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ANALYTICAL AVAILABLE BANDWIDTH ESTIMATION IN WIRELESS AD-HOC NETWORKS CONSIDERING MOBILITY IN 3-DIMENSIONAL SPACE

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Abstract. Estimation of available bandwidth for ad hoc networks has always been open and active challenge for the researchers. A lot of literature is proposed in the last 20 years to evaluate the residual bandwidth. The main objective of the work being admission of new flow in the network with the constraint that any existing current transmission is not affected. One of the prime factors affecting the estimation process is the collision among packets. These collisions trigger the backoff algorithm that leads to wastage of the usable bandwidth. Although a lot of state of art solutions were proposed, but they suffer from various flaws and shortcoming. Other factor contributing to the inaccuracy in existing solution is the mobility of nodes. Node mobility leads to instability of links leading to data losses and delay which impact the bandwidth. The current paper proposes an analytical approach named Analytical Available Bandwidth Estimation Including Mobility (AABWM) to estimate ABW on a link. The major contributions of the proposed work are: i) it uses mathematical models based on renewal theory to calculate the collision probability of data packets which makes the process simple and accurate, ii) consideration of mobility under 3-D space to predict the link failure and provides an accurate admission control. Extensive simulations in NS-2 are carried out to compare the performance of the proposed model against the existing solutions.

Key words: QoS, available bandwidth, analytical, collision, mobility, fixed point analysis, 3 dimensions

AMS subject classifications. 68M10, 68M20, 60K05, 60K25

1. Introduction.

Recently, the development of multimedia applications like live movies, video on demand, e-learning etc. has necessitated the provision of QoS in MANETs. All these applications have diversified requirement in terms of QoS parameters. Some are sensitive to delay while others may demand guaranteed bandwidth for the smooth flow in the network. Thus, an accurate prediction of the available resources is required for the QoS flow guarantee. Bandwidth is one of the scarce resources and should be distributed wisely among the different flows such that admission of new flows doesn't deteriorate the performance of existing flows. Therefore, an accurate estimation of its availability is much required for the true admission control. Imprecise estimation of the ABW leads to false admission control whose bandwidth consumption is more than the estimated ABW. Some approaches like BRuIT [1], CACP [2], AAC [3] didn't address the impact of collisions while estimating the ABW thus provide false admission control, whereas ABE [4] addressed this issue but may results erroneous estimation. It was observed that estimation errors are mainly due to two reasons: first is the bad computation of the considered network criteria such as collision and integrating the same in the estimation; the second is failure to capture each of the network criteria affecting the bandwidth.

ABE [4] focused on few main challenges to evaluate the ABW on a link: idle period synchronization, collision probability and average backoff period between two transmissions. Authors in [4] utilizes the rate of exchange of HELLO packets to compute the collision probability. To handle the discrepancy that arises due to the smaller size of HELLO packets, the resultant is interpolated using Lagrange interpolating polynomial to get the collision rate of data packets. This leads to followings limitations: i) polynomial is calculated at a node for a specific scenario and same is applicable for all nodes or for any scenarios, ii) experiment needs to be executed in advance to calculate the collision probability, iii) HELLO packets that are sent late or lost due to network congestion or overloaded medium are combined with the computed collision rate which overestimates its impact. To remove all these limitations, we proposed to use an analytical approach using fixed point analysis based on renewal theory for the computation of collision probability under heterogeneous network conditions. Most of the available literature assumed homogeneous condition to simplify the process involved. But real time network conditions are heterogeneous in nature consisting of nodes having different capabilities and resources such as transmission rate, battery life, radio range, etc. The major benefits of our proposed solution include: predict the result set when the network parameters get varied, simple and easy approach to compute the collisions without using Hello packets.

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Another cause of error is neglecting the important criteria such as mobility which is not addressed in many of the available literature. Mobility of nodes causes the frequent link breakage and re-construction of links leading to delay and loss of data packets. To overcome the above issue, the current paper considered the bandwidth loss due to mobility of nodes under 3-dimensional space and observed its effects on admission control. Results obtained using our proposed solution is compared with existing solutions which show the improvement done by our proposed approach.

The paper is organized as follows: Section 2 gives an insight into existing available bandwidth estimation techniques and admission control solutions. Section 3 presents our proposed approach AABWM for the estimation of ABW considering all the network criteria affecting the bandwidth under heterogeneous conditions. Section 4 introduces the mobility model under 3-dimensional space to predict the link persistent factor for the improvement in ABW estimation and thus the admission control. Section 5 presents the comparative analysis of results obtained using our proposed solution with the existing approaches under two cases: stationary nodes and mobile nodes. Finally, Section 6 concludes the paper.

2. Related work. The bandwidth estimation techniques can be classified into three main categories: Active techniques, Passive techniques and Analytical techniques. Active techniques emit probe packets at multiple rates between sender and receiver node. By measuring the packets inter-arrival time at the receiver node estimates the end-to-end ABW along a path. The emission rate of these probe packets is increased gradually by the sender node until the congestion arises in the network. SLoPS [5] and TOPP [6] approaches come under this category. Active techniques burden the network with probe packets which can lead to network congestion and consuming precious network resources. Loss of probe packets due to network congestion or overloaded medium may provide the erroneous measurement. These drawbacks make such techniques inefficient to be employed in mobile ad hoc networks. To avoid these drawbacks, the passive techniques monitor the radio channel activities including transmission, reception or idle periods of channel in its vicinity over a certain period of time. The available bandwidth is determined by evaluating the channel usage ratio of nodes in the network. These techniques are non-intrusive in nature. Some major solutions that falls in this category includes: BRuIT [1], CACP [2], AAC [3]. Most of these techniques failed to address the problem associated due to collisions among the packets. The packet collisions consumes the network resources and adversely affect the ongoing transmission in the network.

Authors in [4] addressed these challenges and proposed a solution by incorporating the impact of collisions and time period consumed due to backoff on the bandwidth estimation. To calculate the collision probability [4] utilizes the HELLO packets. By counting the total number of received HELLO packets in a given interval of time and comparing this number with the actual number of received HELLO packets provides the collision probability of HELLO packets. The authors interpolate the resultant using Lagrange interpolating polynomial to compute the collision probability for the data packets of varying size. This approach suffers from the limitations as mentioned in Sec. 1 which makes this technique inefficient for ABW estimation. IAB [7] is a similar approach as that of [4] except that it differentiates the channel busy state due to packet transmission or reception from that of carrier sensing mechanism. Authors in [8] proposed a solution DLI-ABE for bandwidth estimation by employing the Distributed Lagrange interpolating polynomial which is to be calculated separately for each node in any scenario before transmitting the data. All the above-mentioned approaches rely on frequent exchange of Hello packets for calculating the collision probability which contradicts the non-intrusive nature of the passive technique. Moreover, the above literature assumes that the position of the node is static, i.e. there is no mobility. No satisfactory solution is obtained from any of above techniques to estimate the collision probability and their effect on backoff. Analytical techniques provide the reliable solution for the above problem. These techniques are having advantage of predicting the result set by varying the network parameters. Different analytical models available in the literature are based on: i) Bi-dimensional Markov chain, ii.) Means value argument, iii) fixed point analysis based on renewal theory. Based on the traffic conditions, these networks are further divided into two sub-categories: saturated and non-saturated networks. In saturated conditions node always has next packet available to transmit after completing the current transmission; whereas, in non-saturated condition node's buffer may be empty some time.

Author in [9] presented the first analytical model based on the bi-dimensional Markov chain to analyze the performance of IEEE 802.11 DCF under the assumption of saturated and idle channel conditions. The models

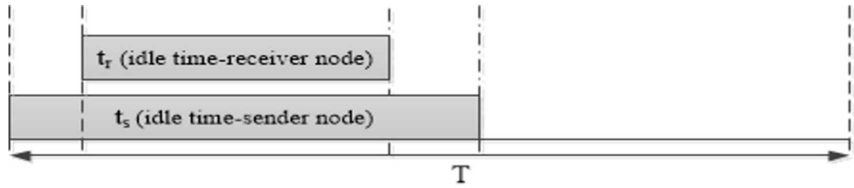

FIG. 3.1. *Total overlap of idle time periods.*

based on the Markov chain were extended to incorporate various challenges like error-prone channel, non-saturated environment, heterogeneous traffic conditions and many other. The major work in literature can be referred in [10, 11, 12, 13, 14, 15]. The solution based on Markov chain are complex and mathematical expressions are computationally extensive. Authors in [16] presented a simple approach using fixed point analysis based on renewal theory. The results obtained are synchronous with the result of [9]. Authors in [17] extended the approach of [16] for non-saturated network condition. Most of analytical models didn't addresses the problem associated with mobility of nodes. The authors in [18] presented a novel approach named Improved Bandwidth Estimation through Mobility incorporation (IBEM) for the estimation of ABW on a link by incorporating the mobility criteria during bandwidth estimation. The authors in [18] ignore the effects of elevation and height while predicting the link failure due to mobility of nodes. Authors in [19] calculate the collision probability based on Markov chain under the assumption of saturated condition.

3. AABWM approach for ABW estimation. The main contribution of this paper is to determine the available bandwidth in mobile ad hoc networks using the analytical models based on renewal theory. To address the various challenges for predicting ABW in mobile ad hoc networks the work is divided into four sections: i) idle period synchronization ii) impact of collision probability iii) effect of average backoff period iv) mobility issues.

3.1. Synchronization of idle time periods between sender and receiver node. For efficient communication to happen, the information about the bandwidth consumption at each node and its neighborhood is much necessitated. The ABW at a node is evaluated by monitoring the radio channel activities of the node in its vicinity. A node is considered as busy when it is either transmitting or receiving information on the channel. Thus, the ABW at a node is evaluated by measuring the idle and busy period of nodes in the network. The upper bound for estimating ABW can be expressed as [20]:

$$ABW_i = \frac{t_i}{T}.C_{max} \tag{3.1}$$

where, t_i represents the idle periods sensed by node i during the total measurement duration T and C_{max} is the raw channel capacity.

Let t_s and t_r represents the idle periods of sender s and receiver r respectively, evaluated using (3.1) during the measurement period T. Fig. 3.1 and Fig. 3.2 depicts the two extreme cases (full overlap and no overlap) of node's overlap period respectively to evaluate the ABW on a link.

Fig. 3.1 represents the case where idle period of both sender node and receiver node completely overlap to each other. In other words, the channel is idle at both the ends make transmission of packet a successful event. Thus, the communication is feasible only when the idle periods of sender (t_s) and receiver (t_r) overlap each other for the period of the transmission as stated in [3]. This type of communication is possible using a precise clock synchronization mechanism. Thus, the ABW on a link constituting between sender s and receiver r is given by [3] as:

$$ABW_{link(s,r)} = \min(\frac{t_s}{T}, \frac{t_r}{T}) \tag{3.2}$$

Fig. 3.2 represent the case when the idle periods of both nodes (sender and receiver) are never synchronized to each other despite the medium availability at both sides. Thus, in this scenario no communication is feasible

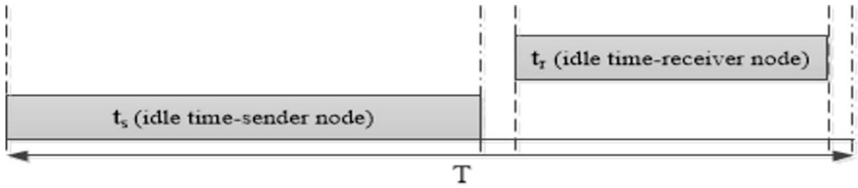

FIG. 3.2. *No overlap of idle time periods.*

and the available bandwidth on a link is counted as null. It can be concluded that the ABW on a link is dependent on the overlap period of idle time at both sender node and the receiver node for successful communication to happen.

Authors in [4] propose to incorporate a probabilistic approach and used the average of the idle time periods of sender and receiver to evaluate the ABW on a link. Thus, the ABW on a link is given as:

$$ABW_{ABE(s,r)} = \frac{t_s}{T} \cdot \frac{t_r}{T} . C_{max} \tag{3.3}$$

Where t_s and t_r represent the idle periods of sender(s) and receiver(r) respectively, during the measurement period T; C_{max} is the maximum channel capacity.

3.2. Collision Probability using Fixed point analysis (FPA). The ABW calculated using (3.3) provides a conservative solution for estimation of ABW. Collision impacts the bandwidth estimation process adversely. Collisions can occur due to various reasons including Hidden terminal problem and Exposed terminal problem. A packet transmitted by a node may collide with the other packet transmitted by other nodes in its vicinity leading to delay and wastage of bandwidth. Thus, it is imperative to accurately predict the collisions in the network otherwise the estimation becomes fallacious. The authors in [4] addressed this issue and presented a mathematical framework for the estimation of ABW on a link on account of the collision. Mathematically the same can be represented as:

$$ABW_{ABE(s,r)} = \frac{t_s}{T} \cdot \frac{t_r}{T} . C_{max} . (1-p) . (1-k) \tag{3.4}$$

Where p represents the collision probability of data packets, and k represent the proportion of bandwidth consumed due to backoff mechanism in the event of the collision.

To calculate the collision probability the authors in [4] make use of the HELLO packets. A counter was deployed at the receiver end to count the number of HELLO packets that are received at the destination in real time. The collision probability of HELLO packets is calculated by dividing the value of the above counter by the actual number of the HELLO packets that should have been received in idealized conditions. Since the size of the HELLO packets is small in comparison to the data packets the above results are interpolated to predict the collision probability of data packets. However, there are several drawbacks attached to this process. It can be observed from Fig. 3.3 that the estimated values of data packet collisions are far away from the real values of data packets collisions measured using NS2. This over-evaluation is because HELLO packets which are delayed or lost due to network congestion or overloaded medium are combined with the collision rate of HELLO packets and further interpolating the same overvalued its effect. This revealed the abortive behavior of [4] approach for the computation of collision probability.

To overcome the computation failure existing due to passive technique proposed in [4], our work uses an analytical approach using fixed-point analysis (FPA) based on renewal theory for the calculation of collision probability. The proposed solution is influenced by [17]. The main assumption being ideal channel conditions. The only reason for the unsuccessful packet transmission is the collision of packets. It is also assumed that all stations use the different backoff parameter thus having different collision probability (p_l) and attempt rate (or transmission probability) (τ_l) where l=1, 2... n. Let n be the number of contending nodes, the attempt by l^{th} node is successful if all other contending nodes are silent. Mathematically, it can be written as:

$$1 - p_l = \prod_{j \neq l} (1 - \tau_j); for j, l = 1, 2, ..., n \tag{3.5}$$

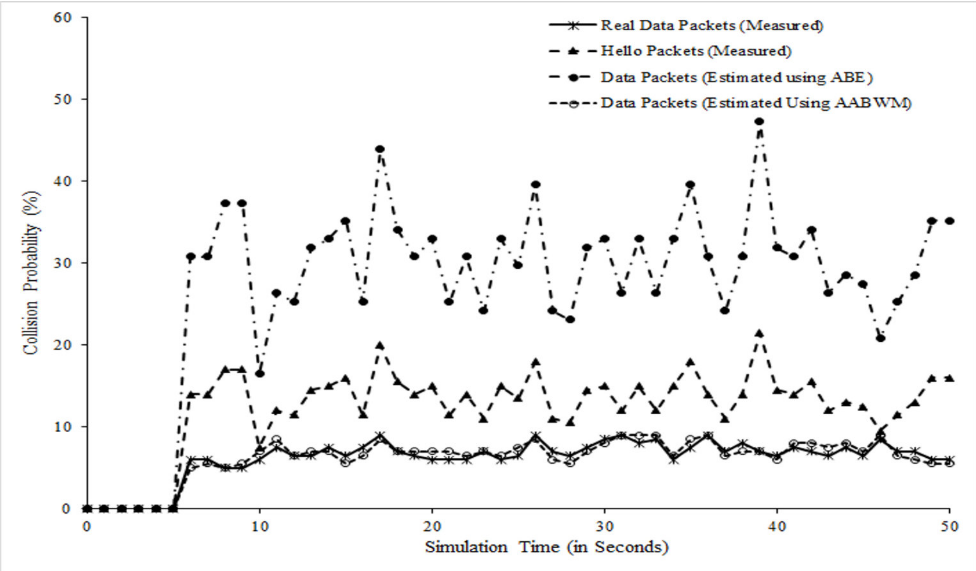

Fig. 3.3. *Estimated results of collision probabilities of packets.*

Let q denotes the probability of a non-empty buffer, i.e. at least one packet is available for transmission after transmitting the current one. According to [17] the attempt rate of a node in non-saturated network condition can be obtained by scaling down the attempt rate of a node in saturated condition with the probability of non-empty buffer. Thus, we have

$$\tau_l = q.\tau_{ls} \tag{3.6}$$

where τ_{ls} represent the l^{th} node's attempt rate (or probability) under saturated network conditions. To solve the fixed-point equation given by (3.5) and (3.6), there is a need to express τ_l i.e. q and τ_{ls}) in terms of collision probability (p_l).

The attempt rate of a node in saturated condition (τ_{ls}) is defined as the ratio of average number of attempts to the average number of backoff time (in slots) spent by a node till the successful transmission of the packet. According to [16], we have:

$$\tau_{ls} = f(p) = \frac{E[attempts]}{E[backoff]} \tag{3.7}$$

where the average attempt rate is given as:

$$E[attempts] = 1 + p_l + {p_l}^2 + ... + {p_l}^m \tag{3.8}$$

According to IEEE 802.11 standard whenever a packet suffers collision, the exponential backoff mechanism is triggered; the backoff associated with the initial transmission attempt by a node is b_0 and it is doubled after every unsuccessful attempt till the maximum limit m is reached. The average backoff time per packet is given as:

$$E[backoff] = b_0 + p_l(2b_0) + ... + {p_l}^{m'}(2^{m'}b_0) + ... + {p_l}^m(2^{m'}b_0) \tag{3.9}$$

where

$$b_0 = \frac{CW_0 + 1}{2} \tag{3.10}$$

CW_0 is the minimum contention window size = 31 slots. And, m' represent a constant where contention window size reaches its maximum value CW_{max}, represented as:

$$CW_{max} = 2^{m'} CW_0 \tag{3.11}$$

Thus, using (3.5) and (3.6) we get,

$$\tau_l = \frac{q.(1 + p_l + {p_l}^2 + ... + {p_l}^m)}{b_0 + p_l(2b_0) + ... + {p_l}^{m'}(2^{m'}b_0) + ... + {p_l}^m(2^{m'}b_0)} \tag{3.12}$$

For simplicity of expression we assumed Poisson traffic arrival rate, however the solution is equally applicable to other traffic arrival types also such as Constant Bit Rate (CBR), exponential on/off traffic and Pareto on/off traffic. Using queuing theory, the traffic intensity ρ is given as:

$$\rho = \rho(\lambda, p) = \lambda.ST \tag{3.13}$$

where λ is packet arrival rate, ST is a mean service time of a packet which is dependent on the average backoff time i.e. E[backoff] waiting till the successful transmission of the packet and the average slot time E_s depending on the channel activity i.e. idle slot time, successful attempt and collision occurrence. Thus, (3.13) can be re-written as:

$$\rho = \lambda.E[backoff].E_s \tag{3.14}$$

The average time E_s spent per slot is given as:

$$E_s = (1 - P_{tr})\sigma + P_{tr}P_{s_i}T_{s_i} + P_{tr}(1 - P_{s_i})T_{c_i} \tag{3.15}$$

where P_{tr} represent the probability that at least one transmission going on in the network; σ is the slot time and P_{si} represents the probability that the transmission by i^{th} station is successful.

$$P_{tr} = 1 - \prod_{i=1}^{n}(1 - \tau_j) \tag{3.16}$$

$$P_{s_i} = \tau_i \prod_{j \neq 1}(1 - \tau_j) \tag{3.17}$$

T_{s_i} and T_{c_i} represent the expected time for successful transmission and unsuccessful transmission respectively. These transmission times are governed by the access mechanism employed i.e. Basic access mechanism and RTS/CTS access mechanism.

$$T_{s_i}^{basic} = DIFS + T_{(H+DATA)} + SIFS + T_{ACK} \tag{3.18}$$

$$T_{c_i}^{basic} = DIFS + T_{(H+DATA)} + ACK_{timeout} \tag{3.19}$$

$$\begin{aligned} T_{s_i}^{RTS/CTS} &= DIFS + T_{RTS} + SIFS + T_{CTS} + SIFS \\ &+ T_{(H+DATA)} + SIFS + T_{ACK} \end{aligned} \tag{3.20}$$

$$T_{c_i}^{RTS/CTS} = DIFS + T_{RTS} + CTS_{timeout} \tag{3.21}$$

where DIFS is Distributed Inter-Frame Space time; SIFS is Short Inter-Frame Space time; T_{RTS}, T_{CTS}, and T_{ACK} are the time required for RTS, CTS, and ACK control packet transmission respectively; $T_{(H+DATA)}$ is the time required for the transmission of DATA packet along with the PHY header and MAC header. $CTS_{timeout}$

and $ACK_{timeout}$ are the waiting time required before declaring unsuccessful transmission for RTS and DATA packet respectively.

To solve (3.12), the value of q needs to be determined. The probability of non-empty buffer is dependent on the node's buffer size as well as offered load. We have taken two extreme cases of buffer sizes to evaluate the value of q; one for small buffer and another for infinite buffer. This is expressed by [17] as:

$$q = \begin{array}{l} 1 - e^{-\rho}; \textit{ for small buffer model} \\ \min(1, \rho); \textit{ for infinite buffer model} \end{array} \tag{3.22}$$

Substituting the value of q from (3.22) in (3.12), we get the following equations under two different cases as considered:

Case-I: Small Buffer case

$$\tau_l = \frac{(1 - e^{-\rho}).(1 + p_l + p_l{}^2 + ... + p_l{}^m)}{b_0 + p_l(2b_0) + ... + p_l{}^{m'}(2^{m'}b_0) + ... + p_l{}^m(2^{m'}b_0)} \tag{3.23}$$

Case-II: Infinite Buffer case

$$\tau_l = \frac{(\min(1, \rho)).(1 + p_l + p_l{}^2 + ... + p_l{}^m)}{b_0 + p_l(2b_0) + ... + p_l{}^{m'}(2^{m'}b_0) + ... + p_l{}^m(2^{m'}b_0)} \tag{3.24}$$

Solving the coupled nonlinear equations (3.5) and (3.23) provide the precise estimation of collision probability p_l and the attempt rate τ_l of the l^{th} node.

3.3. Special case for Homogeneous Network Model. Consider homogeneous network conditions where all stations are having same backoff parameters. Let n be the number of stations in the network, then average attempt rate τ and collision probability p of each station are same. Under the decoupling approximation, the probability of collision p of an attempt by a node is obtained by reducing the equations mentioned in Sec. 3.2 as:

$$1 - p = (1 - \tau)^{n-1} \tag{3.25}$$

The expected time spent per state reduces to:

$$E_s = (1 - P_{tr})\sigma + nP_sT_s + (P_{tr} - nP_s)T_c \tag{3.26}$$

where, the probability of successful transmission P_s of any sending station is given by:

$$P_s = \tau(1 - \tau)^{n-1} \tag{3.27}$$

The probability P_{tr} that at least one transmission is going on in the network reduces to:

$$P_{tr} = 1 - (1 - \tau)^n \tag{3.28}$$

The probability of non-empty buffer under homogeneous network condition is obtained by re-writing (3.23) and (3.24). Thus, we have:

Case-I: Small Buffer case

$$\tau = \frac{(1 - e^{-\rho}).(1 + p + p^2 + ... + p^m)}{b_0 + p(2b_0) + ... + p^{m'}(2^{m'}b_0) + ... + p^m(2^{m'}b_0)} \tag{3.29}$$

Case-II: Infinite Buffer case

$$\tau = \frac{(\min(1, \rho)).(1 + p + p^2 + ... + p^m)}{b_0 + p(2b_0) + ... + p^{m'}(2^{m'}b_0) + ... + p^m(2^{m'}b_0)} \tag{3.30}$$

Solving the coupled nonlinear equations (3.25) and (3.29) provide the estimation of collision probability p and the average attempt rate (or transmission probability) τ of the node. We calculated the collision probability using (3.25) for the simplicity reasons and plotted the same in Fig. 3.3 under same simulation scenario. It can be clearly seen that the computed values using our fixed-point approach (3.25) closely match with the real values of collision probability measured using NS2 which proves the accurate calculation of collisions in the network.

3.4. Bandwidth consumed due to backoff mechanism . Whenever a packet transmission occurs between sender and receiver node, the packets may suffer collision at sender s or receiver node r. In both cases the exponential backoff mechanism is triggered at sender node. The time lost due to backoff mechanism is not used for transmitting the packet, even if the medium is idle. Thus, a proportion of idle time wasted due to backoff mechanism having a significant impact on the ABW. The average backoff time associated with the collision probability p_l is obtained using (3.9). Thus, the loss of local ABW of sender node due to backoff mechanism can be mathematically represented as given in [19]:

$$LocalABW_s = \frac{(t_s - E[backoff])}{T} C_{max} \tag{3.31}$$

where t_s is the idle time of sender(s) obtained using (3.1) and E[backoff] is the average backoff time calculated using (3.9) and C_{max} is the raw channel capacity.

3.5. Link Prediction Factor in 3-Dimensional space . Mobility causes the frequent link breakage and re-construction leading to delay and data losses which eventually impact the ABW. Limited literature is available on the issue of mobility while calculating the available bandwidth. Most of the work addressing the mobility has considered two dimensional space only. The current work predicts the link expiration caused due to mobility of nodes under 3-dimensional space. The approach is equally applicable to all channel environments.

Fig. 3.4 represents the 3-dimensional mobility model for the movement of sender and receiver nodes. Let the initial position of sender station and receiver station be (X_s, Y_s, Z_s) and (X_r, Y_r, Z_r) respectively. Sender station is moving in 3-dimensional world with velocity V_s making an angle γ with z-direction and angle α with x-direction. As V_s is making an angle of γ in z-direction, the vector component of V_s in X-Y plane is $V_s.\cos\gamma$ and vector component of V_s in z-axis is $V_s.\sin\gamma$. Further, as the angle with respect to x-direction is α, the vector component of $V_s.\cos\gamma$ in x-axis is $V_s.\cos\gamma.\cos\alpha$ and in y-axis is $V_s.\cos\gamma.\sin\alpha$.

Receiver station is moving in 3-dimensional world with velocity V_r making an angle δ with z-direction and angle β with x-direction. As V_r is making an angle of δ in z-direction, the vector component of V_r in X-Y plane will be $V_r.\cos\delta$ and vector component of V_r in z-axis is $V_r.\sin\delta$. Further, as the angle with respect to x-direction is β, the vector component of $V_s.\cos\delta$ in x-axis is $V_s.\cos\delta.\cos\beta$ and in y-axis is $V_s.\cos\delta.\sin\beta$.

After time t let the coordinates of sender station and receiver station are (X_s, Y_s, Z_s) and (X_r, Y_r, Z_r) respectively. The new coordinates of the sender and receiver station can be mathematically written as:

$$X'_s = X_s + tV_s \cos\gamma \cos\alpha \tag{3.32}$$

$$Y'_s = Y_s + tV_s \cos\gamma \sin\alpha \tag{3.33}$$

$$Z'_s = Z_s + tV_s \sin\gamma \tag{3.34}$$

$$X'_r = X_r + tV_r \cos\delta \cos\beta \tag{3.35}$$

$$Y'_r = Y_r + tV_r \cos\delta \sin\beta \tag{3.36}$$

$$Z'_r = Z_r + tV_r \sin\delta \tag{3.37}$$

Therefore, the distance between sender and receiver after time t in X, Y and Z directions can be determined as:

$$X'_s - X'_r = (X_s - X_r) + t(V_s \cos\gamma \cos\alpha - V_r \cos\delta \cos\beta) \tag{3.38}$$

$$Y'_s - Y'_r = (Y_s - Y_r) + t(V_s \cos\gamma \sin\alpha - V_r \cos\delta \sin\beta) \tag{3.39}$$

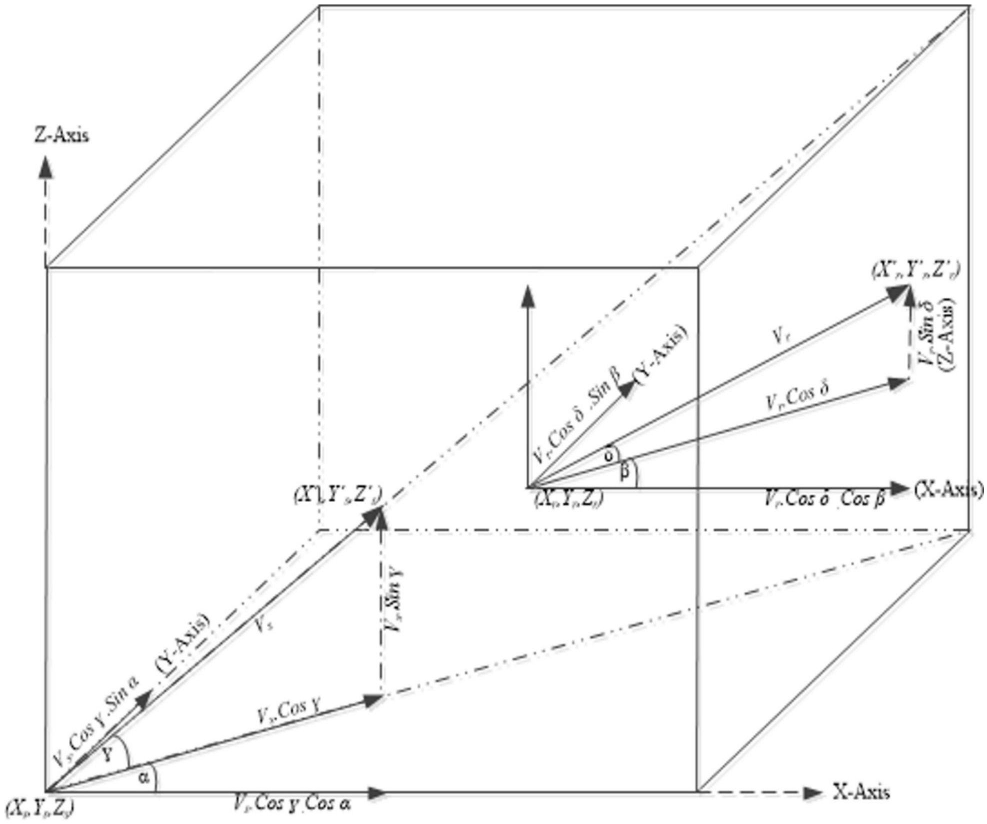

FIG. 3.4. *3-Dimensional reference model.*

$$Z'_s - Z'_r = (Z_s - Z_r) + t(V_s \sin\gamma - V_r \sin\delta) \tag{3.40}$$

Let the vector distance between sender and receiver after time t be D. Then, using Pythagoras Theorem the D can be calculated as:

$$D^2 = (X'_s - X'_r)^2 + (Y'_s - Y'_r)^2 + (Z'_s - Z'_r)^2 \tag{3.41}$$

Substituting the values from (3.38), (3.39) and (3.40) in (3.41), we get

$$\begin{aligned} D^2 = &= ((X_s - X_r) + t(V_s \cos\gamma \cos\alpha - V_r \cos\delta \cos\beta))^2 \\ &+ ((Y_s - Y_r) + t(V_s \cos\gamma \sin\alpha - V_r \cos\delta \sin\beta))^2 \\ &+ ((Z_s - Z_r) + t(V_s \sin\gamma - V_r \sin\delta))^2 \end{aligned} \tag{3.42}$$

This can be re-written as:

$$D^2 = (a + tf)^2 + (b + tg)^2 + (c + th)^2 \tag{3.43}$$

where $a = X_s - X_r$, $b = Y_s - Y_r$ and $c = Z_s - Z_r$ are the initial distance between sender and receiver station in X, Y and Z directions respectively. The relative velocity component between the two in X, Y and Z directions respectively can be mathematically expressed as $f = V_s.\cos\gamma.\cos\alpha V_r.\cos\delta.\cos\beta$, $g = V_s.\cos\gamma.\sin\alpha V_r.\cos\delta.\sin\beta$; and $h = V_s.\sin\gamma V_r.\sin\delta$. Solving (3.43) for the value of time t, we get:

$$t = \frac{-(af + bg + ch) \pm \sqrt{(f^2 + g^2 + h^2).D^2 - (ag - bf)^2 - (bh - gc)^2 - (ah - cf)^2}}{(f^2 + g^2 + h^2)} \tag{3.44}$$

Global positioning system in [21] facilitates the coordinate's information. With each Hello packet, station broadcasts starting and terminus coordinates along with its velocity. The sender station, receiving the hello packet from receiver station evaluates the link availability time duration t and thereby the mobility factor MM.

$$MM = \frac{t}{T} \tag{3.45}$$

where T is the measurement period, t is the duration for which the sender-receiver stations are within communication range.

The final ABW on a link(s,r) constituting between sender s and receiver r is computed by combining all the major factors discussed in the sub-sections of the current section (i.e. Sec. 3) of this paper. The final ABW estimated on link(s,r) is given as:

$$ABW_{AABWM} = (\frac{t_s - E[backoff]}{T}.\frac{t_r}{T}.C_{max})(1 - p_l)(MM) \tag{3.46}$$

where t_s and t_r represent the sum of idle times sensed at sender and receiver node respectively computed using (3.1) during measurement period T; E[backoff] represent the local ABW wasted at the sender node as given by (3.9); C_{max} is the maximum channel capacity; p_l represents the collision probability of data packets as driven in Sec. 3.2 obtained by solving (3.5) and (3.23) or (3.24); and a MM link persistence factor representing the mobility effect of nodes in 3-dimensional space is given in (3.46).

3.6. Throughput efficiency (S). Saturation throughput of a system is defined as the maximum data that the system can transfer successfully under steady state conditions. Mathematically, the throughput S of a system can be expressed as the summation of each individual source station's throughput efficiency.

$$S = \sum\nolimits^{n}_{i=1} S_i \tag{3.47}$$

where S_i represents the throughput efficiency of i^{th} source station, $i \in [1, n]$ and n is the total number of source stations in the network. The throughput efficiency of the individual source station can be calculated as the fraction of the time used by source station for successfully transferring the payload information and is expressed as:

$$S_i = \frac{P_{si} L_i}{E_s} \tag{3.48}$$

where P_{si} represents the probability that the transmission by i^{th} station is successful and is derived in (3.17); L_i is the time taken to transmit payload data by i^{th} source station; and E_s is the expected time spent per state as derived in (3.15).

3.7. Protocol Design. To provide comparative analysis and visualizing the impact of mobility factor in (3.46), our proposed approach AABWM employs AODV [22] as routing protocol. Assuming a node having data to transmit. It first determines it's local ABW using (3.1) based on idle/busy periods sensed by the node by monitoring the radio channel activities. If it's local ABW is enough for the flow transmission, it broadcasts a route request packet (RREQ) consisting of the required bandwidth for its flow. All the nodes within its range receive this RREQ packet, and perform admission control by comparing the required bandwidth within the RREQ packet with the computed ABW using (3.46) on the link composed with its fore goer node. If bandwidth is enough, then node combines its own information with the fore goer and forwards the RREQ packet otherwise drop the packet. When the intended destination node receives the packet, it reverts with the uni-cast RREP (route reply packet) packet to the initiator along with the reverse path.

If the bandwidth estimation is done after admitting the flow and link has no enough bandwidth then the node sends a route error packet (RERR) to the initiator. On receiving the RRER packet, the initiator takes immediate action to prevent the losses and stops the ongoing transmission.

4. Validation and Simulations. In this section a comparative analysis is done between the AODV protocol, ABE [4], IAB [7], IBEM [18] and our proposed approach AABWM incorporated in AODV [22] protocol. The results are obtained through simulations in NS-2.

TABLE 4.1
Simulation parameters values for comparative analysis

Raw channel capacity	2 Mbps
Topology size	700x700x700 meter
Routing protocol	AODV
Medium access protocol	CSMA
Packet size	1000 Bytes
Transmission range	250 m
Carrier sensing range	550 m
Simulation time	100 seconds
Flow-1 CBR	250 kbps
Flow-2 CBR	500 kbps
Flow-3 CBR	400 kbps
Flow-4 CBR	550 kbps
Flow-5 CBR	450 kbps
Flow-6 CBR	300 kbps
Minimum contention window (CW_{min})	31 slot
Maximum contention window (CW_{max})	1023 slot
Maximum retry limit (m)	6

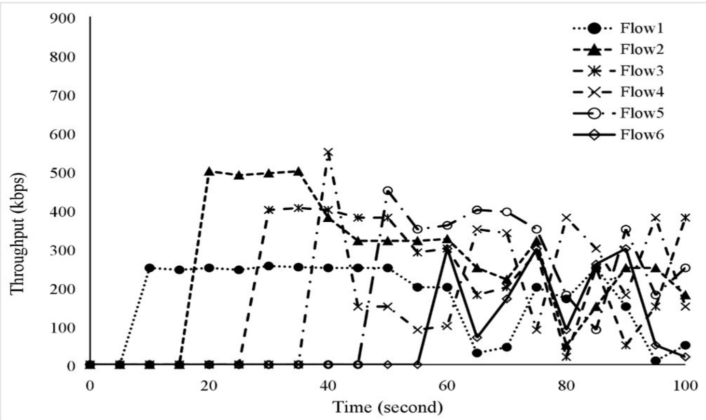

FIG. 4.1. *Throughput of flows using AODV [22] without any admission control.*

4.1. Simulation Scenario. A network consists of 48 nodes randomly distributed over a small area (700m x 700m x 700m) is considered. Six CBR single-hop flow connections (Flow-1 to Flow-6) are established. Each flow is having a different transmission rate to make the network heterogeneous. The parameters used for simulation are derived from IEEE 802.11b and are listed in Table 4.1.

4.2. Simulation results and Comparative Analysis. The comparative analysis is split into two cases: a) Case-I, consists of stationary nodes to evaluate the accuracy of our proposed approach AABWM with the traditional approaches; and b) Case-II, consists of mobile nodes which are free to move in 3-dimensional space, thereby giving us an opportunity to visualize its effect on link persistence and thus on the admission control.

Case-I: Considering no mobility of nodes

Flows 1 to 6 are generated at an interval of 10 seconds starting from $t = 5$ second. Fig. 4.1 to Fig. 4.5 plots the throughput of six flows obtained when AODV [22], ABE [4], IAB [7], IBEM [18] and AABWM approaches are activated respectively.

In AODV [22], all flows are admitted as no admission control is employed. However, with the introduction of flow-4(550kbps) at a time, t=35s channel capacity is reached; the performance of existing flows gets deteriorated. The throughput further got worse by the introduction of flow-5(450kbps) and flow-6(300kbps).

When ABE [4] is used, due to the underestimation of ABW, flow-4 (550kbps) and flow-5 (450kbps) are rejected. However, flow-6 (300kbps) got admission at t=55s as it was accommodated under ABW estimated by

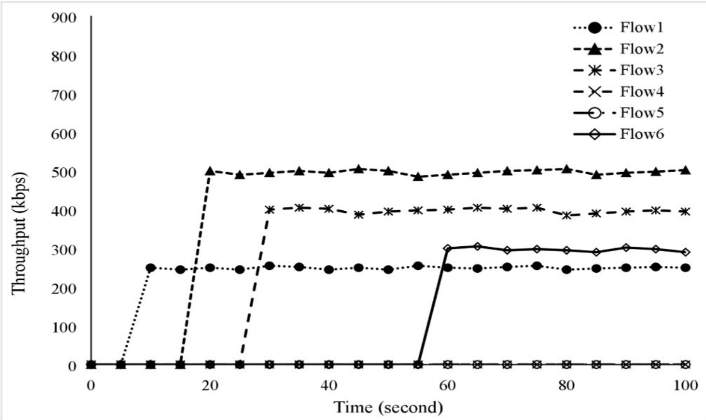

Fig. 4.2. *Throughput of flows using ABE [4] for admission control.*

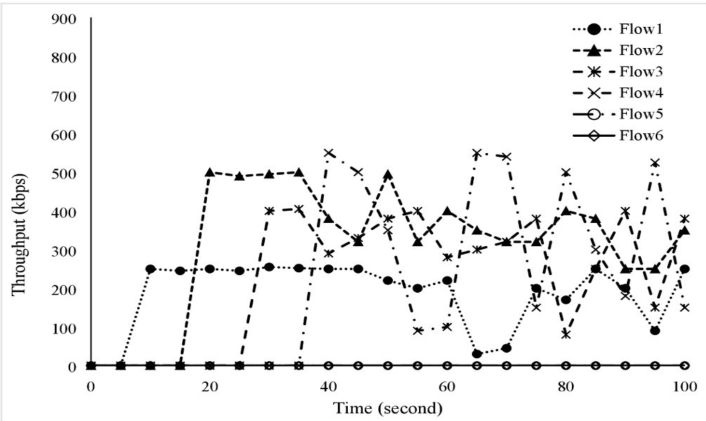

Fig. 4.3. *Throughput of flows using IAB [7] for admission control.*

ABE [4]. The system resources are not optimally utilized, the total system throughput is far below maximum channel capacity. This underestimation of ABW is due to the bad computation of collision probability and assimilates the same in bandwidth estimation.

In IAB [7], over-estimation of ABW takes place, thereby allowing flow-4(550kbps) which leads the channel congestion and all existing flows got suffered in terms of throughput performance. Due to collisions arising from network congestion, a lot of bandwidth got wasted; thereby degrading overall system performance. However, flow-5(450kbps) and flow-6(300kbps) are rejected as ABW estimated using IAB [7] is not enough for these flows.

Fig. 4.4 represent the throughput of six flows along the simulation duration when IBEM approach is enabled. To calculate the collision probability IBEM assumed the saturated condition as in [19] and ignore the empty state of nodes buffer. Thus, overestimating the impact of collisions leading to underestimate the ABW; thereby admission of flows (flow-4 and flow-5) is not permitted. Further, Flow-6(300kbps) is accepted as ABW estimated using IBEM is enough for this flow.

The throughput of all six flows is shown in Fig. 4.5 for proposed approach AABWM is enabled. Due to the more precise estimation of ABW, at t=35s. flow-4 (550kbps) is rejected due to unavailability of ABW, however at t=45s flow-5(450kbps) is allowed by the admission control protocol as its required bandwidth is below the estimated ABW obtained using (3.46). Further, at t=55s, flow-6 (300kbps) is rejected as no enough bandwidth left for allowing this flow admission. We can observe that all admitted flows exhibit a stable throughput performance. Moreover, the network resources are optimally utilized as clearly seen by the safe admission of flow-5 (550kbps) instead of flow-6 (300kbps).

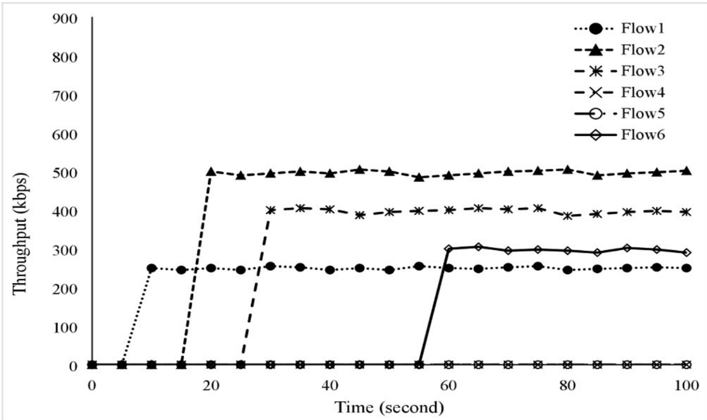

FIG. 4.4. *Throughput of flows using IBEM [18] for admission control.*

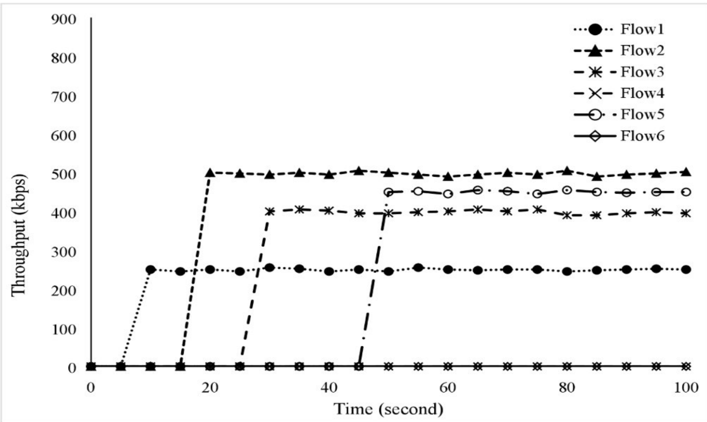

FIG. 4.5. *Throughput of flows using proposed AABWM for admission control.*

Case-II: Considering the 3-Dimensional mobility of nodes

To visualize the impact of mobility of nodes, the Random way point mobility model is used in the 3-dimensional space to assign random movement to the nodes with random direction and velocity. Initially the flows 1 to 6 are generated at random time interval. The start and stop of flows are automated by the admission control protocol depending on the ABW estimation technique employed. The simulation results obtained using AODV [22], ABE [4], IAB [7], IBEM [18] and AABWM under the influence of 3-dimensional movement of nodes is represented in Fig. 4.6 to Fig. 4.10.

Fig. 4.6 represents the throughput of all flows when the AODV [22] routing protocol is enabled. Absence of any admission control in AODV [22], all flows are admitted leading to high network congestion and increased collisions. There is no QoS guarantee given to any flow, even the flows having a shorter duration of link existence (Flow-4 and Flow-5) is allowed causing a lot of bandwidth and data loss.

Fig. 4.7 depicts the throughput of all six flows when ABE [4] approach is activated. Inability of ABE [4] to predict link failure caused due to mobility permit the admission of short persisted flow-4(550kbps) at time t=10s and flow-5(450kbps) at t=15s. Although the admitted flows are less in ABE [4] as compared to AODV [22] and flow's throughput are also stable, but still due to false admission of flows (Flow-4 and Flow-5) the network resource is not adequately utilized. Incomplete transmission due to link failure causes loss of data and thus the bandwidth.

Fig. 4.8 depicts the case of IAB [7], where an overestimation of ABW is observed. It is also inefficient in predicting the link expiration due to absence of mobility criteria in the ABW estimation. This leads to serious

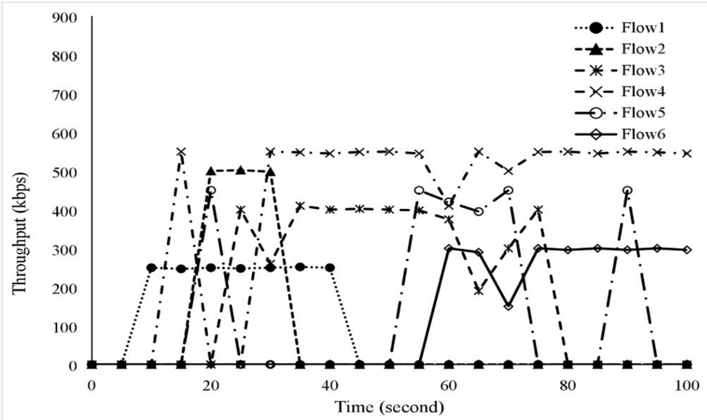

FIG. 4.6. *Throughput of flows using AODV [22] without any admission control.*

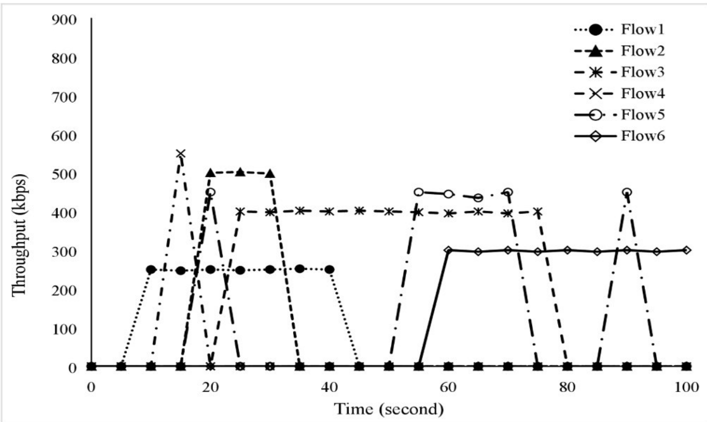

FIG. 4.7. *Throughput of flows using ABE [4] for admission control.*

network congestion by allowing short lived flows such as flow-4(550kbps) at t=25s and flow-5(450kbps) at t=55s despite of non-availability of enough ABW leading to performance degradation of existing flows. We observed poor individual flow's throughput performance and a lot of data packets loss in this scenario due to higher collisions.

Fig. 4.9 depicts the throughput of the flows when IBEM [18] approach is enabled. IBEM restricted its study to 2-dimensional plane only and ignored the movement of nodes under 3-dimensional space. Thus, it predicts the link failure of flow-5(450kbps) at t=15s and not allowed it to admit at this instance. IBEM admitted short lived flows (flow-4 at t=10s and flow-5 at t=85s) due to the inability to predict link failure at 3-dimension leading to data losses. Moreover, the admission of flow-3(400kbps) is delayed and started at t=25s due to false admission of flow-4(550kbps). IBEM performed better than earlier approaches, but still admission control is severe in this due to ignoring the effects of elevation and height while predicting the link failure.

Fig. 4.10 shows the received throughput when AABWM is enabled. Short lived flow-4 at (t=10s and t=25s) is rejected by admission control protocol due to the prediction of link failure. Similarly, flow-5 at (t=15s and t=85s) is also not permitted due to identification of link failure under 3-dimension. Rest all other flows (flow-1, 2, 3 and 6) are admitted and fitted well in the network gaining stable throughput. The proposed solution AABWM is more accurate in estimating the ABW. The approach AABWM also computes the collision probability analytically without stressing the network and can work well during the dynamic environment.

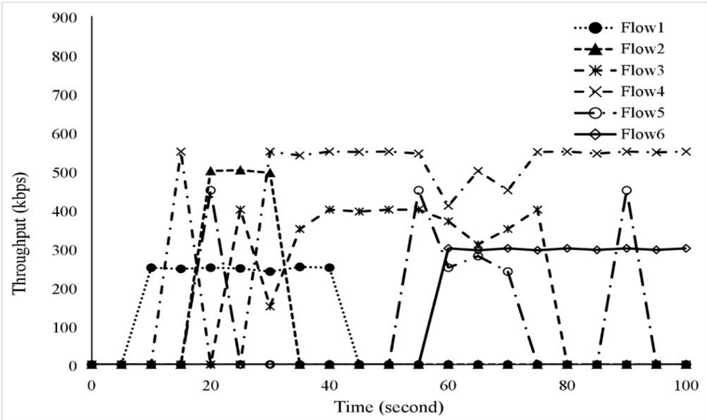

Fig. 4.8. *Throughput of flows using IAB [7] for admission control.*

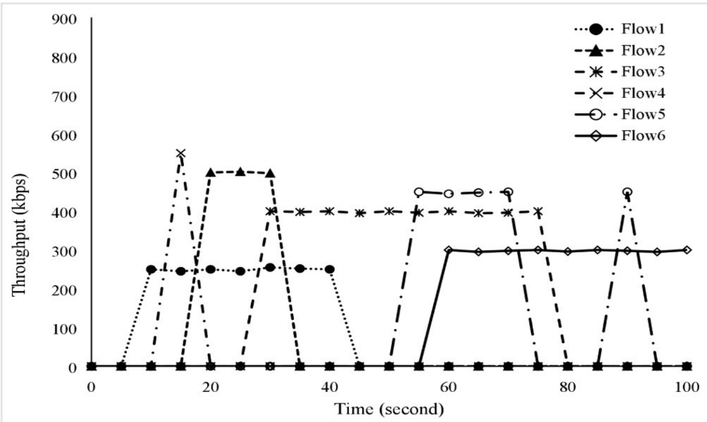

Fig. 4.9. *Throughput of flows using IBEM [18] for admission control.*

4.3. Packet Loss Ratio. The packet loss ratio is defined as the ratio of the number of data packets lost to the number of data packets sent by the sender. The number of lost data packets is calculated as the difference of the number of packets sent by the sender and the number of packets received at receiver node. Mathematically, this can be written as:

$$\textit{Packet Loss ratio} = \frac{\textit{number of sent packets} - \textit{number of received packets}}{\textit{number of sent packets by the sender}} \tag{4.1}$$

Fig. 4.11 depicts the packet loss ratio measured under the effect of mobility in the above experiment using NS2. We observe the packet loss ratio is negligible for all flows when AABWM is incorporated in admission control protocol. Whereas, other techniques resulting in an elevated packet loss ratio for flow 1 to 6.

4.4. Data Packets Delivery. The data packets delivery is calculated as the total number of data packets received at receiver node. The data packets delivery does not necessarily mean the useful data, rather it represents the total number of data packets delivered irrespective of the communication is completed. Fig. 4.12 represents the data packets delivery under the influence of node's mobility.

5. Conclusion. The current paper presents an analytical approach for estimating the available bandwidth in mobile adhoc network. The introduction of analytical models overcomes the disadvantages associated with active and passive approaches as discussed in the literature. The proposed analytical model is based on fixed point analysis based on renewal theory which helps in reducing the computations in comparison to Markov

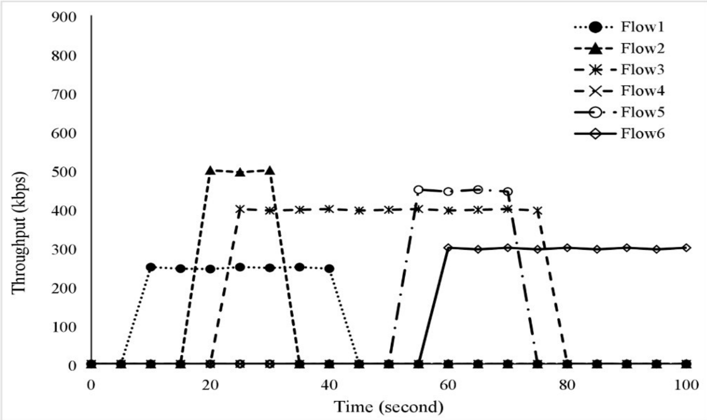

FIG. 4.10. *Throughput of flows using proposed AABWM approach for admission control.*

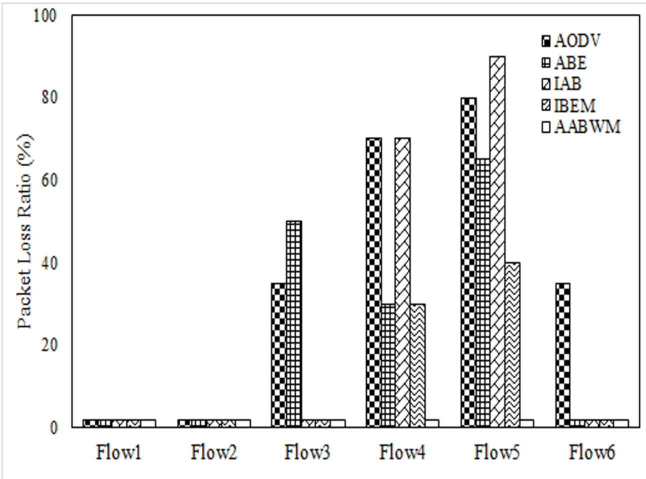

FIG. 4.11. *Packet loss ratio.*

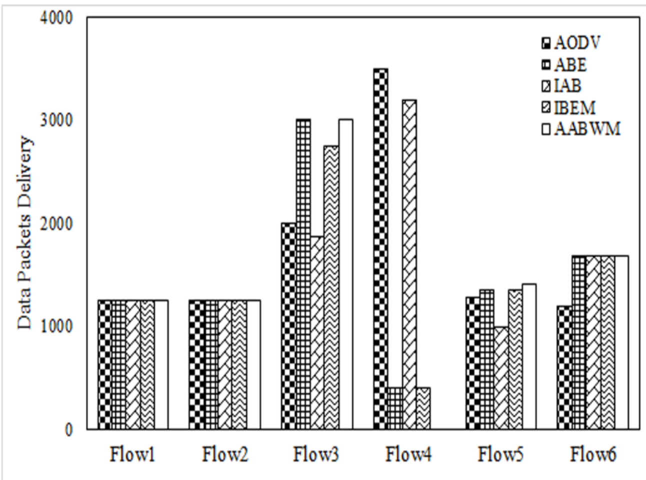

FIG. 4.12. *Data packet delivery.*

Chain based solutions. The link failure due to mobility of nodes leads to wastage of bandwidth resources and needs to be addressed while evaluating the available bandwidth. We incorporate the mobility issue and observed that link failure due to mobile nodes adversely affect the bandwidth estimation efforts. The proposed model is compared against the existing approaches in terms of bandwidth consumption and admission control solution using ns-2 simulations. The results indicate that in both static environment and dynamic environment the proposed model has most stable performance. The packet loss ratio is found to be least in comparison to other algorithms. The increased value of packet delivery ratio indicates the improvement in terms of delivery and throughput achieved by the proposed solution.

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