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Modeling packet loss probability and busy time in multi-hop wireless networks

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Abstract
Throughput imbalances among contending flows are known to occur when any carrier sense multiple access (CSMA)-based protocol is employed in multi-hop wireless networks. These imbalances may vary from slight difference in throughput to complete starvation in which some flows are unable to acquire channel accesses. The root cause of such imbalances is the lack of coordination when CSMA medium access control (MAC) protocols are employed in multi-hop wireless networks. In this paper, we accurately predict per-flow throughput in general multi-hop wireless networks while addressing CSMA's coordination problem. Unlike the previous work, our analytical throughput prediction model can clearly differentiate between links interfering from transmission range and carrier sensing range. Modeling of conditional packet loss probability and busy time sensed by each station is critical for per-flow throughput prediction in arbitrary networks. The calculation of both these parameters largely depends on MAC behavior due to geometrical configuration of interfering stations; we accurately compute conditional packet loss probability and busy time based on geometrical configuration of the interfering stations and predicted per-flow throughput. Our analytical results demonstrate improved accuracy, indicate throughput imbalances, and provide better understanding of CSMA-based protocol behavior in multi-hop wireless networks that can be used to design fair, scalable, and efficient MAC layer protocols.

Keywords: Two-flow analysis, Wireless mesh network (WMN), MAC behavior, Throughput imbalances, Starvation, Packet loss probability, Carrier sense range (CSR)

1 Introduction

After quite a few years of research in multi-hop wireless network, we are still unable to see these technologies in widespread commercial use because of many reasons such as lack of experimental deployments and industrial entrust. However, multi-hop wireless networks have a promising future; their immediate application may be extension of network coverage area and improved connectivity, but many variants of multi-hop wireless networks have already made their way, and deployments will increase in near future. These may include but not limited to medical, emergency, environmental, battlefield sensor networks, telematics applications for individual drivers, public safety and security, broadband internet, vehicular network/MANETs, home/office networks, cognitive radio networks, and even data center networks. In short, deployment of multi-hop wireless technologies will surely transform our daily life with innovative applications having greater impact.

When all stations in multi-hop wireless networks are not in a single-radio range, carrier sense multiple access-based medium access control (MAC) protocols (two-way or four-way handshake) are known to exhibit severe throughput imbalances and few flows are even starved completely. It is very critical to analytically model such behavior and predict per-flow throughput for designing efficient networking protocols. Flow starvation can be modeled by computing conditional packet loss probability and busy time duration sensed by each station in the network. Accurate modeling of MAC behavior is very critical for modeling starvation and predicting per-flow throughput. However, traditional metrics like aggregate throughput and latency are not suitable for this purpose. In this work, we develop analytical model for conditional packet loss probability, computation of busy time, and per-flow

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throughput prediction for all the flows in multi-hop wireless network.

Modeling packet loss probability is very critical in per-flow throughput prediction, and it depends on MAC behavior which is strongly tied with geometry of contending links. Per-flow throughput prediction and starvation modeling in [1] are based on embedded two-flow classification of [2], which actually defines geometrical relations between two contending flows and their MAC behavior. Two-flow classification of [2] assumes the same transmission and carrier sense range and do not clearly differentiate between links interfering from transmission and carrier sense range. Therefore, the proposed throughput modeling in [1] is for radio range, i.e., carrier sense range and such modeling do not differentiate between interference from transmission and carrier sense range. Interfering link being in transmission range means that stations can receive and decode each other's request to send/clear to send (RTS/CTS) and are able to set network allocation vector (NAV), but this is not the case when stations are in sensing range of each other, and this is a fundamental differentiation to consider while modeling throughput due to MAC behavior in wireless mesh network (WMN).

Most of the existing literatures address some aspects of per-flow throughput prediction; few [3, 4] of them ignored the inherent coordination discrepancy when carrier sense multiple access (CSMA)-based MAC protocols are employed in multi-hop WMN. This inherent coordination discrepancy was first modeled in [1] and is largely due to information asymmetry between contending flows. Some of the literature is unable to model behavior of comprehensive MAC protocol like 802.11 [5–8]. Analysis of 802.11 protocols is mostly done for backlogged stations [3, 9, 10]; only model in [1] predicts per-flow throughput for any given flow rates in the WMN. In [1], they also highlighted that few dominant flows acquire the maximum transmission opportunities where as most of the flows are starved and this starvation is due to an inherent coordination discrepancy in CSMA-based MAC protocols when employed in WMN.

Understanding wireless interaction between two contending flows, their MAC behavior and impact on each other's throughput are critical in predicting per-flow throughput of links in general WMNs. In our prior work [11, 12], we identified 25 unique two-flow scenarios that can occur in general WMN and classified them into six categories based on link location, MAC behavior, and throughput imbalances. We compute the occurrence probability of each identified category and also show which categories of two-flow wireless interactions are more common than others. We also compute and simulate throughput profile of each category to show how these flows affect each other's throughput. Unlike a prior work on two-flow [2], two-flow classification in [12] takes more realistic assumption of different transmission and carrier sense range, and it can clearly differentiate between links interfering from transmission and carrier sense range.

In this work, we model packet loss probability of individual station based on our prior geometric analysis of a two-flow classification in [12], and unlike [1], our proposed model can clearly differentiate between interference from transmission and carrier sense range. We also devised a simplified disk model for computation of busy time durations and rate of their arrival sensed by a station in dense wireless network. We calculate per-flow throughput based on our modeling of packet loss probability and busy time. We validate our packet loss probability and busy time modeling along with throughput prediction via comparison of analytical and simulation results. We also compare our analytical results with those of [1], and a higher accuracy in throughput prediction is achieved by our proposed throughput prediction model and also provides a better understanding of throughput imbalances between contending flows when CSMA-based MAC protocols are employed in multi-hop wireless network.

The main challenges in per-flow throughput prediction in WMN include accurate calculation of conditional packet loss probability and busy time sensed by each station. The calculation of these both parameters is totally dependent on geometrical location of contending stations and clear differentiation between links interfering from transmission range and carrier sense range whereas prior art is unable to make this differentiation. We devise a simplified disk model for measuring busy time sensed by a station in dense wireless mesh network. We accurately model conditional packet loss probability for each station based on geometrical locations of all the interfering stations around it. Our modeling of busy time and packet loss probability can clearly make the differentiation between interference from transmission and carrier sense range. The following are the main contributions of our work:

(i) We devised a simplified disk model for calculating busy time sensed by a station in dense multi-hop WMN, and this model inherently embed geometrical location of all interfering transmitters and receivers around that particular station. This also helps differentiate between stations interfering from transmission and carrier sense range.
(ii) We accurately model packet loss probability for each station in multi-hop WMN, and this modeling can clearly differentiate between interference from transmission range and carrier sense range.
(iii) We predict per-flow throughput for each station based on its packet loss probability and busy time experienced. Knowledge of per-flow throughput and MAC behavior is very critical for designing future

protocol for all variants of multi-hop WMN and this greatly helps in identifying dominating and starving flows in the arbitrary network.

(iv) Model validation and simulation results show that our packet loss probability, busy time, and throughput modeling improved the accuracy and overall understanding of MAC behavior in multi-hop WMN.

In the remainder of the paper, related literature on modeling CSMA-based MAC protocol is discussed in Section 2. Section 3 presents modeling of throughput whereas model for packet loss probability is described in Section 4 and busy time computation algorithm in Section 5. In Section 6, the proposed models are validated by simulations and analytical results, and Section 7 concludes this work.

2 Related work

Analytical modeling of MAC protocol for single-hop wireless network was presented in [13] for Aloha protocol and in [14] for CSMA-based MAC. Recently, analytical models for throughput characterization have been proposed for 802.11 with backlogged stations [9, 10]. Analysis of single-hop networks is easy and straightforward as all the stations are within same contention region, have same picture of the channel, and can coordinate for efficient channel utilization. However, this is not the situation for multi-hop general wireless mesh networks. Prediction of per-flow throughput and starvation is more challenging for multi-hop WMN and existing literature either worked with limited analytical details or detailed analysis only exists for restricted geometric topologies. We will first discuss IEEE standardization efforts for multi-hop wireless mesh networks and then talk about more relevant work in existing literature.

The latest version of IEEE 802.11s standard released in 2012 [15] specifies the MAC and physical specifications for mesh networks. It comprises of a mandatory coordination function called enhanced distributed channel access (EDCA) and an optional coordination function named mesh coordination channel access (MCCA). EDCA is a modified version of distributed coordination function (DCF of 802.11n) with smaller durations for arbitration inter frame space (AIFS) and reduced maximum window size values to accommodate priority traffic in the wireless network. Smaller AIFS are used for higher priority flows whereas larger AIFS is used for low priority flows. Similarly lower value of maximum window size is selected for priority flows and vice versa. EDCA was originally designed to provide quality of service (QoS) at MAC layer for single hop wireless local area network (WLAN) in IEEE 802.11e, but later, it is also recommended to be used as MAC for multi-hop WLAN in IEEE 802.11s. EDCA is known to incur throughput imbalances among the same or even higher priority flows and there are known situations in which higher priority flows also starve [16]. Researchers have made many efforts to make improvements in EDCA, but more work is done for QoS provisioning analysis for real time flows in WLAN.

MCCA is an optional coordination function in IEEE 802.11s mesh mode. MCCA is a distributed transmission opportunity allocation algorithm in which mesh stations coordinate their intended transmission duration using request and acknowledgment procedures. MCCA-enabled mesh stations also coordinate their resource allocation vectors (RAV) to two-hop neighbors using regular MCCA opportunity (MCCAOP) advertisements [16, 17]. MCCA enabled mesh stations are also required to contend for channel access among non-MCCA stations within their reserved duration. Even after reservation, MCCAOP owner cannot have guaranteed access because of simultaneous transmissions made by non-MCCA mesh stations [18].

Talking about coexistence of EDCA and MCCA with traditional DCF, EDCA was originally designed to provide QoS at MAC layer in single hop WLAN, i.e., IEEE 802.11e. The same is recommended as MAC for 802.11s; it translates traffic into four different priority classes by differentiating the arbitration inter frame space (AIFS) slot length and backoff windows size [15]. While co existing with DCF, EDCA with AIFS value equal to 2 performs well and provides an effective mechanism for priority flows to get channel access whereas the performance of EDCA is almost the same as that's of legacy DCF when AIFS is equal to 3. Differentiated AIFS length is more effective in providing QoS as compared to differentiation of backoff window size [19]. MCCA is an optional access mechanism for mesh stations whereas EDCA is mandatory, so it is most likely that MCCA enabled mesh stations will be contending with non-MCCA stations (both EDCA and legacy DCF), who are unaware of reservations made by MCCAOP owner. Any reservation made by MCCA enabled stations will not be guaranteed due to collision introduced by non-MCCA mesh stations; hence, the performance of MCCA enabled station is very deteriorating in general WLAN [15, 18, 19]. Being an optional access mechanism, no efforts have been made to improve the performance of MCCA.

In [20], the authors analyzed the delay and capacity of CSMA-based access protocol for two-hop wireless networks. Analyzing 802.11, [21] developed a Markov chain throughput analysis model for flow-in-middle (FIM) geometric configuration of stations and [22] presented queuing theoretic analysis for Information Asymmetric configuration of stations. But both of these are based on specialized geometric configuration and also do not model per-flow throughput in multi-hop wireless networks.

Michele Garetto et al. in [1] classified existing models for CSMA based protocols into two groups, one group follows transmission set approach whereas other follow station based approach. Authors in [5] presented a continuous Markov chain model based on transmission set approach to check if the given input rate can be supported by a network. An iterative method results in product form solution and decides whether the given input data rate is feasible to transmit on a network or not. Same model was extended by [7, 8] replacing links by stations. But [5] was not able to capture the comprehensive access mechanism behavior specifically did not model packet loss due to MAC behavior and also lacked binary exponential backoff mechanism. Being an NP-complete problem, it is also not feasible to compute all the independent sets in a general wireless networks as proposed by [5].

Each flow in the network is viewed in isolation in station-based approach, and packet loss probability is a function of transmission probabilities of contending flows in the radio range. Approach based on station is more efficient than transmission set as it does not include computation of independent sets [1]. Employing station based approach, [4] models 802.11 with captured effects and also addressed the hidden station problem but did not used binary exponential backoff. Carvalho and Garcia-Luna-Aceves [3] proposed a model for throughput computation of backlog link in flows and employed most of the 802.11 mechanisms including RTS/CTS, network allocation vector (NAV) and also modeled channel errors for all links. But the proposed model do not consider inherent coordination discrepancy which CSMA-based protocols incurs when employed in multi-hop wireless network.

Michele Garetto et al. in [1] highlighted inherent coordination discrepancy when CSMA based protocol is employed in multi-hop wireless networks. They modeled per-flow throughput prediction and identified dominant and starving flows in the network. For throughput prediction, they computed unknown variables in throughput formula like busy period b experienced by an individual station and its average busy duration T_b, also computed most complicated variable in an arbitrary topology that is conditional packet loss probability p. As mentioned earlier that computation of packet loss probability depends on geometric configuration of the stations in the network and computation of conditional packet loss probability in [1] depends on two flow analysis in [2] and both approaches do not differentiate between interfering links in transmission and carrier sense range.

Researchers proposed few throughput estimation models for multi-hop wireless networks. Beakcheol Jang et al. [23] proposed analytical model for saturated throughput but only addresses interference from hidden terminal for infrastructure 802.11 network. Bruno Nardelli et al. in [24] derived a closed form expression for throughput characterizing hidden terminals, information asymmetry, and flow-in-the-middle. Thomas Begin et al. [25] proposed a throughput prediction modeling framework which caters the effect of interference on capacity of contending flows in scenarios including two flows in opposite directions and hidden node problem. These models [23–25] address subset of the overall problem and are unable to characterize throughput imbalances due to location of interfering links.

Among other related literatures, few studies tried to estimate and model the throughput of flows in the network based on gathered measurements [26–28]. Both the studies [27, 28] are limited as they are simulation-based and both use general DCF as underlying MAC protocol. There are some studies on capacity scaling for mobile nodes in multi-hop wireless networks. Michele Garetto et al. [29] did an asymptotic capacity analysis for general mobile ad hoc networks. In [30], Authors extended previous capacity scaling laws [29] for more wider class of wireless networks. In another extension of the same study [31], they also considered correlated movements of a group of nodes and assume fast mobility with an objective to maximize throughput of individual node. They discovered that correlated movement of wireless nodes have impact on delay and throughput of the network and at times can lead to better throughput performance as compared to independent node mobility. S. Razak et al. in [32] also tried to predict imbalance based on two-flow analysis but again their work is unable to clearly differentiate between interference form transmission and carrier sense range.

Few studies are also done on proposing programmable MAC to adopt to temporal interference profiles in general multi-hop wireless network. Ilenia Tinnirello et al. [33] proposes wireless MAC processor with an ability to execute programmable MAC commands on runtime to achieve desired MAC operation using low cost hardware wireless cards. They implemented wireless MAC processor for only three wireless scenarios as a proof of concept and validated that future wireless MAC needs access flexibility and adaptability. Giuseppe Bianchi et al. in [34] propose MAClets, a software program that can be executed over wireless cards, reconfigures MAC protocol seamlessly and enable MAC adaptation to current spectrum conditions for optimized performance. They validate the viability and flexibility of the proposed concept with help of different experiments. Later in [35], Giuseppe Bianchi et al. argued that an abstract description of MAC logic as extensible finite state machine appears to be viable and effective solution for deploying and modeling realistic programmable MAC protocols.

Taking an overview of more recent literature, authors in [37] proposed a game theoretic distributed channel assignment algorithm for assigning partially overlapped channels in wireless mesh network. The proposed algorithm achieved near optimal performance in average care, and this work concluded that overlapping channel assignment can exhibit improved performance as compared to traditional channel assignment strategies with orthogonal channels. The authors in [38] proposed a semi-random backoff counter only after a successful transmission by a wireless node. After a successful transmission, a wireless node is recommended to set its backoff to a deterministic value but behave normally after a failed transmission attempt. Such a solution can easily be implemented with slight modification in 802.11 DCF and 802.11e EDCA. The results demonstrated higher performance for both small- and large-scale wireless mesh networks. CodePipe [39], a reliable multi-cast protocol in proposed which is energy efficient, achieves a higher throughput and is quite fair in lossy wireless networks. It proposes four key techniques including inter-batch coding, opportunistic feeding, LP-based opportunistic routing structure, and fast batch moving. Simulation analysis shows that proposed protocol outperforms two existing multi-cast protocols including Pacifier and MORE.

A cooperative MAC protocol is proposed in [40]; it improves the multiple access performance and cooperation efficiency in wireless ad hoc networks. It employs three different techniques for rapid relay selection including contention resolution phase (CRP), priority differentiation phase (PDP), and rate differentiation phase (RDP). Theoretical and simulation analyses revealed the fact that proposed MAC protocol outperforms both 2rcMAC and CoopMACA protocols. The work in [41] propose orthogonal frequency division multiple access-based coordinated and distributed resource allocation algorithm for cellular networks with an objective to improve their self organization and stabilize their frequency reuse patterns. The authors in [42] insist that careful spatial reuse-ability can greatly improve throughput in multi-hop wireless network. To support their argument, they proposed spatial reusability-aware single-path routing (SASR) and anypath routing (SAAR) protocols and compared them with existing routing protocols to demonstrate significant end to end throughput.

A femtocell downlink cell-breathing control framework is proposed in [43] to maintain a good balance between data rate and coverage. It also propose a voting based FEmtocell Virtual Election Rule (FEVER) direct mechanism that requires users to only share their channel quality statistics to the base station of femtocell. Enhanced system performance is verified by extensive simulations. ITCD, a cross layer distributed topology control algorithm, is proposed in [44] which jointly considers both the delay constraint and interference constraint. The proposed algorithm considers node mobility along with three types of delay including queuing, contention, and transmission delays. Simulation results supported the argument that proposed algorithm is capable of reducing delay and improving performance specifically in delay constrained wireless networks.

3 Throughput modeling

In this section, we describe throughput modeling of a station in multi-hop wireless network. It is evident from existing literatures [1, 2, 10] that modeling private view of a station serves better purpose in predicting per-flow throughput. We follow the same approach to evaluate the CSMA/CA-based channel access mechanism in WMN. We made following assumptions: (i) ignore physical layer issues; (ii) fix transmission and carrier sense range; (iii) stations within transmission range can decode message and also set NAV whereas stations in carrier sense range can sense the channel busy but cannot decode the message (RTS/CTS/DATA/ACK); (iv) collision is considered when a station receives more than one packet at the same time from different stations within its carrier sensing range; and (v) error-free channel and packets received from stations within transmission range is decoded correctly when there is no collision. The assumption of simplified physical layer channel does not affect the analysis as we are modeling MAC layer parameters.

While considering private view of a station, four different states of a channel can be identified: (i) successful transmission; (ii) idle channel; (iii) busy channel due to other station's activity; and (iv) collision; and these states are denoted by T_s, T_σ, T_b, and T_c, respectively, and their probabilities are denoted by ÏΠ_s, ÏΠ_σ, ÏΠ_b, and ÏΠ_c. τ is the probability that the station tries to transmit after an idle slot, p is the probability that transmitted packet will be lost, and b is the probability that the channel becomes busy after an idle slot due to activity of other stations [9]. The occurrence probabilities of each of the above channel states are Ï$\Pi_\sigma = (1 - \tau)\ (1 - b)$, Ï$\Pi_s = \tau\ (1 - p)$, Ï$\Pi_c = \tau\ p$, and Ï$\Pi_b = (1 - \tau)\ b$. The throughput of a station is given by $T_P = \frac{\Pi_s}{\Delta}$, where Δ (in seconds) is the average duration of all states on the channel and throughput is given in [1]:

$$T_P = \frac{\tau(1-p)}{\tau\,(1-p)\,\overline{T}_s + \tau p \overline{T}_c + (1-\tau)\,(1-b)\,\sigma + (1-\tau)\,b\overline{T}_b} \qquad (1)$$

G. Bianchi. in [9], computes an expression for τ which actually is function of p, and in [36], it is also shown that similar expression for τ can be driven for general multi-hop wireless networks employing arbitrary windows distribution and exponential backoff multipliers. Complete expression of τ for CSMA Multi-hop network considering maximum window size and maximum retransmit limit is given as [1]:

$$\tau = \frac{2q\left(1-p^{m+1}\right)}{q\left(1-p^{m+1}\right) + W_0\left[1-p-p(2p)^{m'}\left(1+p^{m-m'}q\right)\right]} \quad (2)$$

where W_0 represents minimum window size, m is upper limit for retry, $q = 1 - 2p$ and m' is the value of back-off stage ($m' <= m$). $\overline{T}_c$ and $\overline{T_s}$ are average durations of a colliding and successful transmission and have already been evaluated in [9], and these two values work the same for both single-hop and multi-hop arbitrary topologies. There are only two unknown quantities in throughput formula in Eq. 1: (i) conditional packet loss probability p and (ii) probability of busy period b and $\overline{T}_b$ is average duration of busy period. We model both these quantities in the following two sections: packet loss probability is modeled in Section 4 whereas occurrence probability b of a busy period and its average duration $\overline{T}_b$ are computed in the Section 5.

4 Packet loss probability modeling

We model conditional packet loss probability p of any station i in an arbitrary network. Conditional packet loss probability is the most critical and complicated variable to be computed for predicting per-flow throughout in multi-hop WMN. Previous literature ignored comprehensive behavior of CSMA based MAC protocol and geometric location of the interfering links, and both these reasons cause stations to have large values of packet loss probability p. Conditional packet loss probability depends on geometric configuration of flows in the immediate neighborhood. When all the stations are within transmission range of each other, then DCF is able to coordinate among stations and transmission attempts are within well defined time durations. Conditional packet loss probability of such scenario is given by $1 - (1 - \tau)^{n-1}$ here n denotes number of stations in the network [9]. But there is inherent problem in DCF when employed in multi-hop network scenario that DCF is unable to synchronize all stations in the network.

With an objective to clearly differentiate between interference from transmission and carrier sense range, we identify and model four possible types of packet losses that can occur due to CSMA-based MAC behavior in multi-hop wireless network: losses because of (i) sender sensing with probability p_{ss}; (ii) asymmetric incomplete state with probability p_{ais}; (iii) symmetric incomplete state with probability p_{sis}; and (iv) destination connected with probability p_{dc}. In the following subsections, we analyze each type and describe exact geometric configuration. The probability of each identified type is calculated independently and then combined to compute the total packet loss probability. Transmissions which do not suffer from any of these losses are successful.

$$p(i) = 1 - \left[1 - p_{\text{ss}}\left(i, i'\right)\right]\left[1 - p_{\text{ais}}\left(i, i'\right)\right] \left[1 - p_{\text{sis}}\left(i, i'\right)\right]\left[1 - p_{\text{dc}}\left(i, i'\right)\right] \quad (3)$$

Figure 1 describes modeling topology in which there are two contending flows l and l', where i and j are the transmitter and receiver of link l and i' and j' are transmitter and receiver of link l'. Each flow's transmitter and receiver are within transmission range of each other to comprise a flow and packet loss probability models how link l' interferes the transmission of link l in different geometrical configuration.

4.1 Loses due to sender sensing (SS)

Collision occurs at a station when it simultaneously receives data from two other transmitting stations. We define sender sensing as scenario in which both the senders are within carrier sense range of each other (outside transmission range) and losses occurs at a receiver who is able to receive packets from these two senders at the same time. We compute expression for $p_{\text{ss}}\left(i, i'\right)$ of collision probability that a link $l(i,j)$ is interfered by station i' due to its simultaneous transmission, assuming distance $d(i,i') < R_{\text{S}}$, $d(j,i') < R_{\text{S}}$ and $d\left(i,i'\right) > R_{\text{T}}$ where R_{S} and R_{T} represent carrier sense range and transmission range. To compute $p_{\text{ss}}\left(i,\ i'\right)$, we need to compute conditional probability $c\left(i'/i\right)$ that station i' tries to transmit a packet at the same time when station i was already transmitting.

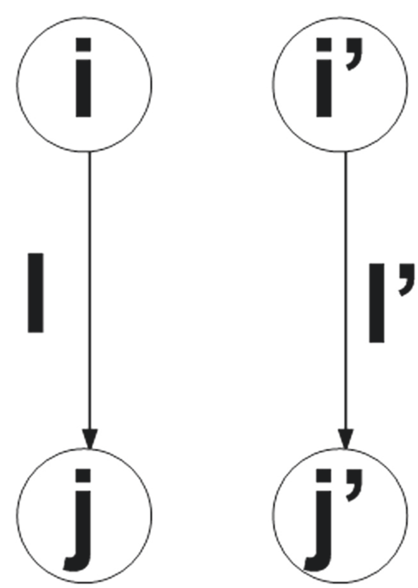

Fig. 1 Two-flow topology

Probability p_{ss} is given by $p_{ss}\left(i,\ i'\right) = c\left(i'/i\right)\ \tau\left(i'\right)$, and conditional probability $c\left(i'/i\right)$ can be computed as:

$$c\left(i'/i\right) = \frac{Q(\Phi)}{\sum_{D\in A(i)} Q\left(D\right)} \tag{4}$$

Equation 4 computes the probability of i' to initiate a transmission when i is already transmitting and does this by dividing the probability of idle system state (no station is active) over probability of all regions where station i can become active. $Q\left(D\right)$, $Q(\Phi)$, and $A\left(i\right)$ are calculated in the next section for busy time computation. $Q\left(D\right)$ represents that the probability of stations in a region are jointly in the On period, $Q(\Phi)$ is an empty set representing a situation when none of the station in any region is active, and $A\left(i\right)$ is a set of regions where station i can become active.

4.2 Loses due to asymmetric incomplete state

Losses due to information asymmetry are of a serious concern as they can cause very large values of packet loss probability, and these losses are more severe than any other type as far as starvation is concerned. Accurate modeling of asymmetric incomplete state (AIS) scenario is very critical in defining the MAC behavior in arbitrary network. In information asymmetric scenario, both the transmitters are not in transmission range of each other ($d\left(i,i'\right) > R_T$) (but they can be in carrier sensing range or disconnected) and one of the receiver is also not in the transmission range of the opposite transmitter ($d\left(j',i\right) > R_T$) (but can be in carrier sense range or disconnected). And further, we identify two types of AIS scenarios: one scenario in which the other receiver is in transmission range of the opposite transmitter ($d\left(j,i'\right) < R_T$), and in second scenario, the other receiver is in carrier sense range of its opposite transmitter $\left(d\left(j,i'\right) > R_T\right)$ *and* ($d\left(j,i'\right) < R_S$). We model these both scenarios independently and that is actually how our model differentiates between these two ranges (transmission and carrier sense range).

In information asymmetric-induced packet losses, link $l(i,j)$ is interfered from link $l'(i',j')$ if the above mentioned geometric configuration stands true for both scenarios. In this scenario, station i only has a chance of successful transmission if it is able to send first packet (DATA for two-way and RTS for four-way handshake) when link l' is not active. The packet loss probability when one of the receivers is in transmission range of its opposite transmitter ($d\left(j,i'\right) < R_T$) is given:

$$p_{ais-tr}\left(i,i'\right) = X\left(i'/i\right)\ \tau\left(i'\right) \tag{5}$$

and $X\left(i'/i\right)$ is given as:

$$X\left(i'/i\right) = \frac{\overline{T}_{OFF}}{T_{ON} + \overline{T}_{OFF}} e^{-\frac{d}{T_{OFF}}} \tag{6}$$

In Eq. 5, $\tau\left(i'\right)$ is the probability that transmitter i' of link l' tries to initiate a transmission right after a busy period ends and $X\left(i'/i\right)$ is the probability that successful transmission of i is only possible when first transmitted packet reached j during a period when link l' was inactive and d is the size of first packet. The activity of link l' is modeled as On/Off periods sensed by receiver j when transmitter i tries to transmit, and On/Off periods are calculated during busy time computation in Section 5. The packet loss probability $p_{ais-csr}\left(i,\ i'\right)$ for the scenario when the second receiver is in carrier sense range of its opposite transmitter $\left(d\left(j,i'\right) > R_T\right)$ and ($d\left(j,i'\right) < R_S$) is given as:

$$p_{ais-csr}\left(i,\ i'\right) = \frac{\overline{T}_{OFF}}{T_{ON} + \overline{T}_{OFF}} e^{-\frac{d}{T_{OFF}}} \tag{7}$$

Equation 7 computes the probability that successful transmission is only possible when first packet transmitted by station i reached its receiver j during a period when link l' is inactive. The total probability of $p_{ais}\left(i,i'\right)$ is given as:

$$p_{ais}\left(i,i'\right) = 1 - \left[p_{ais-tr}\left(i,i'\right) + p_{ais-csr}\left(i,\ i'\right)\right] \tag{8}$$

4.3 Loses due to symmetric incomplete state

Losses due to symmetric incomplete state (SIS) incur between two link $l(i,j)$ and $l'(i',j')$ when both the transmitters are disconnected $\left(d\left(i,i'\right) > R_S\right)$ and both the receivers are within transmission or carrier sense range of the opposite transmitters. This geometric configuration is also known as near hidden terminal problem in existing literature. Packet loss in SIS happens when one transmitter attempts to transmit during the time when the other transmitter was already transmitting its first packet and both packets collide at the receivers. We model these types of losses independently; the packet loss probability when both the receivers are in carrier sense range of their opposite transmitters $\left(d\left(j,i'\right) > R_T\right)$, $\left(d\left(j,i'\right) < R_S\right)$, $\left(d\left(i,j'\right) > R_T\right)$, and $\left(d\left(i,j'\right) < R_S\right)$ is given as:

$$p_{sis-csr}\left(i,i'\right) = c\left(i',i\right)\ \left[1 - \left(1 -\ \tau\left(i'\right)\right)^m\right] \tag{9}$$

And when both the receivers are in transmission range of their opposite transmitter $\left(d\left(j,i'\right) < R_T\right)$ and ($d\left(i,j'\right) < R_T$), the receivers within transmission range can set their NAV and coordinate transmission attempts. This probability is given as:

$$p_{\text{sis-tr}}\left(i,i'\right) = c\left(i',i\right)\,\left[1-\,\tau\left(i'\right)\right]^{m} \quad (10)$$

We compute $c\left(i',i\right)$ in Eq. 4, $m = \lfloor d/\sigma \rfloor$, m is transmission opportunities of station i' during station i was sending its first packet and d is duration of first packet sent by station i. Depending on the packet size, these losses can be higher, but being symmetric, these affect both the flows equally and decrease in value of τ decreases chances of repeated collisions. Equation for total probability of losses due to SIS is given as:

$$p_{\text{sis}}\left(i,i'\right) = \; p_{\text{sis-csr}}\left(i,i'\right) + \; p_{\text{sis-tr}}\left(i,i'\right) \quad (11)$$

4.4 Losses due to destination connected

In destination connected scenario, link $l(i,j)$ suffers losses because of the activity of link $l'(i',j')$ when both transmitters are in carrier sense range or disconnected $\left(d\left(i,i'\right) > R_{\text{T}}\right)$; both the receivers are also in carrier sense range or disconnected from their opposite transmitters $\left(d\left(i',j\right) > R_{\text{T}}\right)$ and $\left(d\left(j',i\right) > R_{\text{T}}\right)$. But both receivers are within transmission $\left(d\left(j,j'\right) < R_{\text{T}}\right)$ or carrier sensing range $\left(R_{\text{T}} < d\left(j,j'\right) < R_{\text{S}}\right)$ of each other. With this geometric configuration, the station that attempts first will have a successful transmission and the station starts second will experience losses as its receiver will not be able to reply CTS due to the activity of opposite transmitter or receiver. For the scenario when two receivers are within carrier sense range of each other $\left(R_{\text{T}} < d\left(j,j'\right) < R_{\text{S}}\right)$, we compute this packet loss probability of station i such that i' attempts to transmit during the active period of link l which is given as:

$$p_{\text{dc-csr}}(i,i') = \; \frac{T_{\text{ON}}(i'\,)}{T_{\text{ON}}(i'\,) + \overline{T}_{\text{OFF}}(i'\,)} \quad (12)$$

The values of the variables $T_{\text{ON}}(i')$ and $\overline{T}_{\text{OFF}}(i')$ are iteratively computed while monitoring activity of link l'. In scenarios when both the receivers are within transmission range of each other $\left(d\left(j,j'\right) < R_{\text{T}}\right)$, the probability of packet loss is much higher because network allocation vector will be set during transmission of CTS by j and hence j' will not be able to reply CTS to its own transmitter, i.e., i and i' will keep on trying to initiate transmission and its backoff windows size will be increased as well. This probability is given as:

$$p_{\text{dc-tr}}\left(i,i'\right) = \; \frac{T_{\text{OFF}}\left(i'\,\right)}{T_{\text{OFF}}\left(i'\,\right) + \overline{T}_{\text{ON}}\left(i'\,\right)}\,\tau\left(j'\right)^{m} \quad (13)$$

where $m = \lfloor d/\sigma \rfloor$ and $d = \text{CTS}$. In this equation, $\tau\left(j'\right)^{m}$ makes sure that station i' is also aware of the activity of link l and is able to set NAV as being in transmission range of station j. The total probability of losses due to destination connected scenario is:

$$p_{\text{dc}}\left(i,i'\right) = \; p_{\text{dc-csr}}\left(i,i'\right) + \; p_{\text{dc-tr}}\left(i,i'\right) \quad (14)$$

5 Busy time computation

In this section, we compute the duration of time when channel is sensed busy by a station due to the activity of other stations around it in WMN. According to IEEE 802.11 MAC, there are two types of situation in busy time sensing: one is virtual carrier sense when network allocation vector (NAV) is set by stations during initial coordination (RTS/CTS) but NAV can only be set to stations within transmission ranges of both transmitter and receiver. The second type of busy time sensed due to physical carrier sense from the stations in transmission/carrier sense ranges of both transmitter and receiver. Busy time computation is simple when all stations are in single transmission range as in single-hop network and they can coordinate their transmission using RTS/CTS mechanism of CSMA carrier avoidance mechanism. But computing busy time becomes very challenging when there are stations in carrier sense range and their transmission can overlap on a sensing station.

Prior work in [1] modeled busy time average durations and rate of arrival of busy events in a four-step process including computation of maximal clique and their reduction, computation of active regions, and then finally, busy time. But their proposed model do not differentiate between busy time senses due to the activity of stations within transmission range or carrier sense range (outside transmission range) because they treated these both ranges as single sensing range. As compared to [1], the uniqueness of our work lies in meticulous differentiation between busy time sensed due to the activity of stations in transmission and carrier sense range are detailed in Algorithm 4. We also devise computationally efficient Algorithms [1–4] for modeling busy probability $b(i)$ and average busy duration $\overline{T}_b(i)$. According to Eq. 1, these two

Algorithm 1 Busy probability and average busy duration

```
1: procedure BUSYTIME(i)                 ▷ any station in WMN
   Compute activation rate and average busy duration of
   all regions
2:     ActivationRateAvgDuration(i)
   Compute busy probability and average busy duration
   of all stations
3:     BusyProbAvgDuration(i)
4:     return b(i) and T̄b(i)             ▷ for throughput
   computation
5: end procedure
```

quantities $b(i)$ and $\overline{T}_b(i)$ along with conditional packet loss probability $p(i)$ computed in Section 4 are required to predict per-flow throughput of each transmitting stations in a dense WMN.

Algorithm 1 details the outline of busy probability and average duration of a busy period sensed by station in network, and for computations of these quantities, it invokes procedures in Algorithms 2, 3 and 4. We now briefly elaborate the functionality of these Algorithms. Algorithm 2 computes activation rate and average busy duration sensed by a station due to the activity of a group of stations called regions around sensing station *i*. Initially *n* number of stations are placed in a rectangular area of width × length ($w \times l$) in pairs of a transmitter and a receiver making sure that each receiver is in transmission range of its receptive transmitter and their coordinates are saved. The next step finds all the stations within transmission and carrier sense range of station *i* and also

Algorithm 2 Activation rate and average busy duration of region

procedure ACTIVATIONRATEAVGDURATION(i)
  Place n stations in $w \times l$ rectangular area and save $Coordinates(n)$
  Find stations within transmission and carrier sense range of station i and save in a vector
  while $i \le n$ **do**
    $TxRange(i) \leftarrow$ All stations in i's Tx range
    $CSRange(i) \leftarrow$ All stations in i's CS range
  end while
  Find regions around station i
  OverlappingRegions(i)
  Initially assume Poisson distribution for activation rate
  $\lambda(i)$ for each station i
  Compute sum of activation rate $\lambda(U_u)$ for all regions
  for $\forall u \in U$ **do** ▷ for all regions in U
    for $\forall i \in U_u$ **do** ▷ for all stations in U_u region
      $\lambda(U_u) \leftarrow \lambda(U_u) + \lambda(i)$
    end for
  end for
  Initially assume Exponential distribution for average duration $\overline{T}_{ON}(i)$ of activity of each station i
  Compute average activity duration $\overline{T}_{ON}$ in all regions
  for $\forall u \in U$ **do** ▷ for all regions in U
    for $\forall i \in U_u$ **do** ▷ for all stations in U_u region
      $X_{U_u} \leftarrow \lambda(i)\overline{T}_{ON}(i)$
    end for
    $\overline{T}_{ON}(U_u) \leftarrow \frac{X_{U_u}}{\lambda(U_u)}$
  end for
  return $\overline{\mathbf{T}}_{\mathbf{ON}}(\mathbf{U_u})$
end procedure

Algorithm 3 Busy probability and average duration of station

procedure BUSYPROBAVGDURATION(i)
  Each region is now considered as a virtual node
  Compute deactivation rate μ_u of all virtual nodes
  for $\forall u \in U$ **do** ▷ for all virtual nodes in U
    $\mu_u \leftarrow \frac{1}{\overline{T}_{ON}(U_u)}$
  end for
  Find independent sets **D** of virtual nodes using conflict graph
  Assign random probabilities $\mathbf{Q_d}$ to independent sets and calculate $\mathbf{Q_D}$ including $\mathbf{Q}_\phi$
  for $\forall d \in D$ **do** ▷ for all independent sets in D
    for $\forall u \in d$ **do** ▷ for all virtual nodes in an independent set d
      $Q_d \leftarrow \frac{g_u}{u_u}$
    end for
    $Q_D \leftarrow Q_D \times Q_d$
  end for
  $Q_D \leftarrow Q_D \times Q_\phi$ ▷ itterative computation of g_u keeping $Q_D \le 1$
  Compute average duration of idle period of station i
  for $\forall u \in U$ **do** ▷ for all virtual nodes in U
    $G_U \leftarrow G_U + g_u$
  end for
  while $i \le n$ **do** ▷ for all stations
    $\lambda_{idle}(i) \leftarrow G_U$
  end while
  while $i \le n$ **do** ▷ for all stations
    $\overline{T}_{idle}(i) \leftarrow \frac{1}{\lambda_{idle}(i)}$
  end while
  Compute average duration of a busy period of i
  while $i \le n$ **do** ▷ for all stations
    $\overline{T}_b(i) \leftarrow \frac{\overline{T}_{idle}(i)[1-Q_\phi]}{Q_\phi}$
  end while
  Compute average number of events $n_e(i)$ sensed by a station i during a busy period
  for $\forall u \in U$ **do** ▷ for all virtual nodes in U
    $\lambda_U \leftarrow \lambda_U + \lambda_u$
  end for
  while $i \le n$ **do** ▷ for all stations
    $n_e(i) \leftarrow \frac{\lambda(U)}{\overline{T}_{idle}(i)+\overline{T}_b(i)}$
  end while
  Compute busy probability $b(i)$ that busy period starts after an idle slot
  while $i \le n$ **do** ▷ for all stations
    $b(i) \leftarrow \frac{\lambda(U)\Delta(i)}{[1-\tau(i)]n_e(i)}$
  end while
  return $\mathbf{b}(\mathbf{i})$ and $\overline{\mathbf{T}}_{\mathbf{b}}(\mathbf{i})$
end procedure

Algorithm 4 Find overlapping regions around station i

procedure OVERLAPPINGREGIONS(i)
Find overlapping regions around station i
  while $i \leq n$ **do** ▷ $\forall i \in n$
    Find stations within carrier sense range of i
    while $j \leq n$ **do** ▷ $\forall j \in n$
      Compare coordinates of i and j
      $CSRange(i) \leftarrow Coordinates(j)$ ▷ If j is in CSR of i
    end while
    Draw three circles ($radius = CSR$) around station i with following points as their centers so that these circles cover all stations within CSR of station i Fig. 2(a, b)
    $Location(x, y) \leftarrow Coordinates(i)$
    $Dist \leftarrow \lceil CSR/2 \rceil$
    $Center1 \leftarrow Location(x + 0, y + Dist)$
    $Center2 \leftarrow Location(x + Dist, y - Dist)$
    $Center3 \leftarrow Location(x - Dist, y - Dist)$
    Save stations in each overlapping region of three circles in U_u
  end while
  return U_u ▷ to Algorithm 3
end procedure

saves the type of station whether it is a transmitter or a receiver.

Next, Algorithm 2 sequentially invokes procedure *OverlappingRegions*(i) to compute overlapping active regions around station i whom transmission activity is sensed by station i. We discuss computation of overlapping regions in more details while describing Algorithm 4. Initially, we assume Poisson distribution for busy period activation rate $\lambda\,(i)$ and exponential distribution for average durations $\overline{T}_{\mathrm{ON}}$ of busy activity, but later, both these quantities are iteratively recomputed until they are converged. Algorithm 2 then computes the activation rate $\lambda\,(U_u)$ of each region by summing activation rates of individual stations $\lambda\,(i)$ in that region, and finally computes average activity duration $\overline{T}_{\mathrm{ON}}$ of all regions. Algorithm 2 returns the value of average activity duration $\overline{T}_{\mathrm{ON}}$ back to main procedure for further throughput computation of each transmitting station i.

Algorithm 3 computes the two required quantities $b(i)$ and $\overline{T}_b(i)$ for throughput computation. It first computes the deactivation rate μ_u for all the virtual nodes (previously referred to as active regions) and also computes independent sets D of these virtual nodes using conflict graph. An independent set consists of virtual nodes in which transmitting stations can make simultaneous successful transmissions, and Q_d is the probability of each independent set d. Activation rate g_u is computed iteratively keeping the total probability Q_D of the system below one ($Q_D \leq 1$); Q_D also includes the probability Q_ϕ when none of the virtual node (i.e., region) is currently active and transmitting. The average duration of idle period $\overline{T}_{idle}(i)$ for each station i is computed based on their activation rate g_u, and then $\overline{T}_{\mathrm{idle}}(i)$ is used to compute the first required quantity that is average duration of busy period $\overline{T}_b(i)$ sensed by each station i. In the later part of Algorithm 3, $n_e(i)$ is computed that are the average number of events sensed by a station i during a busy period, and then finally, $n_e(i)$ is used to compute second required quantity, i.e., probability $b(i)$ that station i senses a busy period right after an idle slot.

Algorithm 4 finds overlapping regions around i to compute activation of each station λ_i as well as for each region λ_u. Figure 2 elaborates region formation in which three circles with radius as carrier sense range are drawn around station i to cover all stations around it and regions are only made within carrier sense range of station i because as per 802.11 CSMA/CA protocol, the stations within transmission range set their network allocation vector to schedule transmissions with coordination using RTS/CTS mechanism. Algorithm 4 returns set of stations, i.e., U_u in each identified region $u \in U$ and Algorithm 3 use these regions for computation of activation rates ($\lambda(i)$ and λU_u).

6 Simulation and model validation

For the validation of busy time, packet loss probability, and throughput modeling, we implemented and compared both analytical as well as simulation results. We first developed both the models (proposed and model in [1]) in Matlab, compared their analytical results, and then simulate the same scenario in Opnet Modeler and made comparison between analytical and simulated throughput. We consider topology in Figs. 3 and 4, in which there are 25 transmitting and receiving pair of stations (total 50 stations) in 200 × 200 unit area. Figure 3 shows the flows in the network with an arrow pointing toward the receiver of each flow, and Fig. 4 expresses connectivity graph in carrier sense range of each station. Each transmitter randomly transmits to its receivers which is within the transmitter's transmission range. With simulation results, we came to know that effective carrier sense range is almost 2.5 to 2.7 times the transmission range and the same is evident in the existing literatures [1, 2, 36].

Table 1 lists the values of analytical parameters taken. We simulate the topology in Opnet's free version with limitation of 80 stations and 5 millions events with standard protocol settings of IEEE 802.11 CSMA/CA-based MAC with data rate of 11 Mbps with a packet size of 1000

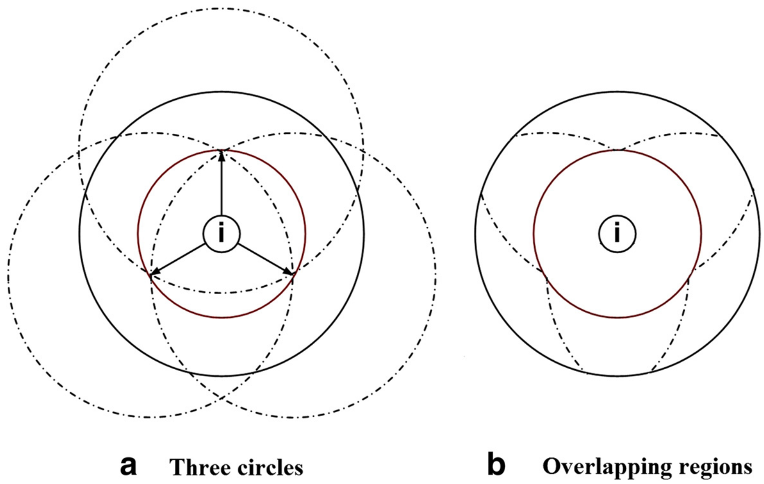

Fig. 2 Overlapping regions of three circles

bytes. As our modeling is specifically on MAC behavior, so using any type of 802.11 radio works the same as long as we are using CSMA/CA-based coordination function. We first make comparison of analytical results of model with those of Michele Garetto's [1] and then compare our analytical results with our own simulation results to validate the model. We discuss each compared parameter individually and exact semantics of the comparison.

6.1 Fraction of busy time sensed

The fraction of busy time sensed by each transmitting node is compared in Fig. 5, for both proposed and reference [1] throughput prediction models. Fraction of busy time sensed depends on geometric location of the interfering flows around the transmitting one. Unlike the reference model, our throughput model can clearly differentiate between interference from transmission and carrier sense range using the following:

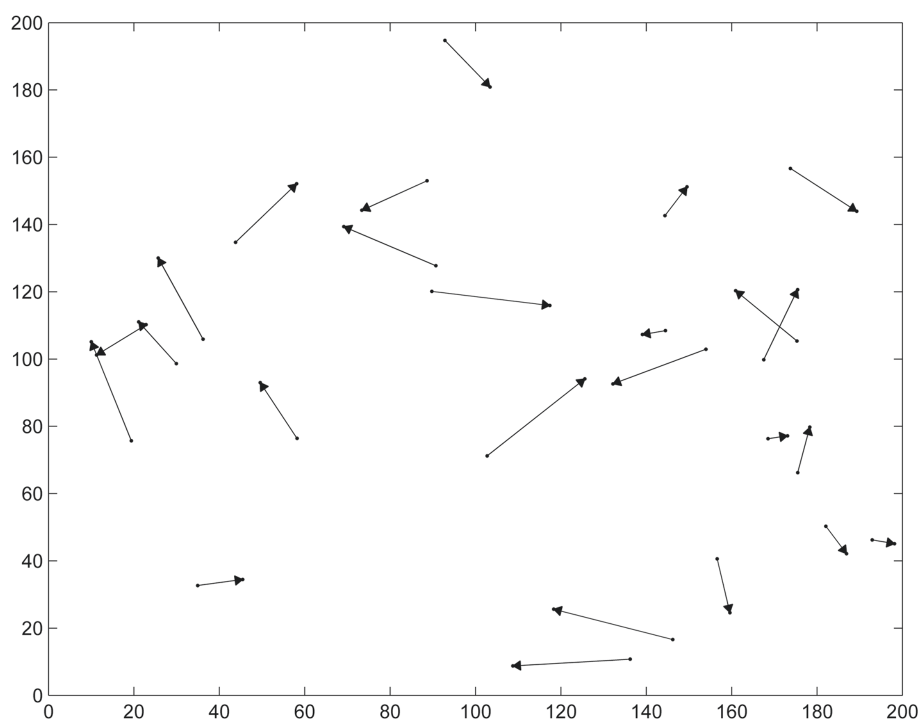

Fig. 3 Flow topology

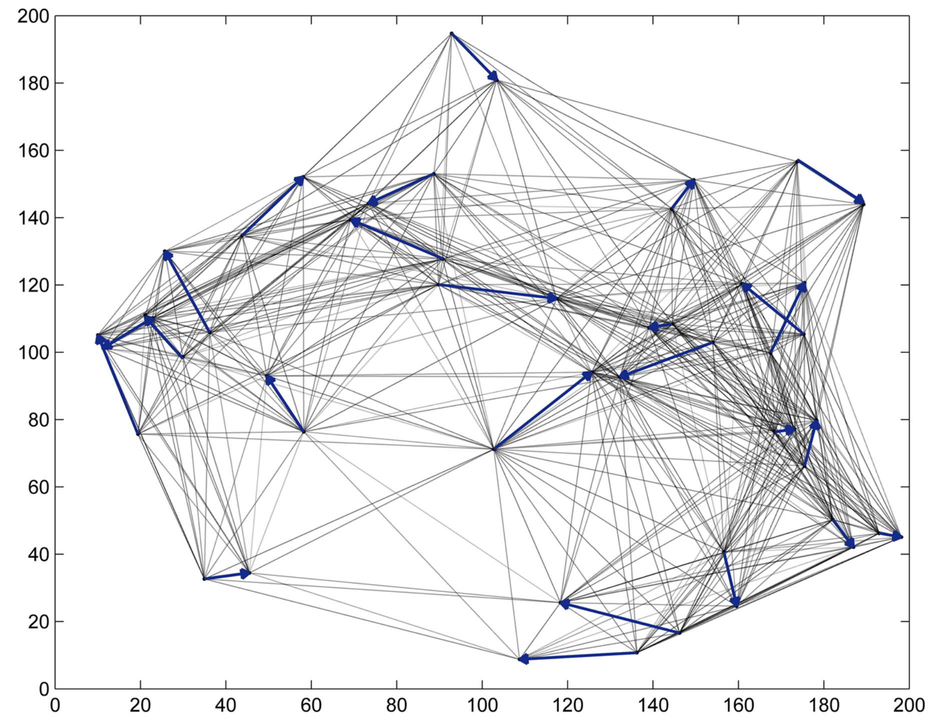

Fig. 4 Connectivity graph

i Do not consider stations within transmission range of station i for modeling its throughput assuming that RTS/CTS mechanism worked to set the network allocation vectors of stations within transmission range.

ii Record the number of other transmitting stations within carrier sense range of station i that are interfering with stations i's transmission.

iii Overlapping region formation in Algorithm 4 during busy time computation only considers stations within carrier sense range of station i as interference from carrier sense range is the worst as hidden and exposed station stations are in carrier sense range of station i.

iv Packet loss probability computation also differentiates between stations interfering from transmission range and carrier sense range and models them separately for accurate computation of packet loss probability.

Figure 5 shows that the fraction of busy time sensed by each transmitting station is higher in proposed model as compared to the reference model [1]. As busy time sense by a stations largely depends on number and location of interfering links around that transmitting station i, these values vary much from each other predicting the realistic

Table 1 Analytical parameters

Parameter	Value (ms)
Channel occupied by successful transmission T_s	9.6
Channel occupied by a collision T_c	0.417
Duration of first packet d	0.288
Duration of CTS d_{cts}	0.24
Idle channel σ_c	0.02
Maximum retry limit m	6
Backoff stage at which window size is max m'	5
Minimum window size W_0	16

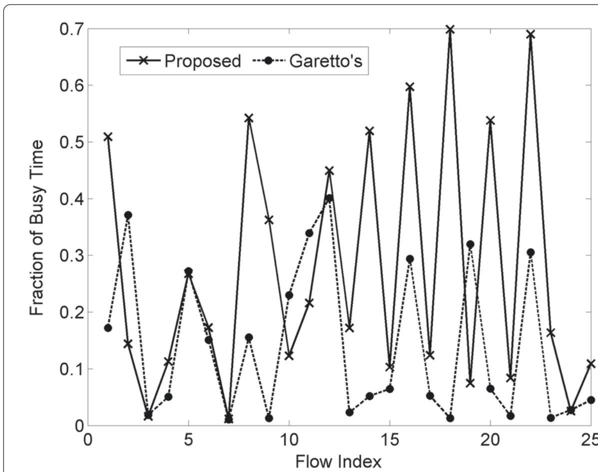

Fig. 5 Analytical comparison of fraction of busy time

nature of general wireless network. The fraction of busy time sensed is high in proposed model due to that fact that now it is able to sense transmissions of links that are outside carrier sense range while the reference model in [1] is only able to sense busy time from within transmission range.

6.2 Conditional packet loss probability

Conditional packet loss probabilities of both the proposed and reference modeled in [1] is compared in Fig. 6. We can observe that conditional packet loss probability for the proposed model is slightly higher for most of the flows. This is due to the fact that proposed model can clearly differentiate between links interfering from transmission and carrier sensing range. Now, the transmitting stations are severely interfered by the stations outside transmission but within carrier sense range. This situation leads to increased number of transmission opportunity losses and more information asymmetric interfering flows which ultimately increase the packet loss probability.

6.3 Contribution of packet loss probability due to information asymmetry

Losses due to information asymmetry are the main contributing in overall packet loss probability of each flow in the network; this also is evident in Fig. 7. This also is a model validation because unlike the rest of the literature, our model separately calculates packet loss probability due to information asymmetry in transmission range from that in carrier sense range. Model proposed in [1] is not able to capture realistic higher packet loss probability due to their limiting assumption of same transmission and career sense range. It also indicated how important it is to accurately capture the effect of information asymmetry on the overall capacity of the network, and calculation of such losses can be greatly helpful in designing efficient future wireless network protocols.

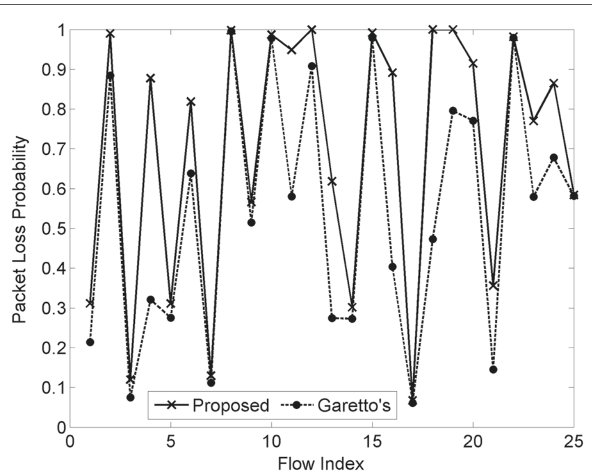

Fig. 6 Analytical comparison of conditional packet loss probability

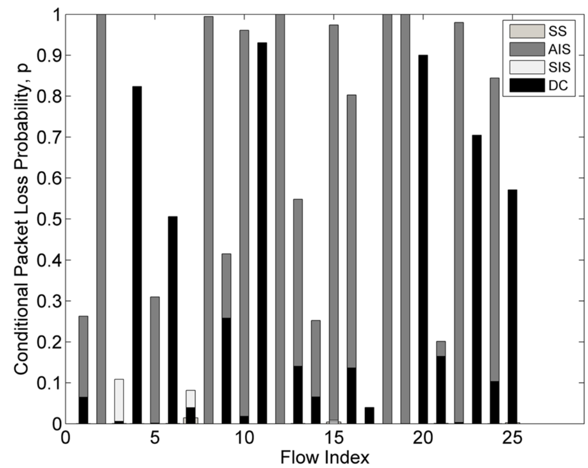

Fig. 7 Contribution of packet loss probability due to information asymmetry

6.4 Transmission probability comparison

As mentioned earlier, the proposed per-flow throughput prediction model accurately caters the effect of links interfering from outside transmission range. It can be seen in Fig. 10 that transmission probability of the proposed model is less than that of [1]; it actually indicates increased interference from contending flows and alternately decreased throughput. The proposed model can clearly differentiate between interfering links from transmission and carrier sense range, and we now have established the fact that links interfering from carrier sense range severely affect the throughput of a flow in general multi-hop wireless network.

6.5 Analytical throughput

Analytical throughput comparison between two models is shown in Fig. 8. It is also prominent here that per-flow throughput achieved in proposed model is slightly lower than the one in [1]. It is very convincing that throughput decreases with an increase in both fraction of busy time sensed and packet loss probability. The increased busy time sensed and packet loss probability will ultimately decrease the throughput. And the reason behind this is, firstly, the stations inside transmission range now can set their NAV and freeze their counter of binary exponential backoff; this reduces the throughput as station now are able to coordinate transmission attempts within transmission range. Secondly, now talking about stations outside transmission range but inside carrier sense range, these stations now interfere more severely because the number of information asymmetric links is increased now which

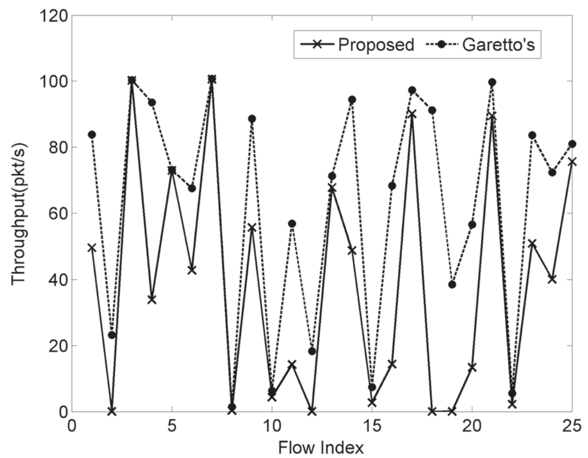

Fig. 8 Analytical comparison of throughput

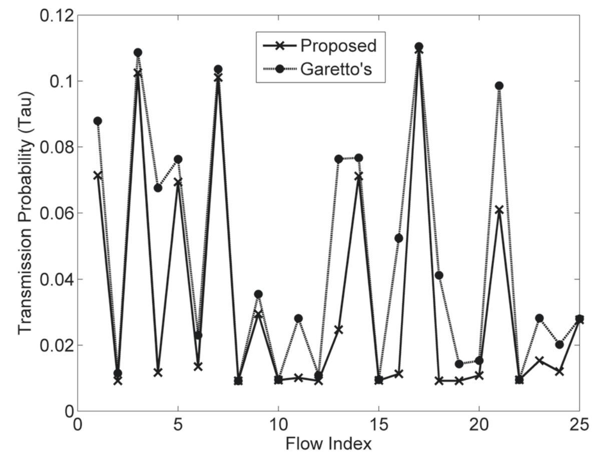

Fig. 10 Comparison between analytical transmission probabilities

ultimately decreases throughput achieved by the flows. Figure 11 compares the normalized analytical throughput between proposed and model in [1]. We can see that the same throughput distribution trend among the flows in the network but the throughput predicted by the proposed model is less than that by the model in [1], and again, this is due to the fact that now, we have increased values for packet loss probability and busy time sensed by each node.

6.6 Simulation throughput

Throughput of analytical model with the simulation results is compared in Fig. 9. We can see high accuracy and throughput matching with the flows with very high and very low throughput, but there is some marginal gap for the flow with intermediate throughput. Regarding the flow with high throughput, they are mostly on the edge of the network and enjoy less interference which allows them to achieve higher throughput, whereas the flows with very low and almost zero throughput are mostly interfered by multiple asymmetric flows hence are unable to achieve any throughput and are starved, whereas the flows with intermediate throughput are mostly among the lightly populated network region and have symmetric interfering flows around them that is why these flows keep on competing most of the time and achieve intermediate throughput due to the fair share nature of symmetric interference. The gap between intermediate flows also shows the fact that proposed analytical model predicts per-flow throughput with higher accurately as compared to the simulation scenario (Figs. 10 and 11). There surely is need to more comprehensive location aware MAC protocols. Most of the current protocols are based on typical CSMA/CA-based MAC whereas general multi-hop wireless networks require efficient location aware MAC protocols for improved performance and achieve higher aggregate network capacity.

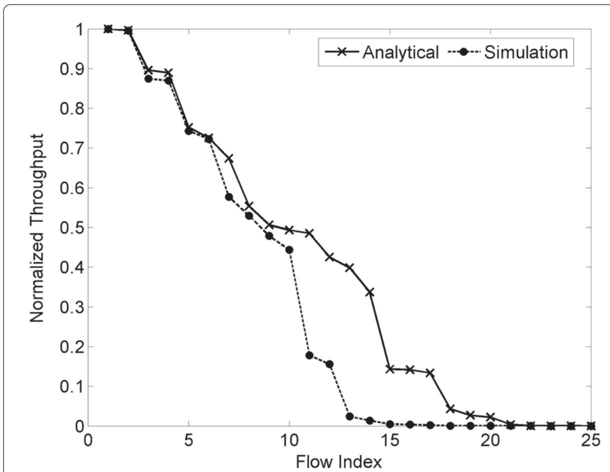

Fig. 9 Comparison between simulation and analytical throughput

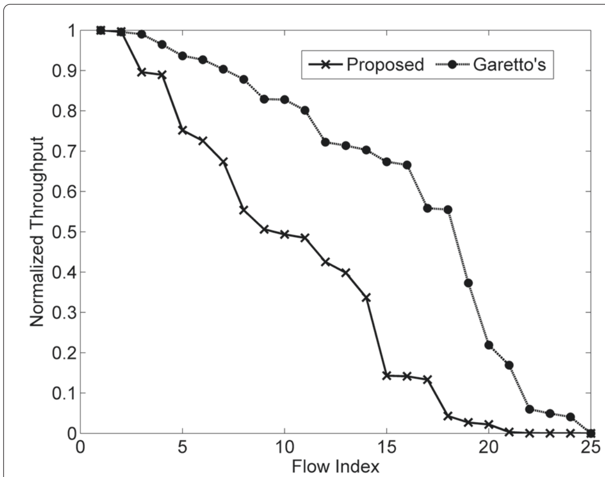

Fig. 11 Comparison between analytical normalized throughput

7 Conclusions

Existing literature for predicting per-flow throughput and starvation in general multi-hop WMS is not able to differentiate between links interfering from transmission and carrier sense range and is independent of geometric location of contending stations. Conditional packet loss probability is very complex and critical parameter as far as throughput prediction is concerned. Packet loss probability and MAC behavior is closely dependent on geometric configuration among the stations in arbitrary network.

We model fraction of busy time and conditional packet loss probability for realistic general wireless mesh scenario based on an accurate geometric configuration of stations. We compute per-flow throughput of all the stations in general multi-hop wireless network. Analytical results validated our model and also supported the argument that our model can clearly differentiate between interfering links from transmission and carrier sense range. The proposed model is more accurate in per-flow throughput prediction in comparison with existing literature. This work provides better understanding of CSMA based MAC protocols in arbitrary networks and aids toward designing more effective future networking protocols.

Competing interests
The authors declare that they have no competing interests.

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