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ENHANCEMENT IN WIRELESS MESH NETWORK INCLUDING ITS CAPACITY PARAMETERS

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Abstract—

Wireless Mesh Networks consist of a fixed topology of devices called Mesh Nodes. These nodes use their wireless interface to form a network. Some Mesh Nodes, called Hot Spots, may provide additional capabilities to the mesh network, like internet access. These capabilities are then shared via wireless multi-hop transmissions within the network. Mobile devices, like laptops, may connect to any Mesh Node with their wireless interface to use the services provided by the Hot Spots.

It is often doubted that mesh networks are scalable in terms of service provision. It is claimed that the bandwidth decreases strongly with multi-hop communications. There data frames are sent several times over the same physical channel, which consumes bandwidth.

This work analyses how much service bandwidth is really lost and it is shown that Mesh Networks are in fact scalable. A set of rules is identified to optimize this service bandwidth. It turns out that the service bandwidth is comparable to direct wireless access to the Hot Spot.

30% of mesh network topologies operate without losing bandwidth when a best effort algorithm is used, although it is NP hard to maximize the service bandwidth in general. Most topologies do only suffer minor bandwidth sacrifices.

Every mesh network topology can always use one third of the service bandwidth. Therefore, a full usage of the service bandwidth can also be guaranteed if at least three network topologies are connected to one hot spot. Further, the impact of reductions in spatial reuse is studied, which may lead into a decreased service bandwidth. This can be avoided by the usage of directional antennas at the hot spot. The remaining mesh network does not require any additional change and the full flexibility of random node placement is maintained.

Wi-Fi is often used in mesh networks. Therefore, its ability to support a full usage of service bandwidth is studied. It turns out that Wi-Fi's collision avoidance mechanisms impose an additional reduction of service Bandwidth. First draft link layer protocol recommendations are therefore elaborated.

I. Introduction

WIRELESS Mesh Networks (WMN) are a rather new technology to deploy wireless networks. The concept is to install fixed wireless devices, called Mesh Nodes or Modes, in a certain region. These Mesh Nodes are equipped with one or more, usually IP [1] based, wireless interfaces, which they use to communicate with each other. As such, the array of Mesh Nodes forms a network that can be accessed by mobile devices by connecting to one of the Mesh Nodes. Additional services, like Internet access can be delivered to the mobile devices in a multi-hop manner if one or more Mesh Nodes provide additional gateway functionality or other capabilities [2].

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The "concept was first proposed in 1995 under a Canadian patent called Massive Array Cellular System (MACS) [3]. The inventor, Victor Pierobon, designed it solely as a disruptive technology to replace all chargeable communication services, such as landline telephones, cellular phones, and cable TV with an entirely free service, a user based, user solely owned communication infrastructure" [4]. Still today, the primary objective is to reduce costs by providing a collaborative infrastructure to share and spread certain communication services, like for instance a high-speed Internet gateway. But also other applications are conceivable. A company may consider to install a mesh network to deliver Internet or intranet access to office rooms instead of installing wires within the entire building. The possibility to direct traffic over different routes is a feature that increases reliability and robustness and thus Wireless Mesh Networks are of interest in disaster and emergency communication. Especially, as they are fast deployable if appropriate self-organizing and self-healing hardware is used.

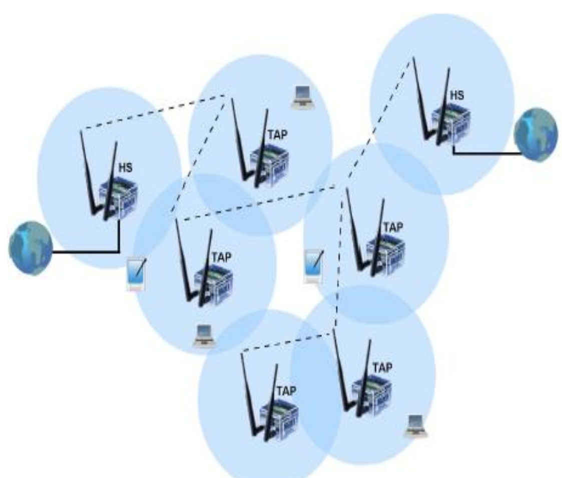

Figure 1: Wireless Mesh Network (WMN)

II. Capacity Constraints of Wireless Mesh Networks

The objective of this work is the study of capacity constraints for HS service provision in Wireless Mesh Networks. Arbitrary topologies of Mesh Nodes with Omni-directional antennas are considered. Hot Spots provide a certain service like Internet access, which is shared among TAPs. It is studied how much bandwidth can be made available to the service at every node.

Although service dissemination is one of the primary applications for mesh networks the scalability in terms of capacity is doubted [5,6,7]. The set of Hot Spots needs to provide sufficient resources to serve the entire mesh network in a multi-hop manner. Unlike wired solutions, frames need to access the same physical channel several times to be sent to the final destination. Therefore, one has to consider that resources have not only to be shared among the network participants, further overhead arises due to multiple allocations of the physical channel by the same frame. Especially, for the usage of Omni-directional antennas it is claimed that the bandwidth might decrease too strong.

Additionally, the media access control becomes a more difficult task. Nodes need to access the channel in an appropriate manner for sharing the services fairly among the mesh nodes. The approach needs to differ from wired media access control techniques as all nodes share the same physical communication media but are not necessarily in communication range to each other. The load for routing traffic increases near to HSs. Therefore, it is not sufficient to let every node access the channel in the same rate. The nearer a node is situated to a HS the more traffic is routed via it. Hence, it requires more access to the communication channel. This enhanced access shall be used to provide sufficient access to nodes at longer distances to the HS but not to utilize it for own access purposes.

II.I Multi-Hop Performance Loss

The main difference from a technology side

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between mesh networks and conventional wireless single-hop or last-hop networks is the wireless multi hop traffic. Frames need to be rerouted within a single physical network until the target station for a message is reached. To ensure proper delivery the nodes need to be cautious not to disturb other transmissions when forwarding frames. The impact is described in the following example. Figure 2 shows a wireless star topology. This could be a Wi-Fi Access Point with a wired Internet connection. Three stations are connected by Wi-Fi to this Access Point. The Access Point is able to forward packets into or from the Internet while it is sending or receiving in the Wi-Fi network. Assume all three stations store a packet to be sent into the Internet. They may alternate their access to the wireless channel to deliver the packets. And this can be repeated as long as packets have to be sent. Without interruption the access point can receive packets and forward these into the internet. Hence, the entire data rate of the wireless channel can be utilized for internet traffic. All stations obtain the same share of bandwidth as access is alternated.

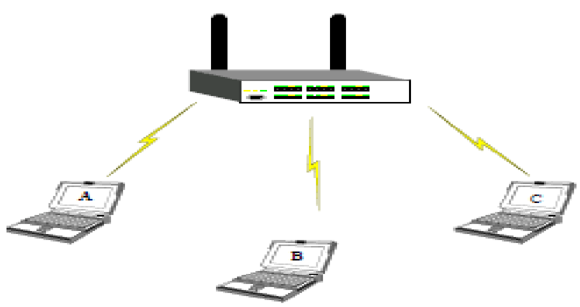

Figure 2: Access Point Network

II.II Fairness

Plenty of work has already been done concerning capacity of wireless networks in general, like [8, 9, 10, 11], neglecting the consideration of fairness.

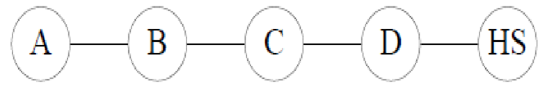

Figure 3: Multiple Hops between Client and HS

Here, we do not run into bandwidth problems when fairness is neglected. We could simply discard traffic of nodes A, B and C to avoid performance loss by multihop traffic. Of course, this is not a reasonable approach. There needs to be some kind of fair share. When sharing the service of the HS fairly among the mesh

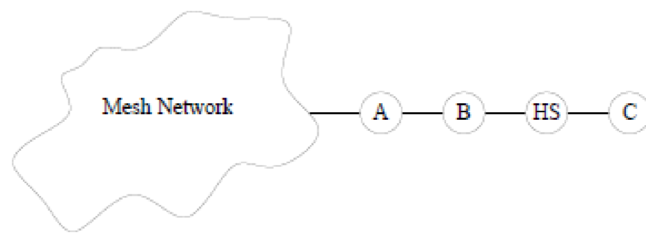

Figure 4: Unbalanced Topology

When sharing the service of the HS fairly among the mesh nodes or clients the needed communication load at the TAPs will differ. Consider Figure 3. If all nodes should obtain the same bandwidth to the HS, node D will have 10 times the communication load compared to node A, as it has to forward every packet to the HS as outlined before. This situation is not covered by current wireless Link Layer protocols. Consider Figure 4. Nodes B and C are connected to the HS. C needs not to forward messages of foreign nodes, while node B serves almost the entire mesh network via node A. Link Layer protocols like Wi-Fi will do its best out of this situation and will grand access to neighbored devices in an almost alternating manner. Hence, node C will obtain much more bandwidth (about 30% of the service bandwidth) than the rest of the network. As

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described before a performance loss will arise if access to the service of the HS is uniformly shared. This uniform share is what is considered as fairness in this work. A mesh network operates in a fair manner if all mesh nodes obtain the same bandwidth for service provision.

III. A Graph Based Model of A Wireless Mesh Network

The multi-hop performance loss was introduced in Section II.I. There, it was identified that parallel transmissions need to be at least in a three hop distance on a multi-hop path. Here, a model based on this situation is introduced. This model is denoted Common Case Model.

A second physical model is introduced, which implements interferences over further hop distances, which is called Strong Interference Model. This is done to analyze the impact of spatial reuse reductions on the service bandwidth. Key to the service bandwidth analysis is the knowledge of traffic patterns

III.I. Traffic Pattern Model

In this model the work considered covers the achievable bandwidth for service deployment in Mesh Networks. The traffic of interest propagates between mobile clients and Hot Spots .Firstly we consider the traffic associated with a single HS. The networks are traditional wireless star topologies, like Wi-Fi [12], WiMAX [13] and GSM and can be considered as performant. We therefore neglect these networks and assume non-interference with the mesh backbone and only consider the traffic between TAPs and HS. We can fully integrate the wireless nodes completely into the mesh network, meaning the mobile clients become a part of the same physical network. Then, the difference between mesh node and mobile client is that the mesh node is a router and the mobile client a traffic generator.

III.II. Physical Layer Model

Central difference to today's wireless single hop networks is the usage of multihop communications. As outlined before only every third node can send at a time on a multi-hop path. This is the case if wireless nodes can send together as long as their receivers are only neighbored to one sending station. This situation is described by the Common Case Model. Further performance loss may arise if non-neighbored nodes may disturb. To identify this loss the Strong Interference Model is introduced. There, senders produce collisions at foreign receivers within 2-hop distances.

We describe mesh networks as undirected graphs

$G = (V, E \subseteq V\ 2, HS \in V)$

Where the vertices V represent mesh nodes, an edge E indicates that nodes are in communication range to each other. The third component represents the HS. The following list summaries the model for a wireless mesh network:

• AWMN is represented as an undirected Graph
$G = (V, E \subseteq V\ 2, HS \in V)$
– V is the set of nodes
– Node a, b $\in$ V are in communication range, if (a, b) $\in$ E
– HS denotes the HS

• A node cannot send and receive at the same time

• If a node interferes a transmission then the transmitted frame is lost

• a can send a frame to b, if (a, b) $\in$ E and no other node interferes

III.III Link Layer Model

We consider three types of link layer access schemes Raw Access, Wi-Fi Basic Access as well as Wi-Fi RTS/CTS Access. Wi-Fi is one of the most popular link layers for wireless

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networks. Therefore, Wi-Fi is introduced, as well to study its performance in WMNs. To explain the models further we need to introduce two Wi-Fi features, namely the Network Allocation Vector (NAV) and the Back off Procedure. All frames exchanged within a Wi-Fi network contain a NAV to indicate the duration for an ongoing payload exchange. This value summaries the time that is needed to send all control frames being involved, the payload itself and the

Interframe spaces between exchanged frames. To avoid collisions, nodes overhearing a transmission remain idle as long as the NAV indicates. After expiration of a NAV and after sensing an idle channel, nodes willing to send start the back off procedure before sending. The back off procedure serves as a jitter to avoid high collision probabilities after allocated channels become unused. Nodes launching the back off procedure wait a randomly chosen time before sending. The random value is selected out of a defined interval. The interval is duplicated if a frame transmission fails, and reset to the primary size after a successful transmission. Being backoffed, nodes sense the wireless channel on allocation. If a node starts sending, the back off procedure is stopped by overhearing nodes. They reuse the current back off value when reentering the back off procedure. The reuse of already decremented back off values provides a certain amount of fairness among nodes being in communication range to each other. A node stops the back off procedure when it overhears a foreign transmission. Afterwards, the node has a better chance to allocate the wireless channel as it has only to wait for the duration that the already decremented back off value indicates.

The Wi-Fi Basic Access Procedure refers to one medium access scheme used in Wi-Fi. IP broadcasts are transmitted in Wi-Fi via Basic Access as well as short messages not exceeding a certain threshold in size. This link access protocol is depicted in Figure 5. If a node senses a busy medium or if its NAV value is not zero, the station defers its own frame transmission. After sensing an idle medium for a DCF Interframe Space (DIFS) period, the node launches the back off procedure and finally sends the frame containing the payload, as long as no other node starts sending before.

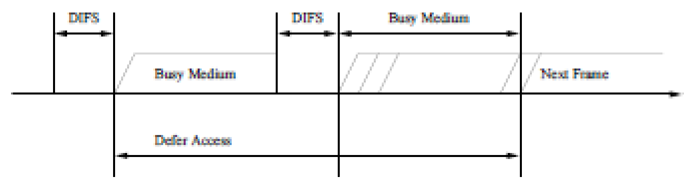

Figure 5: WiFi Basic Access

Wi-Fi RTS/CTS Access, depicted in Figure 6, is the second access procedure used in Wi-Fi to transmit

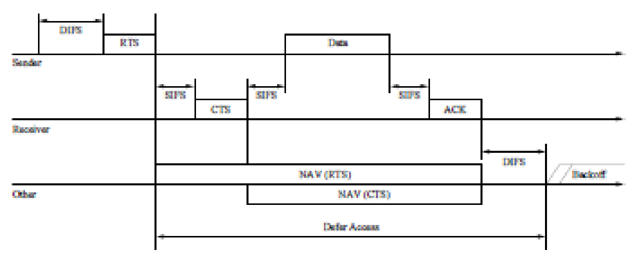

Figure 6: Wi-Fi RTS/CTS Access

unicast frames exceeding a certain threshold in size. It is an extension on the Basic Access method and uses therefore the mechanism of the Basic Access, as well. Prior to sending the payload the sender queries the availability of the receiver by sending out a Request-to-Send Frame (RTS). As long as the receiver is not deferred by a non-zero NAV value it replies with a Clear-to-Send (CTS). After receiving the CTS the sender starts transmitting the payload, which is finally acknowledged by the receiver on successful reception. All these

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frames are separated from each other by Short Interframe Spaces (SIFS) being shorter than DIFS to obtain indivisible frame exchanges. Other nodes overhearing the frame exchange are deferred by the containing NAVs. The RTS/CTS sequence is invoked to avoid the Hidden-Terminal-Problem [14] and to avoid disturbances of long frames.

Raw Access is not part of Wi-Fi and is introduced here to provide a bandwidth benchmark for later estimations. It is only used to transfer the basic Physical Layer properties that have been defined by the Common Case Model and the Strong Interference Model to the Link Layer. As such, the Raw Access does not have any kind of collision avoidance mechanism. Neither there is any kind of algorithm to obtain mutual exclusion, like RTS/CTS, nor do nodes sense for an allocated channel prior to sending a frame. This means payload frames are immediately sent without checking the channel on allocation and without querying the receiver on availability.

IV. Conclusion

Multi-hop transmissions restrict the utilization of the channel's data rate. If the network topology provides a sufficient parallelism by having several Multi-hop paths the lost utilization can be masked. Different regions in the network can by served while multi-hop transmissions are ongoing in other regions. This requires that the potential loss does not increase too much which is the next question to be answered below. Parallelism in the network topology can only be utilized when transmissions do not mutually exclude each other over large distances.

In other words the spatial reuse needs to be sufficient. For wireless mesh networks the region near to the HS -the source of the service to be shared- is of most importance for efficient service dissemination. If interferences are not too strong near to the HS, about 30% of randomly chosen wireless multi-hop topologies operate without losing service bandwidth. This can also be enforced by composing mesh networks out of arbitrary wireless sub networks that are connected to central HSs over isolated wireless links; for example isolated by the usage of directed antennas.

Link layer protocols need to be designed in such way that their collision avoidance strategies do not avoid a full utilization of the service bandwidth Wi-Fi does only allow a full service bandwidth with Basic Access and this only for upstream traffic. Wi-Fi RTS/CTS and downstream in general will always cause a capacity resource loss for the transmission of multi-hop traffic. This is mainly because neighbored senders are not allowed in Wi-Fi.

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