Rethinking available bandwidth estimation in IEEE 802.11-based ad hoc networks

where

$$K = \frac{DIFS + Backoff}{T}$$
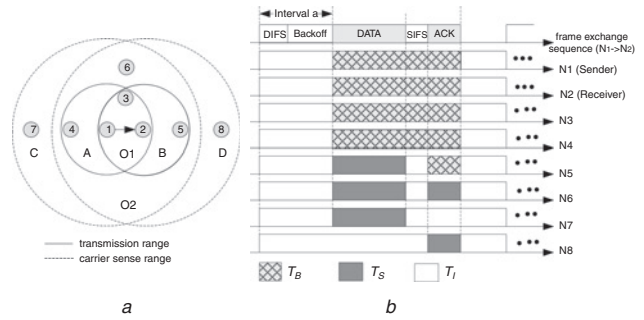
and $AB_{expected}$ is the 'AB' in (1).

Fig. 1 *From frame exchange sequence to channel occupation*

Overlap probability of idle periods: The estimation inaccuracy of ABE and AAC mainly rises from the fact that they do not consider the actual dependence of the sender's idle periods and the receiver's idle periods. We illustrate in Fig. 2 how under certain events there is dependence between the sender and the receiver idle periods. All the possible states of N_1 and N_2 are sketched in Fig. 2a, and the corresponding event of each period is listed in Fig. 2b. Note that some periods experienced by N_1 and N_2 may be shifted together so channel states can appear for clarification of the problem. We can see that periods I, II, III, IV and VII are naturally overlapped and only periods V and VI will in fact decrease the bandwidth because of the 'un-overlap' of the idle periods between the sender 's' and the receiver 'r'. During these periods one of the nodes is in SENSE BUSY state while the other is in IDLE state.
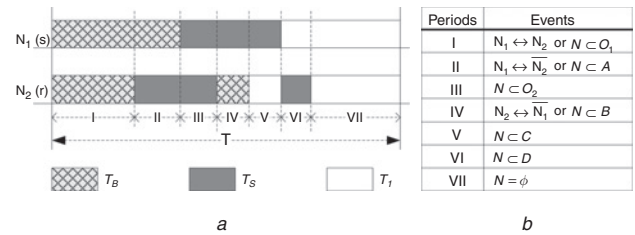

Fig. 2 *Sketch to explain dependence of two adjacent nodes' idle periods*

Notes: N is the union of the interfering nodes of N_1 and N_2. $N \subset X$ means all interfering nodes are located in area X. $N_x \leftrightarrow N_y$ represents N_x is communicating with N_y. $N_x \leftrightarrow \bar{N}_y$ represents N_x is communicating with a node that is not N_y

Let p_1 (resp. p_2) represent the probability that s (resp. r) is in the state of SENSE BUSY when r (resp. s) is in the state of IDLE. The probability of period V and VI occurring is, respectively,

$$P(Period\ V\ occurs) = p_1 \times T_S^s/T$$

$$P(Period\ VI\ occurs) = p_2 \times T_S^r/T$$

where T_S^x is the SENSE BUSY duration sensed by node x during the measurement period T. Then, according to (2), the 'AB' from the point of view of s and r may be rewritten as:

$$AB_s = (1 - K) \times \left[\frac{T_I^s \times (1 - P(Period\ VI\ appears))}{T} \right] \times C$$
$$= (1 - K) \times \left[\frac{T_I^s \times (1 - p_2 \times T_S^r/T)}{T} \right] \times C \quad (3)$$

$$AB_r = (1 - K) \times \left[\frac{T_I^r \times (1 - P(Period\ V\ appears))}{T} \right] \times C$$
$$= (1 - K) \times \left[\frac{T_I^r \times (1 - p_1 \times T_S^s/T)}{T} \right] \times C \quad (4)$$

Introduction: Research in providing Quality of Service (QoS) in IEEE 802.11-based ad hoc networks has received much attention recently. To perform QoS aware functions, e.g. QoS routing and admission control, it is critical to get the estimation of available bandwidth ('AB') in a given link, and many brilliant studies have been carried out on 'AB' estimation in IEEE 802.11-based ad hoc networks. However, the result is still not satisfactory [1].

Based on the published literature and considering how the IEEE 802.11 MAC protocol operates, at least four considerations have to be taken into account to give an accurate 'AB' estimation in ad hoc networks: carrier sense range interference, packets collision probability, backoff procedure and synchronisation of sender-receiver pairs' idle periods. The recent work, i.e. AAC [2] and ABE [3], can represent the state of the art. However, the assumption in [2] is that the sender and receiver idle periods are totally synchronised by considering that AB = min{ABs, ABr}, where ABs and ABr are the 'AB' sensed by the sender and the receiver, respectively. Hence, it overestimates the real 'AB' on this link. This problem is supposed to be solved in [3], where the authors use the overlap probability of two nodes' idle periods to consider the synchronisation between the sender and the receiver. But, to calculate this probability, it is assumed that each node's surrounding medium occupancy is a uniform random distribution and that is independent to each other, which ignores the factual dependence of the interfering around the sender and the receiver. This results in an underestimation of 'AB' in most cases. The challenge of considering the synchronisation between the sender and the receiver results from the difficulty of telling the dependence of idle channel periods that is sensed by the sender-receiver pair. The aim of this Letter is to give a solution to this problem.

Differentiate SENSE BUSY state from BUSY state: Let us first review a wireless node's four basic states: *Transmitting*, if it is currently emitting through its antenna; *Receiving*, if there is any node transmitting within its transmission range; *Sensing*, when the medium is sensed busy but no frame is being received because the energy level is below the receive power threshold. The other time the node is *Idle*. According to its influence on the surrounding media, we define that a node is BUSY when it is in the state of Transmitting or Receiving, and SENSE BUSY when it is in the state of Sensing. The other time the node is IDLE. Note that the aforementioned research does not differentiate SENSE BUSY from BUSY, and considers them the same state. The 'AB' estimated by a single node can be written as

$$AB = \frac{T_I}{T} \times C = \frac{T - T_B - T_S}{T} \times C \quad (1)$$

where T_I, T_B, T_S are the time duration of IDLE, BUSY and SENSE BUSY states, respectively, in the measurement period T. C is the maximum capacity of the link.

We consider the typical scenario in Fig. 1a where N_1 (we use N_x to represent node x for brevity) is transmitting to N_2, where the radius of the carrier sense range is supposed to be more than twice that of the transmission range [4]. Fig. 1b depicts the basic IEEE 802.11 frame exchange sequence (at the top) and the channel states sensed by all the nodes. Note that nodes within the transmission range of N_1 can successfully decode a packet from it and thus know the exact time it takes to finish transmitting this packet. During this time they are in the state of Receiving and thus BUSY. Although we arbitrarily define N_1 is IDLE in 'Interval a', this period cannot be used by nodes within its carrier sense range for the coming packet to be sent successfully. To eliminate this inaccuracy, a coefficient, 'K', is adopted as [3]:

$$AB = (1 - K) \times AB_{expected} = (1 - K) \times \frac{T_I}{T} \times C \quad (2)$$

and the 'AB' at the link between s and r is

$$AB_{\{s,r\}} = min\{AB_s, AB_r\} \tag{5}$$

Simulation results: In a 1300×1100 m area we evenly deploy 100 nodes, among which 10 sender-receiver pairs are randomly picked out. Each sender-receiver pair has a flow with a constant bandwidth x. We set T in (1) equal to 1s as [3] does, and the maximum capacity 1.6 Mbit/s. The transmission range and carrier sense range is 250 m and 550 m, respectively. We then add two more nodes, s and r with co-ordinate of (525 m, 550 m) and (775 m, 550 m), respectively, into the network. We chose these co-ordinates to ensure that they are in the centre of the network and can just communicate directly to represent a one-hop link. We let s and r evaluate the 'AB' on Link (s, r) as a function of x. We deliberately keep the network load below 90% so that collision rates do not have a high influence on the problem that we are evaluating. The average values of estimated 'AB' by AAC, ABE and the proposed approach, with the legend of 'IAB Estimation' (improved available bandwidth), are plotted in Fig. 3. Note that in AAC the authors did not consider the time consumed by waiting and backoff, which will make the bandwidth estimation deviate considerably from the real value. For a fair comparison, we add this factor into AAC. The results clearly show that IAB outperforms the estimations achieved by AAC and ABE just by considering the dependence of the two adjacent nodes' channel occupations and giving a more accurate estimation on the overlap probability of their idle periods.
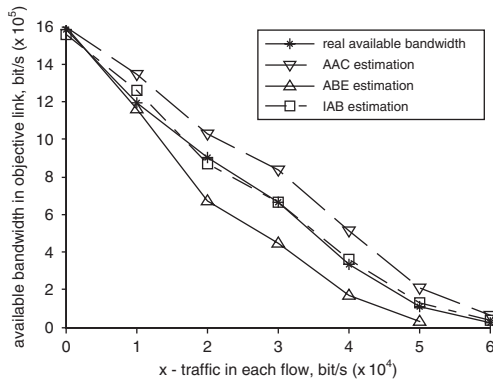

Fig. 3 *Simulation validation*

Conclusions: We give a solution to calculate the overlap probability of the idle periods between two adjacent nodes, taking into consideration the factual dependence of the interfering around them. We consequently improve the accuracy of 'AB' estimation in IEEE-802.11-based ad hoc networks. This work is, of course, far from complete. The objective of this Letter is to give readers a clue to rethink the problems in available bandwidth estimation in ad hoc networks.

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References

1 Nafaa, A.: 'Provisioning of multimedia services in 802.11-based networks: facts and challenges', *IEEE Wirel. Commun.*, 2007, **14**, (5), pp. 106–112
2 de Renesse, R., Friderikos, V., and Aghvami, A.H.: 'Cross-layer cooperation for accurate admission control decisions in mobile ad hoc networks', *IET Commun.*, 2007, **1**, (4), pp. 577–586
3 Sarr, C., Chaudet, C., Chelius, G., and Lassous, I.G.: 'Bandwidth estimation for IEEE 802.11-based ad hoc networks', *IEEE Trans. Mob. Comput.*, 2008, **7**, (10), p. 1228–1241
4 Zhai, H., Wang, J., and Fang, Y.: 'DUCHA: a new dual-channel MAC Protocol for multihop ad hoc networks', *IEEE Trans. Wirel. Commun.*, 2006, **5**, (11), pp. 3224–3233