An Analysis of the Interference Problem in Wireless TDMA Networks

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***Abstract*—Communication in wireless networks raises the so-called *interference problem*, which means that the transfer of a message from some node *a* to a receiving node *b* can be disturbed by the overlapping transmission of another node *c* in interference range of node *b*. There are several approaches to solve this problem, such as the exclusive reservation of network-wide synchronized time slots in interference range of both sender and receiver, which we formalize and study in this paper. We first show that the interference problem can be solved if each node knows the current communication and interference topology of the network and the transmission reservations of all nodes at any time, and if reservations take place in a coordinated manner. We then analyze how far this global status information can be reduced while preserving the solvability of the interference problem. We apply our findings to evaluate some existing reservation protocols concerning their abilities to solve the interference problem, and identify possible shortcomings.**

Keywords*—*interference problem; reservation; TDMA; neighborhood; wireless network.

I. Introduction

Wireless networks are a commonly used technology these days. Basic problems of wireless networks, such as varying channel quality, interference due to concurrent transmissions, and energy shortage, have been addressed by a variety of sophisticated approaches to channel coding and medium arbitration. However, today's prevailing contention-based medium access techniques are highly prone to frame collisions when applied in multi-hop networks, due to the interference problem, which is illustrated in Figure 1. The figure shows the topology and a scenario of a wireless multi-hop network. The topology distinguishes communication links for data transfer, and interference links that may prevent successful data transfer if used concurrently. For simplicity, we assume that in this network, all nodes use the same frequency and code. In the scenario, nodes a and b want to exchange a message m. For a successful transfer, it is necessary but not sufficient that all nodes in *communication range* of node b (except a) stay silent while m is being transmitted. If, e. g., a transmission of node c, which is in *interference range* of node b, overlaps with a's transmission, the transfer would fail.

To solve the interference problem, a variety of exclusive reservation schemes using TDMA (*Time Division Multiple Access*), FDMA (*Frequency Division Multiple Access*), CDMA (*Code Division Multiple Access*), SDMA (*Space Division Multiple Access*) or combinations thereof are conceivable (see [1]).

In this paper, we study exclusive reservation schemes based on TDMA, where time slots are synchronized network-wide with an upper bound for clock offset. A synchronization protocol with this property has been published in [2]. To improve bandwidth usage, we additionally consider SDMA. We stipulate that if two nodes a and b want to communicate, they must reserve a free time slot s exclusively in interference range of a and b. More precisely, this means that s is not yet reserved for reception by any other node in interference range of a, nor for transmission by any other node in interference range of b. It is obvious that by always following these reservation rules, overlapping transmissions are safely avoided, and the interference problem is solved.

In this paper, we formalize the interference problem and define a global reservation criterion that builds on complete status information to solve the problem in a TDMA / SDMA setting. Because this criterion is too expensive to be implemented, we then examine how far the complete status information can be reduced while still solving the interference problem. This, finally, leads to a local reservation criterion based on a reduced network view and derived localized reservation status predicates, which we prove to be equivalent to the global criterion. Finally, we assess existing reservation protocols concerning their abilities to solve the interference problem, and identify possible shortcomings. In our future work, we plan to devise efficient reservation protocols based on the local reservation criterion, with nodes learning about their relevant reservation status by simply observing reservation traffic.

This paper is organized as follows: In Section II, we formally define our network model. The global reservation criterion is defined in Section III. In Section IV, we provide an equivalent local reservation criterion that is based on a reduced network view. In Section V, we analyze existing reservation protocols, discuss related work in Section VI, and draw conclusions in Section VII.

II. Network Model

We now introduce our network model, which distinguishes between (wireless) communication and interference links. We say that a node a is in *communication range* of a node b if a transmission of a is received correctly by b. Node a is in *interference range* of b if a transmission of a can prevent the correct reception of a concurrent transmission of some other node c to b.

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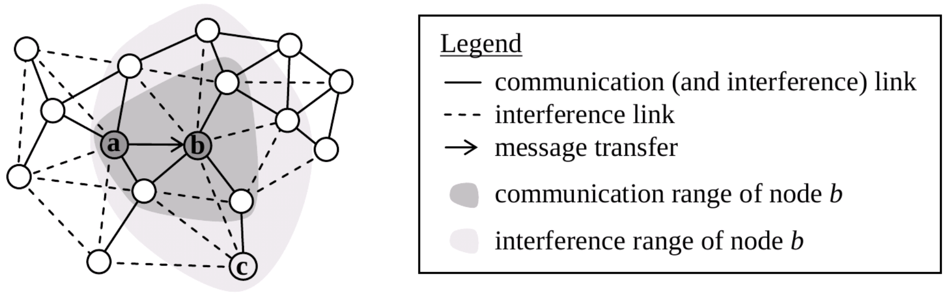

Figure 1. Illustration of the interference problem.

Definition 1. *Let V be a set of nodes. Then* (wireless) communication *and* interference links *are formally expressed by the following relations:*

- $CL =_{Df} \{(a,b) \in V \times V : a \textit{ is in communication range of } b\}$
- $IL =_{Df} \{(a,b) \in V \times V : a \textit{ is in interference range of } b\}$

We assume that there is only one antenna per node, which means that a node can neither receive nor detect any interference while transmitting. Furthermore, we assume that all links are bidirectional, which can be achieved in practice by taking suitable detection measures. These assumptions are formalized by requiring CL and IL to be irreflexive and symmetric. In addition, $CL \subseteq IL$ holds (we call this *consistency criterion*).

Based on the relations CL and IL, we define our model of a (wireless) network, which is a graph with two kinds of edges representing communication and interference links, and where all pairs of nodes are connected through a path of communication links.

Definition 2. *Let V be a set of nodes, CL and IL be relations expressing communication and interference links, respectively. A* (wireless) network *is formally modeled as a directed graph $G = (V, L, E)$, where $L = \{cl, il\}$ is a set of* labels*, and $E \subseteq V \times V \times L$ is a set of* edges*. The set $E = E_{cl} \cup E_{il}$ is composed of the following subsets:*

- $E_{cl} =_{Df} \{(a,b,l) \in V \times V \times L : l = cl \wedge CL(a,b)\}$ *(communication links)*
- $E_{il} =_{Df} \{(a,b,l) \in V \times V \times L : l = il \wedge IL(a,b)\}$ *(interference links)*

In addition, the communication subgraph $G_{cl} =_{Df} (V, \{cl\}, E_{cl}\}$ has to be connected, i. e., $\forall\, a, b \in V : \exists p =_{Df} (v_1^p, \ldots, v_{|p|+1}^p) \in V^+$ such that $\forall\, i \in \{1, \ldots, |p|\} : (v_i^p, v_{i+1}^p, cl) \in E_{cl}$, $v_1^p = a$ and $v_{|p|+1}^p = b$. We require that p is a cycle-free path*, i. e., no node occurs more than once in p. The length $|p|$ of p is its number of edges. The* communication distance *between two nodes $a, b \in V$ is defined as*

$$d_{G_{cl}}(a,b) =_{Df} \min_{p \in P_{G_{cl}}(a,b)} |p| \,,$$

where $P_{G_{cl}}(a,b)$ is the set of all cycle-free communication paths starting in a and ending in b. The interference distance *$d_{G_{il}}$ is defined analogously.*

Since CL and IL are irreflexive, no node has a communication or interference link to itself. Since the relations are symmetric, all links are bidirectional, i. e., $\forall\,(a,b,l) \in E : (b,a,l) \in E$, which is equivalent to regarding an undirected graph. In the following, we write $G = (V,E)$ to refer to a network $G = (V,L,E)$, since the labeling is fixed.

We assume that the *Single Network Property* holds, which means that all nodes are connected via some path of communication links (this is already covered by Definition 2), and no other nodes in interference range that apply a different MAC protocol are active in the same frequency band. This property can be satisfied in real environments by sufficient topology control combined with standardization measures and / or frequency and spatial division. Furthermore, slot reservation is a long-term functionality, which requires a sufficiently stable network topology to prevent frequent loss of reservations due to link breaks.

Next, we introduce several notions of neighborhood between nodes:

Definition 3. *Let $G = (V,E)$ be a (wireless) network, $a \in V$ and $i \geq 0$ an integer value.*

i) The i-hop communication *and* interference neighborhoods *of a are defined as*

$$CN_i(a) =_{Df} \{b \in V : d_{G_{cl}}(a,b) = i\} \,.$$

$$IN_i(a) =_{Df} \{b \in V : d_{G_{il}}(a,b) = i\} \,.$$

ii) The maximal i-hop communication *and* interference neighborhoods *of a are defined as*

$$CN_{\leq i}(a) =_{Df} \{b \in V : d_{G_{cl}}(a,b) \leq i\} \,.$$

$$IN_{\leq i}(a) =_{Df} \{b \in V : d_{G_{il}}(a,b) \leq i\} \,.$$

In the following, we also denote 1-hop communication neighbors simply as neighbors. From the definition, it follows that the 0-hop communication / interference neighborhood of a node is the node itself. Since neighborhood is defined w. r. t. the shortest path, i-hop neighbors are not $(i+j)$-hop neighbors for any $j > 0$. However, i-hop neighbors are also *maximal* $(i+j)$-hop neighbors for every $j \geq 0$. Because of the consistency criterion, $CN_1(a) \subseteq IN_1(a)$ holds for all $a \in V$.

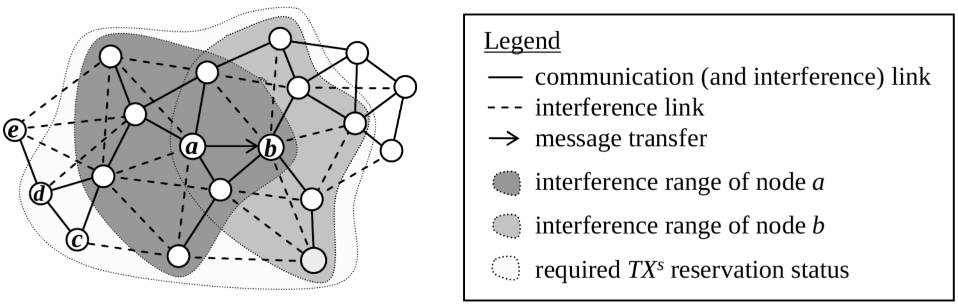

Figure 2. Illustration of the global reservation criterion.

Definition 4. *Let $G = (V, E)$ be a (wireless) network, $a \in V$, $P(a) \subseteq V$ and $R(a) \subseteq V$ be unary relations over V. Then we define*

$$P(R(a)) =_{Df} \{c \in V : \exists\, b \in R(a) : c \in P(b)\}$$

Note that for all $a \in V$ and $i \geq 0$, the sets $CN_i(a)$, $CN_{\leq i}(a)$, $IN_i(a)$ and $IN_{\leq i}(a)$ are relations according to Definition 4.

An example illustrating Definition 4 is the (1-hop) interference neighborhood of the communication neighborhood of a node a, which is denoted by $IN_1(CN_1(a))$. Note that $a \in IN_1(CN_1(a))$ holds, provided $CN_1(a) \neq \emptyset$.

III. Global Reservation Criterion

We assume that time is structured into macro slots, which are subdivided into consecutively numbered micro slots. The set of micro slots will be denoted by S in the following; the notions micro slot, time slot and slot will be used interchangeably. If a slot is reserved, then this reservation holds for all following macro slots, until it is released.

We now formally state the *global reservation criterion* $F^s_{TX}(a, b)$, defining whether a time slot $s \in S$ is free for transmissions from node a to node b, where b is in communication range of a. Informally, this means that s is currently reserved neither for reception by any node in interference range of a, nor for transmission by any node in interference range of b. The reservation criterion is called *global*, because it is based on global knowledge about network topology and reservation status.

Definition 5 (Reservation status)**.** *Let $G = (V, E)$ be a network, and $s \in S$ be a time slot. The* reservation status *$TX^s \subseteq V \times V$ of slot s defines, for all pairs of nodes $a, b \in V$, whether s is reserved for transmissions from a to b, provided $b \in CN_1(a)$. The following relations are derived from TX^s:*

- $TX^s(a) =_{Df} \exists\, b \in V : TX^s(a, b)$
  s reserved for transmission by node a
- $RX^s(a, b) =_{Df} TX^s(b, a)$
  s reserved by node a for reception from b
- $RX^s(a) =_{Df} \exists\, b \in V : RX^s(a, b)$
  s reserved for reception by node a

Please note that the derived relations do not carry any additional status information, but are introduced for better readability of the global reservation criterion:

Definition 6 (Global reservation criterion)**.** *Let $G = (V, E)$ be a network, $a, b \in V$, $b \in CN_1(a)$, $s \in S$ be a time slot, and TX^s be the reservation status of slot s. The* global reservation criterion *F^s_{TX} defines whether s is free for transmissions from a to b:*

$$F^s_{TX}(a, b) =_{Df} \forall\, c \in IN_{\leq 1}(a) : \neg RX^s(c) \wedge \forall\, d \in IN_{\leq 1}(b) : \neg TX^s(d)$$

We recall that $IN_{\leq 1}(a)$ and $IN_{\leq 1}(b)$ include nodes a and b, respectively. Therefore, the definition covers the necessary condition that both a and b have reserved s neither for transmission nor for reception. From the definition, it follows immediately that the interference problem can be solved if each node knows the current communication and interference topology of the network and the sending reservations of all nodes.

Figure 2 illustrates the global reservation criterion $F^s_{TX}(a, b)$. In the figure, all nodes whose TX^s reservation status is required to solve the interference problem are highlighted by the outer shape. This includes all nodes in interference range of a and b (inner shapes), and nodes c and d, but not node e. Nodes outside the interference range of a (e. g., c and d) have to be considered if the relation RX^s is not directly available but is derived from TX^s. If, for example, a value $RX^s(f, g)$ is needed, it is derived from $TX^s(g, f)$.

IV. Local Reservation Criteria

In this section, we transform the definition of the global reservation criterion $F^s_{TX}(a, b)$ into two *local* forms by replacing global predicates with local ones, thereby reducing the status information required to solve the interference problem. *Local predicates* are predicates that are defined from the point of view of a *single* node. We proceed in two steps: In Section IV-A, we introduce a local definition that is based on local knowledge about nodes in interference neighborhood, and show that it is equivalent to the global definition. In Section IV-B, we introduce an assumption about interference neighborhood such that only local knowledge about nodes in communication neighborhood is required to solve the interference problem, which provides a basis for feasible reservation protocols.

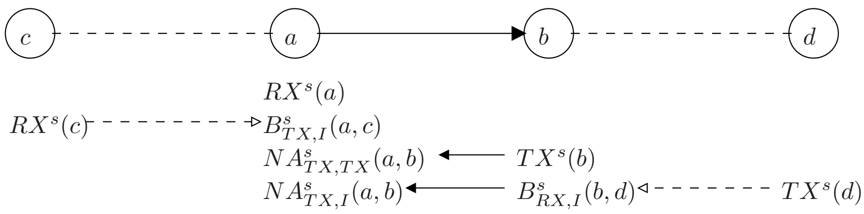

Figure 3. Topology pattern and local predicates to define the local reservation criterion with interference neighborhood.

A. Local Reservation Criterion with Interference Neighborhood

In this section, we assume that nodes have access to reservation status information of nodes in communication *and* interference neighborhood. From this status information, nodes can derive local predicates, which they can use to determine whether the reservation criterion is satisfied. Figure 3 shows a topological pattern that we use to define the local reservation criterion. Interference links are represented by dashed lines, communication links (which are also interference links) by solid lines. The arrow indicates that there is a request to reserve some slot s for transmission from a to b. To check the reservation criterion, status information expressed by local predicates that are listed beneath the nodes is required. An arrow from a predicate P to a predicate Q denotes that P is used to derive Q. A dashed arrow indicates that predicate values may not be directly available, which is the case if the corresponding node is in interference range, but not in communication range.

The global reservation criterion $F^s_{TX}(a,b)$ (see Definition 6) assumes $b \in CN_1(a)$ and is based on global predicates TX^s and RX^s:

$$\begin{aligned} F^s_{TX}(a,b) =_{Df}\ & \forall\, c \in IN_{\leq 1}(a) :\ \neg RX^s(c) \wedge \\ & \forall\, d \in IN_{\leq 1}(b) :\ \neg TX^s(d) \\ \equiv\ & \neg RX^s(a) \wedge \forall\, c \in IN_1(a) :\ \neg RX^s(c) \wedge \\ & \neg TX^s(b) \wedge \forall\, d \in IN_1(b) :\ \neg TX^s(d) \end{aligned}$$

To finally replace global predicates in this definition, we start by defining two local predicates:

Definition 7. $B^s_{TX,I}(a,b) =_{Df} b \in IN_1(a) \wedge RX^s(b)$
Slot s is blocked (B) for transmission (TX) at node a because of possible interference with a reception of b, with b in interference range (I) of a.

Definition 8. $B^s_{RX,I}(a,b) =_{Df} b \in IN_1(a) \wedge TX^s(b)$
Slot s is blocked (B) for reception (RX) at node a because of possible interference with a transmission of b, with b in interference range (I) of a.

Obviously, $TX^s(a,b)$ implies $B^s_{TX,I}(a,b)$ and $RX^s(a,b)$ implies $B^s_{RX,I}(a,b)$. However, the predicate TX^s (RX^s) carries the additional information which node is the sender (receiver) in slot s. Inserting these predicates, $F^s_{TX}(a,b)$ can be restated as:

$$\begin{aligned} F^s_{TX}(a,b) \equiv\ & \neg RX^s(a) \wedge \forall c \in IN_1(a) : \neg B^s_{TX,I}(a,c) \wedge \\ & \neg TX^s(b) \wedge \forall d \in IN_1(b) : \neg B^s_{RX,I}(b,d) \end{aligned}$$

In this definition, some predicates are local to the transmitting node a, while others are local to the receiving node b. We now define further predicates to obtain a definition of $F^s_{TX}(a,b)$ that is entirely local to a:

Definition 9. $NA^s_{TX,TX}(a,b) =_{Df} b \in CN_1(a) \wedge TX^s(b)$
Slot s is not available (NA) for transmission from a to b, because b has already reserved this slot for transmission.

Definition 10. $NA^s_{TX,I}(a,b) =_{Df} b \in CN_1(a) \wedge \exists c \in IN_1(b) :\ B^s_{RX,I}(b,c)$
Slot s is not available (NA) for transmission from a to b because of a possible interference with a transmission of some node c in interference range of b.

Inserting these predicates into the restated predicate $F^s_{TX}(a,b)$ above yields:

$$\begin{aligned} F^s_{TX}(a,b) \equiv\ & \neg RX^s(a) \wedge \forall c \in IN_1(a) : \neg B^s_{TX,I}(a,c) \wedge \\ & \neg NA^s_{TX,TX}(a,b) \wedge \neg NA^s_{TX,I}(a,b) \end{aligned}$$

Please note that first, this restatement of $F^s_{TX}(a,b)$ is equivalent to the definition of the global reservation criterion. Second, it is based on local knowledge about the reservation status of nodes in interference neighborhood of node a only, therefore, it is a local definition of $F^s_{TX}(a,b)$. It now remains to be shown how node a can determine its local values of these predicates.

We observe that the value of $RX^s(a)$ can directly be obtained from the list of current reservations of a. To determine the values of $B^s_{TX,I}$, the RX^s values of all *interference* neighbors of a are needed, which, however, may be out of communication range. $NA^s_{TX,TX}(a,b)$ can be derived from the TX^s values of b. Finally, to calculate $NA^s_{TX,I}(a,b)$, the $B^s_{RX,I}$ values of b are needed. For b to calculate its $B^s_{RX,I}$ values, the TX^s values of its interference neighbors are needed.

Obviously, although the above definition of $F^s_{TX}(a,b)$ is local, there still exists no reservation protocol that can solve the interference problem in the general case, as an exchange of status information with all nodes in interference neighborhood would be required.

B. Local Reservation Criterion with Communication Neighborhood

To determine the values of predicates $B^s_{TX,I}(a,c)$ and $B^s_{RX,I}(b,d)$ of nodes a and b, status information of interference neighbors c and d is needed. Since these neighbors may not be in communication range, it is not obvious how this information can

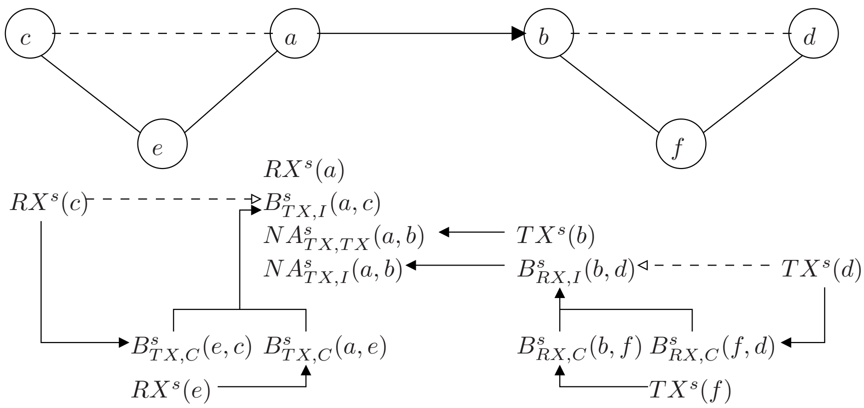

Figure 4. Topology pattern and local predicates to define the local reservation criterion with communication neighborhood, with $IN_1(a) = CN_1(a) \cup CN_2(a)$.

be acquired. Recall that in our definition of *network*, we stipulate that all nodes are connected via some path of communication links. Therefore, two nodes in interference range are always connected by a path of length $\leq n-1$, where n is the number of nodes in the network. If we additionally assume that we can control the topology to a certain extent, we may limit the communication distance of nodes in interference range to a value d, with $2 \leq d$. This means that $\forall\, a \in V : IN_{\leq 1}(a) \subseteq CN_{\leq d}(a)$ holds. For conservative decisions, we further assume that all nodes with a communication distance of at most d are in interference range, i. e., $\forall\, a \in V : IN_{\leq 1}(a) \supseteq CN_{\leq d}(a)$. On the whole, this means $\forall\, a \in V : IN_{\leq 1}(a) = CN_{\leq d}(a)$ or $\forall\, a \in V : IN_1(a) = CN_{\leq d}(a) \setminus a$, respectively.

In the following, we assume $d = 2$, which means that all nodes in interference range, but not in communication range have a communication distance of 2. This means that in the following, $\forall\, a \in V : IN_1(a) = CN_1(a) \cup CN_2(a)$ holds. Figure 4 extends the topological pattern of Figure 3, capturing this assumption and adding auxiliary predicates of nodes in communication range that are used to replace predicates of nodes in interference neighborhood. The meaning of arrows is as in Figure 3.

Definition 11. $B^s_{TX,C}(a, b) =_{Df} b \in CN_1(a) \wedge RX^s(b)$
Slot s is blocked for transmission at node a because of a possible interference with a reception of b, with b in communication range (C) of a.

Definition 12. $B^s_{RX,C}(a, b) =_{Df} b \in CN_1(a) \wedge TX^s(b)$
Slot s is blocked for reception at node a because of a possible interference with a transmission of b, with b in communication range (C) of a.

Note that the definition of $B^s_{TX,C}(a, b)$ ($B^s_{RX,C}(a, b)$) slightly differs from the definition of $B^s_{TX,I}(a, b)$ (see Definition 7) ($B^s_{RX,I}(a, b)$ (see Definition 8)), as nodes in communication range instead of interference neighborhood are considered. We remark that the formal definitions of $NA^s_{TX,TX}(a, b)$ and $B^s_{RX,C}(a, b)$ are the same. However, for conceptual clarity, we prefer to use two predicates.

Based on the assumption $IN_1(a) = CN_1(a) \cup CN_2(a)$, the predicates $B^s_{TX,I}$ and $B^s_{RX,I}$ can be derived from the reservation status of nodes in communication range as follows:

$$\begin{aligned} B^s_{TX,I}(a, b) &=_{Df} b \in IN_1(a) \wedge RX^s(b) \\ &\equiv b \in (CN_1(a) \cup CN_2(a)) \wedge RX^s(b) \\ &\equiv (b \in CN_1(a) \wedge RX^s(b)) \vee \\ &\quad\ (b \in CN_2(a) \wedge RX^s(b)) \\ &\equiv B^s_{TX,C}(a, b) \vee \exists\, c \in CN_1(a) : \\ &\quad\ (b \in CN_1(c) \wedge RX^s(b)) \\ &\equiv B^s_{TX,C}(a, b) \vee \exists\, c \in CN_1(a) : \\ &\quad\ B^s_{TX,C}(c, b) \end{aligned}$$

$$\begin{aligned} B^s_{RX,I}(a, b) &=_{Df} b \in IN_1(a) \wedge TX^s(b) \\ &\equiv (b \in CN_1(a) \wedge TX^s(b)) \vee \\ &\quad\ (b \in CN_2(a) \wedge TX^s(b)) \\ &\equiv B^s_{RX,C}(a, b) \vee \exists\, c \in CN_1(a) : \\ &\quad\ B^s_{RX,C}(c, b) \end{aligned}$$

This way, a can derive the $B^s_{TX,I}$ values from its own $B^s_{TX,C}$ values and those of its neighbors (in general, the $B^s_{TX,C}$ values of all nodes in $CN_{\leq d-1}(a)$ would be needed). The $B^s_{TX,C}$ values can in turn be determined by each node from the RX^s values of its neighbor nodes. The $B^s_{RX,I}$ values of b can be calculated from its own $B^s_{RX,C}$ values and those of its neighbor nodes (again, in general the $B^s_{RX,C}$ values of all nodes in $CN_{\leq d-1}(b)$ would be needed). The $B^s_{RX,C}$ values can in turn be determined by each node from the TX^s values of its neighbors. This way, a can derive $F^s_{TX}(a, b)$ by aggregating the predicates of its neighbors.

V. Assessment of Existing Reservation Protocols

In this section, we apply the local reservation criterion with communication neighborhood to assess existing reservation protocols for wireless networks. In many protocols, available bandwidth is modeled as an abstract number (*statistical* reservations), for example *Ticket-Based Probing* [3], the *Liao01 Protocol* [4] or *Trigger-Based Distributed Routing* [5]. By their nature, these reservation protocols do not guarantee collision freedom, since bandwidth cannot be reserved exclusively. Therefore, we restrict ourselves to protocols with TDMA approaches, i. e., protocols supporting the exclusive reservation of time slots (*deterministic* reservations).

Some deterministic approaches, namely *Bandwidth Routing* [6], *On-Demand QoS Routing* [7] and *On-Demand Link-State Multi-Path QoS Routing* [8] use CDMA in addition to TDMA to resolve conflicts between neighboring nodes. However, they do not distinguish whether slots are free for sending or free for receiving, which can lead to an unnecessary blocking of slots. Other protocols can be classified as pure TDMA approaches, which in addition make this distinction. The *Forward Algorithm* [9] is based on AODV [10] and calculates local maxima for adjacent links, which are propagated during route discovery. The slot reservation is done during route reply. In the *Liao02 Protocol* [11], each node keeps track of the slots of all nodes in its 2-hop-neighborhood and the corresponding slot states (*reserved* or *free*) in send and receive tables. Information about the 1-hop and 2-hop neighborhood of a node is recorded in a separate table. The reservation is done during route reply. We observe that these reservation protocols consider the slot states $B^s_{RX,I}$, $B^s_{TX,I}$ and $NA^s_{TX,I}$ only for nodes in communication range, but not in interference range. This clearly limits their scope and functionality, as collision freedom cannot be guaranteed despite reservation.

In the following, we will look at two protocols supporting deterministic reservations in more detail, namely the *Race-Free Bandwidth Reservation Protocol* [12] and the *Distributed Slots Reservation Protocol* (DSRP) [13].

A. Race-Free Bandwidth Reservation Protocol

The *Race-Free Bandwidth Reservation Protocol* [12] is an improvement of [11]. It is an on-demand, source-based protocol, whose objectives are to support parallel reservations and to avoid reservation races, which can occur if reservations are processed simultaneously.

The protocol structures time into TDMA frames consisting of control phase and data phase. In the control phase, each node has an exclusive control slot, which can be used to dynamically reserve data slots in the data phase.

For each node in 1-hop and 2-hop neighborhood, send and receive tables recording slot states are maintained. Besides the states *free* and *reserved* of [11], an additional state *allocated* is used for unconfirmed reservations. We note that the distinction between confirmed and unconfirmed reservations is useful for a (distributed) reservation algorithm, but not required in our analysis of the interference problem.

A wait-before-reject strategy is used, which means that a QoS request is not rejected, if enough slots are expected to become available with a predetermined acceptable delay. To realize this, time-to-live timers are used, which reset a slot status from *allocated* to *free* if the corresponding request is not confirmed within a predefined amount of time. Thus, reservation races can occur, if the slot status is set back to *free* too soon.

All nodes periodically broadcast their send and receive tables to their 1-hop and 2-hop-neighbors. In addition, status updates are sent asynchronously when a slot state is changed from *free* to *allocated* or from *allocated* to *reserved*. It follows that the status information of the predicates RX^s and $NA^s_{TX,TX}$ is available, typically with some delay. In addition, the values of the predicates $B^s_{TX,I}$ and $NA^s_{TX,I}$ are available, however, restricted to nodes in communication range. From this, it follows that collision freedom of data frames cannot be guaranteed despite reservations. Also, propagation of slot status information can only take place in the (exclusive) control slot of a node, leading to some delay. Therefore, a QoS request could be started by a neighbor before the status update has been made. This could in fact lead to interference due to double reservations of slots by neighboring nodes, which the protocol claims to eliminate.

B. Distributed Slots Reservation Protocol

The *Distributed Slots Reservation Protocol* (DSRP) [13] is an on-demand slot reservation protocol for QoS routing in TDMA networks. The main objective is the reuse of time slots. For example, slots with least conflict to other mobile hosts or slots used by other mobile hosts can be preferred.

As in [12], time is structured into TDMA frames consisting of control and data subframe, which are subdivided into slots. However, control slots are not exclusively reserved for a particular node, which means that there is contention for medium access, which may cause collisions and unpredictable delays (e. g., of QoS requests).

Besides the hidden and exposed terminal problems, two main problems considered are *slot shortage for self-route* (because of an inappropriate slot choice, a pending QoS request cannot be granted) and *slot shortage for neighboring routes* (because of an inappropriate slot choice, another QoS request cannot be granted).

The slot states forming the (global / local) reservation criterion are considered by the *slot inhibited policies*, but interference is only considered between nodes in communication neighborhood. Since the information is not maintained proactively as in [12], it has to be exchanged when needed. A potential sender x collects information from its neighbors, determines its valid sending slots and forwards them to the potential receiver y, which derives the valid slots for a transmission on the corresponding link. This means that the slot states RX^s, $B^s_{TX,I}$ (limited to nodes in communication range) and $NA^s_{TX,TX}$ are determined by x, and $NA^s_{TX,I}$ (also limited to nodes in communication range) is evaluated by y.

Since this information exchange must happen in the control subframe, there may be collisions and inaccurate information due to delays. Furthermore, since the sending slots are not reserved in x when they are forwarded to y, another QoS request could allocate these slots. Slot reservation is not done until the QoS reply is propagated through the network.

A *slot adjustment protocol* is used to solve the resulting problems. But since this protocol is only invoked if reservations collide directly at a node, problems could arise if a neighboring node has reserved this slot in the meantime, since this information is only kept in the reserving node.

To alleviate the slot shortage problems mentioned above, *slot decision policies* are used to determine the slots allowing the greatest reuse among the available slots. According to the slot decision policies, the slots used for a certain link are determined by the node three hops apart, in order to find the most suitable slots. But this means that the information on valid slots can already be outdated when the slots to be assigned are calculated.

VI. Related Work

The interference problem in wireless networks has been extensively studied in previous work, using different models to identify conditions for (non-)interference. For a comprehensive survey of interference models in wireless ad-hoc networks, we refer the reader to [14]. The purpose of an interference model is to determine whether a transmission between a pair of nodes may be successful. In general, this depends on many factors, such as spatial placement of nodes, environmental conditions, transceiver and channel characteristics, signal characteristics and propagation, and temporal channel usage. This makes the accurate treatment of interference a complex task. In this section, we focus on network models, which can be classified as graph-based models, physical models, and statistical models:

- *Graph-based models* define a network as a set of vertices representing, e. g., nodes, connected by edges representing, e. g., communication links. The network model we use in this paper belongs to this category.
- *Physical models* capture the characteristics of transceiver and channel with different degrees of detail, taking, e. g., Signal to Interference plus Noise Ratio (SINR) into account.
- *Statistical models* express relevant aspects, e. g., the transmission characteristics, in terms of a probability density function.

Graph-based models may be seen as an abstraction of physical and statistical models, leaving out parameters such as received signal strength or the probability of a successful reception. Different kinds of graph-based models have been applied to interference modeling:

- In the *connectivity graph*, vertices and edges represent nodes and communication links, respectively. In simple interference models, a transmission from a to b is only disturbed by the overlapping transmission of another node $c \neq a$ directly connected to b. In more sophisticated models, the transmission is also disturbed by the overlapping transmission of other nodes with a distance to b of up to 2 or 3 hops.
- In the *interference graph*, vertices and edges often represent nodes and interference links, i. e., interference between nodes. In [15], vertices represent links, and edges model interference between links. In both cases, it is straightforward to identify conditions for (non-) interference.
- In [16], the connectivity and interference graph are merged and augmented by sensing links. Here, a connectivity link implies an interference link, which in turn implies a sensing link. Connectivity links are directed (whereas interference and sensing links are undirected) and exist only if there is at least one transmission according to the link.

In this paper, we have merged the connectivity and interference graph to define the global reservation criterion (Section III) and the local reservation criterion with interference neighborhood (Section IV-A). We have then reduced this graph to a connectivity graph in which interference occurs if a receiver is in maximal 2-hop neighborhood of another sender. This way, it is feasible to define a local reservation criterion that is actually implementable (Section IV-B). We have decided against modeling sensing links, as concurrent transmissions of nodes in sensing range, but not in interference range would not be harmful.

VII. Conclusion and Future Work

In this paper, we have analyzed the interference problem in wireless networks, considering exclusive reservation schemes based on TDMA, where time slots are synchronized network-wide with an upper bound for clock offset. For this analysis, we have used a graph-based network model with edges representing communication and interference links. In a first step, we have defined an obvious global reservation criterion that solves the interference problem, however, at the expense of global up-to-date topology and reservation status. In a second step, we have rewritten the global criterion into an equivalent local form, thereby reducing the status information to solve the interference problem. In a third step, we have rewritten the local form, assuming that the interference range is limited to maximal 2-hop communication neighborhood, and have argued that this local form is actually implementable. Based on this local form, we have assessed a selection of existing reservation protocols and have identified a number of shortcomings.

In our future work, we will broaden our study of existing reservation protocols and develop a taxonomy for their assessment. Furthermore, we will make an effort to develop reservation protocols that solve the interference problem by implementing the second local reservation criterion. We note that it is not clear which additional assumptions are to be made to solve the problem of inaccurate or outdated topology and reservation status.

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