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Available Bandwidth Estimation and Prediction in Ad hoc Networks

Haitao Zhao, Jibo Wei, Shan Wang and Yong Xi
*National University of Defense Technology
China*

1. Introduction

Wireless ad hoc networks provide quick and easy networking in circumstances that require temporary network services or when cabling is difficult. With the widespread use of multimedia applications that require Quality of Service (QoS) guarantees, research in providing QoS support in wireless ad hoc networks has received much attention recently (Nafaa, 2007). The term QoS gathers several concepts. Some efforts, like admission control, intend to offer guarantees to the applications on the transmission characteristics, for instance bandwidth, delay, delay jitter, or packet loss. Other solutions, like QoS routing, only select the best path among all possible choices regarding the same criteria. In both cases, an accurate evaluation of the amount of resources available (i.e., available bandwidth) on a given path is necessary. Therefore, obtaining accurate information of available bandwidth is a crucial basis for QoS-aware controls in wireless ad hoc networks. In the followed analysis, the term available bandwidth will be denoted by "AB" for brevity.

Since the IEEE 802.11 Distributed Coordination Function (DCF), based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), is the most popular MAC protocol used in ad hoc networks, the AB estimation problem in 802.11-based ad hoc networks has been a focus of recent research. Some approaches that used to be applied in wired networks have been adopted in wireless scenario, e.g., (Hu & Steenkiste, 2003; Jain & Dovrolis, 2003; Melander, Bjorkman et al., 2000; Ribeiro, Riedi et al., 2003; Strauss, Katabi et al., 2003). Meanwhile, some new proposed approaches that specialize for wireless networks have been proposed, e.g., (de Renesse, Friderikos et al., 2007; Sarr, Chaudet et al., 2008; Wu, Wang et al., 2005). So far, however, there is neither consensus on how to precisely measure the AB in ad hoc networks nor a practical approach that has been widely adopted, which makes all these approaches on the stage of experiment or simulation and no standard is agreed yet. So it's time to rethink the AB estimation in ad hoc networks, and find out the challenges that make it so difficult to arrive at an agreement. In this chapter we'll review the existing approaches for AB estimation, presenting the efforts and challenges to AB estimation in 802.11 or 802.11-alike ad hoc networks, and we will also give some proposals to tackle these challenges. Analyzing these problems will help to not only develop an accurate AB estimation approach but also design QoS support schemes in ad hoc networks.

This chapter is based on our work that previously, in parts, have been published in (Zhao, Garcia-Palacios et al., 2009; Zhao, Wang et al., 2009; Zhao, Wang et al., 2010). And the rest of

this chapter is organized as follows. In Section 2, we first give a review of the state-of-the-art of AB estimation in ad hoc networks. Then in Section 3, we present the challenges of sensing-based approaches for AB estimation in 802.11 or 802.11-alike ad hoc networks and also give some solutions to them via analysis and simulation experiments. And in Section 4, we present the model-based approaches for AB prediction. In the end, we conclude this chapter in Section 5.

2. State of the art

In ad hoc networks, AB is defined in the context of end-to-end network path. Specifically, the path is a sequence of nodes, i.e., $N_1, N_2, N_3 \dots$ and N_{n+1} (n is the hop count), that communicate using identical, half-duplex wireless radio based on 802.11 DCF mode. The data packets are relayed from N_1 till N_{n+1} . The link (or hop) between N_i and N_{i+1} is referred to as Link i . See the illustration in Fig. 1.



Fig. 1. n -hop path to calculate the end-to-end AB

The state of Link i at time t is

$$S_i(t) = \begin{cases} 0, & \text{when Link } i \text{ is idle} \\ 1, & \text{when Link } i \text{ is busy} \end{cases} \quad (1)$$

Note that the node being busy can be caused by its transmitting, receiving or the neighboring interference. In the time period of $[t, t+\tau]$, the utilization of Link i is

$$U_i(t) = \frac{1}{\tau} \int_t^{t+\tau} S_i(t) dt \quad (2)$$

The AB is defined as the unused bandwidth over the time interval τ , here τ is usually referred to as the *estimation period* (namely the time needed for estimating AB once). It is not a constant value and can be changed in different estimation tools, or even in a tool according to the network scenario. Then the AB of Link i in the time period of $[t, t+\tau]$ can be expressed as

$$AB_i(t) = C_i(1 - U_i(t)) \quad (3)$$

where C_i is the channel capacity of Link i . And the end-to-end AB of a path is mainly determined by the link with minimum AB along the path.

AB estimation has generated several contributions in the wired and wireless networking communities. Several classifications of these solutions may be imagined. We chose to classify the approaches that could be adopted to estimate AB in 802.11 ad hoc networks into three categories: probe-based approaches, sensing-based approaches and model-based approaches.

2.1 Probe-based approaches

Probe-based approaches estimate the AB along a path via sending end-to-end probe packets. All these approaches are principally based on Probe Gap Model (PGM) or Probe Rate Models (PRM) (Strauss, Katabi et al., 2003). In PGM, the AB is obtained by first building the

mathematical formula of AB regarding the sending gaps and receiving gaps between probe packets, and then measuring the sending gaps and receiving gaps between probe packets to obtain AB. While PRM adopts a more straightforward principle as follows: if the probe packets sending rate is faster than AB, the probe packets will queue at some routers so that end-to-end delay increase gradually; On the other hand, if the probe packets sending rate is slower than AB, the probe packets will experience little delay. Therefore, the AB can be obtained while observing the delay variation and deciding the time when congestion begins. Furthermore, PGM can be cooperated with PRM, for instance in IGI (Initial Gap Increasing) method that proposed in (Hu & Steenkiste, 2003).

In the past decade, many probe-based AB estimation tools have been developed, such as Spruce (Strauss, Katabi et al., 2003), TOPP (Melander, Bjorkman et al., 2000), Pathchirp (Ribeiro, Riedi et al., 2003), IGI (Hu & Steenkiste, 2003), Capprobe (Kapoor, Chen et al., 2004) and Pathload (Jain and Dovrolis, 2003) to name a few. The developing course of these approaches is to build a more accurate relationship between AB and metrics in probe packets and thus increase the AB estimation accuracy. And a survey of them can be found in (Zhou, Wang et al., 2006). This type of approaches is most proposed originally for wired networks, and with the requirement of estimating AB in wireless ad hoc networks they are also adopted in wireless scenario. However, the difference between wired networks and wireless networks, especially that wireless ad hoc networks cannot bare the heavy overhead brought by the probe packets, impulses approaches specifically for wireless ad hoc network to be proposed. These approaches are trying to reduce the amount of probe packets and thus decrease the estimation overhead, among which the representative work are SenProbe (Sun, Chen et al., 2005) and the approach in (Hoang, Shao et al., 2006). SenProbe uses a return-way technique to estimate the unidirectional path capacity in wireless sensor networks, and thus simplify the path capacity estimation process. To further decrease the estimation overhead, authors in (Hoang, Shao et al., 2006) use a one-way probe (The destination node sends the probe to the source node and the source node estimates the AB). In theory, (Hoang, Shao et al., 2006) can reduce half of the overhead comparing to SenProbe. Whereas, reducing the probe packets will inevitably decrease the estimation accuracy.

Though the research on probe-based approaches is still moving on to find a balance between accuracy and overhead, some practical drawbacks of this type of approaches make it difficult to break through in its application in wireless ad hoc networks. First, the accuracy of probe-based approaches is not satisfactory. C. Dovrolis etc. (Dovrolis, Ramanathan et al., 2004) proved that PGM model actually estimates the Asymptotic Dispersion Rate (ADR) instead of the AB (The ADR is asymptotic dispersion rate between AB and channel capacity, and is an upper bound of the AB). At the same time, authors in (Lakshminarayanan, Padmanabhan et al., 2004) showed that in a CSMA- based wireless networks, a new probe packet enqueued at one of the stations might in fact be transmitted sooner than the older cross-traffic packets waiting at other stations. So the probe packet may not experience a delay commensurate with the total volume of cross-traffic, leading to over-estimation of the AB. On the other hand, (Lao, Dovrolis et al., 2006) arrived to a conclusion that contrary to the former two research: in general cases PGM can significantly under-estimate the AB of an end-to-end path. Maybe this can explain why Lakshminarayanan etc. (Lakshminarayanan, Padmanabhan et al., 2004) had arrived to the conclusion, via experiments, that most of probe-based approaches can only used in wired networks, and if they are used in 802.11 wireless networks, the measurement result will have big error without obvious disciplinarian. Second, there are some practical problems when deploying existing probe-

based bandwidth measurement approaches in ad hoc networks. It was observed (Johnsson, Melander et al., 2005), for instance, that the measured link capacity show dependence on the probe packet size and a smaller probe packet size will result in a lower bandwidth estimation. Besides, the source node is supposed to have the ability to send probe packets at a higher rate than AB via using PGM model. And the most but not the last drawback is that when every node in an ad hoc network needs to perform such an estimation for several destinations, the number of probe packets introduced in the network can be important and interact on the traffic as well as on other probes.

2.2 Sensing-based approaches

With the effort to avoid the presented problems in probe-based approaches, recent research contributes to estimate the AB on a given wireless link via sensing-based approaches. These approaches need not to send probe packets, but sense nodes' channel utilizations and eventually exchange this information via local broadcasts to calculate the AB. Usually these local broadcasts are performed using Hello packets that are used in many routing protocols to discover local topology. If these exchanges are not too frequent, this technique can be reasonably considered as non intrusive (Sarr, Chaudet et al., 2008). And thus sensing-based approaches are very suitable for wireless networks.

In (Zhai, Chen et al., 2006), the authors proposed the index CBR (channel busyness ratio) for AB estimation, which is easy to obtain and can timely represent channel utilization. Though this algorithm is proposed for single-hop WLAN, it is straightforward to get the idea that the AB of the multi-hop path as illustrated in Fig. 1 can be got by calculating $\min\{1 - CBR_i, i = 1, 2, \dots, n + 1\}$, where CBR_i is the channel busy ratio that sensed by node N_i . K. Xu, etc. (Xu, Tang et al., 2003) adopted this idea and added a smoothing factor to mask transient effects. But they only considered the AB estimation at each node within the path and did not consider any possible distant interfering nodes. To fix this problem, QoS-AODV proposed in (de Renesse, Ghassemian et al., 2004) also performs such per-node AB estimation, but the bandwidth available to a node is computed as the minimum of the AB over its single-hop neighborhood. However, with 802.11 protocol, two nodes within carrier sense range share the medium and thus the bandwidth, even if they cannot directly communicate. To consider carrier sense range interfering, most existing literatures such as FAT (Wu, Wang et al., 2005) and CACP (Yang & Kravets, 2005), approximate the carrier sense area by the two-hop neighborhood. The basic ideas of them are alike: each node provides information about the total bandwidth it uses to route flows and about its one-hop neighbors as well as their usage of the bandwidth, by periodically broadcasting a Hello message containing this information. Then, each node can compute the bandwidth usage and then derive the AB in its two-hop neighborhood.

Since the interference ranges of nodes within the same multi-hop path overlap, this phenomenon prevents a node from forwarding transmissions while any path members within its interference range are sending. Thus multiple links on the path of a flow contend for bandwidth, which is known as the *intra-flow contention problem* and was first studied in (Sanzgiri, Chakeres et al., 2004). Because of intra-flow contention, the actual AB for a flow should be further divided by the *contention count* (CC), namely the number of nodes that contend for bandwidth. The CC at node N_i can be represented as

$$CC_i = |CSN_i \cap NoP| + 1 \quad (4)$$

where CSN_i is the set of nodes that within N_i 's carrier sense range, NoP is the set of the nodes in the path. This problem is nontrivial because of the difficulty to find out the nodes within one node's carrier sense range. In literature, four methods were proposed to calculate CC: (1) based on the assumption that the interference range is the two-hop range, CC equals the hop count if the hop count is not more than 4, or 4 otherwise. This is the most popular approach in literature, e.g., (Chen & Heinzelman, 2005; Sarr, Chaudet et al., 2008); (2) increase the transmit power so that the packet can be successfully received by all the nodes in carrier sense range, e.g., CACP (Yang & Kravets, 2005); (3) sense the duration of the packet to determine the nodes in its carrier sense range, e.g., (Sanzgiri, Chakeres et al., 2004); or (4) use localization information with the help of Global Position System (GPS) (Gupta, Musacchio et al., 2007).

In the end, besides considering the carrier sense range media usage, the recent study ABE (Available Bandwidth Estimation) (Sarr, Chaudet et al., 2008) further considered the overlap probability of two adjacent nodes' idle time (P_o), packet collision probability (P_c) and the proportion of bandwidth (K) consumed by the waiting process of 802.11 to improve the accuracy of AB estimation. Then the end-to-end AB of the path $\{N_1, N_2, N_3 \dots N_{n+1}\}$ at time t is

$$AB(t) = \min \left\{ P_o \cdot (1 - P_c) \cdot (1 - K) \cdot \frac{AB_i(t)}{CC_i}, i = 1, 2, \dots, n \right\} \quad (5)$$

Sensing-based approaches were first proposed for single-hop wireless networks and then extended to multi-hop wireless scenarios. In this research, improving the estimation accuracy acts as the main driver. And so far, there is still work to do. For instance, AAC (Adaptive Admission Control) protocol (de Renesse, Friderikos et al., 2007) and ABE scheme (Sarr, Chaudet et al., 2008) are recently proposed schemes for AB estimation in 802.11-based ad hoc networks, but both of them need further improving in the consideration of the overlap probability of two adjacent nodes' idle time, i.e., P_o . In AAC, the transmitter and receiver are assumed to obtain perfectly synchronization, i.e., $P_o = 1$. But, in fact, there is possibility that when the transmitter is sensing idle the receiver is busy and thus cannot receive the packets from the transmitter, and vice versa. Under this case, AAC will over-estimate AB on the link between this transmitter-receiver pair. To resolve this problem, ABE use probability analysis to calculate P_o under the assumption that each node's surrounding medium occupancy is a uniform random distribution and independent to each other. This assumption, however, ignores the factual dependence of the interfering around the sender and the receiver, and thus will also result in inaccurate estimation of AB. This observation inspired our work in (Zhao, Garcia-Palacios et al., 2009) to calculate the overlap probability for two adjacent nodes' idle periods while taking into consideration the factual dependence of the interfering around them. And consequently improve the accuracy of AB estimation in IEEE 802.11-based ad hoc networks.

2.3 Model-based approaches

The AB estimation approaches that utilize currently sensed information are often insufficient because they lack predictive power and scalability, just considering that the entrance of a new flow will result in the change of network parameters (i.e. collision probability) and further the real AB. We need an approach that with predictive power and

has the ability and scalability to find the quantitative consequences of the entrance of new flows, and to achieve this goal, a proper model is necessary.

In the seminal work of Bianchi (Bianchi, 2000), the authors provided an analysis model for the behavior of 802.11 DCF protocol assuming a two dimensional Markov model at the MAC layer. The main assumptions in this work are (i) every node is saturated (i.e. always has a packet waiting to be transmitted), (ii) transmission error is a result of packets collision and is not caused by channel errors and (iii) the network is homogeneous (i.e. each node acts the same). Provided that these assumptions are satisfied, the resulting model is remarkably accurate. However, these assumptions are not necessarily true in practical networks.

First, the saturation assumption is unlikely to be valid in real multi-hop wireless networks. And even in WLANs, it is proved that the optimal work point¹ of a network lies before it entering saturation (Zhai, Chen et al., 2005). Thus more recent studies have shifted the focus onto 802.11 networks operating in non-saturated conditions, such as (Malone, Duffy et al., 2007) and (Kun, Fan et al., 2007), where the authors extended the underlying model in order to consider unsaturated traffic conditions by introducing a new idle state that accounts for the case in which the node buffer is empty, after a successful packet transmission.

To relax the dependence on the second assumption in (Bianchi, 2000), authors in (Chatzimisios, Boucouvalas et al., 2003) deal with the extension of Bianchi's Markov model in order to account for channel errors. And in (Qiao, Choi et al., 2002), the authors look at the impact of channel errors and the received SNR (Signal-to-Noise Ratio) on the achievable throughput in a system with rate adaptation, where the transmission rate of the terminal is adapted based on the link quality. (Daneshgaran, Laddomada et al., 2008) extends the previous works on this subject by looking at a more realistic channel condition for unsaturated traffic, and their assumptions are essentially similar to those of Bianchi's with the exception that they do assume the presence of both channel errors and capture effects due to the transmission over a Rayleigh fading channel.

To relax the dependence on the third assumption in (Bianchi, 2000), authors in (Ergen and Varaiya, 2005) propose a novel Markov model for the 802.11 DCF in a scenario with various nodes contending for the channel and transmitting with different transmission rates. An admission control mechanism is also proposed for maximizing the throughput while guaranteeing fairness to the involved transmitting nodes. And (Qiu, Zhang et al., 2007) develops a more general model to estimate the throughput, based on SNR or RSSI (Received Signal Strength Index) measurements from the underlying network itself and thus is more accurate than abstract propagation models based on distance. Their model also takes into account the general case of heterogeneous nodes with different traffic demands and different radio characteristics. While management decisions can be based on SNR or RSSI measurements from the PHY layer, it is known that these may be only weakly correlated with the actual channel behavior perceived at the MAC layer (Aguayo, Bicket et al., 2004).

Model-based approaches are very useful for network performance analysis, but the challenge is that to build an accurate analysis model for multi-hop wireless networks is not an easy job.

¹ The optimal work point is the turning point that the network should work around. Before that point, as the input traffic increases, the throughput keeps increasing, the delay and delay variation does not change much. After that point, the throughput drops quickly and the delay and delay variation increase dramatically.

3. Sensing-based approaches for AB estimation

We already mentioned that the probe-based approaches presented above do not yield accurate results in a wireless ad hoc context because of their practical drawbacks. In this section, we will mainly focus on sensing-based approaches, considering the challenges for accurate AB estimation and then presenting some solutions to them.

3.1 Identification of the nodes in the carrier sense range

Under the DCF mode, a transmission within one node's carrier sense range will interfere its receiving, which means while estimating one node's busy time (which is the first step to obtain the AB) we have to consider the interference in the carrier sense range. Thus identifying the nodes in one node's carrier sense range, which is represented by CSN in (4), is important to accurately estimate end-to-end AB.

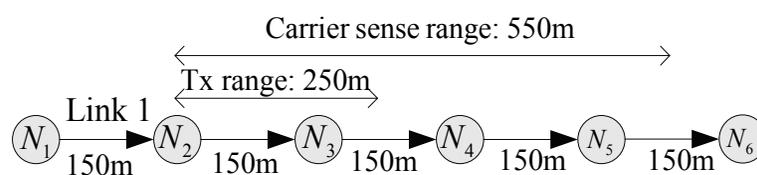


Fig. 2. Example scenario

In the majority approaches to identify the CSN, the node's carrier sense range is commonly expressed in terms of number of hops, k . And then use hello messages broadcast over the k -hop range to identify CSN. The most popular value of k is 2, e.g., (Chen & Heinzelman, 2005; Sarr, Chaudet et al., 2008; Wu, Wang et al., 2005) and the CACP-multihop in (Yang & Kravets, 2005). However, this is not necessary true in real wireless scenarios. Take the case shown in Fig. 2 as an example. Node N_5 is within the carrier sense range of N_2 , but 3 hops away from it. When N_5 is transmitting to N_6 , the transmission will reduce the AB on Link 1 (N_2 will sense the transmission from N_5 and thus shut itself down according to 802.11 protocol, which prevents Link 1 being on). But this effect is not counted by the aforementioned approach which assumes the carrier sense range is two-hop range. To resolve this problem, in AAC (de Renesse, Friderikos et al., 2007), the value of k switches between 2 and 3 with respect to the roughness of the path. And it is claimed that the roughness of the path is very likely to depend on the network node density. A high node density involves more paths existing between two mobile hosts. If nodes are uniformly distributed, there is a high possibility that the shortest path will be the smoothest. However, this theory holds only when assuming all nodes have an identical circular propagation region.

In (Yang & Kravets, 2005), Yang and Kravets also proposed two other different approaches, CACP-power and CACP-CS, to identify CSN. CACP-power assumes that the transmission power is variable. This approach consists of increasing the transmission power for bandwidth query messages such that all carrier sense nodes are able to decode it, which implies high power consumption and potential interferences as drawbacks. CACP-CS analyzes channel activity at a power threshold called *Neighbor-carrier-sensing Threshold*, which is set much lower than the carrier sensing threshold. Thus, each node is able to derive the bandwidth consumption of all its CSN. This technique minimizes overhead but could include isolated nodes that do not belong to any carrier sensing range. In real scenarios

where noise interferes with almost any signal, such a low power threshold detection system might wrongly interpret channel activity.

Without increasing the transmission power or decreasing the analysis power threshold, K. Sanzgiri, etc. (Sanzgiri, Chakeres et al., 2004) propose two methods, Pre-Reply Probe (PRP) and Route Request Tail(RRT), to obtain the number of CSN along a multi-hop path, i.e., CC in (4). The highlight of the proposed solutions is that carrier-sensing metrics such as the duration of sensed transmissions, is used to deduce the information of neighbors within carrier sense range, and no high power transmissions are necessary. But they either requires an additional message (PRPM) to be transmitted during route discovery (in PRP) or a tail is attached to RREQ packets (in RRT), which will increase the network overhead. Furthermore, counting sensed packets of a particular duration can enhance computing complexity and thus increases the route acquisition latency.

3.2 Estimation of the collision probability under unsaturated ad hoc networks

Collision is one important characteristic of wireless networks (Bianchi, 2000; Zhai, Chen et al., 2005). There are two main reasons to bring collision: (1) after each node's backoff, two nodes start to transmit packet to a same node at the same time; (2) the collision brought by the problem of hidden node. After collision, a node has to backoff and waits to retransmit. So the airtime taken by collision and backoff can not be used to transmit data, thus should be eliminated from the AB, see (5). And to do that we have to first estimate the collision probability.

The overwhelming majority of the analysis on collision probability is based on saturated scenario, i.e., Bianchi's landmark Markov model (Bianchi, 2000) and some research following it (Kuan & Dimyati, 2006). Unfortunately, as aforementioned that a very important task of network control is to avoid the network from saturation and keep it work at an unsaturated "optimal work point" (Zhai, Chen et al., 2005). It means the controlled network will work under unsaturated scenario. Thus recent research is focus on the analysis or estimation of the collision probability under the unsaturated scenario.

The first inspiration is that we can rely on the models for non-saturated networks. In (Malone, Duffy et al., 2007), (Ahn, Campbell et al., 2002) and (Ergen & Varaiya, to appear), modifications of (Bianchi, 2000) are considered where a probability of not transmitting is introduced that represents a node which has transmitted a packet, but has none waiting. With these models, we can derive the collision probability in non-saturated networks. However, it is important to note that the Markov chain's evolution is not real-time, and so the estimation of collision probability and throughput requires an estimate of the average state duration. Furthermore, as aforementioned that accurate analysis models for multi-hop networks are difficult to build up and maintain in distributed networks.

Without relying on analysis model for network behavior, ABE (Sarr, Chaudet et al., 2008) considered the real-time estimation of collision probability via calculating the collision rate of Hello packets. The idea is that since every node knows how many Hello packets should be received from one neighbor during a specific period (usually defined by the routing protocol) thus it can measure the collision rate of Hello packets, p_{Hello} , via keeping an account on the number of Hello packets it actually received. And then obtain the collision probability of data packets, p_c , by multiplying a Lagrange interpolate polynomial to compensate the different packet size between data packets and Hello packets as follows,

$$p_c = f(m) \cdot p_{Hello} \quad (6)$$

$$f(m) = am^3 + bm^2 + cm + d \quad (7)$$

where m is the size of data packets; a , b , c and d are polynomial parameters, which are obtained after different simulations varying data packet sizes and network load in (Sarr, Chaudet et al., 2008). However, there are two main shortcomings when using this approach. The first issue is that Hello packets are sent at a much lower rate than that of data packets. For instance, when considering AODV routing protocol (Perkins, Royer et al., 2001), Hello packets are usually sent at the frequency of 1 packet per second. Only to recognize that at a rate of 2 Mbps and assuming packet sizes of 1K bytes around 250 data packets are sent for just 1 Hello packet. In theory we could adopt a wider measurement period (e.g., 10 seconds), however the ratio to data packets is still as high and the measurement period can be too long for fast changing topology scenarios that are likely to emerge in Ad hoc networks. Therefore, although collisions on Hello packets can give some idea on collisions rates of Data packets, it is impossible to get an accurate estimate. A second issue is that experiments have to be run in advance in order to get a relative accurate expression of the Lagrange interpolating polynomial ($f(m)$) for a given scenario, and this expression will change when varying the scenario (e.g. number of stations, topology and packet size profile).

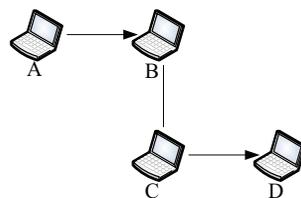


Fig. 3. A typical collision scenario

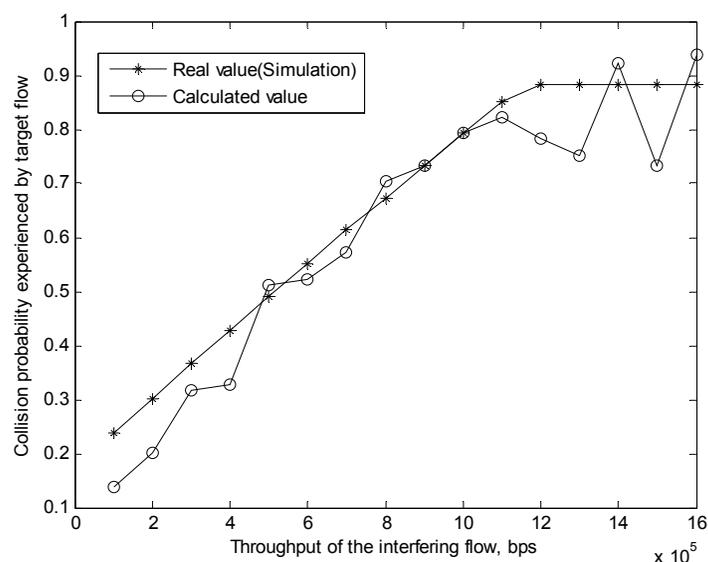


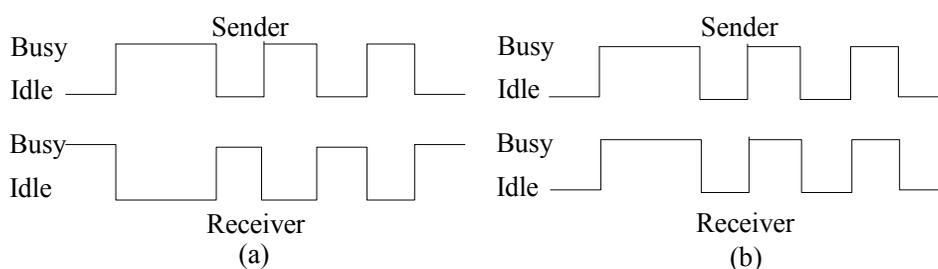
Fig. 4. Evaluation results

Let's consider the same typical collision scenario as in (Sarr, Chaudet et al., 2008), shown in Fig. 3, where C is a hidden node to A. Our aim is to use the aforementioned approach to estimate the collision probability over the target link A-B, which caused by the interfering flow C-D. As the throughput in the interfering flow changes, the collision probability over our target link changes. The simulated medium capacity is set 2 Mbps with a packet size of

1K bytes. And the results are plotted in Fig. 4, which shows the instability and the inaccuracy of estimating p by using Hello packets as in (Sarr, Chaudet et al., 2008).

3.3 Airtime synchronization

For the communication to happen, the medium has to be free on the sender's side so that the sender gains access the medium. On the receiver's side, the medium has to be free during the time required to transmit the whole data frame to avoid colliding. In other words, the medium availability on the sender and receiver sides has to somehow synchronize for the communication to take place. Fig. 5 (Sarr, Chaudet et al., 2008) shows two extreme case of the airtime availability at the sender side and the receiver side: (a) when they are never overlapped and (b) when they are totally overlapped. We can see that though in both cases, the idle airtime values measured at each node are the same but in case (a), the periods of airtime availability of both peers never overlap and the AB on the link is null. In the opposite case, the scenario depicted in (b) offers several communication opportunities on the link, when both sides are idle. So we have to consider this synchronization problem of the airtime at the sender and receiver side when estimate the AB.



(a) when they are never overlap; (b) when they are totally overlap

Fig. 5. Airtime at the sender side and the receiver side

Many existing publications, e.g., AAC (de Renesse, Friderikos et al., 2007) and (Wu, Wang et al., 2005), calculating the idle time ratio on Link i , enoted as R_i , as

$$R_i = \min\{r_i, r_{i+1}\} \quad (8)$$

where r_i and r_{i+1} are the idle time ratio sensed by N_i and N_{i+1} . These works actually assume that the airtime is totally overlapped. In order to obtain a more accurate consideration of the airtime synchronization, ABE (Sarr, Chaudet et al., 2008) assumes that the each node's surrounding medium occupancy is a uniform random distribution and the idle time ratio on Link i is represented by

$$R_i = r_i \cdot r_{i+1} \quad (9)$$

But for adjacent nodes, neither their airtime could be synchronized naturally nor are they independent to each other. In our recent research (Zhao, Garcia-Palacios et al., 2009), we have evaluated the approaches proposed in AAC and ABE to reveal the insufficiency of them. And we further proposed an AB estimation approach IAB (Improved Available Bandwidth estimation) which achieves more accurate estimation in [25]. The main contribution of IAB is that it considered the natural dependence between the medium state that sensed by two adjacent nodes. And this consideration is realized as follows. We first

differentiate the channel busy state caused by Transmitting/Receiving and the channel Sensing state. And this differentiation results in a more accurate estimation of the overlap probability of the idle times between two adjacent nodes and consequently a more accurate estimation of the AB between these nodes.

3.4 Intra-flow contention

Intra-flow contention prevents a node from forwarding transmissions while any path members within its interference range are sending, thus reduce the end-to-end AB of a multi-hop path. Therefore, we have to take this phenomenon into consideration when estimate the end-to-end AB in multi-hop ad hoc networks.

As described in Section 2.2, the overwhelming approaches to consider the intra-flow contention is to divide the AB further by the contention count, i.e., CC , and in literature there are three methods to calculate the CC . These methods are not satisfactory in that they either too simplified to reflect the real scenario (Chen & Heinzelman, 2005; Sarr, Chaudet et al., 2008), or increase the power consumption (Yang & Kravets, 2005) or complexity (de Renesse, Friderikos et al., 2007; Sanzgiri, Chakeres et al., 2004) of the network control. And what makes the problem worse is that even if we can accurately get the value of CC , dividing the bottleneck link's AB by CC (this method is referred to as the *average-based method* for brevity) cannot provide the accurate information of the end-to-end AB. The reason lies in that there is a throughput deviation of each link which leads to overlapping of simultaneously transmitting packets and collisions. Recently, authors in (Jae-Yong & JongWon, 2007) use the central limit theorem to model the throughput deviation, assuming the summation of uniformly distributed backoff times, which is referred to as the *deviation-based method*. Unfortunately, the proposed throughput deviation model can only consider the collisions due to two simultaneous transmissions along a path. This is invalid when there are more than 4 hops, in which case more collision scenarios exist. For clarity, let's consider an n -hop path, as illustrated in Fig. 1. The distance between two adjacent nodes is kept 200m in order to ensure that a flow generated in N_1 will go through each intermediate node and reaches the destination while we set transmitting range and carrier sense range respectively as 250m and 550m. In Fig. 6, we vary the number of hops, i.e., n , and plot the calculated end-to-end AB using average-based method, deviation-based method as well as the real value via simulation (The simulated medium capacity is also set 2 Mbps with a packet size of 1K bytes as in Fig. 4).

Fig. 6 clearly shows that the average-based method does not reflect the real value when the hop count is 4 or more because it neglects the collision due to throughput deviation of each link. Note that there is no collision for 3 or less hops, in which case the throughput average method matches the real value. Deviation-based method still accurately estimates the AB when the hop count is 4. However, it disagrees with the real AB after the path exceeds 4 hops, which keeps on decreasing. This estimation error can be explained by that more collisions appear when the hop count exceeds 4 which will further decrease the AB. (The average collision probability is also showed in Fig. 6.) The results demonstrate that the model in (Jae-Yong & JongWon, 2007) which only considers the collisions due to two simultaneous transmissions will produce an inaccurate AB calculation when the hop count is more than 4.

To solve this problem, our recent study (Zhao, Wang et al., 2010) proposes and validates a model to analyze the intra-flow contention of a given path in multi-hop wireless networks.

The basic idea is twofold: (i) We consider the intra-flow contention problem with an analysis model that account for the contenting links' behavior, instead of just calculating the contention count. (ii) The model envelops important factors for intra-flow contention, i.e., neighboring interference, hidden-node collision and possible multi-rate scenario, which make it approach reality and obtain accurate results. (The results obtained by our proposed model under the aforementioned scenario are also shown in Fig. 6, with the legend of *Model-based AB estimation*.)

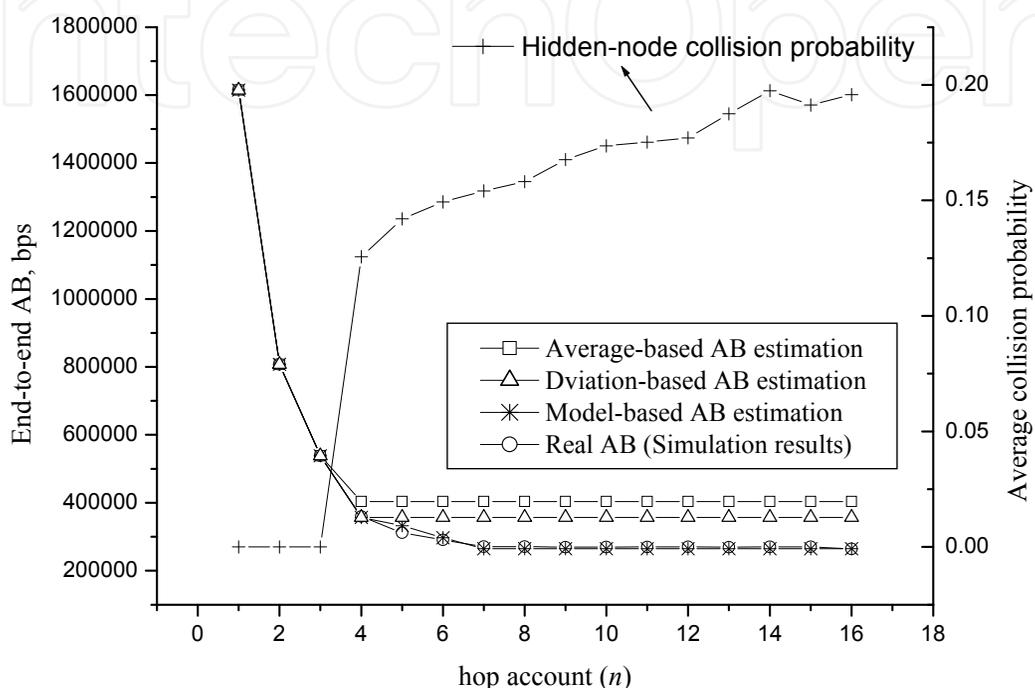


Fig. 6. End-to-end AB while varying the hop count

4. Model-based approaches for AB prediction

The model-based approaches are of redictive power and the current challenge is to derive more accurate and scalable analysis model. We will show our effort on this topic in this section.

4.1 Analytical model

For a better understanding, we give an overview of our model as shown in Fig. 7. Our model takes network information (topology and existing traffic), radio-dependent parameters and incoming traffic throughput demands as input and outputs the predictive throughputs of both the incoming flow and existing flows. Such a model is a powerful tool for performing what-if analysis and facilitating network optimization and diagnosis. Although in this chapter we focus on the throughput demands, or bandwidth requirement, of the flow, there is coupling of bandwidth and delay over a wireless link as shown in (Chen, Xue et al., 2004). So the model in this chapter can potentially be extended to analyze other QoS requirements, such as delay, by relating them to the network parameters, however this is out the scope of this chapter.

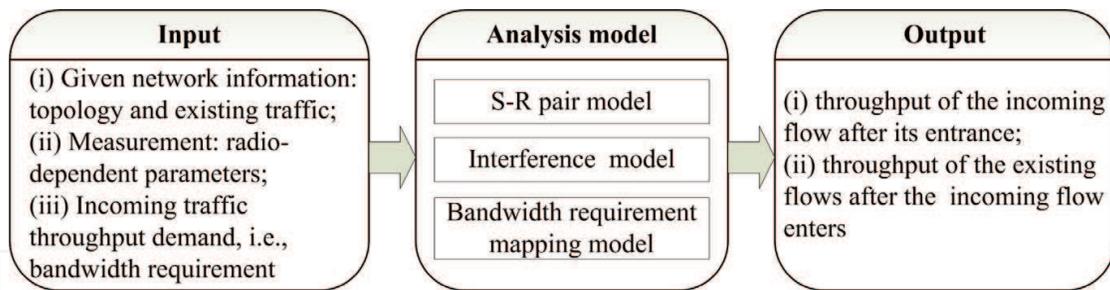


Fig. 7. Model structure

The model consists of three major components: S-R (i.e., sender-receiver) pair model, interference model and bandwidth requirement mapping model. These models will be covered in Sections 3.2, 3.3 and 3.4 respectively. The S-R pair model gives the link state from the view of an S-R pair, and considers important probabilities such as the transmission probability, the unsuccessful transmission probability, the sense busy probability and the non-empty transmission buffer probability. The interference model constructs the contention graph of the network, in order to analyze the interference of contending links. The bandwidth requirement mapping model relates the network parameters in the S-R pair model and interference model to the bandwidth requirement of the incoming flow(s). It is also important to initiate some key parameters that used in this model, which is explained in Section 3.5.

4.1.1 S-R pair model

The behavior of an S-R pair that employs an 802.11 protocol is dictated by the occupation of the 'air' around it (the channel). We denote the sender and receiver respectively as N_{k-1} and N_k , and the link between them as Link k .

We adopt the concept of generic *slot* used in (Dao & Malaney, 2008) (which is also denoted as variable length slots (VLS) in (Li, Qiu et al., 2008)), thus for the channel sensed by the Link k , 4 different states can be identified:

- i. Idle – N_{k-1} has seen the medium as idle and, either it has no data to send or its backoff counter has not reached 0 (i.e. backoff is in process).
- ii. Successful transmission – N_{k-1} has transmitted a packet, received an ACK from N_k and is about to resume backoff.
- iii. Unsuccessful transmission – N_{k-1} has transmitted, timed-out while waiting for an ACK from N_k and is about to resume its backoff.
- iv. Sense busy – N_{k-1} has detected the medium busy due to one or more other nodes transmitting, by means of either physical or virtual carrier sensing (i.e., the Network Allocation Vector, NAV), and has suspended its backoff until the NAV and DIFS/EIFS indicate that the backoff can resume.

The average time intervals during which Link k remains in idle, successful transmission, unsuccessful transmission and sense busy are denoted by σ , T_k , C_k , and B_k , respectively. σ is constant, equal to the backoff slot. The duration of the other intervals can be variable, depending on the access mechanism, the frame size, and the sending rate. From the perspective of the S-R pair, the evolution of the channel state of Link k can be abstractly represented by a temporal diagram such as the one exemplified in Fig. 8(b).

So the average length of the Generic slot of link k can be expressed as:

$$E_k = \tau_k p_k C_k + \tau_k (1 - p_k) T_k + (1 - \tau_k) b_k B_k + (1 - \tau_k) (1 - b_k) \sigma \quad (10)$$

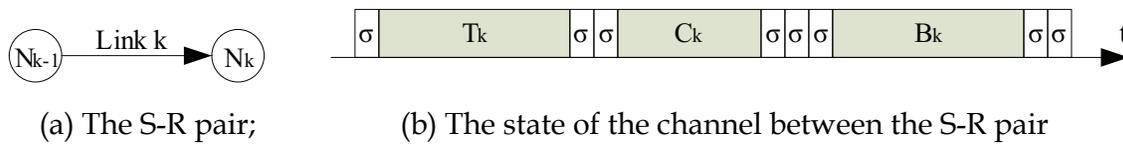


Fig. 8. S-R pair model

where τ_k represents the transmission probability on one time slot; p_k is the unsuccessful transmission probability. b_k is the channel busy probability. Then the normalized channel utilization ratio (i.e., the normalized transmitting airtime whether successfully or not, represented by x_k) and the successful transmission time ratio (represented by y_k) of Link k can be expressed as:

$$x_k = \frac{\tau_k p_k C_k + \tau_k (1 - p_k) T_k}{E_k} \quad (11)$$

$$y_k = \frac{\tau_k (1 - p_k) T_k}{E_k} \quad (12)$$

The throughput of Link k is, in pkt/s

$$S_k = \frac{\tau_k (1 - p_k) \Lambda}{E_k} \quad (13)$$

where Λ is the effective load fraction.

In equation (10), the average durations of a successful transmission and of an unsuccessful one are known a priori according to the 802.11 DCF standard (see (Bianchi, 2000), here we neglect the propagation delay). They are as follows under the Basic mode and RTS/CTS mode:

$$\begin{cases} T_k^{(Basic)} = DIFS + DATA + SIFS + ACK \\ C_k^{(Basic)} = DIFS + DATA + ACK_{timeout} \end{cases} \quad (14)$$

$$\begin{cases} T_k^{(RTS/CTS)} = DIFS + RTS + CTS + DATA + ACK + 3 \cdot SIFS \\ C_k^{(RTS/CTS)} = DIFS + RTS + CTS_{timeout} \end{cases} \quad (15)$$

In single-hop 802.11 networks all nodes are synchronized and the duration of a busy period equals the sum of the other nodes' transmitting duration. However, in the multi-hop case, transmissions of different nodes can overlap randomly due to the lack of coordination, which makes the determination of one node's busy period more complex. We take the assumption that if two links, for instance Link i and Link j , cannot sense each other, their action is independent to each other, this assumption is shown reasonable in (Gao, Chiu et al., 2006). So the overlap probability, denoted by $P_{overlap}(i, j)$, of these two links' transmitting airtime can be approximated as

$$P_{overlap}(i, j) = \frac{x_i \times x_j}{1 - \sum_{c \in v(i, j)} x_c} \quad (16)$$

where $v(i)$ represents the set of contending links (i.e., the links that contend with each other, and we will present them in Section 3.3) of Link i and $v(i,j)$ the set of common contending links of Link i and Link j . In Eq. (16), the numerator is the normalized probability that they transmit at the same time. When their common contending links are transmitting, neither of them can transmit, therefore the denominator represents the total time that they can use to transmit. Eq. (16) is referred to as the *second-order approximation*, which will be used again in our future analysis. Thus the sense busy time of Link k can be obtained via

$$B_k = \left(\sum_{i \in v(k)} x_i - \sum_{\substack{i_1, i_2 \in v(k); \\ i_1 \notin v(i_2) \cup i_2}} \frac{x_{i_1} x_{i_2}}{1 - \sum_{c \in v(i_1, i_2)} x_c} \right) E_k \quad (17)$$

A. Calculating the transmission probability τ

We should keep in mind that to support an application throughput along one route, the nodes on this route may have different transmission probabilities considering they may experience different collision probabilities. But in this section we temporarily drop the subscript, k , of the symbols for brevity.

A node can begin transmission when the following three conditions are satisfied: i) the node has data to transmit; ii) the link is idle; and iii) its random backoff counter reaches 0. The first one is related to the transmission queue. The last two are related to the interference by neighboring nodes. More specifically, one node's backoff counter is related to the unsuccessful transmission probability it experiences.

The transmission probability τ is a function of unsuccessful transmission probability p , which is first given in (Bianchi, 2000) under saturated situations. Recently, in (Kumar, Altman et al., 2007) and (Malone, Duffy et al., 2007) similar expressions of τ as a function of p are derived respectively for a large class of backoff mechanisms and for unsaturated situations. The complete expression of τ for 802.11 that takes into account the maximum retransmission limit jointly with the maximum window size and non-saturation case is given by

$$\tau = \eta \cdot \left(\frac{q^2 W_0}{(1-q)(1-p)(1-(1-q)^{W_0})} - \frac{q^2(1-p)}{1-q} \right) \quad (18)$$

where η is the stationary probability of a node being in the state where the backoff process is complete, but the node's transmission queue is empty (Malone, Duffy et al., 2007).

$$\begin{aligned} \frac{1}{\eta} = & (1-q) + \frac{q^2 W_0 (W_0 + 1)}{2(1-q)(1-(1-q)^{W_0})} + \frac{q(W_0 + 1)(p(1-q) - q(1-p)^2)}{2(1-q)} \\ & + \frac{pq^2}{2(1-q)(1-p)} \left(\frac{W_0}{1-(1-q)^{W_0}} - (1-p)^2 \right) \left(\frac{2W_0(1-p - p(2p)^{m-1})}{(1-2p)} + 1 \right) \end{aligned} \quad (19)$$

And q is the probability that there is at least one packet in the queue after a transmission, which is mainly related to the traffic load and it will be discussed in Subsection D. W_0 and $2^m W_0$ are respectively the node's minimum and maximum contention window.

B. Calculating the unsuccessful transmission probability p

The unsuccessful transmission probability p may arise from collisions or channel failure. We identify three different categories of unsuccessful transmissions as follows: (i) due to collision between synchronized nodes, which occurs with the probability of l_{sc} ; (ii) due to hidden nodes, which occurs with the probability of l_{hc} ; (iii) due to channel errors, which occurs with the probability of l_e . And we assume that these three probabilities are statistically independent, then a transmission is successful if it does not suffer from any of the three types of unsuccessful transmission mentioned above (they may occur simultaneously) and thus the unsuccessful transmission probability is:

$$p = 1 - (1 - l_{sc})(1 - l_{hc})(1 - l_e) \quad (20)$$

Collisions between synchronized nodes are the traditional type of packet losses due to the MAC protocol considered in single-hop 802.11 networks (Bianchi, 2000). Indeed, when all senders are in range of each other, the DCF function is able to synchronize all nodes in such a way that all transmission attempts happen at well defined slot boundaries recognized by all nodes. As a result, in this network scenario the conditional unsuccessful transmission probability for Link k is simply given by

$$p_{sc}^k = 1 - \prod_{i \neq k, i \in v(k)} (1 - \tau_i) \quad (21)$$

If each node has the same transmission probability then we will obtain the same result as in (Bianchi, 2000): $1 - (1 - \tau)^{n-1}$, where n is the total number of nodes in the WLAN. However, in a multi-hop topology the DCF function fails to synchronize all nodes and the hidden node collision usually account for an important component of the overall packet collision probability. The hidden node collision has been modeled in (Zhao, Wang et al., 2010). If node j is node k 's hidden node, the collision probability experienced at node k due to node j is as follows (using $p_{hc}^{k,j,(1)}$ and $p_{hc}^{k,j,(2)}$ to respectively denote the case when node j is the Type I and Type II hidden node² to node k)

$$p_{hc}^{k,j,(1)} = \frac{x_j}{1 - \sum_{c \in v(j,k)} x_c + \sum_{\substack{m,n \in v(j,k); \\ m \notin v(n) \cup n}} \frac{x_m \times x_n}{1 - \sum_{c \in v(m,n)} x_c}} \quad (22)$$

$$p_{hc}^{k,j,(2)} = \frac{x_k + x_j}{1 - \sum_{c \in v(j,k)} x_c + \sum_{\substack{m,n \in v(j,k); \\ m \notin v(n) \cup n}} \frac{x_m \times x_n}{1 - \sum_{c \in v(m,n)} x_c}} \quad (23)$$

Once we know the type of hidden node to Link i , the overall hidden node collision probability is the union of $p_{hc}^{k,j}, j \in h(k)$ ($h(k)$ represents the set of hidden node to Link k), namely:

² Please refer to (Zhao, Wang et al., 2010) for further detail.

$$p_{hc}^k = \sum_{j \in h(k)} p_{hc}^{k,j} - \sum_{\substack{m,n \in h(k); \\ m \notin v(n) \cup n}} \frac{p_{hc}^{k,m} \times p_{hc}^{k,n}}{1 - \sum_{c \in v(m,n)} x_c} \quad (24)$$

Here, we also use the *second-order approximation* to unfold the union expression.

Note that the collision may not necessarily result in packet loss, considering the *capture effect*. The capture effect is the ability of certain radios to correctly receive a strong signal from one transmitter despite significant interference from other transmitters. It means that even when two nodes simultaneously transmit, the one with stronger power still has chance to be correctly received. We introduce a parameter $0 \leq \alpha \leq 1$ to reflect the average impact of the capture effect, which is referred to as the *capture indicator* in this chapter, thus

$$l_{sc} = (1 - \alpha)p_{sc} \quad (25)$$

$$l_{hc} = (1 - \alpha)p_{hc} \quad (26)$$

To obtain p , the problem is reduced to obtaining the channel error probability l_e and the capture indicator α . We show how to obtain them via measurement in Section 4.1.4.

C. Calculating the sense busy probability b

The sense busy probability, b , is the probability that the channel becomes busy after an idle slot due to the activity of other nodes, under the condition that link k does not start its own transmission. It is equal to the probability that at least one contending link is transmitting, whether it is successful or not

$$b_k = 1 - \prod_{i \in v(k) \cup k} (1 - \tau_i) \quad (27)$$

D. Calculating the non-empty transmission buffer probability q

The variable q represents the probability that there is at least one packet in the queue after a transmission. In the previous models, to analyze the performance of saturated wireless networks, each node in the network is assumed to always have a packet to transmit (i.e., $q=1$). But according to the work in (Zhai, Chen et al., 2006), the network does not perform best when it is saturated and extensive research has been undertaken to prevent the network from saturation. So the effect of q must be considered in the model.

We introduce a parameter λ representing the rate at which packets arrive at the node buffer from the upper layers, and measured in *pkt/s*. The mean time between two packet arrivals is defined as the *mean inter-packet time*, and thus its value can be calculated as $1 / \lambda$.

A crude approximation in the unsaturated setting is to assume that packet arrivals are uniformly distributed across slots and set

$$q = \min \left\{ \frac{E}{\text{mean inter - packet time}}, 1 \right\} = \min \{ \lambda \cdot E, 1 \} \quad (28)$$

where E is the average length of the Generic slot obtained via Eq. (1) and measured in *seconds*.

If the traffic arrives in a Poisson distribution, then probability q can be well approximated in a situation with small buffer size through the following relations as (Malone, Duffy et al., 2007) and (Daneshgaran, Laddomada et al., 2008) revealed:

$$q = 1 - e^{-\lambda E} \quad (29)$$

Here the packet arrival probability is assumed independent to the channel state. A more accurate model can be derived upon considering different values of q for each backoff state. However, it has been proved in (Malone, Duffy et al., 2007) that as state-dependent models are more computational involved, there seems little advantage in employing a state-dependent model instead of the state-independent model. Thus it is a reasonable solution using a mean probability valid for the whole Markov model.

Note that, in (29), placing the node in saturation by taking the limit $q \rightarrow 1$, the model is reduced to a model for saturated scenarios.

4.1.2 Interference model

Given a set of wireless nodes, a network can be mapped into a contention graph (Chen, Low et al., 2005). This contention graph is used to represent interference (i.e. which link is interfering with which link) which has a consequent impact upon throughput. We use contention graphs to model the interference between contending links. In the literature, contention graph models have not considered contention due to hidden nodes which is an important difference in our work.

The process of mapping a network topology into a contention graph is introduced in (Chen, Low et al., 2005) and (Gao, Chiu et al., 2006). To illustrate this concept, we take the 4-hop chain network in Fig. 9(a) as a simple example, where nodes on the route are placed with the transmission distance R_{tx} . And R_{CS} represents the carrier-sense range.

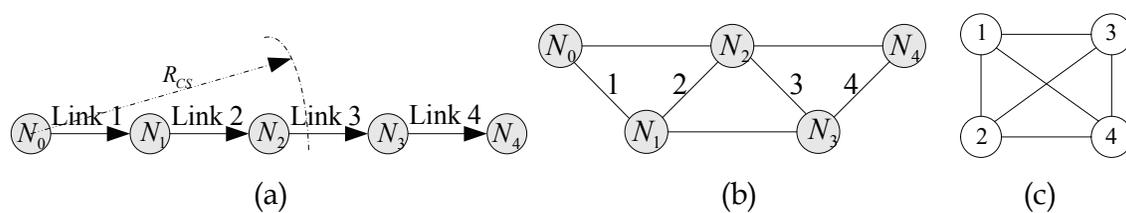


Fig. 9. Process of mapping a multi-hop route to its contention graph: (a) Example network; (b) undirected graph of the network; (c) contention graph

In Fig. 9 (b), nodes that can sense each other are connected. For instance, N_0 is connected to N_1 and N_2 because these two nodes are within the carrier-sense range of N_0 and they are considered neighbors of N_0 . However N_3 and N_4 cannot be sensed by N_0 and therefore are not connected to N_0 . The numbers beside each edge are used to label all active links in the wireless network, i.e., Link 1, Link 2, Link 3 and Link 4. Finally, in the contention graph in Fig. 9 (c), all active links are transformed into vertices. An edge between two vertices denotes contention between two links. This can be deduced from Fig. 9(b). Two links contend with each other when either the sender or the receiver of one link is within the R_{CS} distance of the sender or the receiver of the other, thus they are called *contending link* to each other. Note that previous work on contention graph only considered the interference due to neighboring nodes; while hidden node interferences were not modeled (i.e. in previous work there is no edge between Vertex 1 and Vertex 4 in Fig. 9(c)). In this research, we will consider interference due to both, neighboring and hidden nodes.

Note that the aggregate successful transmission time ratio of contending links in the network should not be more than 1, thus we have the following interference constraint

$$\sum_{i \in v(k)} y_i \leq 1, \quad \forall k \in \mathbb{N} \quad (30)$$

where \mathbb{N} is the set of all active links in the given network.

4.1.3 Mapping bandwidth requirement to the model parameters

In this section, we related the bandwidth requirement of a flow, to the network parameters. For instance, to satisfy the application bandwidth requirement (BW , bps), given the traffic packet size (PS , bits), the packet arrival rate is

$$\lambda = \frac{BW}{PS \cdot \Lambda} \quad (31)$$

And according to (13), we can easily obtain that the transmission probability used for this application by a link (Link k) along the path of this application is at least

$$\tau_k = \frac{BW \cdot E_k}{PS \cdot (1 - p_k) \cdot \Lambda} = \frac{\lambda \cdot E_k}{(1 - p_k)} \quad (32)$$

Recalling equations (18) and (21), the transmission probability will further affect the packet collision thus the unsuccessful transmission probability p , which will in turn affect the transmission probability, see (32). The coupling of the network parameters relates the bandwidth requirement of a flow to all the network parameters.

4.1.4 Parameters initialization

We still need to obtain two radio-dependent parameters to complete the model. Those are the conditional capture indicator α and the channel failure probability l_e . In this section, we estimate these two parameters by conducting broadcast measurement. The key idea is that we can estimate unicast interference using broadcast packets.

First, we have one node, Node i , broadcasts packets and we keep track of the delivery rate of the packets at all other nodes in the network. Only one node is active at a time. We denote the broadcast rate as R_i and the delivery rate from Node i to Node j as R_{ij} . Then each node broadcasts in turn. We then select a pair of nodes, Node i and Node k , and have them broadcast packets together. All remaining nodes measure the delivery rate of packets they receive from each of the two broadcasting nodes. For example, at node j , the delivery rate of packets from i is denoted by $R_{ij}^{i,k}$. Then each pair of nodes simultaneously broadcast in turn. Thus, we have carried out a total of $o(n^2)$ experiments, where n is the number of nodes in the network.

Using the data gathered from the above methodology, we can obtain the maximum-likelihood estimators for the channel error probability for the channel from node i and node j (denoted by $l_e^{i \rightarrow j}$) and the average capture effect experienced by the link from node i to node j (denoted by α_{ij}) as:

$$l_e^{i \rightarrow j} = \frac{R_i - R_{ij}}{R_i} \quad (33)$$

$$\alpha_{ij} = \sum_{k \in \mathbb{N}, k \neq i} \tau_i \tau_k \frac{R_{ij}^{i,k}}{R_{ij}} \quad (34)$$

4.2 Model-based algorithms for AB prediction

We have built up a model considering the bandwidth requirement of a new flow and some other parameters: transmission probability, collision probability. After constructing the contention graph for a given network, we can easily perform admission control and end-to-end AB estimation in order to guarantee throughputs to applications in multi-hop wireless networks.

4.2.1 Admission control

<p>▷ Input: bandwidth requirement, i.e., BW, of the incoming flow; given route $\Gamma = \{N_0, N_1, \dots, N_r\}$</p> <p>▷ Output: whether the flow can be admitted</p> <p>1: Initialization : $admission = 0; \tau_k = \tau_k^{old} + \frac{BW \cdot E_k^{old}}{PS \cdot (1 - l_e) \cdot \Lambda}, k = 1, 2, \dots, r$ <i>// iterative admission control (MaxIter = 20 and THD = 0.01 by default)</i></p> <p>2: for $iter = 1$ to $MaxIter$</p> <p>3: <i>update</i> ($\{p_{i \in v(k)}, \tau_{i \in v(k)}\}$ and $\{p_k, \tau_k\}$) <i>// according to (18) and (20)</i></p> <p>4: <i>calculate</i> ($y_{i \in \mathbb{N}}$) <i>// according to (12)</i></p> <p>5: if any k satisfies ($\sum_{i \in v(k)} y_i > 1$) <i>// interference constraint is violated</i></p> <p>6: $admission = 0; break$ <i>// early stop : reject</i></p> <p>7: end if</p> <p>8: $\tau_k^\circ = \frac{BW \cdot E_k}{PS \cdot (1 - p_k) \cdot \Lambda}, k = 1, 2, \dots, r$</p> <p>9: if ($\max_{k=1,2,\dots,r} \{ \tau_k^\circ - \tau_k \} < THD$) <i>// convergence test</i></p> <p>10: $admission = 1; break$ <i>// early stop : admit</i></p> <p>11: end if</p> <p>12: end for</p> <p>13: return $admission, \tau_k^\circ$</p>
--

Table 1. Admission control

Given the bandwidth requirement of a coming flow, the goal of admission control is to make a decision on whether the requesting flow can be admitted without impairing the QoS of existing flows. The main challenge is that we cannot make the accurate decision according to the network states before the flow entered because the entrance of the flow will change the transmission probability and collision probability. So the idea in this research is to adopt a what-if analysis, namely to check what will happen if the new flow is admitted. Since there is strong inter-dependency between the transmission probability and the loss rate of contending links: the transmission probability of Link k , τ_k , depends on its packets loss probability as well as the transmission probability of its contending links, which in turn depends on τ_k (refer to Eq. (18) and (21)). To address the inter-dependency, we use an iterative procedure to jointly estimate the transmission probabilities and loss probabilities.

We initialize that after a new flow entering, the collision probabilities (including collisions due to both synchronized nodes and hidden nodes) at all links for this flow are zero. We then iteratively update link transmission probabilities and packet loss probabilities based on the other links' transmission probabilities and loss probabilities derived in the previous iteration. The iterative procedure continues until the number of iterations reaches a threshold (MaxIter), or the transmission probability no longer change significantly (Less than a threshold THD), or a interference constraint (see (30)) is violated. The algorithm is outlined in Table 1.

In line 1, τ_k^{old} and E_k^{old} are the corresponding parameters estimated on Link k before the entrance of the new flow. If there is no traffic on Link k before the entrance of the new flow, then $\tau_k^{old} = 0$ and $E_k^{old} = T_k$. This algorithm performs the admission control along a given route, and it also calculates the sending rate of the sender to guarantee the bandwidth requirement (obtained via Line 8). This algorithm can also help to perform route selection, namely find a route that can support the requested bandwidth.

4.2.2 End-to-end AB prediction

<p>▷ Input: given route $\Gamma = \{N_0, N_1, \dots, N_r\}$; ▷ Output: λ (the available bandwidth of Γ)</p> <p>1: initialization : $\lambda = \lambda_0 / 2$ // λ_0 is the theoretic maximum capacity // iterative process (MaxIter = 20 and THD = 1kbps by default)</p> <p>2: for $i = 2$ to MaxIter</p> <p>3: $\lambda^\circ = \frac{1}{2^i} \lambda_0$</p> <p>4: if ($\lambda^\circ < THD$) // convergence test</p> <p>5: break // early stop</p> <p>6: end if</p> <p>7: if (admission control(λ, Γ))</p> <p>8: $\lambda = \lambda + \lambda^\circ$</p> <p>9: else</p> <p>10: $\lambda = \lambda - \lambda^\circ$</p> <p>11: end if</p> <p>12: end for</p> <p>13: return λ</p>

Table 2. End-to-end AB prediction

Let's exploit the following property in 802.11 networks (Kun, Fan et al., 2007): if the throughput of λ is feasible along a given route without violating the QoS of ongoing traffic, all throughputs smaller than λ are also feasible; while if the throughput is unfeasible, all the values larger than λ are also unfeasible. Thus, we can increase the value of λ until it is not feasible to find the end-to-end AB of path Γ without breaking the QoS demands of all existing traffic. Hence the solution can be obtained with logarithmic complexity by applying a binary search algorithm (half the search space each time).

It is worth mentioning that to find the end-to-end AB is different to performing admission control, the latter is only the answer to whether a flow along a given route with a specific bandwidth requirement can be admitted, while the former need to further find out the maximum bandwidth of a flow that can be admitted. Table 2 outlines the algorithm, which takes the admission control as a sub function.

In Line 1, λ_0 is the theoretic maximum capacity, which is the upper bound of our algorithm's searching space. Since the algorithm will converge very fast, the accuracy of this value will not affect the result significantly only if it is bigger than the estimated end-to-end AB. In an n -hop network, representing C as the channel physical capacity, λ_0 is set according to the following equations (i.e., the maximum capacity is limited by the number of hops due to the existence of intra-flow contention):

$$\lambda_0 = \begin{cases} C / n, & 1 \leq n \leq 4 \\ C / 4, & n > 4 \end{cases} \quad (35)$$

5. Conclusion

With the IEEE 802.11-based ad hoc networks deployed as the vital extension to wired networks and the widespread use of multimedia applications that require QoS support, AB estimation is such an important operation that it is very necessary for research community to create an effective, general-purpose estimation method. This chapter reviews the state-of-the-art of AB estimation in IEEE 802.11-based ad hoc networks, gives an analysis of the challenges on this topic. The analysis mainly focuses on fundamental problems, which rise from the nature of wireless networks and operation of DCF mode. To develop estimation tools that can work accurately in 802.11 or 802.11-alike ad hoc networks, researchers are expected to think over all these challenges. It then gives some solutions to these challenges. In particular, it presents our solutions to improve the accuracy of sensing-based AB estimation and model-based AB prediction. We hope that this analysis can help to spur further work on this topic.

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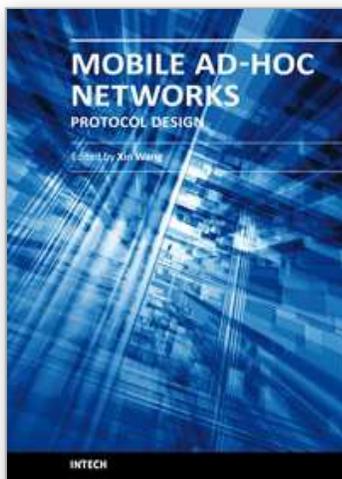
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Being infrastructure-less and without central administration control, wireless ad-hoc networking is playing a more and more important role in extending the coverage of traditional wireless infrastructure (cellular networks, wireless LAN, etc). This book includes state-of-the-art techniques and solutions for wireless ad-hoc networks. It focuses on the following topics in ad-hoc networks: quality-of-service and video communication, routing protocol and cross-layer design. A few interesting problems about security and delay-tolerant networks are also discussed. This book is targeted to provide network engineers and researchers with design guidelines for large scale wireless ad hoc networks.

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