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Optimising multi-rate link scheduling for wireless mesh networks

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ABSTRACT

Traffic in an infrastructure wireless mesh network is routed over multiple hops between clients and gateways, hence performance can be significantly reduced where links interfere with each other. In this paper we consider the problem of optimising link scheduling for wireless mesh networks, making a number of contributions. Adopting a protocol-based model, we introduce an integer programming approach for an optimised schedule using a time-slot model. This model compares favourably against previously published methods and we introduce a rapid heuristic approximation that can present near-optimal solutions in a fraction of the time. We show that taking into consideration the affect of varying data rates across individual links during different time slots can further enhance the throughput achieved. This decreases the local data rate on some links but concurrently reduces the interference range of the transmitted signal which increases spatial reuse across the network. We present efficient heuristics to rapidly find near-optimal solutions to an integer programming model of this problem and provide rigorous justification on benchmark problems.

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1. Introduction

Wireless mesh networks (WMNs) represent a technology that economically increases the geographical area within which mobile clients may access broadband communication. Mesh routers facilitate multi hop wireless transmission to relay data over extended distances without need for the cost, delay and disruption of installing cabled access points.

In this paper we consider infrastructure WMNs, which aim to provide internet access from a single gateway to a number of mesh routers (which may be clients themselves or support a number of local clients). We assume 802.11b/g/n is used for wireless connectivity, where control of the transmissions is governed by the distributed coordination function (DCF) [1]. The DCF ensures that each router avoids transmitting data in the presence of another mesh routers interfering transmission. This is achieved with a combination of first-come first-served access and the use of back off periods. This method, whilst highly decentralised and scalable with respect to the number of mesh routers in the network, starts to become inefficient when the network is heavily loaded. Furthermore, the use of DCF within wireless mesh networks means that the decision on which link is allowed to transmit is largely random in nature, giving no guarantee of fair access for mesh routers which may compromise quality of service. DCF is effectively giving equal forwarding priority to all mesh routers. However these networks are predominantly acting as a back-haul network to an internet gateway and therefore some mesh routers, particularly those close to a gateway, will be required to forward their neighbour's data in addition to their own traffic [2].

To get high performance throughput utilisation from a wireless mesh network it is possible to adopt a schedule for communication via the medium access control (MAC) layer that allows certain router pairs to transmit and receive data at specified times. This imposed scheduling of the communication activity is commonly referred to as *link scheduling*. The overall benefit of this approach is that optimal link activity can be coordinated via the schedule taking into account a given network's topology. Determining link schedules is a complex task with many possible degrees of freedom for modelling. As such there is much current work seeking to find optimal methods [3–5].

Consistent with previous literature, we start by modelling WMN scheduling in terms of graph colouring and propose an initial model for reference which is compared with previous work. This initial graph uses weighted vertices to represent the network links and the relative amount of data that those links are required to carry. Graph edges are used to represent the potential for interference between links. In Section 3 we present an integer program for vertex colouring to maximise the throughput that can be fairly allocated to each mesh router. We show that further improvements in throughput are possible by imposing discrete time slots on the model by developing further integer programs. Given the high performance of the slotted approach and the significant time required to determine solve the integer program, we introduce a fast heuristic approximation that presents near optimal solutions

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in a fraction of the time. As well as determining individual schedules, these fast heuristics are also suitable to be used as objective functions in other optimisation problems, such as routing.

Note that we do not address the practical issues of implementing a scheduled transmission framework in this paper as issues such as synchronisation of network nodes, and dissemination of scheduling information, are discussed in other papers. For example, Soft-TDMAC [6] presents a TDMA scheduling protocol which is run over 802.11 commodity hardware. This layer provides synchronisation between network nodes, sending scheduling information in dedicated time slots. Our work would only require slight modificationto fit into this or similar models (e.g. [7]).

In Section 4 we further enhance the time allocation concept to take into consideration the effect of varying data rates across individual communication links used during different time slots. The power of the signal is adjusted to keep the transmission range constant thereby eliminating the need to recalculate the network routing. This potential reduction in the data rate has the effect of decreasing the amount of data transmitted along an individual link, but concurrently it reduces the interference range of the transmitted signal which improves spatial reuse across the network. These effects are shown to combine to provide an overall benefit to the network's performance. Integer programming is used to formally model this as an optimisation problem and we provide a further efficient heuristic to achieve a near optimal solution with fractional computational effort. The fast heuristic models could then also be used in the evaluation of routing and deployment decision making schemes such as [10,11]. Throughout we provide rigorous comparisons between our work and with others from the literature.

2. Related work

Establishing the capacity of a wireless mesh network is very useful in network evaluation. A method to calculate the nominal capacity of a wireless mesh network is detailed by the work of Jun and Sichitiu [2]. In Jun and Sichitiu's paper, each mesh router is allowed to contribute a maximum allocation of data, T Mbps. In this model, all mesh routers are sending data destined for the gateway. This requires that other mesh routers which are on a pre-defined route to the gateway, retransmit that data in addition to their own data allocation. A dimensionless multiplier, w_u, is applied for each link $u \in L$ (where L is the set of wireless links in the network). Each w_u allows allocations to be defined in terms of T. The amount of data that each link is required to pass onto the next mesh router in the network is determined by the pre-defined route. Interference is modelled through the definition of a *collision domain* for each link $u \in L$, consisting of all other links that would interfere with u if active at the same time. Given the link rate r of each link $u \in L$ in the network, Jun and Sichitiu's work can give the maximum value of T by finding the collision domain that collectively needs to transmit the largest amount of data across its links [2].

Fig. 1 shows a network with collision domains outlined for a subset of the links. The maximum value of T is determined by the collision domain for link (3,4) which must carry traffic of $18T$. Since the maximum data rate that the link can support is r, this gives $T = r/18$ Mbps. This capacity can only be achieved if there is no overhead caused by the contention.

Whilst Jun and Sichitiu's method of calculating the nominal throughput is a fast method it does not produce a schedule for link activation, and also it does not provide an optimum solution to the maximum throughput. Link scheduling can lend toward this bound by the careful management of time allocation for link activations. Diverse work on providing link schedules for wireless mesh networks is already in existence, with each method having particular contributions [3–5,12].

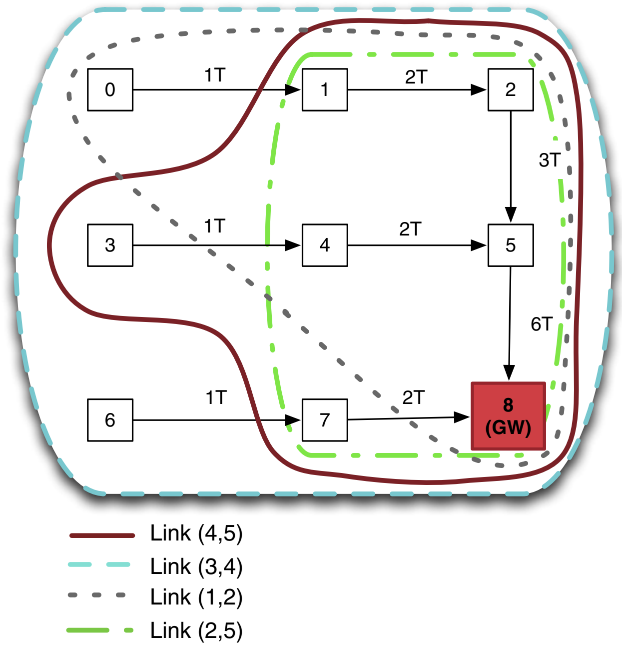

Fig. 1. An example network with collision domains as defined in Jun and Sichitiu [2].

The aim of link scheduling is to maximise the throughput that can be offered to each node by defining specific times where each link may be active. At each point in time there may be more than one link active as long as no concurrently active links are within interference range of each other. The advantage of link scheduling is that it can increase the potential throughput of the wireless mesh network. Link scheduling is an *NP*-hard problem [13] and accordingly this has led to a range of approaches and heuristics that attempt to provide high performance solutions for network throughput. Frequently this involves applying surrogate objective functions whose optimisation implies desirable characteristics in the resultant schedule [13].

A well cited example is Salem et al. [3], who show a method of obtaining a fair schedule which ensures that the mesh access points are allocated sufficient capacity to service each of their clients in the same manner. The solution presented deals with up and down stream traffic, but in doing so they allocate a separate channel for each direction, thus reducing the problem to two copies of the unidirectional transfer problem that is commonly addressed. A so-called compatibility matrix is used, which is a matrix of all the links that can be transmitting at the same time. From this compatibility matrix, all possible cliques within the equivalent graph are constructed and a 'gain' metric is applied to assess and choose which cliques to use. Effectively this works out the number of slots saved by using the cliques, rather than transmitting the data over one link after another. They show that by using the clique method, the total time for the cycle is reduced from the non-spatial reuse method. A further approach is that of Guan and Zhu [14] who use a weighted vertex colouring technique on a graph $G = (V, E)$ where V is the set of links and E is the set of collision domains. This is formulated as an integer program (IP) with a specific objective function to minimise the sum of the 'maximum weight in each of the colour sets' across all colour sets. Guan and Zhu use the solution to solve a bus network problem.

Malaguti et al. [13] provide a similar solution to Guan and Zhu [14] with the novelty of this solution being applied to scheduling on a batch machine. Their objective function minimises the cost of all colour classes used (effectively the minimum cycle time), where all links are included in at least one colour class. An additional model reduces the solution space by utilising the fact

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