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MODIFIED PASSIVE AVAILABLE BANDWIDTH ESTIMATION IN IEEE 802.11 WLAN

Yoanes Bandung & Joshua Tanuraharja

School of Electrical Engineering and Informatics,
Institut Teknologi Bandung, Indonesia

bandung@stei.itb.ac.id; joshua.tanuraharja@hotmail.com

ABSTRACT

Quality of Service provisioning for real-time multimedia applications is largely determined by a network's available bandwidth. Until now, there is no standard method for estimating bandwidth on wireless networks. Therefore, in this study, a mathematical model called Modified Passive Available Bandwidth Estimation (MPABE) was developed to estimate the available bandwidth passively on a Distributed Coordination Function (DCF) wireless network on the IEEE 802.11 protocol. The mathematical model developed was a modification of three existing mathematical models, namely Available Bandwidth Estimation (ABE), Cognitive Passive Estimation of Available Bandwidth V2 (cPEAB-V2), and Passive Available Bandwidth Estimation (PABE). The proposed mathematical model gave emphasis on what will be faced to estimate available bandwidth and will help in building strategies to estimate available bandwidth on IEEE 802.11. The developed mathematical model consisted of idle period synchronisation between sender and receiver, the overhead probability occurring in the Medium Access Control (MAC) layer, as well as the successful packet transmission probability. Successful packet transmission was influenced by three variables, namely the packet collision probability caused by a number of neighbouring nodes, the packet collision probability caused by

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traffic from hidden nodes, and the packet error probability. The proposed mathematical model was tested by comparing it with other relevant mathematical models. The performance of the four mathematical models was compared with the actual bandwidth. Using a series of experiments that have been performed, it was found that the proposed mathematical model is approximately 26% more accurate than ABE, 36% more accurate than cPEAB-V2, and 32% more accurate than PABE.

Keywords: Available bandwidth estimation, distributed coordination function, IEEE 802.11, hidden nodes.

INTRODUCTION

Estimating bandwidth in a wireless network is necessary but not a simple task (Tursunova, Inoyatov, & Kim, 2010a). It is necessary because estimated bandwidth is valuable for Quality of Service (QoS) provisioning for multimedia real-time applications in the network (Chou & Miao, 2006). Additionally, it helps Internet of Things (IoT) devices to choose the best access point (Dai et al., 2017), especially in limited bandwidth networks. Nevertheless, there is no standard method to estimate the available bandwidth on Distributed Coordination Function (DCF) as the main medium access.

Although new wireless network standards continue to emerge (i.e. IEEE 802.11n and IEEE 802.11ac), the existence of IEEE 802.11g is still commonly found in various developments and applications. Currently, many access point devices support several standards, including the IEEE 802.11g standard. IEEE 802.11g is still widely used due to its low usage and maintenance costs, thereby reducing capital and operational costs (Valadares et al., 2020). The standard is still popular for use in many areas such as in residential and industrial domains (Catherwood et al., 2019; Valadares et al., 2020). Therefore, the study on bandwidth estimation in wireless networks based on the IEEE 802.11g standard is still very relevant today.

Nowadays, there are numerous methods for estimating available bandwidth in wireless networks, and it can be classified into two categories, which are active techniques and passive techniques (Chaudhari & Biradar, 2015). Active techniques use packet probes as a way to measure the available bandwidth in a network. The packet probes flood the network and decrease the available bandwidth to be measured. For this reason, passive techniques are gaining more popularity as they do not add extra overhead on the network. Instead, passive techniques observe the network quietly and thoroughly in order to obtain a network's variables.

This research aims to develop an enhanced available bandwidth estimation method by investigating several research works related to passive available bandwidth estimation on a Wireless Local Area Network (WLAN). There are eight methods developed from several works conducted by researchers in the past few years. Those methods are Adaptive Admission Control (AAC) (de Renesse et al., 2007), Available Bandwidth Estimation (ABE) (Sarr et al., 2008), Improved Available Bandwidth (IAB) (Zhao et al., 2009), cognitive Passive Estimation of Available Bandwidth V1 (cPEAB-V1) (Tursunova, Inoyatov, & Kim, 2010b), cognitive Passive Estimation of Available Bandwidth V2 (cPEAB-V2) (Tursunova, Inoyatov, & Kim, 2010a), Distributed Lagrange Interpolation Available Bandwidth Estimation (DLI-ABE) (Chaudhari & Biradar, 2014), Accurate Passive Bandwidth Estimation (APBE) (Park & Roh, 2010), and Passive Available Bandwidth Estimation (PABE) (Rizal & Bandung, 2017).

This study compares the proposed model with those eight methods to identify the more effective method for a certain scenario such as in the presence of hidden node problems. From the comparison, it could be concluded that not all methods are suitable for estimating available bandwidth in the wireless networks that have hidden node problems.

The rest of the paper is organised as follows. The next section explains eight available bandwidth estimation methods. It is followed by the research methodology used in the study. A novel method for estimating the availability of bandwidth on wireless networks, known as Modified Passive Available Bandwidth Estimation (MPABE), is explained in the next section. After that, the following section explains the scenarios being used to run simulations by considering the real available bandwidth. The second last section describes the evaluation of the simulations as bar charts, followed by a discussion. Finally, the result of this research is concluded by presenting a conclusion and suggestions for the next research in the last section.

RELATED WORKS

Adaptive Admission Control (AAC)

AAC was proposed a way for estimating the available bandwidth by considering the sending node's idle time (T_i^s) and the receiving node's idle time (T_i^r)(de Renesse et al., 2007). The availability of bandwidth is calculated by multiplying the smallest idle time with the medium capacity. AAC is proven to estimate the available bandwidth; however, it is less accurate as compared to the other methods because it only considers the idle time of the sending node and the receiving node without noticing the idle time overlapping probability between the two nodes (Sarr et al., 2008; Tursunova, Inoyatov, & Kim, 2010a). AAC tends to overestimate the estimated available bandwidth (Sarr et al., 2008). The available bandwidth can be calculated using Equation 1:

$$AB_{AAC} = \min\{\frac{T_i^s}{T}, \frac{T_i^r}{T}\}\ x\ C \tag{1}$$

where T_i^s is the idle time of the medium felt by the sending node (s). T_i^r is the medium idle time perceived by the recipient node (s), T is the observation time (s), while C is the maximum capacity of medium (bps).

Available Bandwidth Estimation (ABE)

ABE considers the idle time overlapping possibility of two adjacent nodes, in this case, the sending node and the receiving node (Sarr et al., 2008). ABE assumes that the use of the medium by the sending node and the receiving node is independent of each other. In addition, ABE introduces several new variables such as the proportion of bandwidth used by the waiting time and backoff (K) and the collision probability of the hello (Pc) packet. ABE provides an equation to calculate the packet collision probability from packet size, but the collision probability does not depend on packet size, latency in the MAC/PHY layer, or acknowledgement timeout. Collision probability depends on the backoff size, the maximum number of retransmissions, and the number of neighbouring nodes (Tay & Chua, 2001). ABE proposes a variable (K), the proportion of bandwidth consumed by the waiting time, and the backoff mechanism during a packet collision. To calculate K, the T_m variable is introduced, which is the time that separates two sequential packets. T_m is strongly influenced by transmission speed and packet size m. K can be stated as in Equation 2:

$$K = \frac{DIFS+\overline{backoff}}{T_{(m)}} \tag{2}$$

ABE states that there are several conditions that must be fulfilled so that a packet is successfully transmitted. First, the medium must be free at least during DCF interframe space (DIFS) at the sending side so the sending node can get enough time to transmit data packets. Second, on the receiving node, the medium must be free for the time needed to transmit the entire data packets; otherwise, there will be a collision. In addition, ABE states that the size of the transmitted packet causes packet collision. ABE assumes that the larger the packet size, the longer the transmission time will be, and the greater the packet collision probability. ABE includes packet length to calculate packet collision probability $P(m)$ based on Equation 3:

$$P(m) = f(m)\ x\ P_{Hello} \tag{3}$$

Based on Equation (3), $f(m)$ is the Lagrange interpolating polynomial obtained through simulation using NS-2. $f(m)$ can be calculated based on Equation 4:

$$f(m) = -5.65 \ x \ 10^{-9} \ x \ m^3 + 11.27 \ x \ 10^{-6} \ x \ m^2 - 5.58 \ x \ 10^{-3} \ x \ m + 2.19 \quad (4)$$

ABE uses the collision probability of $hello$ packet (P_{Hello}) to identify the collision probability of a packet size m. The collision probability of the hello packet can be calculated using Equation (5). The number of hello packets is measured by counting packets being sent from the sender to the receiver during the measurement time (T). It can be inferred from Equation 5 that to calculate the collision probability of a hello packet, the lost hello packets are divided with the expected hello packets.

$$P_{Hello} = \frac{number \ of \ lost \ Hello \ packets}{Number \ of \ expected \ Hello \ packets} \quad (5)$$

ABE calculates the overlapping probability as a result of multiplication between two idle times from the sending node and the receiving node. Suppose that T_i^s and T_i^r each have a value of 0.6, then the idle period overlaps between the sender and the receiver and becomes 0.6 x 0.6 = 0.36. However, ABE does not consider the overhead generated by control messages, such as short interframe space (SIFS) and acknowledgement (ACK), so ABE produces an inaccurate bandwidth estimation (Tursunova, Inoyatov, & Kim, 2010a). Based on Equations 2 and 4, ABE calculates the estimated available bandwidth by considering the synchronisation of the idle period, the hello packet collision probability, and the proportion of bandwidth used by the waiting time and backoff mechanism (K). ABE is calculated according to Equation 6:

$$AB_{ABE} = (1 - \mathrm{K}) \ \mathrm{x} \ (1 - \mathrm{Pc}) \ \mathrm{x} \ \frac{T_i^s}{T} x \frac{T_i^r}{T} \ x \ C \quad (6)$$

where K is the proportion of bandwidth consumed by waiting time and backoff. Pc is a packet collision probability, T_i^s is the idle time of the medium felt by the sending node (s), and T_i^r is the idle time of the medium felt by the receiving node (s). T is the observation time (s), while C is the maximum capacity of medium (bps).

Improved Available Bandwidth (IAB)

IAB considers synchronisation between the sending node and the receiving node's idle period and distinguishes busy conditions into BUSY and SENSE_BUSY. Although synchronisation between nodes and node condition differentiation improves the accuracy of the available bandwidth estimation, IAB has not considered the overhead generated by the control message. IAB also has not considered the relationship between packet size and throughput. Just like ACC and ABE, IAB is simulated using an NS2-simulator. The available bandwidth is calculated using Equation 7:

$$AB_{IAB} = (1 - K) \text{ x } [\frac{T_s \, x \left(1 - P_r \, x \frac{T_s^r}{T}\right)}{T} - \mu] \, x \, C \tag{7}$$

where K is the proportion of bandwidth consumed by waiting time and backoff mechanism. P_r is the probability of the receiving node being SENSE_BUSY and the sending node being IDLE. T_s is the medium idle time perceived by the sending node (s). T_s^r is the SENSE_BUSY period that is felt by the recipient node (s). T is the observation time (s), C is the maximum capacity of medium (bps) and μ is the safety coefficient to prevent nodes from using bandwidth excessively.

Cognitive Passive Estimation of Available Bandwidth (cPEAB-V1)

cPEAB-V1 (Tursunova, Inoyatov, & Kim, 2010b) is a mathematical model that enhance ACC, ABE and IAB. cPEAB-V1 does not take into account idle time synchronisation between the receiving node and the sending node, because only the sending node's idle time is considered. This model considers the effect of hidden nodes on the estimated available bandwidth because hidden nodes can cause a new type of collision, which is called collision probability by hidden nodes. By adding that collision probability by hidden nodes in the mathematical model, the available bandwidth estimation of cPEAB-V1 becomes more accurate as compared to ACC, ABE, and IAB. There are two types of collision probabilities used by cPEAB-V1, namely collision probability by neighbouring nodes and collision probability by hidden nodes, all of which are represented as P_{coll}. Despite considering the presence of hidden nodes, cPEAB-V1 has not considered other factors such as ACK and packet error. Bandwidth availability on cPEAB-V1 can be calculated using Equation 8:

$$AB_{cPEAB-v1} = (1 - K) \, x \, (1 - Pcoll) \, x \, \frac{T_i}{T} \, x \, C \tag{8}$$

where K is the proportion of bandwidth consumed by waiting time and backoff mechanism. P_{coll} is the packet collision probability caused by neighbouring nodes and hidden nodes. T_i is the medium idle time perceived by the sending node (s), T is the observation time (s), and C is the maximum capacity of medium (bps).

Cognitive Passive Estimation of Available Bandwidth V2 (cPEAB-V2)

cPEAB-V2 (Tursunova, Inoyatov, & Kim, 2010a) is an improved version of the cPEAB-V1 (Tursunova, Inoyatov, & Kim, 2010b). In the previous version of cPEAB-V2, a technique was proposed to estimate the available bandwidth by considering the presence of hidden nodes. Nevertheless, it was found that there were other parameters that also influenced the available bandwidth estimation, namely successful packet transmission probability. In cPEAB-V2, the successful packet transmission probability is determined by three factors: the collision probability by neighbouring nodes, the collision probability by hidden nodes, and the packet error probability.

cPEAB-V2 also considers the time used by the control message, which is the ACK message. In accordance with the DCF mechanism, each packet received by the receiving node will reply to the ACK packet. The mathematical model developed by cPEAB-V2 considers the packet error probability and the time used by ACK mechanism. Notwithstanding, cPEAB-V2 has not implemented idle period synchronisation of the sender and receiver nodes. The idle period used by cPEAB-V2 is the medium idle period(T_i).Just like the APBE model, the mechanism to calculate T_i is not explained in detail, so T_i in cPEAB-V2 is assumed to be the smallest idle node period.

The available bandwidth is calculated according to Equation 9:

$$AB_{cPEAB-V2} = (1 - K)\ x\ (1 - ACK)\ x\ P_{Success}\ x\ \frac{T_i}{T}\ x\ C \tag{9}$$

where$K$is the proportion of bandwidth consumed by waiting time and backoff mechanism.ACK is the proportion of bandwidth consumed by ACK. $P_{Success}$ is the packet collision probability caused by neighbouring nodes, hidden nodes, and packet error. T_i is the medium idle time perceived by the sending node (s). T is the observation time (s),Cwhile is the maximum capacity of medium (bps).

Distributed Lagrange Interpolation Available Bandwidth Estimation (DLI-ABE)

DLI-ABE is a mathematical model for estimating the available bandwidth on a wireless network developed based on ABE and IAB (Chaudhari & Biradar, 2014). DLI-ABE modifies the idle period synchronisation and the collision probability belonging to ABE and IAB. There are two DLI-ABE proposals to overcome the weaknesses of ABE and IAB: (1) using the actual medium utility; and (2) using Lagrange Interpolation to calculate the probability of a collision. DLI-ABE assumes usage (RTS/CTS) on a wireless network so that the K variable used is modified to accommodate the RTS/CTS mechanism. In fact, the access point (AP) does not use mechanisms (RTS/CTS) by default, so DLI-ABE can only be used in certain cases. The availability of bandwidth in DLI-ABE can be calculated using Equation 10:

$$AB_{DLI-ABE} = (1 - K)\ x\ (1 - P_m)\ x\ (\min\left(\left[\frac{T_i^s\left(1-p\left(\frac{T_S^r}{T}\right)\right)}{T}\right]C\ ,\left[\frac{T_i^r\left(1-p\left(\frac{T_S^S}{T}\right)\right)}{T}\right]C\right) \quad (10)$$

where K is the proportion of bandwidth consumed by waiting time and backoff mechanism. P_m is the proportion of bandwidth used by the RTS/CTS mechanism. p is the probability of the receiving node being SENSE_BUSY and the receiving node being IDLE and vice versa. T_i^s is the idle time of the medium perceived by the sending node (s). T_i^r is the medium idle time perceived by the recipient node (s). T is the observation time (s), and C is the maximum capacity of medium (bps).

Accurate Passive Bandwidth Estimation (APBE)

APBE is a mathematical model for estimating the availability of bandwidth on wireless networks developed based on cPEAB-V2 (Tursunova, Inoyatov, & Kim, 2010a). APBE was developed by applying variables that are not taken into account by cPEAB-V2, namely the Request To Send (RTS) and Clear To Send (CTS) message exchange mechanisms. According to APBE, the RTS/CTS mechanism affects the estimated available bandwidth if the mechanism is activated. The APBE model is similar to cPEAB-V2 by considering the proportion of bandwidth used by the waiting time and backoff (K) and ACK. There is one variable that changes its meaning in APBE, namely the collision probability. Calculated collision does not involve hidden nodes as in CPEAB-V2, but only calculates the collision probability experienced by the RTS/CTS packet. In the RTS/CTS mechanism, it is assumed that there are no hidden node cases because all the nearest nodes can hear RTS or CTS packets so that the surrounding nodes know that the medium is busy. The availability of bandwidth can be calculated using Equation 11:

$$AB_{APBE} = (1 - K)\ x\ \left(1 - \frac{R}{C}\right) x\ (1 - ACK)\ x\ (1 - P_c)\ x \frac{T_i}{T} xC \quad (11)$$

where K is the proportion of bandwidth consumed by waiting times and backoff mechanism. $\frac{R}{C}$ is the proportion of bandwidth used by the RTS/CTS mechanism. ACK is the proportion of bandwidth consumed by the ACK period. P_c is the probability of collision of RTS messages. T_i is the medium idle time perceived by the sending node (s). T is observation time (s), while C is the maximum capacity of medium (bps).

Passive Available Bandwidth Estimation (PABE)

PABE is a mathematical model for estimating the bandwidth availability proposed by Rizal and Bandung (2017). This mathematical model was developed by analysing and combining APBE (Park & Roh, 2010) and DLI-ABE (Chaudhari & Biradar, 2014) methods. The idle period synchronisation of the sender and recipient nodes is taken from the DLI-ABE proposal, while the variable proportions of waiting time by ACK mechanism and packet collision opportunities are taken from APBE and cPEAB-V2. This model is produced by combining features of existing mathematical models.

PABE considers three points: (1) idle node synchronisation between the sending node and the receiving node; (2) possible overhead that occurs in the media access control (MAC) layer; and (3) packet collision probability caused by neighbouring nodes and hidden nodes. Synchronising the idle period in the mathematical model is done by considering the condition of the new node, which is sensed busy. SENSE_BUSY is defined as a period when the node senses that there is data transmission in the medium but no packet is received because the transmission signal is very weak and below the reception limit by the physical (PHY) layer. In general, the idle period synchronisation mechanism of PABE is similar to the AAC synchronisation mechanism that determines the idle period synchronisation value by selecting the sending node's idle period or the smallest idle node of the receiving node. In the PABE proposal, there is a P variable, which is the probability when the sending node is being IDLE but the receiving node is being SENSE_BUSY or the probability of the receiving node being IDLE when the sending node is being BUSY. The way to calculate P is not explained explicitly. PABE assumes that the P value in the experiment is exactly the same as in the DLI-ABE model. The formulae for calculating the idle period synchronisation between the sending node (T_{sen}) and the receiving node (T_{rec}) are expressed in Equations 12 and 13:

$$T_{sen} = \left[\frac{T_i^s (1 - p\left(\frac{T_s^r}{T}\right))}{T} \right] \tag{12}$$

$$T_{rec} = \left[\frac{T_i^r (1 - p\left(\frac{T_s^S}{T}\right))}{T} \right] \tag{13}$$

Variables considered by PABE in estimating the available bandwidth are better than ABE. There are two types of MAC layer overhead that are considered, namely the proportion of time by waiting time and backoff (*K*), and the *ACK* mechanism. The proportion of time used by (*K*) and ACK is not too much, but both variables still affect the estimation results. The coefficients (*K*) and *ACK* are calculated based on Equations 14 and 15:

$$K = \frac{DIFS + \overline{backoff}}{T} \quad (14)$$

$$ACK = \frac{ACKTimeout + SIFS}{T} \quad (15)$$

where K is the proportion of bandwidth used by waiting time and backoff mechanism.*DIFS* is the DCF interframe space (μs), while T is the observation time (s). Based on Equations 11, 12, 13, and 14, the available bandwidth according to PABE can be determined using Equation 16:

$$AB_{PABE} = (1 - K)\ x\ (1 - ACK)\ x\ P_c\ x\ (\min[T_{sen}\ x\ C], [T_{rec}\ x\ C]) \quad (16)$$

where K is the proportion of bandwidth consumed by waiting time and backoff mechanism. ACK is the proportion of bandwidth consumed by ACK. P_c is the probability of packet collision caused by neighbouring and hidden nodes. T is the observation time (s), T_{sen} is the idle period synchronisation of the sender node, and T_{rec} is the idle period synchronisation of the receiver node. *C* is the maximum capacity of medium (bps).

Problems in Estimating Available Bandwidth

Estimating available bandwidth passively in a wireless network is a quite challenging task because it requires many information about the network being analysed. There are several questions that need to be answered before performing available bandwidth estimation, such as how many APs in the area, what channels are being used by those APs, what wireless protocol is being used by each AP, how many wireless devices are trying to connect to the network, what kind of interference is happening in the network, etc. The most important thing is the understanding of the DCF mechanism in IEEE 802.11 to obtain a comprehensive mathematical model. A mistake in modelling the IEEE 802.11 behaviour could lead to overestimating or underestimating the available bandwidth on the network.

Several studies had tried to overcome that problem by continuously adding new variables important to estimating available bandwidth accurately. AAC can estimate the available bandwidth by choosing the minimal idle time from the sending node or receiving node. This method has a flaw because it does not consider the idle time synchronisation between the sending node and receiving node. ABE and IAB are two methods that proposed idle time synchronisation between the sending and receiving nodes to overcome AAC's weakness. ABE calculates the idle time synchronisation by multiplying the sending node's idle time with the receiving node's idle time. Similar to ABE, IAB considers synchronisation between the sending node and the receiving node by classifying the node's status into BUSY and SENSE_BUSY. Nevertheless, it is still not enough because the overhead generated by control messages is not considered.

As the wireless network grows, network interferences caused by the overlapping channel between AP will occur. This condition leads to a problem called hidden node problems and makes the wireless network suffer (Maesako et al., 2019). Unfortunately, those three methods did not realise that hidden nodes in the network could cause that packet collision; therefore, their mathematical models are insufficent to estimate real-life available bandwidth. cPEAB-V1 was proposed by considering the effect of the hidden node on the estimated available bandwidth. cPEAB-V2 was proposed later by adding overhead caused by Acknowledgement to enhance the mathematical model, but it lakced idle time synchronisation between the sending node and the receiving node.

Knowing that hidden node problems affect the way of estimating available bandwidth, two methods were proposed by considering the *RTS/CTS* mechanism. This mechanism can mitigate hidden node problems; however, overhead due to RTS/CTS handshaking can cause a new problem in the network (Sanada & Mori, 2019). DLI-ABE considers *RTS/CTS* to eliminate collision probability caused by hidden nodes, however, it does not consider Acknowledgement. Therefore, this method still has a flaw. APBE is very similar to cPEAB-V2 and it considers *RTS/CTS*. Nevertheless, it does not consider idle time synchronisation just like cPEAB-V2. The *RTS/CTS* mechanism on network devices is disabled by default and needs to be activated manually that make these methods too rigid. PABE is the latest passive available bandwidth estimation method that combines two other methods, which are APBE and DLI-ABE. This method considers every parameter proposed by previous studies, such as idle time synchronisation, the overhead caused by *backoff* and *ACK*, and overhead caused by collision probability due to neighbouring nodes and hidden nodes. Even so, PABE does not consider collision probability caused by packet error.

RESEARCH METHODOLOGY

This study was conducted by adopting the Design Science Research Methodology (DSRM) (Peffers et al., 2007). There were six steps performed according to DSRM, which are: (i) problem identification; (ii) definition of objectives for a solution; (iii) design and development; (iv) demonstration; (v) evaluation; and (vi) communication. Steps (i) and (ii) were conducted to design the proposed solution by analysing eight methods and comparing three of them. The design was stated as a mathematical model that combines and enhances previous methods. Later, simulations and evaluation were conducted in order to demonstrate and test the proposed solution.

THE PROPOSED MODIFIED PASSIVE AVAILABLE BANDWIDTH ESTIMATION

There were three passive available bandwidth estimation methods considered in this research, namely ABE, cPEAB-V2, and PABE. This study compared those methods and analysed their features thoroughly. The most important parameters that were compared were idle node synchronisation period, overhead on the MAC layer, and packet collision probability. The result of the comparison was used for developing an enhanced passive available bandwidth estimation method.

Comparison of ABE, cPEAB-V2, and PABE

In Table 1, it can be seen that all the three models had similarities and differences with one another. ABE was the first estimation method that considered idle node synchronisation period by multiplying the sender's idle time and receiver's idle time as a cross product. ABE did not consider any overhead on the MAC layer and was unaware of the hidden node problems. cPEAB-V2 was the first method that considered the overhead caused by ACK and packet collision caused by hidden node problems. cPEAB-V2 was not equipped with a proper equation to compute the idle node synchronisation period. As a result, it was not clear what was the idle time period to be used in this method. PABE, on the other hand, was a method that tried to combine the idle node synchronisation period from DLI-ABE with cPEAB-V2. Even though PABE seemed to include all parameters necessary for estimating available bandwidth in a wireless network, it had one flaw by not considering another overhead on the network, which was packet error as proposed in cPEAB-V2.

From Table 1, it was possible to propose an enhanced model by modifying those three models. Based on the analysis of Table 1, an enhanced model for estimating available bandwidth in WLAN was developed. This study proposed an enhanced method named MPABE by combining features from ABE, cPEAB-V2, and PABE. MPABE used idle node synchronisation period from ABE, overhead from PABE, and packet error from cPEAB-V2. There were three main components considered in MPABE in order to estimate the available bandwidth in the wireless network accurately:

1. Idle node synchronisation period between sender and receiver
2. Overhead probability on the MAC layer

3. Packet collision probability: (i) packet collision caused by the number of neighbouring nodes, (ii) packet collision caused by traffic from hidden nodes, and (iii) packet error.

Table 1

Comparison of ABE, cPEAB-V2, and PABE

Method	Idle Node Synchronisation	Overheads on MAC	Packet Collision Probability
ABE	$\frac{T_i^s}{T} x \frac{T_i^r}{T}$ Cross product of the sender's idle period with the receiver's idle time period	K Bandwidth used by waiting time and backoff mechanism	Pc Packet collision probability by counting hello packets received by the receiver's side
cPEAB-V2	$\frac{T_i}{T}$ Not stated clearly	K & ACK Bandwidth used by Acknowledgement mechanism	$P_{Success}$ Packet collision is calculated by considering the number of neighbouring nodes, hidden node problems, and packet error
PABE	$(\min[T_{sen}\ x\ C], [T_{rec}\ x\ C])$ Calculating the idle node synchronisation period by adding SENSE_BUSY status as a parameter to be considered	K & ACK Bandwidth used by Acknowledgement mechanism	P Packet collision is calculated by considering the number of neighbouring nodes and hidden node problems

Idle Node Synchronisation Period between Sender and Receiver

Each node in a Basic Service Set (BSS) has two types of periods, i.e. busy period and idle period. The busy period is the period when the node is transmitting a frame or receiving a frame. An idle period is a period when the node is not doing anything, or in other words, is idle. According to Sarr et al. (2008), it was stated that the transmission of frames on a wireless network would be successful if the sending node and the receiving node in the same condition were idle. If the sending and receiving nodes have different conditions, the packet transmission may not succeed. The idle period of a node can be calculated through Equation 17:

$$T_i = T - T_B \tag{17}$$

where T is the observation time (s), T_i is the medium idle time perceived by a node (s), and T_B is the medium busy time perceived by a node (s).

Figure 1 is an example of the idle period overlap between the sender and the receiver. The overlap is a condition when the status of the medium perceived by the sending node is the same as the receiving node. Figure 1(A) shows that both nodes had never had the same conditions. When the sending node is idle, the receiving node is busy and vice versa. Under these conditions, bandwidth availability is zero because the transmission of the frame will never occur. On the other hand, in Figure 1(B), the condition of the sending node and the receiving node overlapped each other. If the sending node is idle, then the receiving node is also idle. Therefore, based on the image, it can be said that the availability of bandwidth between the sending node and the receiving node is around 50%.

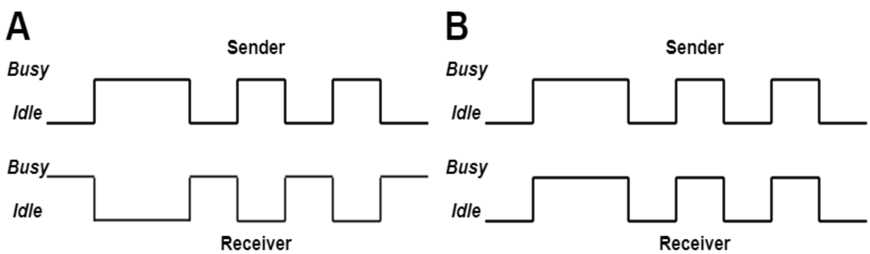

Figure 1. Example of idle period synchronisation.

The cPEAB-V2 mathematical model did not take into account the idle node synchronisation between the sending node and the receiving node. In contrast, the PABE model used the DLI-ABE synchronisation period idle technique by calculating the SENSE_BUSY time. The synchronisation technique of the two models was less accurate in estimating bandwidth availability, especially cPEAB-V2 because it only considered the idle period of one node, while PABE did not explain the technique to obtain a clear SENSE_BUSY calculation so that it is difficult to reproduce. cPEAB-V2 did not explain in detail the mechanism for obtaining the value of the idle period.

Therefore, the idle period of cPEAB-V2 is assumed to be the idle period of the smallest node. By only considering one idle period by the sending/receiving node, the cPEAB-V2 estimation results were less accurate than PABE.

In accordance with the synchronisation technique of the idle period proposed by ABE, in this study, the idle period of the medium was calculated as the result of multiplication between the idle period of the sending node and the idle period of the receiving node. For example, if the proportion of the sending node's idle period is 0.8 and the proportion of the receiving node's idle period is 0.8, the proportion of the medium idle synchronisation period is 0.64. In this study, synchronising the idle period of the sending node and the receiving node is calculated using Equation 18:

$$T_{Sync} = \frac{T_i^S}{T} \, x \, \frac{T_i^R}{T} \tag{18}$$

where T_{Sync} is the proportion of idle period synchronisation between the sending node and the receiving node. T_i^S is the medium idle time perceived by the sending node (s). T_i^R is the medium idle time perceived by the receiving node (s), while T is the observation time (s).

Overhead Probability on the MAC Layer

Exchange frames on wireless networks with the IEEE 802.11 protocol and DCF medium access mode are governed by the specific procedure shown in Figure 2. It can be seen that the DCF mechanism consists of three intervals. Each interval contains interframe space and overhead in the form of backoff and ACK. There are two types of interframe space used in the DCF mechanism, namely DIFS and SIFS. DIFS is used in Interval I and SIFS is used at Interval III. Only Interval II has no interframe space and only contains data packets.

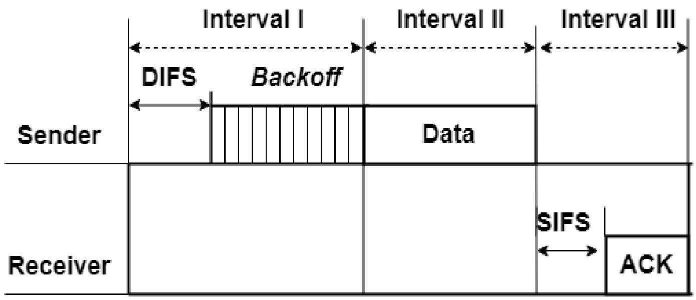

Figure 2. Basic 802.11 DCF (Tursunova, Inoyatov, & Kim, 2010a).

Based on Figure 2, at Interval I, every node that wants to transmit the packet must listen to the medium and wait for at least DIFS. If the medium is idle during this period, then the packet can be transmitted. However, if the packet has been scheduled and has a counter backoff greater than zero, the sending node must reduce the backoff counter to zero before transmitting the frame. Each packet that will be sent will be scheduled and gets a random backoff period depending on the number of slots generated. In order to spend the counter backoff period for each packet, each node must wait again outside the DIFS waiting time. The node's backoff period can be different from the other node's backoff. Due to this, the coefficient K considered in this study is as in Park and Roh (2010). K is the proportion of bandwidth used by waiting time and backoff mechanism. The backoff value of each packet can be different because it is generated randomly; therefore, the backoff average is used to calculate K as in IAB, cPEAB-V2, APBE, and PABE. The coefficient can be calculated using Equation 19:

$$K = \frac{DIFS + \overline{backoff}}{T} \quad (19)$$

Packet Collision Probability

Based on the frame exchange mechanism on DCF that generates random backoff depending on the CWmin and CWmax values, it is possible to have a collision between packets as a result of the same backoff value. When the backoff counter is more than one node to zero at the same time, the medium will be accessed by both nodes simultaneously, which ends with a collision between packets at the receiving node. The collision between packets can reduce network performance because this problem has a systemic impact on the DCF mechanism as a whole. If the recipient node fails to transmit the packet, which is marked by not getting the ACK packet from the receiving node, the packet will be rescheduled a maximum of seven times with a new counter backoff. The CWmax value will be doubled so that the selected average CW will increase as in the previous transmission. A large contention window (CW) has the probability of delaying the packet transmission longer. The backoff period on one side can reduce the probability of collision between packets. On the other hand, it increases waiting time. The waiting time by the backoff mechanism that is too high reduces the number of packets that can be sent and ultimately decreases network throughput.

According to a research conducted by Vu (2006), it was stated that other nodes could cause packet transmission failure. The number of neighbouring nodes in the same BSS or the transmission range on the same channel can result in a collision between packets. In addition, according to cPEAB-V2

(Tursunova, Inoyatov, & Kim, 2010b), the collision between packets is not only caused by the presence of neighbouring nodes, but also by the position of the neighbouring nodes. Certain configurations on BSS can cause hidden node problems. Based on cPEAB-V2 (Tursunova, Inoyatov, & Kim, 2010a), which is an improvement of cPEAB-V2, it is stated that there is one other factor that causes packet delivery failure, namely error packet (P_{err}).

Collision Probability Caused by Neighbouring Nodes

The packet collision probability caused by neighbouring nodes is determined by the number of surrounding nodes. The collision between packets will occur more frequently when the number of neighbouring nodes increases. Packet transmission failure will increase CW, which affects the backoff time. The more often the packet fails to send, the more the number of retransmissions by doubling the size of CWmax. Due to this matter, the backoff value varies by the packet. In a previous study (Vu, 2006), it was proposed to consider the average backoff $(\overline{backoff})$ to calculate the collision probability caused by neighbouring nodes (P_{Coll}).

Collision Probability Caused by Hidden Node Traffic

ABE does not take into account the influence of the position of other nodes in the wireless network so that the estimation results are less accurate. cPEAB-V2 then states that node position can affect network throughput due to a collision between packets caused by traffic from hidden nodes. The higher the hidden node traffic, the higher the packet collision probability. cPEAB-V2 and PABE adopt the packet collision probability caused by hidden node traffic because they also affect the estimation results. Based on the results of a previous study (Tursunova, Inoyatov, & Kim, 2010a), the method of calculating P_h is done through the following equation.

Packet Error Probability

ABE assumes that packet size affects the collision probability between packets. Nevertheless, the collision probability between packets is not affected by the size of the packet, because collision can occur on the sender and the receiver. Although packet size does not affect the packet collision probability, packet size determines the packet error probability. If the packet size gets bigger, the packet error probability also increases. Random bit error rate channel is p, and packet size is L. The packet error probability (P_{err}) can be calculated based on Equations 20 and 21:

$$P_{err} = 1 - (1-p)^L \quad (20)$$

$$P_{Success} = (1 - P_{Coll})\ x\ (1 - P_h)\ x\ (1 - P_{err}) \quad (21)$$

Modified Passive Available Bandwidth Estimation

The mathematical model developed estimates the availability of bandwidth on the link that connects between the sending node and the receiving node. This model was developed by taking into account three features, namely synchronisation of the idle period of the sending and receiving nodes, the overhead probability at the MAC layer, and the successful packet transmission probability. Therefore, the proposed mathematical model for estimating bandwidth, known as MPABE, can be expressed in Equation 22:

$$AB_{MPABE} = (1-K)\ x\ (1-ACK)\ x\ P_{Success}\ x\ T_{Sync}\ x\ C \quad (22)$$

MPABE consists of four main parts, which are the proportion of bandwidth used by the waiting time and ACK, the proportion of bandwidth used by the ACK mechanism, the successful packet transmission probability, and the idle period synchronisation of the sender and receiver. Variable K is calculated using Equation 13 that comprises DIFS and $\overline{backoff}$. ACK can be calculated through Equation 14 while $P_{Success}$ can be determined using Equation 20. A successful transmission probability $(P_{Success})$ on MPABE is determined by three points, namely the packet collision probability by neighbouring nodes, the packet collision probability by hidden nodes, and the packet error probability.

EVALUATION

The network simulation model was developed as a tool to test the mathematical model of estimating bandwidth on the wireless network proposed in the previous chapter. The development of the network simulation model was performed using the OMNeT ++ software and INET framework. The network topology used in this simulation was adapted from experiments conducted by cPEAB-V2 and PABE. The network simulation topology used in this study can be seen in Figure 3.

Based on the network topology in Figure 3, there are four nodes and two APs on the network simulation model developed. All nodes were placed taking into account the distance and transmission range of each node.*Sender*1 and *Sender*3 were nodes that acted as senders of packets, while *Rec*1 and *Rec*3 were nodes that acted as recipients. *Sender*1 and *Rec*1 were located in the same Basic Service Set (BSS) that is within the range of AP1 with SSID

"111111". Likewise, with *Sender*3 and *Rec*3 , the two nodes were connected to the BSS with the SSID name "222222" and located within the *AP2* transmission range. Both *AP1* and *AP2* operated in IEEE 802.11g operating mode and used the number one channel at 2.4 GHz radio frequency.

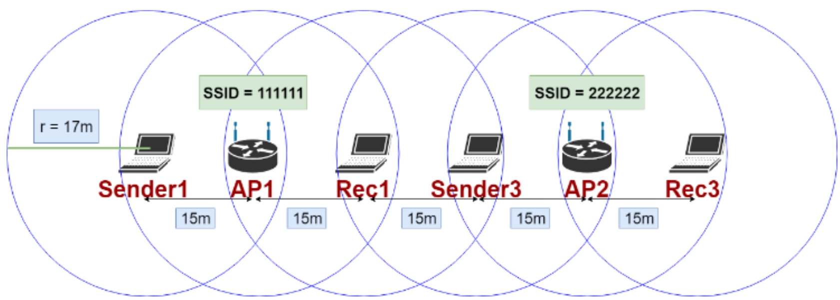

Figure 3. Network Topology.

Both BSS used the same channel, which was Channel 1, to simulate interference caused by the presence of hidden nodes. Utilising a channel on the same number would lead to the creation of a condition called Co-Channel Interference (CCI). This condition would result in nodes being able to hear packet transmissions belonging to nodes from another BSS. In this case, *Rec*1 as the receiving node would experience interference from *Sender*3 . The *Sender*3 position that was close to *Rec*1 caused the transmission range *Rec*1 and *Sender*3 to overlap, or in other words, *Rec*1 could hear *Sender*3 and vice versa.

Based on the explanation above, to compare four mathematical models estimating bandwidth availability on wireless networks, a network simulation model was developed with OMNeT++ with topology as shown in Figure 4.

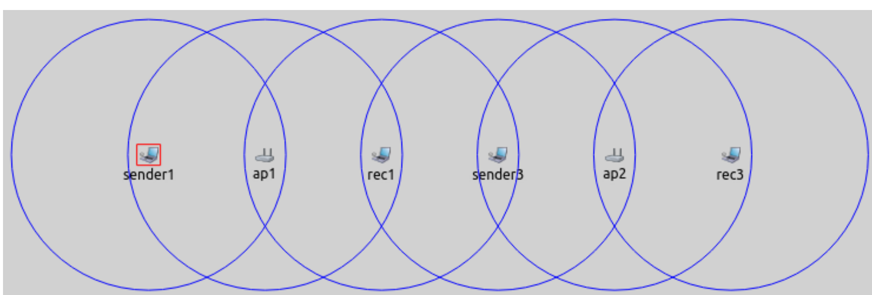

Figure 4. The network topology in OMNET++.

In Figure 4, there are two sending nodes, $Sender1$ and $Sender3$. In addition, there are two receiving nodes, namely $Rec1$ and $Rec3$. In this study, it was assumed that $Sender1$ was the sending node that transmitted the packet to $Rec\ 1$ via $AP1$, and at the same time,$Sender3$ transmitted the packet to $Rec\ 3$ via $AP2$. Each node had a transmission range that was visualised with a circle. $Sender1$ reached $AP1$ but did not reach $Rec\ 1$. Similarly, $Rec\ 1$ could reach $AP1$ but was unable to reach $Sender1$. Sender1 and $Rec\ 1$ could not feel the presence of each node, so sending packets from $Sender1$ to $Rec\ 1$ depended on $AP1$.

The circle in Figure 4 represented the transmission range and was regulated through the transmission power parameter. In the developed network simulation, it was assumed that the transmission range of each node was the same, so the transmission strength value was set at 0.02mW (miliwatts) for all nodes. Based on this configuration, the distance between $Sender1$ and $AP1$ and $Rec1$ was determined by $AP1$ by 15 metres as in Figure 4. This distance also applied to $Sender3$, $AP2$, and $Rec3$. Meanwhile, the distance between $Rec1$ and $Sender3$ remained 15 metres so that $Sender3$ reached $Rec1$. Sending packets to other nodes within the transmission range would always be received by the PHY layer of the receiving node even though it could experience collision and packet errors. As for sending packets to nodes outside the transmission range, the packet would not be received because the packet energy was below the acceptance threshold.

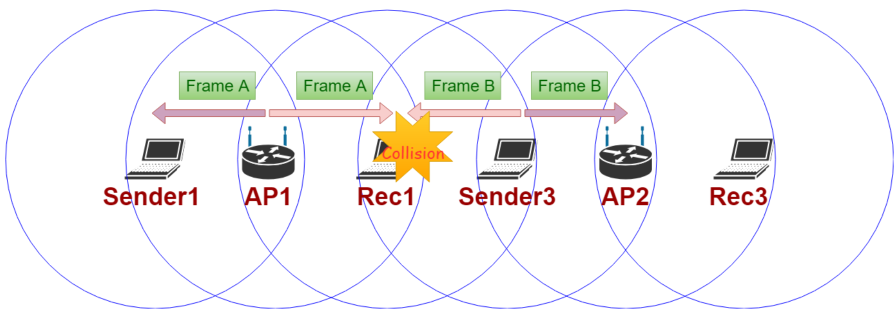

Figure 5. The collision caused by the hidden node.

Network topology for simulation was developed by considering the possibility of a packet collision as a result of the presence of hidden nodes. Based on Figure 5, it can be seen that $AP1$ with $Sender3$ and $Rec1$ with $AP2$ were hidden nodes with each other. $AP1$ and $Sender3$ could not hear each other so that there is a probability that $AP1$ and $Sender3$ transmitted the packet at the same time. Nodes on a wireless network transmitted packets via broadcasting in all directions. This caused the packet from *Sender*3 to also go to *Rec*1, resulting in a collision in *Rec*1due to the emergence of packets from *AP*1 and *Sender*3 at the same time. Packets from *AP*1 and *Sender*3 would be received by the PHY layer that belonged to *Rec*1 . Nevertheless, after being verified by the MAC layer, both packets were declared to have errors so that they were discarded.

In this study, five scenarios were developed to compare the four mathematical models in estimating bandwidth availability. Every scenario was performed as in Park and Roh (2010) and Rizal and Bandung (2017) with parameters as stated in Table 2. It is certain that *Sender*1, *AP*1, and *Rec*1 were connected to each other in BSS with SSID "1111". *Sender*1 transmitted data packets with User Datagram Protocol (UDP) traffic type to *Rec*1 with a bit rate of 500 Kbps. The send interval parameter for *Sender*1 was set at 0.016 s so that *Sender*1 could transmit data packets with 500 Kbps bit rates as well (Rizal & Bandung, 2017). At the same time, *Sender*3 transmitted data packets with bit rates increasing linearly from 500 Kbps to 2.5 Mbps with an increased bit rate of 500 Kbps.

Table 2

Simulation Parameters

Parameter	Value
Medium	802.11g
Link capacity	9 Mbps
Slot time	20 μs
SIFS	10 μs
DIFS	50 μs
Codecs	CBR
Internet protocol	UDP
Packet size	1024 *bytes*
ACK size	14 *bytes*
Maximum retry	7
CwMin	15
CwMax	1023
Channel	1

Simulations of all scenarios were carried out for two seconds; the first second was used to associate nodes with AP, while the second one was then used to transmit the packet. The packet calculated in the simulation was a video packet with the Video Strm Pk packet type so that other packets included in the control packet category or other types of packets did not count. The control packets that were not considered are ProbeReq, Auth, Assoc, ArpReply, ProbeResp, Auth-ok, AssocResp-ok, and beacons. VideoStrmReq was a video packet, but this packet was not counted because it was not needed in calculating bandwidth estimates. The control packet was transmitted to the medium during the first second of the simulation when all nodes were connected to the AP, the control packets that were still transmitted were VideoStrmReq and beacon.

Based on the network topology of Figure 5, a packet collision always occurred in each simulation scenario. The most affected node from packet collision was $Rec1$ because of the emergence of a hidden node case by $Sender3$. The simulation scenario focused on the availability of bandwidth perceived by $Rec1$ as the node most affected by the presence of hidden nodes. Consequently, in each scenario, the simulation of bandwidth availabilityobserved was the availability of bandwidth along $AP1$ to $Rec1$, especially the availability of bandwidth perceived by $Rec1$.

Each scenario was simulated ten times as in the prior study (Chaudhari & Biradar, 2014; Rizal & Bandung, 2017). Each simulation produced statistics containing parameters that were useful for estimating bandwidth availability according to the proposed mathematical model. After the simulation, the next step was to copy the values of the required parameters such as numBackoff, numSlot, numSent, numRecSent, and AVGBackoff into a Microsoft Excel file. Calculation of the estimated bandwidth availability to test the mathematical model was proposed using Excel. There were several constants assigned to the OMNeT ++ software. In this study, the maximum bandwidth at the physical link used by the transmission medium was 9 Mbps. In addition, the transmitted traffic load followed the Constant Bit Rate (CBR) pattern with the same packet size totalling 1,024 bytes (Rizal & Bandung, 2017).

Actual bandwidth (Rizal & Bandung, 2017) was calculated by using the network topology as shown in Figure 6. There were two new nodes called $Sender2$ and $Rec2$ near $AP1$.$Sender2$ sent a video stream to $Rec2$ with a steady increase of 100 Kbps.$Sender2$ had the task of flooding the network in order to measure the actual bandwidth. The actual bandwidth was the maximum bandwidth being sent by $Sender2$ to $Rec2$ without disturbing the video stream traffic from $AP1$ to $Rec1$. For example, when $Sender1$ used 1 Mbps to transmit video packets to $AP1$, there was a chance that the unused bandwidth in the network was approximately 8 Mbps. The topology in Figure 6 was used to determine the unused bandwidth available in the network, known as actual bandwidth.

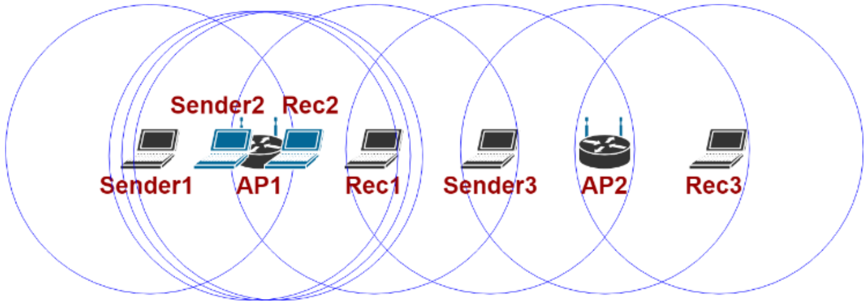

Figure 6. Network topology to measure actual available bandwidth.

RESULTS AND ANALYSIS

Performance testing was carried out by comparing the proposed MPABE with other models, namely ABE, cPEAB-V2, and PABE. ABE provided an idea to consider idle time synchronisation of the sending node and the receiving node in a concise mathematical model. Meanwhile, cPEAB-V2 proposed packet error as a new source of packet collision. PABE also considered idle time synchronisation using the DLI-ABE technique, which made this method unique as compared to ABE and cPEAB-V2. Performance measurement used actual bandwidth as a comparison. In Figure 7, it can be seen that cPEAB-V2 overestimated the available bandwidth too much as compared to the other models. PABE was a little more accurate than cPEAB-V2. When the traffic load was 1 Mbps, the bandwidth estimated by PABE was almost the same as ABE. In contrast, when the hidden node traffic load was 2 Mbps, the bandwidth estimated by cPEAB-V2, PABE, and ABE were almost the same, i.e. 2.709 Mbps, 2.8 Mbps, and 2.853 Mbps, respectively. Of the four mathematical models compared, MPABE was a model that approached the actual bandwidth.

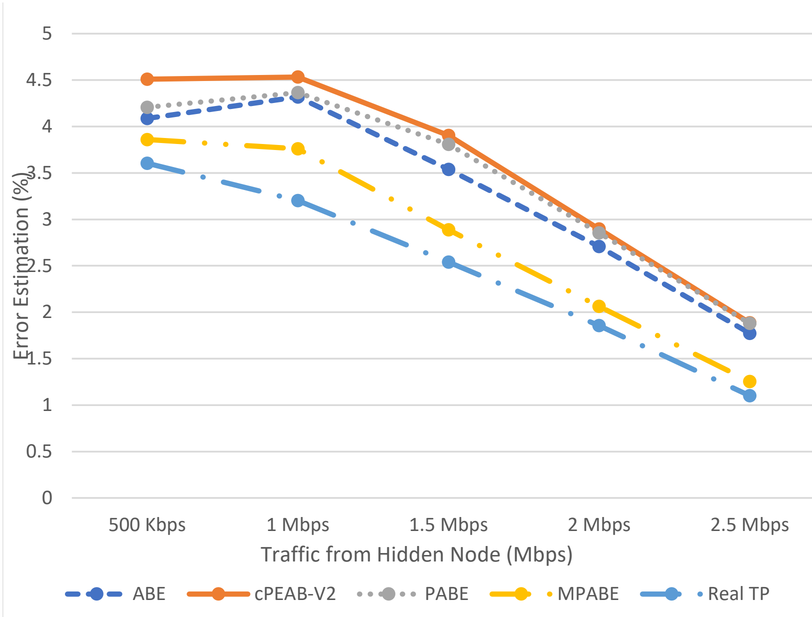

Figure 7. Comparison of the accuracy of each mathematical model.

Based on the bandwidth availability estimation shown in Figure 7, the error rates of each model were calculated by comparing them with the actual bandwidth using a mathematical equation stated in Rizal and Bandung (2017). Table 3 contains the error percentage of each mathematical model in each simulation scenario after being compared with the actual bandwidth. cPEAB-V2 consistently overestimated as compared to PABE and ABE; perhaps because cPEAB-V2 only used the idle period of the medium. In this case, it is assumed that the recipient's idle period was the smallest. The three other mathematical models that used node synchronisation periods had better performance. In general, the greater the traffic load from hidden nodes, the worse the performance of the estimated bandwidth availability model. It can be seen that the trend of the error estimation continued to grow when the load of the hidden node touched 1 Mbps and above. The average error estimation of mathematical models from other studies ranged from 38% to 45%, while MPABE had a better performance with an average error estimation of 12.65%. The model with the highest error rate was cPEAB-V2 when the hidden node was 2.5 Mbps loads with an error of 71.27%.

Table 3

Error Estimation of Each Mathematical Model

Traffic Load (Mbps)	ABE (%)	cPEAB-V2 (%)	PABE (%)	MPABE (%)
0,5	13.40	25.13	16.69	7.08
1	34.79	41.46	36.23	17.38
1,5	39.27	53.72	49.98	13.70
2	45.90	56.02	53.70	11.17
2,5	61.03	71.27	70.62	13.94
Total	194.41	247.62	227.23	63.28
Average	38.88	49.52	45.44	12.65
Min	13.40	25.13	16.69	7.08
Max	61.03	71.27	70.62	17.38

Based on Table 3 and Figure 8, it can be seen that the proposed mathematical model had a lower estimated error rate. In general, the mathematical model developed also experienced a trend of increasing errors with the increasing traffic load from hidden nodes. Sorted by the average error rate from the smallest to the largest was the MPABE model with an average error of 12.65%. The second-best sequence was ABE with an average error of 38.88%. This is followed by the PABE model with an average error of 45.44%. cPEAB-V2 was a mathematical model with the highest errors. It can be stated that idle period synchronisation was the key parameter. The overhead probabilities on the MAC layer such as the proportion of bandwidth used by the waiting time and the backoff mechanism (K) and the overhead caused by ACK were less significant as compared to idle period synchronisation. cPEAB-V2 considered both parameters coupled with the collision probability caused by neighbouring nodes, collision probability caused by hidden nodes, and packet error probability. ABE did not take into account several parameters considered in cPEAB-V2; however, it was concerned with the idle period synchronisation of nodes. For this reason, ABE was more accurate than cPEAB-V2.

Based on Figures 8 and 9, it can be stated that among the many influential variables to estimate the availability of bandwidth on wireless networks with the mode of accessing DCF medium is the period of synchronisation of nodes. Other variables also had an effect, but the effect was not as significant as the idle period synchronisation between sender and receiver nodes. The proposed MPABE model adopted ABE's idle period synchronisation and the estimated available bandwidth was more accurate than other models that did not consider the idle period synchronisation parameter. MPABE considered packet error probability as proposed in cPEAB-V2. Although the P_{err} value was small, it still had an influence on the estimated available bandwidth. MPABE was different from PABE in two parameters, namely the idle period synchronisation and P_{err}. Based on a previous research, it can be concluded that MPABE had the lowest error rate in a simulated network topology that had a hidden node problem.

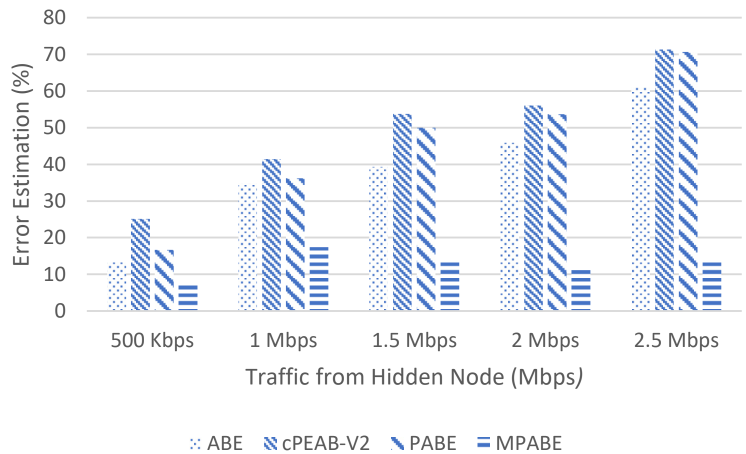

Figure 8. Comparison of the error estimation from each mathematical model.

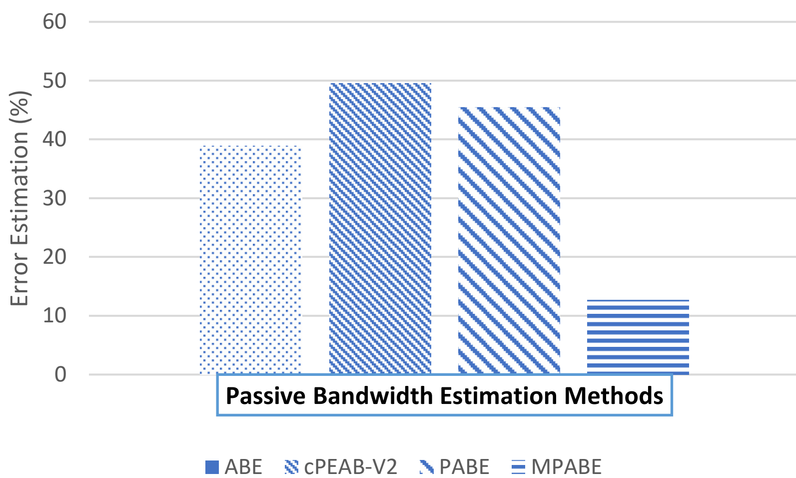

Figure 9. Average estimated error.

CONCLUSION

Based on the analysis of the development and testing of mathematical models, two conclusions are obtained from this study. First, the mathematical model developed called Modified Passive Available Bandwidth Estimation has succeeded in estimating the bandwidth availability of network topologies that have hidden node problems. The mathematical model of estimating bandwidth availability is developed by involving idle period synchronisation between the sending and receiving nodes, the overhead probability at the MAC layer, and the successful packet transmission probability. There are three kinds of probabilities that are considered in the opportunity of packet transmission success, namely the packet collision probability caused by the number of neighbouring nodes, the packet collision probability caused by traffic from hidden nodes, and the packet error probability. Second, the proposed mathematical model is able to estimate the availability of bandwidth 26% more accurate than the ABE mathematical model, 36% more accurate than the cPEAB-V2 mathematical model, and 32% more accurate than the PABE mathematical model.

Several matters are suggested to be carried out in the next study. Future studies should consider amending the latest IEEE 802.11 protocols including IEEE 802.11n and IEEE 802.11ac in developing mathematical models to estimate available bandwidth. Subsequent research should consider a larger network topology and use bidirectional communication to simulate a real network characteristic. In addition, the simulation topology should involve ad-hoc BSS to complement the infrastructure BSS topology that has been used in this study. Subsequent research also needs to consider the exposed node problem so that the mathematical model can handle various cases of node positions at once.

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