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Design of Wireless Mesh Networks for Aggregating Traffic of Fast Moving Users

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ABSTRACT

In this paper, we examine wireless mesh networks and present a theoretical model for evaluating the expected throughput for fast moving users. We propose intelligent techniques for improving the throughput: distribution of neighbour nodes over the available wireless interfaces and distributed channel assignment for minimising the interference. Evaluations show that the neighbour nodes should be equally distributed over the wireless interfaces based on the relative difference in hop count to the closest gateway. We also present load-aware techniques which dynamically adapt the nodes according to the current traffic conditions. Load-aware techniques are able to achieve larger throughput but in many cases gain margins are smaller than expected. It is also shown that a poor choice in neighbour interface binding or channel assignment technique leads to a decreased performance in such a way that adding interfaces or channels would not further improve the throughput.

Categories and subject descriptors: C. Computer Systems Organization; C.2 Computer-Communication Networks; C.2.1 Network Architecture and Design: Wireless communication
General terms: Algorithms, Design
Keywords: wireless mesh, mobility, mesh throughput

1. INTRODUCTION

1.1 Motivation

One of the most critical challenges in wireless networks is improving the capacity of the network. Profit can be gained at the physical layer by using OFDM (Orthogonal Frequency Division Multiplexing) [1], antenna diversity, smart-antennas or MIMO (Multiple-Input Multiple-Output) [2]. However, in general still a lot of challenges have to be tackled before wireless mesh networks (WMNs) will have a similar throughput or QoS experience as can be expected in a wired environment [3]. If high concentrations of wireless nodes occur, shared channels and radio interference lead to rapid diminishment of the end-to-end throughput of multi-hop paths [4,5]. Despite this inherent vulnerability of the wireless technology for all kinds of interference, wireless mesh networking will become important in access and aggregation networks. It is expected that network installation costs will be lower than the wired equivalent. WMNs diminish the amount of cables and save on expensive digging costs. The techniques of mesh networking are largely independent of the underlying physical wireless technology. We focus in this paper on IEEE 802.11 but promising technologies such as WiMax could also be used for mesh networking.

1.2 Related work

Evaluation of a multi-hop network's throughput is a complex problems. In [4,5] multi-hop communications are studied in simulation or test bed environment. However, we require a more mathematical throughput calculation method and we will base our model on [6] where a fairly good method is proposed for calculating the expected throughput in multi-hop wireless networks. In the latter, the authors validated their models with simulations which matched the calculated theoretical mesh throughput results.

In [7,8] good proposals are presented for optimizing the mesh throughput such as intelligent channel assignment or load balanced routing. However, in [7] the load-sensitive path weight functions may cause network instabilities because they are depending on traffic variations which may be very large and irregular. In [9] experiments with adaptive routing protocols based on load-sensitive metrics have been conducted in large wired environments and instabilities made deployment already very difficult. In a wireless environment this problem may be worse. While in large networks larger amounts of users are multiplexed, a wireless mesh network will have a smaller scale (which is more likely with the current bandwidth limitations) and hence lack a similar smoothing effect on the real-time traffic metrics. Therefore, [8] suggests topology-dependent path weight functions that base weights on topological properties such as hop count or link capacity. However, both still use load-dependent distributed algorithms which take time to converge while fast changing traffic conditions are never considered. We will propose a technique which can combine load-aware statistics under fast moving user conditions.

1.3 Contribution

In this paper we examine infrastructure-based mesh networks and we present a theoretical model for evaluating the expected throughput of WMNs for fast moving user conditions. We propose techniques for improving the through-

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put: intelligent distribution of neighbour mesh nodes over the available amount of wireless interface cards (NIB = Neighbour Interface Binding) and distributed techniques for minimising the link interference levels by assigning different communication channels to the physical interfaces (DCA = Distributed Channel Assignment). We will also present a load-aware NIB/DCA technique which dynamically adapts the binding and channel usages according to current traffic demands and which doesn't require a convergence time. All these techniques are extensively evaluated with relation to their mesh throughput for various train scenarios. The influence of well-positioned multiple service gateways and the influence of multiple interfaces per wireless mesh node on the overall mesh throughput will also be evaluated.

The paper is structured as follows: first, we introduce the architecture. Next, we present the design approach and the methods that are used to optimize the mesh throughput. In order to evaluate the network solution's throughput we present models that expect full coverage to calculate the end-to-end throughput for fast moving users. Finally, we present extensive simulation results which evaluate various train scenarios and network parameter settings.

2. MESH THROUGHPUT CALCULATION FOR FAST MOVING USERS

In order to increase the spectral efficiency WMNs will use multiple interfaces per node which will communicate on different channels. We developed a tool for calculating the WMN throughput for moving users in trains. It is a combination of our previously developed motion-aware capacity flow assignment problem [10] for trains and a wireless mesh throughput calculation technique, which introduced the bottleneck collision domain concept [6]. Our calculation tool solves a dynamic traffic engineering problem by calculating the paths that are required for every train at every moment. In this section we will present design methods and models but first, the architecture is presented.

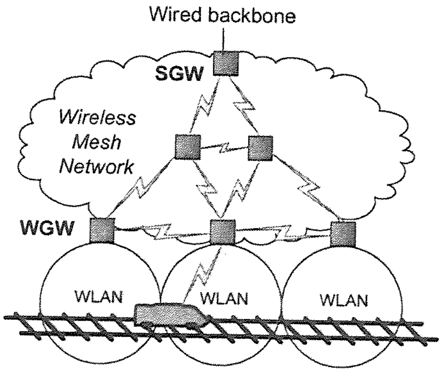

Figure 1: Wireless aggregation networks for fast moving users

2.1 Wireless aggregation network architecture

The architecture (see Figure 1) aims at aggregation networks where typically a lot of leave nodes require connectivity from and to a limited set of service gateways (SGWs). The leave nodes are connecting one or more WLANs where vehicles can connect to, they are called WLAN gateways (WGWs). With the current bandwidth limitations of IEEE 802.11 WMNs a wired backbone is still indispensable [11] in order to achieve a reasonable throughput: service gateways must be positioned geographically at remote locations and path lengths can be further minimised by selecting the closest SGW. Every SGW will be root of a one or more ST instances and WMN nodes will be member of multiple ST (Spanning Tree) instances. Our architecture will be optimised for root-leaf traffic but leaf-leaf communication will still be possible without necessarily passing the root node. In the wired aggregation network bandwidth (BW) guarantees are delivered by means of VLAN (Virtual LAN) tunnels and an associated Layer 2 reservation protocol [12]. This enables an up-to-date view of the resource usage. This view can be used by the central management that handles the fast moving aspect by reserving for every moving vehicle the best path towards the WGW. In order to have continuous bandwidth guarantees the reservation system has to be activated by the centralized system shortly before train traffic will effectively be using the next WGW on its track. This paper won't detail this reservation mechanism but we will present the design and capacity planning of WMNs which can cope with dynamically changing traffic scenarios.

2.2 Wireless Ethernet mesh network

In previous work we presented a wireless Ethernet mesh network which extended a standard VLAN-aware multi- spanning tree Ethernet switch for wireless environment [13]. By adding a fast and efficient failure detection mechanism and by adapting the spanning tree parameters to the effective link rates a reliable and flexible Layer 2 mesh architecture can be build. During the initialisation phase of the WMN a tree is constructed which connects all authorized WMN nodes: the *connectivity tree*. This tree is however different from the trees that are used for forwarding data traffic. These spanning trees will use feedback from a link rate adaptation protocol in order to adapt their topology. As a result, the widest paths (instead of the shortest paths) towards the SGWs are part of the tree topologies: *forwarding trees*. Wifi-dependent control traffic such as probes, beacons or control messages are used for distributing wireless information in the WMN. This information is used for creating the single-hop neighbourhood table and even multi-hop neighbourhood tables. The results presented in this paper are however architecture independent and can be applied for every wireless routing architecture. The only assumption made in this paper is that the routing mechanism of the WMN favorably is able to determine the widest path to the wired backbone. If only the path with shortest hop count towards the wired backbone can be determined or if traffic cannot be load-balanced over the multiple gateways, the mesh networking efficiency will decrease; however the findings of this paper will remain mostly unchanged.

3. MODELS AND METHODS

In Figure 2 an overview is given of the design phases for creating and optimizing a WMN for fast moving users. For a given railroad and train scenario, we create a method to automatically place the WMN nodes to guarantee the connectivity between the SGW and the track-side WGWs. This method is presented in Section 3.1. Once the WMN is in place, we can start to extract the neighbourhood informa-

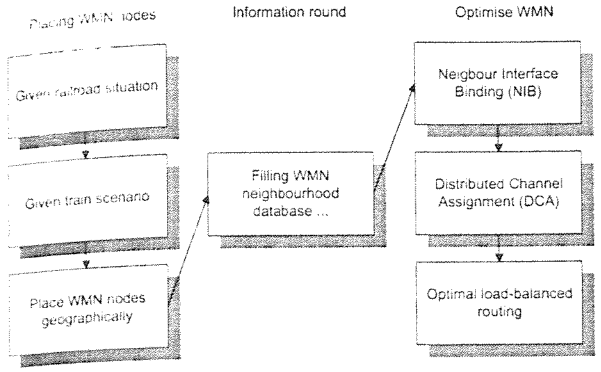

Figure 2: **Wireless aggregation networks for fast moving users with track-side wireless LANs.**

tion. Identifying the interfaces within communication range and deriving which nodes could interfere with a communication link, can be done by means of the path loss model presented in Section 3.2. Next, every node will identify a set of nodes for direct communication and will assign specific wireless interfaces to realize the communications. Methods for establishing neighbour interface bindings are described in Section 3.3. This step is followed by the channel assignment which tries to minimize the interference levels between all communications links. We will propose different methods which are described in Section 3.4. Finally, we will use a theoretical model which calculates the maximum throughput of the WMN in the given train scenario. In Section 3.6 we present our throughput calculation model.

3.1 WMN node placement

The goal of the WMN node placement algorithm is to construct a WMN that connects the service gateway with the WLAN gateways. The algorithm will try to minimise the hop count of the SGW-WGW paths because long paths must anyhow be avoided in mesh networking. While the main focus of this paper is on the NIB and DCA techniques, this placement method doesn't claim to find the optimal solution. It is anyhow very hard to verify the optimality due to the many associated degrees of freedom. The WMN will be built originated from the SGWs: every existing WMN node will be considered as a parent node which has to connect an associated subset of the WGWs and child nodes will be placed at the maximal allowed communication distance of their parent node until all WGWs are connected. Every time child nodes are oriented towards their associated set of WGWs. In this way, a minimal amount of WMN nodes will be used to establish SGW-WGW connectivity and interference is kept minimal. However, in order to benefit from the load-balanced routing alternative routes to the SGW need to be present. Therefore, a parameter σ is introduced which equals the number of child nodes of the SGW. If σ is increased, a more geographically spread network can be built which contains typically more WMN nodes. As will be shown later, this implies increased load-balancing possibilities but it might also imply that more channels are required in order to achieve low interference levels. The WMN node placement is illustrated for σ=1 on Figure 3. Keep in mind that typically the WGWs have a smaller communication distance with their closest WMN node than WMN nodes higher up the tree. The figure displays two different communication ranges because the communication range of the WMN may be different from the communication range of the WLAN. In any case, WGWs will have two types of interfaces: one type to connect with the wireless device on the train in the WLAN and one with the closest WMN node.

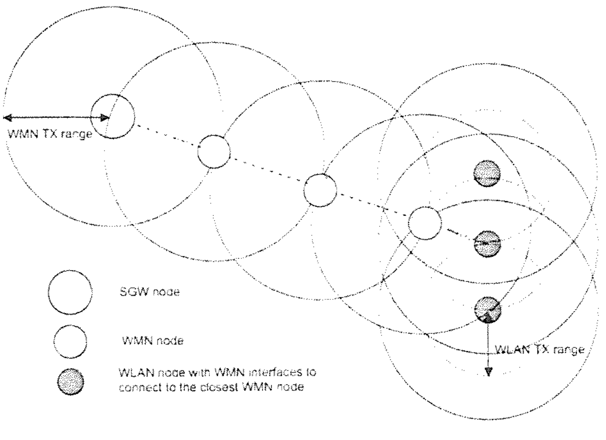

Figure 3: Simple example of WMN placement for 3 WLANs (σ=1).

3.2 Path loss model

In the WMN evaluation we need to take interference levels into account. Interference is hard to prevent because it is not only caused by senders within communication range but also by senders which are beyond communication range. Due to the large distribution of WMN nodes interference in WMNs is location dependent. Basically, this means that sender and receiver of a wireless link could be experiencing different interference levels. When a signal from a sender arrives at the receiving wireless NIC (Network Interface Card), it largely depends on the receiving power at the receiver if the signal can be received correctly. In open space environments the receiving power P_{rx} can be derived from the transmission power P_{tx} by the following signal loss model:

$$P_{rx} = P_{tx} \cdot G_{tx} \cdot G_{rx} \frac{h_{tx}^2 \cdot h_{rx}^2}{d^k} \quad (1)$$

where G_{tx} and G_{rx} are the antenna gains of transmitter and receiver respectively, h_{tx} and h_{rx} are the antenna heights. In open space environment, the two-ray ground model signal loss model is generally adopted [14]. It states that the receiving signal power is inverse proportional to d^4 if sender and receiver are far away from each other (located outside the Fresnel zone [14]). Due to the assumptions made in the WMN node placement algorithm, we can safely assume that sender-receiver distance will always be large enough. A signal is assumed to be valid if the Signal to Noise Ratio (SNR) is above a certain threshold. In practice, this threshold is set to 10. If d is the receiver-transmitter distance in meters and r is the distance from the interfering node to the receiver, than we can denote the SNR as the fraction P_{rx}/P_i where P_i is the interference signal at the receiver. Here, we ignore the thermal noise since it can be neglected compared to the interference signal. Under the assumption of homogeneous

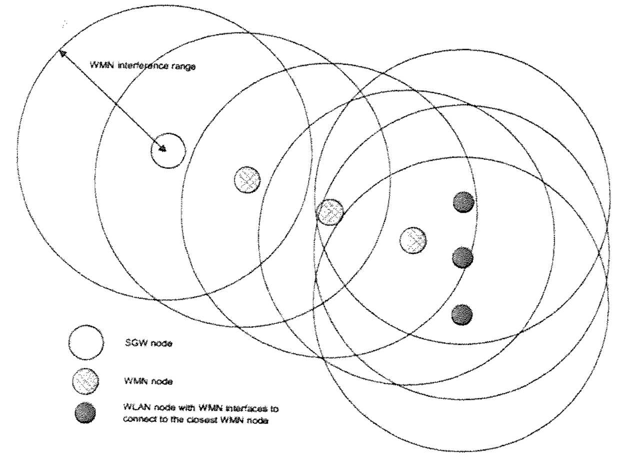

Figure 4: Illustration of WMN interference ranges for the simple example of Figure 3.

antenna conditions, the SNR can be noted as follows:

$$SNR = \frac{P_{rx}}{P_i} = (\frac{r}{d})^k \qquad (2)$$

This means that for a specific transmitter-receiver distance d interfering nodes must be at least at $R_i = \sqrt[k]{SNR} \cdot d = \sqrt[4]{10} \cdot d = 1.78 \cdot d$ from the receiver in order to successfully receive the transmission signal. We assume that the path loss coefficient k equals 4 in this paper. The methodology is the same for other k-values but interference levels will be significantly different. The interference ranges R_i in the WMN of Figure 3 are illustrated on Figure 4. These mathematics will be used to estimate interference levels which can be used to determine the optimal achievable throughput in WMNs.

3.3 Neighbour Interface Binding (NIB)

The Neighbour Interface Binding is an important building block in the node architecture because the NIB chooses how the set of neighbours is distributed amongst the set of wireless interfaces. The choice of sharing a wireless NIC with multiple neighbours or reserving two wireless NICs for the same neighbour can make a big difference in expected throughput. In this paper we will look at four different NIB modules. First, the node's neighbours are divided in two sets: neighbours with better path to the closest root and neighbour with worse path to the closest. Neighbours which have equivalent root paths, are alternately assigned to the set containing better paths or the set containing worse paths. A first NIB module reserves half of its interfaces for WMN nodes which have a better path to the closest root and half for the WMN nodes which have a worse path to the closest root. We refer to this equally balanced NIB method as NIB_{even}. We take two extremes as alternative methods: a NIB which reserves a single NIC for WMNs with worse paths and the rest for WMN nodes with better paths (called NIB_{up}) and the reverse, which favors links to WMNs with worse paths and uses a single NIC for links to WMNs with better paths (called NIB_{down}). These NIB methods are illustrated on Figure 5. In some cases free interfaces can be used to increase the capacity between nodes by setting up two parallel links between nodes. The final NIB which takes load-awareness as a metric, is detailed in Section 3.5. In this paper we assume that every node has four separate wireless NICs unless mentioned otherwise.

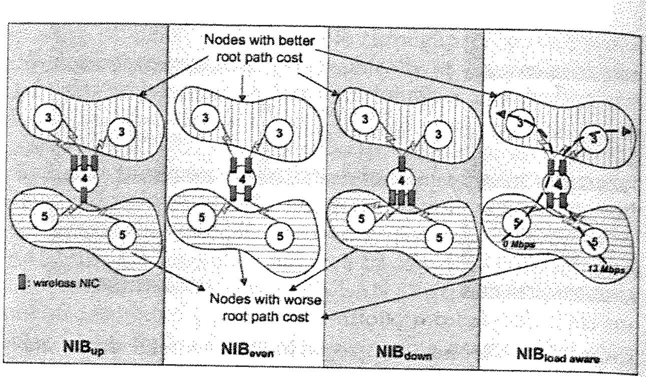

Figure 5: Illustration of NIB methods, viewed from the node in the middle which has four wireless NICs. The number, written inside the nodes, indicates its minimal distance towards the closest SGW.

3.4 Distributed Channel Assignment (DCA)

Once the NIB module has defined the set of neighbours with whom a direct communication link has to be maintained and these links are assigned to a physical interface, the Distributed Channel Assignment (DCA) tries to minimise interference levels of the links by assigning different communication channels to the physical interfaces. For single-channel systems collisions can occur with every transmission of nodes within interference range while in multi-channel systems multiple simultaneous transmissions in the same neighbourhood are possible. Channel diversity in the mesh network decreases the amount of neighbours that effectively can interfere. Because in practice the set of available non-interfering channels is limited, geographical reuse of the same channels is necessary. The DCA module must be loyal to the commitments that were made in the NIB module and established link bindings must be maintained by the channel assignment module.

The interference level of the links is minimised by examining the channel usage in the nearby environment, referred to as the neighbourhood. We define three kinds of neighbourhoods: a single-hop neighbourhoud, two-hop neighbourhood and three-hop neighbourhood. It will be shown for the assumed propagation path loss models that nodes further away have no influence. The methodology is likewise for other path loss models (such as for indoor environments) but results will clearly differ due to changed interference levels. The single-hop neighbourhood of a node A contains the WMN nodes within direct communication range of node A. The two-hop neighbourhood of node A contains the previously defined single-hop neighbourhood and contains additionally the single-hop neighbourhood of every member of the single-hop neighbourhood of node A. Similarly, the definition of the three-hop neighbourhood is easily derivable.

Important for DCA, being a distributed technique, is the hierarchical order for assigning channels. We propose a system in which WMN nodes are ordered based on their minimum distance to the closest SGW. This set of WMN nodes is divided in a number of hierarchical levels, where the level indicates the root distance. First, the nodes on the highest level assign their channels based on the multi-hop neighbourhood channel usage. Obviously, every assignment has implications on the channel assignments at lower levels because the DCA is constrained by the link assignment of the NIB. This process continues until the lowest level WMN nodes have assigned channels to their remaining physical NICs.

The channel usage metric that is used in the assignment, is defined as the number of wireless NICs on a specific channel. It will be shown that mesh throughput is indeed increased by taking this metric into account. Apart from these distributed channel assignment methods, we will make the comparison with two other DCAs: the *single channel CA* to illustrate the gain of using multiple channels and the *local CA* where WMN nodes are not aware of the channel usage of neighbour nodes to illustrate that CA must be coordinated in order to achieve considerable performance gains.

3.5 Load-awareness of NIB and DCA

The NIB and DCA are not taking the effective link loads into account. In fact, interference reduction is only required if the loads that have to be transported on these links, are causing saturation of the wireless medium. We present a method which combines a load-aware NIB and a load-aware DCA. It is based on load-aware metrics which however are not determined by the effective routing process. The process of adapting the channels or the neighbour interface bindings according to the effective loads, which are influenced by the outcome of the routing process, is an iterative approach. However, we desire a fast and simple solution and therefore, we start with the assumption that load information is not the actual load of an interface but that this information will be virtually distributed in control messages which will flow from the sources over the widest path (not necessarily the same as the shortest path) to the wired backbone. In this way, every WGW will notify the nodes on its widest path to the wired backbone of its current load and the WMN nodes will maintain the virtual traffic metrics for every link to a neighbour node. This allows to locate easily the highly loaded parts of the network without knowing the exact routing decisions or measuring data flow properties. It are these load-aware metrics that will be used to determine the assignment of channels to wireless NICs. The fact that load-aware metrics cannot be influenced by the deployed routing protocol or medium conditions, implies that the load-aware mesh optimization is well suited to be used for rapidly changing traffic conditions and for wireless conditions where properties such as channel bandwidth and medium access delays can fluctuate easily. Danger of system instabilities, as presented in Section 1.2, is avoided with this method. The load-aware channel usage metrics that we use, are the virtual loads on a specific channel, distributed via the connectivity tree (instead of the number of wireless NICs on a specific channel). The load-aware NIB works similarly and is illustrated on Figure 5 where a double interface path is constructed based on the load information that is distributed across the connectivity tree. This allows the NIB to adapt to the current distribution of active sources/sinks in the WMN. We will prove that the effective throughput increases compared to NIB/DCA combinations which are not load-aware. We will refer to this method as the *load-aware CA* but note that this always combined with the load-aware NIB method.

3.6 Mathematic model for load-balanced forwarding in the WMN.

In this section we will mathematically define the forwarding and load-balancing possibilities that are deployed in the WMN architecture. The model is used to evaluate the throughput after the completion of the following phases: WMN node placement, neighbour interface binding and channel assignment. It will solve the dynamic traffic engineering problem by calculating the paths that are required for every train at every moment. More information on deriving motion-aware traffic information and the mobility model can be found in [10]. The presented formulation is linear which means it can be solved with ILP (Integer Linear Programming) solution techniques [15]. In a first phase, radio interference is determined based on the assigned channels and the geographic positioning of the mesh nodes. Next, routing will be optimised and load-balanced in order to satisfy the demand matrix during the entire journey of the moving users.

3.6.1 Pre-processing

Two matrices which will be used as input data for the ILP formulation, have to be defined on before-hand.

- Available set of paths Φ:
  We will determine a limited set of candidate paths Φ that will be explored to find the optimal routing for a specific flow at a specific time. Therefore, we use an algorithm to determine the M-shortest paths for every WGW to every SGW in the network graph of the WMN [16]. We choose a high M-value (M=35) which will be used in all simulations presented in this paper. Lowering M lowers the ILP calculation time but the ILP solution technique will inevitably explore less of the solution space and the outcome might be less optimal. These paths are ordered in a three-dimensional matrix Φ: for every SGW k and every WGW i, Φ contains an ordered vector $\Phi[k][i]$ with up to M different elements that represent a route in the mesh between WGW i and SGW k.

- Interference matrix I:
  Based on Section 3.2 and the pre-assigned channels of the NICs we can calculate the interference level for every communication link in the WMN. However, interference cannot be expressed per communication link because it can only be expressed per receiver. Therefore, the set of bi-directional communication links will be split into a pair-wise set of directed edges E. Interference is expressed per receiver which is e.g. the target node of the directed edge. Therefore, we define an two-dimensional interference matrix $I(p,e)$ with variable $p \in \Phi$ and $e \in E$. The interference matrix I can simply be created: every element $I(p,e)$ equals the number of senders on the path p that are within interference range for the communication associated with the edge e. With this definition interference levels are properly linked to the traffic engineering problem which determines the best forwarding paths.

3.6.2 Decision variables

We define a variable to indicate which path $p \in \bigcup_{i,k} \Phi[k][i]$

is used:

$$y_{pijk} = \begin{cases} 1 \text{ if path } p \text{ is used between WGW i} \\ \text{ and SGW } k \text{ for flow } j \\ 0, \text{ otherwise} \end{cases} \quad (3)$$

In some cases, we are more interested in the intrinsic forwarding capability of a network with optimal load-balancing: in this case we allow that the load of a flow can be scattered in multiple fractions over an arbitrary amount of paths. While this is in fact difficult to realize in reality, it leads to a better evaluation metric for analysing the intrinsic forwarding capabilities of a network solution. In the case of optimal load-balancing, formula (3) is altered by making y_{pijk} a real value ($y_{pijk} \in [0,1]$) instead of a boolean value and y_{pijk} represents the share of the flow j that is routed on path p between WGW i and SGW k. Unless mentioned otherwise, we assume load-balancing with $y_{pijk} \in [0,1]$.

We define an additional variable f which will be used as indication of how much the demand matrix can be scaled up before the traffic cannot be transported anymore by the WMN. As shown in equation (4), up-scaling of the demand matrix implies the multiplication of decision variables. Due to the fact that ILP cannot cope with non-linear formulations, the variable f ($0 \leq f \leq 1$) will be used for down-scaling the medium capacity. This means that up-scaling is not an option; if the network cannot transport the traffic for one specific demand matrix the value of f cannot be determined and we assume f to be infinite.

3.6.3 Link Capacity constraint

This constraint sets the medium's capacity seen by every wireless NIC and imposes that the traffic that can be received and sent by a NIC does not exceed the capacity at any time. Traffic demands are defined as $d_{ijk}(t)$: the demand at time t between AGW i and SGW k for flow j.

$$\forall e, \forall t : \sum_{k=1}^{|SGW|} \sum_{i=1}^{|WGW|} \sum_{j} \sum_{p=1}^{|\Phi[k][i]|} y_{pijk} \cdot \delta_{pe}^{ik} \cdot d_{ijk}(t) \leq f \cdot C_{medium} \quad (4)$$

$$\delta_{pe}^{ik} = \begin{cases} I(p,e), \text{ if path } p \text{ uses edge } e \text{ to get to} \\ \text{destination k from source } i \\ 0, \text{ otherwise} \end{cases} \quad (5)$$

where $I(p,e)$ equals the amount of senders on the path p that interfere with the receiver associated with edge e (as defined in Section 3.6.1). This illustrates why the variable f was introduced to scale down the medium capacity (noted as C_{medium}) instead of scaling up the demand matrix: the ILP formulation needs to remain linear.

3.6.4 Path activation constraint

For both levels of load-balancing we can define the constraints for y_{pijk} as follows:

$$\forall i, \forall j, \forall k : \sum_{p} y_{pijk} = 1 \quad (6)$$

In load-balancing systems where $y_{pijk} \in \{0,1\}$ this implies that we only need a single path for a specific flow j for every SGW-WGW pair.

3.6.5 Objective function and goodput gain factor

We would like to know if the traffic of the moving trains can be routed in such a way that the constraints are met and additionally, we would like to know how much the train load can be further increased before the WMN isn't able to transport all the traffic towards the wired backbone. Therefore, we try to minimize the variable f which is used for down-scaling the medium capacity:

$$f_{min} = Minimize(f) \quad (7)$$

Before we continue, we first have to introduce an important metric for classification and evaluation of the different network designs. In previous work mesh networks are often evaluated on their global routing ability for a specific traffic demand matrix which is static in time. For example, [7] defines the cross-section goodput (CSGP) of a network as

$$CSGP = \sum_{i=1}^{|WGW|} Min(\sum_{k=1}^{|SGW|} c(wgw_i, sgw_k), d(wgw_i)) \quad (8)$$

Here, $c(wgw_i, sgw_k)$ is the useful network capacity available between a leaf node wgw_i and a gateway node sgw_k and $d(wgw_i)$ is the demand for a leaf node wgw_i with the fixed network. This metric tells something about the general forwarding capability of the network but it doesn't ensure that the demanded bandwidth can be guaranteed at all times. Therefore, we will use a different metric which is able to take dynamically changing traffic demands into account, referred to as the *goodput gain factor* (GPGF). This metric will also guarantee the demanded bandwidth for a specific train scenario at all times. If the goodput gain factor however equals zero (which implies f_{min} is infinite), it means that the traffic scenario cannot be supported at all times.

$$GPGF = 1/f_{min} \quad (9)$$

where f_{min} is defined in formula (7).

4. WIRELESS MESH EVALUATION

First of all, the various NIB and DCA techniques are evaluated for single train scenarios with a single service gateway. After the introductory results this evaluation is further extended for multiple train scenarios, multiple service gateways and variable amounts of wireless interfaces per node.

4.1 Single train study for NIB and DCA

As a start, we considered 20 scenarios with a single train moving on a single rail line. The scenarios have various rail line lengths, single or two SGWs and different SGW positionings. We evaluate the three NIB methods that are discussed in section 3 (NIB_{equal}, NIB_{up} and NIB_{down}) and three distributed channel assignments (single-hop, two-hop and three-hop). The WMN topology is constructed as described in Section 3.1 and for every scenario multiple topologies are constructed with up to four first level WMNs, in other words parameter σ can vary from one to four. We evaluated which NIB and DCA methods consume the least amount of channels to obtain the maximal throughput for a single passing train. Under the assumed propagation model, this maximal throughput for a single train with 2 Mbps bidirectional demand is achieved if f_{min} equals 0.13333. We gradually increase the amount of free channels until f_{min} reaches the optimal value. Figure 6 and Figure 7 present in how many cases a specific NIB or DCA was the best choice for obtaining this maximal throughput for a minimal number of used channels. In this section flows are non-dividable: $y_{pijk} \in \{0,1\}$. Figure 6 illustrates clearly that NIB_{up} is in

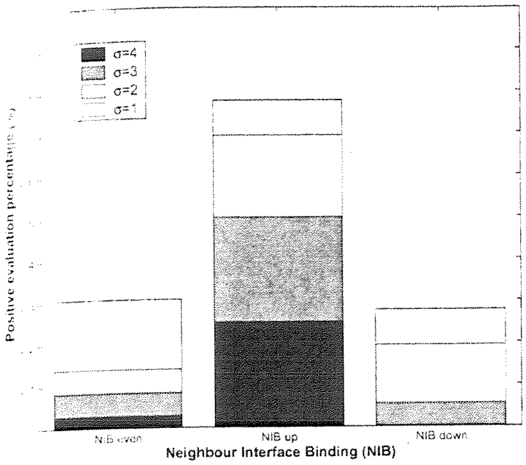

Figure 6: **Positive evaluation percentage for various neighbour interface binding techniques.**

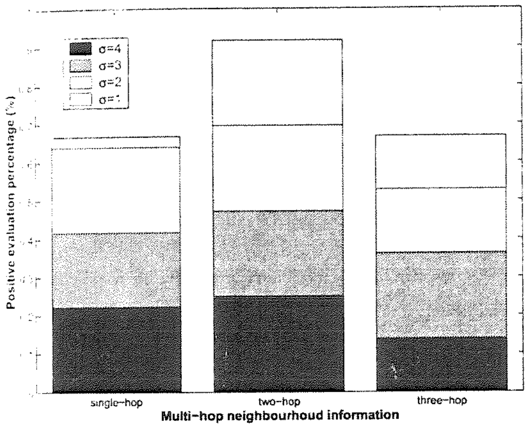

Figure 7: **Positive evaluation percentage for distributed channel assignment techniques based on different multi-hop neighbourhoods.**

almost 80% of the cases the best choice, while in 20% of the cases one of the other NIB methods performed better. This can easily be explained. Because we considered single train scenarios, only a single WGW will be simultaneously forwarding traffic. This means that a single interface for transporting down link traffic is most of the times sufficient. Additionally, a maximum amount of interfaces is reserved for the up links which maximizes the load-balancing possibilities for traffic flows towards the service gateway. Only for $\sigma = 1$ the equally balanced NIB_{even} achieves better throughput. This can be explained due to the decreased load-balancing possibilities for low σ-values. The experiment was repeated for multiple train scenarios and there NIB_{even} was clearly the best method. Intuitively, this matches our expectations due to the aggregation network environment. In aggregation networks the traffic that comes from "down" links goes eventually to "up" links and vice versa due to the assumption of soleiy leaf-root communication. The comparison of NIB_{even} and NIB_{up} is repeated in the next section for multiple train scenarios.

Figure 7 shows clearly that for all σ-values the two-hop neighbourhood gives the best results. As mentioned earlier the interference range of a receiver is 1.78 times the transmitter-receiver distance. This propagation model implies that the single-hop neighbourhood gives perhaps a too narrow view on the environment and that the three-hop neighbourhood takes NICs into account which cause rather no interference. This result is of course strongly influenced by our WMN node placement method where WMN nodes are maximally spread. For the remainder of this paper DCA will always use a two-hop neighbourhood.

The measurements also showed that for distributed channel assignments the minimal amount of required channels increases with the size of the multi-hop neighbourhood or with the number of WMN nodes. In our case, increasing σ-values increases the number of WMN nodes and increases the number of routing alternatives between WGWs and SGWs. Heuristical channel assignment methods which do not take the effective bandwidth usage into account, will divide channels equally amongst their neighbours and they will always tend to need more channels for higher σ-values.

4.2 Study of multiple train scenarios

In this section, we will extend our single-train scenarios towards multiple train scenarios. Figure 8 and figure 9 present the goodput gain factor for respectively NIB_{up} and NIB_{even}. The scenario is a single railway fully covered by 8 WGWs and a single SGW. We simulate a variable amount of passing trains riding in one or two directions, with each 2 Mbps bi-directional demand. The amount of available free channels in the WMN equals four. The goodput gain factor for single channel CA is of course the same on both figures and for scenarios with more than two trains the goodput gain factor drops to zero, meaning the WMN can no longer forward this amount of traffic. It is clear that for increasing number of trains NIB_{up} is outperformed by NIB_{even}. For NIB_{up} GPCF drops already to zero for the 4 train scenario with local CA while for NIB_{even} the local CA is able to cope with this scenario. Distributed CA goodput values are also

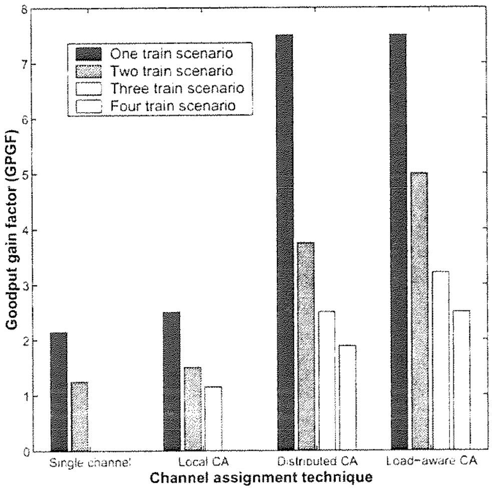

Figure 8: **Goodput gain factor for various train scenarios (# channels=4) and various channel assignment techniques with NIB_{up}.**

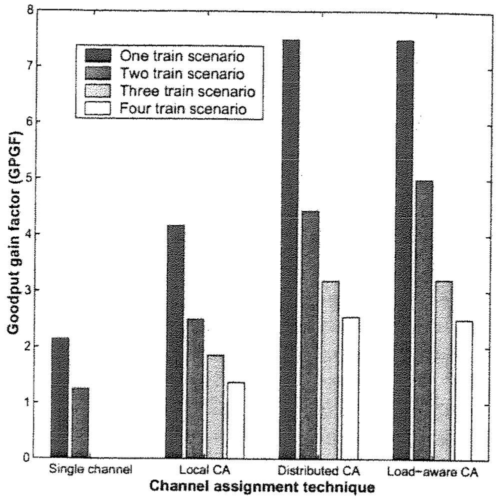

Figure 9: Goodput gain factor for various train scenarios (# channels=4) and various channel assignment techniques with NIB_{even}.

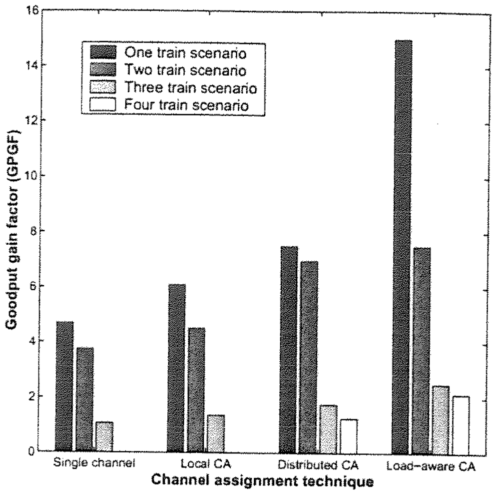

Figure 10: Goodput gain factor for various train scenarios (# channels=8) and various channel assignment techniques with NIB_{even}.

clearly better for NIB_{even}. For the remainder of the paper, NIB_{even} will be used for the mesh throughput calculation, unless mentioned otherwise.

On both figures it is shown how the distributed CA outperforms the single channel and local CA. The throughput of single channel assignments drops rapidly and even poorly chosen multi-channel assignments do not succeed in obtaining high throughputs. This proves that a coordinated approach where WMNs nodes communicate their channel usages, is desirable. On Figure 9 the GPCF for load-aware DCA is presented and it shows that the GPCF is not much higher than for the distributed CA: only for the two train scenario GPCF reaches a higher value. Load-aware DCA for aggregation networks can optimally adapt the NIB and DCA to the specific time-dependent needs but in many concrete cases the gains might be lower than expected if not enough free channels are available. A similar trend can be shown for other traffic profiles or other wireless mesh network topologies.

Figure 10 presents results for the same scenario but this time the amount of available channels is doubled: eight free channels instead of four. If every node has four NICs, the minimum amount of channels is six in theory to obtain higher gains. As you can notice, the gain reaches 100% for the single train scenario because the load-aware NIB assignment could be matched with a proper channel assignment. This shows that considerable gains can be achieved by deploying load-aware techniques if more channels are available. In the case of a single train scenario and four wireless interfaces, the NIB module is able dedicate two parallel interfaces for connecting down- and upward-oriented nodes which are on the routing path. The amount of available channels must be high enough due to the presence of a double interface path from WGW to SGW. In order to remove entirely all radio interference along the path, a path consisting of two parallel wireless interfaces requires more channels than a path consisting of single interfaces. For multiple trains the gain is reduced because interfaces must be more equally divided amongst neighbour nodes but in extreme scenarios (that differ strongly from an equally balanced situation) load-aware methods will always achieve considerable gains.

4.3 WMNs with multiple service gateways

The positive impact of adding gateways towards a wired infrastructure is already indicated in [7, 11]. Additional service gateways increase the throughput of the mesh network, concordantly the GPGF will be higher if we add a second SGW. However, the position of this SGW will also have an important influence on the throughput performance. Figure 12 and Figure 13 show the influence on the goodput gain factor if the second SGW is added respectively on position (0,30) and (0,5). The first SGW is always positioned at the origin (0,0) as shown on Figure 11. If an additional SGW is placed at the first position, the GPGF is clearly improved (e.g. 46% for a single train in the case of distributed capacity assignment) while the improvement at the second

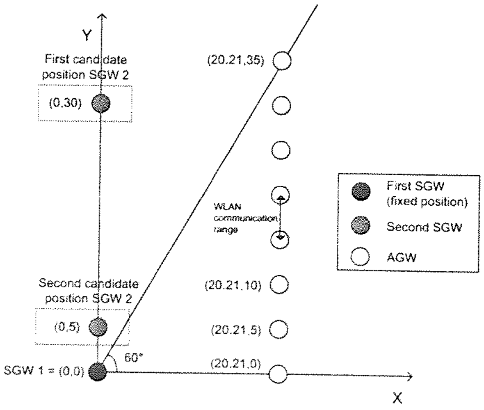

Figure 11: Arbitrary example with 8 AGWs and two candidate positions for the second SGW.

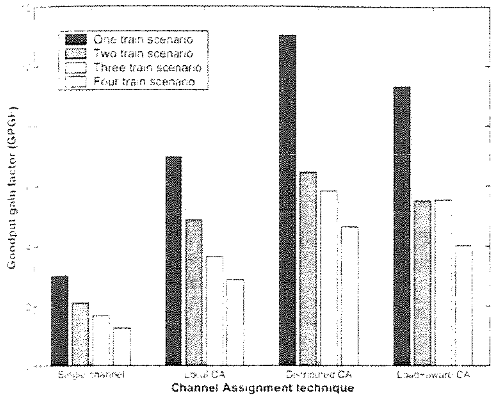

Figure 12: GPGF for various DCA techniques (# channels=4) in case of SGW 2 at position (0,30).

position is less than at the first position (e.g. 19% for a single train in the case of distributed capacity assignment). This is obvious due to the fact that the single SGW is a bottleneck and that load-balancing over the different gateways further improves the throughput. However, the multiple SGW must be placed at geographically separated locations else the gain will be less. The first position is considered as good positioning because traffic of the WMN can be load-balanced towards geographically separated gateways. The second position however is considered as bad positioning because the gateways are practically at the same physical location. At first sight it is extraordinary that load-aware assignment is outperformed by distributed capacity assignment in Figure 12, even for the single train scenario. This is however a consequence of the limited amount of available channels. The number of available channels equals 4. In this case load-aware assignment is less efficient and it is the ability to load balance traffic that will determine the best solution. This means that in some cases (as is clear in this example) that the GPGF can be worse in case of load-aware assignment. In Figure 10 it is already shown that for a higher number of available channels the load-aware technique has the potential to achieve higher throughput gains.

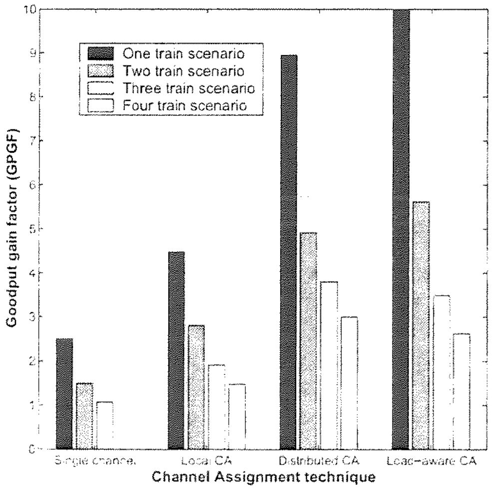

Figure 13: GPGF for various DCA techniques (# channels=4) in case of SGW 2 at position (0,5).

4.4 Variable number of wireless NICs per node

In this section we will study the relation between the amount of interfaces and the achieved mesh throughput. Figure 14 shows how increasing the number of available channels and interfaces influences the GPGF for NIB_{even}. This is done for a three train scenario on a single rail line, fully covered by 8 WGWs. In this section flows are non-dividable: $y_{pijk} \in \{0, 1\}$. Other traffic conditions or other WMN topologies would give similar results. It is shown that increase of the amount of available channels above 24 doesn't further improve the throughput for NIB_{even}. However, in case of NIB_{up} the GPGF stops already improving at 6 used channels. This shows again that NIB_{even} is a better binding method than NIB_{up} and that poor binding methods or a poor channel assignments could be a bottleneck for the multi-channel multi-radio architecture in such a way that adding interfaces or channels doesn't improve the effective throughput.

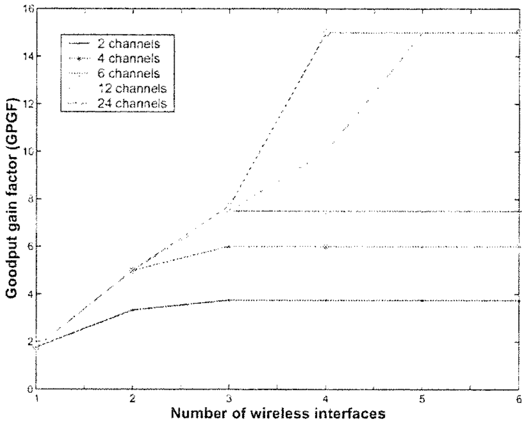

Figure 14: Goodput gain factor as function of the number of wireless interfaces for various amount of channels and NIB_{even}.

In any case, we notice a saturation point where the goodput gain factor can no longer be improved by adding extra interfaces. This saturation of the goodput gain factor can only be avoided by using techniques which take the effective traffic demand matrix into account and adapt the network to the current load conditions. We illustrate this for a single train scenario on Figure 15: it is shown that addition of extra interfaces will always further increase the mesh throughput if enough free radio channels are available. In practice, IEEE 802.11b/802.11g standards provide 3 non-overlapping radio channels while IEEE 802.11a provides 12 non-overlapping radio channels. Based on the availability of non-overlapping channels IEEE 802.11a is clearly preferred for building wireless mesh networks. The suboptimal curves of Figure 15 take into account that our WMN placement method might have a single node which isn't at maximum communication range due to the fixed position of the AGWs, causing higher interference levels. This explains why sometimes the load-aware assignment doesn't achieve its maximum potential.

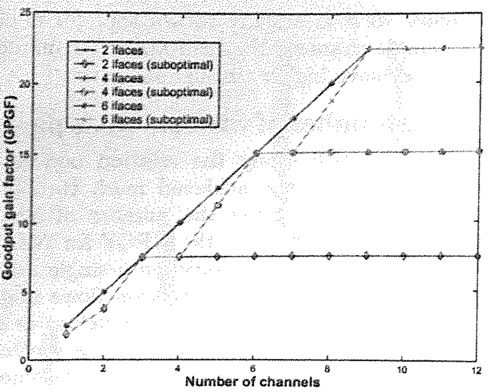

Figure 15: Optimal GPGF value for the load-aware method for a single train scenario.

5. CONCLUSIONS

In this paper we examined infrastructure-based mesh networks and developed a theoretical model for evaluating the expected throughput for fast moving user conditions. We proposed techniques for improving the mesh throughput: distribution of neighbour mesh nodes over the available amount of wireless interface cards (NIB = Neighbour Interface Binding) and distributed techniques for minimising the link interference levels by assigning different communication channels to the physical interfaces (DCA = Distributed Channel Assignment). We evaluated the mesh throughput for single train scenarios and multiple train scenarios. Under the assumed path loss model we found that the DCA is optimal if channel usage of the two-hop neighbourhood is taken into account. For the NIB we found that the available wireless interfaces are best equally distributed for binding of the neighbouring nodes higher up the tree and for the neighbouring nodes lower down the tree. Intuitively, this matches our expectations due to the aggregation network environment. In aggregation networks the traffic that comes from "down" links goes eventually to "up" links and vice versa due to the assumption of solely leaf-root communication. We also developed a load-aware NIB/DCA technique which dynamically adapts the binding and channel usages according to current traffic demands. Load-aware techniques are clearly able to achieve larger throughput but full coverage for multiple train scenarios most often lead to smaller gain margins. The presence of multiple well-positioned service gateways improves the mesh throughput significantly due to increased load-balancing possibilities. Gains for load-aware techniques are however also very sensitive for the level of uniformly spread traffic. Therefore, the presence of multiple gateways makes load-aware techniques less favorable due to fact that data traffic is again more uniformly spread. Gains for load-aware techniques are also very sensitive for the amount of available channels. Variation of the amount of interfaces is also studied and demonstrates that a poor choice in NIB or DCA could lead to a decreased mesh performance in such a way that adding interfaces or channels would not further improve the effective throughput.

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