfair to the individual transceivers.

For the sake of completeness, we present some standard graph theoretic terminology. An *independent set* in a graph $G = (V, E)$ is a subset $V' \subseteq V$ such that no two nodes in V' are adjacent in G. An independent set whose size cannot be increased any further is known as the *maximal* independent set. There are five maximal independent sets in the graph of figure 4 and they are {ACEGH, ACFH, BEGH, BFH, D}. The maximal independent sets in this graph represent the set of transceivers that can transmit simultaneously without causing type 1 or type 2 interference.

The traditional approach to scheduling *partitions* the node set of the graph modeling the network using minimum number of independent sets. This enables every transceiver to transmit with the least amount of delay. However, as we have noticed from the discussion in the previous section, this approach does not maximize the network throughput. Network throughput can be increased by scheduling large independent sets in the frame more than once. However, this will introduce longer wait time for the transceivers belonging to the smaller independent sets and may be *unfair* to them. As a compromise between two conflicting interests, we suggest that instead of *partitioning* the node set (representing the transceivers) into *minimum* number of independent sets, we *cover* them with *optimal* number of maximal independent sets. To obtain the solution that will maximize the throughput, we suggest two different ways of covering the node set with maximal independent sets - *minimal cover* and *non-redundant cover*.

A *cover* by maximal independent sets of the node set of a graph $G = (V, E)$ is a set of maximal independent sets $S = \{V_1, V_2, \ldots, V_k\}$ such that $\cup_{i=1}^{k} V_i = V$. In this case, the *size* of the cover is k.

A cover by maximal independent sets $S = \{V_1, V_2, \ldots, V_k\}$ is said to be a *minimal* cover if $S - V_i$ is *not* a cover of V for any i, $1 \leq i \leq k$.

A cover $S = \{V_1, V_2, \ldots, V_k\}$, where $|V_1| \geq |V_2| \geq \ldots \geq |V_k|$, is said to be a *non-redundant cover* if all independent sets in S are distinct and $V_{j+1} \not\subset \cup_{i=1}^{j} V_i$ for all j, $1 \leq j \leq k-1$.

A non-redundant or minimal cover by maximal independent sets $S = \{V_1, V_2, \ldots, V_k\}$ is said to be *optimal*, if $\sum_{i=1}^{k} |V_i|/|S|$ is maximum over all S.

From the definition of the minimal cover and non-redundant cover it is clear that a minimal cover is a non-redundant cover, however a non-redunadant cover is not necessarily a minimal cover. In the graph of figure 4, the covers {ACEGH, BFH, D} and {ACFH, BEGH, D} are minimal covers whereas the cover {ACEGH, ACFH, BEGH, D}is a non-redundant cover. The ratio of the sum of the sizes of the maximal independent sets to the number of maximal independent sets for the above three covers are 3, 3 and 3.5. This ratio can be taken as a measure of the *average throughput* per slot.

It may be noted that the transmitter corresponding to the node D gets to transmit in every three slots if a minimal cover like {ACEGH, BFH, D} or {ACFH, BEGH, D} is used as a frame and in every four slots if a non-redundant cover like {ACEGH, ACFH, BEGH, D} is used as a frame. Thus it can be noted that although the average throughput per slot increases if the non-redundant cover is used as a frame, throughput for transmitters like D decreases in this schedule.

In the packet radio schedule construction problem, we like compute the schedule that will maximize the average throughput per slot without being unduly unfair to the individual transceivers. Since this scheme will maximize the average throughput per slot, it will also maximize the total throughput over some specified time period T.

In the following table, we show the results of (i) traditional (chromatic number) schedule - Schedule 1, (ii) schedule using optimal minimal cover - Schedule 2 and (iii) schedule using optimal non-redundant cover - Schedule 3. In schedule 1, transceivers A, C, E, G, H transmit during slot 1, transceivers B, F transmit

Table 1: Performance comparison between three schedules.

Schedule 1 (traditional chromatic number schedule) ⇒ {ACEGH, BF, D}									
Schedule 2 (optimal minimal cover schedule) ⇒ {ACEGH, BFH, D}									
Schedule 3 (optimal non-redundant cover schedule) ⇒ {ACEGH, ACFH, BEGH, D}									
Changes in Network Throughput									
Schedule 2 over Schedule 1 = +12.5%									
Schedule 3 over Schedule 1 = +31.25%									
Schedule 3 over Schedule 2 = +16.67%									
Changes in Individual Transceiver Throughput									
Tr/Rec	Schedule 1		Schedule 2		Schedule 3		Change in throughput 2 over 1	Change in throughput 3 over 1	Change in throughput 3 over 2
	per frame (3 slots)	12 slots	per frame (3 slots)	12 slots	per frame (4 slots)	12 slots			
A	1	4	1	4	2	6	0%	+50%	+50%
B	1	4	1	4	1	3	0%	-25%	-25%
C	1	4	1	4	2	6	0%	+50%	+50%
D	1	4	1	4	1	3	0%	-25%	-25%
E	1	4	1	4	2	6	0%	+50%	+50%
F	1	4	1	4	1	3	0%	-25%	-25%
G	1	4	1	4	2	6	0%	+50%	+50%
H	1	4	2	8	3	9	100%	+125%	+12.5%

during slot 2 and transceiver D transmit during slot 3. In schedule 2, transceivers A, C, E, G, H transmit during slot 1, transceivers B, F, H transmit during slot 2 and transceiver D transmit during slot 3. In schedule 3, transceivers A, C, E, G, H transmit during slot 1, transceivers A, C, F, H transmit during slot 2, transceivers B, E, G, H transmit during slot 3 and transceiver D transmit during slot 4. For simplicity, we assume that the number of packets transmitted by one transceiver in one slot is $x = 1$. We also assume that the total period of transmission is 12 slots. It can be seen from the table that the network throughput increases (i) by 12.5% if schedule 2 is used instead of schedule 1, (ii) by 31.25% if schedule 3 is used instead of schedule 1 and (iii) by 16.67% if schedule 3 is used instead of schedule 2. It is possible that the new approach (*optimal minimal cover by maximal independent sets*) may sometimes result in a decrease in throughput of individual transceivers when compared with the traditional approach (chromatic number partition). However, this decrease is more than compensated by an overall increase in the network throughput. In our example it results in a 31.25% increase in overall throughput, whereas change in the individual transceiver throughputs vary from -25% to +125%. These results are summarized in table 1.

5 Conclusion

In this paper we have presented a new approach to schedule construction in packet radio networks. The goal of this approach is to maximize the network throughput without significant adverse impact on the individual nodes of the network. The throughput produced by the new scheme is at least as large as the ones produced by the traditional schemes.

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