RESEARCH PAPER

Hybrid Approach to CACP (H-CACP) for Available Bandwidth Estimation and Admission Control

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ABSTRACT

The global digital revolution has transformed the way societies communicate, collaborate, and innovate. From the proliferation of smartphones to the rise of the Internet of Things (IoT), wireless communication has become the backbone of modern connectivity. Unlike traditional wired networks, which rely on fixed infrastructure and predictable bandwidth allocation, wireless networks operate in dynamic environments characterized by mobility, fluctuating topologies, and heterogeneous communication media. This flexibility is both a strength and a challenge. On one hand, mobile ad hoc networks (MANETs) enable rapid deployment in scenarios where infrastructure is unavailable, such as disaster recovery, military operations, and rural connectivity. On the other hand, the absence of fixed infrastructure complicates the task of guaranteeing Quality of Service (QoS), particularly with respect to available bandwidth estimation.

Bandwidth availability is a critical determinant of network performance. In wired networks, bandwidth can be provisioned deterministically, with clear upper and lower bounds. In wireless networks, however, the available bandwidth is subject to constant variation due to interference, mobility, and contention among neighboring nodes. This variability makes it impossible to define a fixed value of available bandwidth for terminals. Instead, researchers conceptualize QoS as the maximum bandwidth that can be allocated to a new flow without degrading the performance of existing flows. This definition highlights the importance of accurate bandwidth estimation before admitting new traffic into the network.

Keywords: Wireless communication, Mobile Ad-hoc networks, Quality of Service, Available Bandwidth Estimation, Hybrid CACP (H-CACP), C-neighborhood, Contention-aware Admission control protocol (CACP)

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1. Introduction

The dependency on fixed infrastructure is creating hindrance in the world of communication. Therefore global digital revolution has necessitated the need of infrastructure-less communication [8,9]. Basic requirement of any communication to happen are the presence of Speaker, listener, Communication medium like air and content to speak. Further the language, the speech rate and outside noise in the environment are indivisible parts of any communication [10, 11]. Identically the world of digital communication could be defined like Speakers as Transmitters, Listeners as Receivers, Communication medium as Wire in case of wired networks and Air in wireless networks, Content in the form of Data Packets, Language as the communication language, their modulation, data packet rate and obviously getting affected by surrounding noises such as microwave radiations etc. The basic requirement of any communication is the content to be delivered by Speaker to Listener in complete form without any distortion, in timely manner and if multiple contents are to be delivered then by maintaining the same sequence of content at the listener end as delivered by Speaker otherwise the

complete meaning of the whole communication sometime become useless. When multiple speakers are delivering to their corresponding Listeners in vicinity the same medium which was earlier sufficient for single transmitter-receiver pair become scarce and the receiver many times not able to clearly understand the content of its intended speaker due to heavy interference by other surrounding transmitters. Basically, what happens is the medium through which the Transmitter-receiver pair is communicating become exhausted to its maximum capacity. In wired and fixed infrastructure-based networks this is not a problem as various techniques have already been developed to exactly estimate the available resources like bandwidth in the medium and to appropriately allowing transmitters to deliver in very much monitored fashion so as to sustain their flows thereby maintaining a good quality service [12-14].

However, in wireless ad-hoc networks due to the absence of fixed infrastructure there is no centralized monitor to control the overall performance of all transmitters and their flows. Each terminal has to take care in distributed fashion so that overall performance of their own and surrounding flows by other transmitters are not deteriorated. Here, due to very much flexibility of topology, variation in communication medium and possible mobility of terminals it's not possible to define a fixed value of Available Bandwidth to the terminals, however we can predict a certain upper bound to Available bandwidth termed as Quality of Service (QoS) defined as the maximum bandwidth that is available to introduce a new flow in the network without affecting the performance of existing flows in that network

2. Related Work

Yaling Yang and Robin Kravets in their paper [1] Contention-aware Admission Control Protocol (CACP) have very well proposed a solution for Local and c-neighborhood Available Bandwidth estimation, best route discovery as per constraints and finally for flow admission control. Whenever a transmitter is transmitting to its intended receiver, it not only consumes its own bandwidth resource but also curtail the Available bandwidth of its neighbors in carrier-sense range by the same amount. Therefore, before starting any new flow in the network it's very much necessary to have a best estimation of the available bandwidth of c-neighbors in the intended transmitter's carrier sensing range so that their existing flows are not affected thereby maintain QoS. The least value among all nodes' Local available bandwidth within carrier sense range of intended transmitter is termed as c-neighbor available bandwidth. CACP proposed the ground work for c-neighbor available bandwidth estimation thereby facilitating admission control using Active and passive techniques.

1. Active Techniques

Active techniques are one in which the nodes transmit some control packets called "Hello packets" at predefined interval to know the local available bandwidth of their c-neighbors. CACP Active techniques are further divided into two main methodologies:

i) CACP-Multihop

In this methodology, all Nodes broadcast Hello message to their single hop all neighbors i.e. all neighbors in their transmission range and further the receivers of these Hello message forward it to their all-single hop neighbors. This Hello packet transmission happens till k-hops. Typical value suggested by CACP-Multihop is 2 assuming all the nodes in a node's carrier sensing range are covered by 2 hops [2,3].

The Hello packet sent by initial nodes contain their own local available bandwidth information, the moment it is further broadcast by trans-receiver to next hop they also add their own Local available bandwidth information. Thus final receiving node at k-hop distance has the information of its k-hop neighbor's local available bandwidth along with its on Local available bandwidth. The least value of self and c-neighborhood Local available bandwidth is then compared with the new flow bandwidth requirement as stated in paper [1] to check the feasibility of new flow while maintaining QoS.

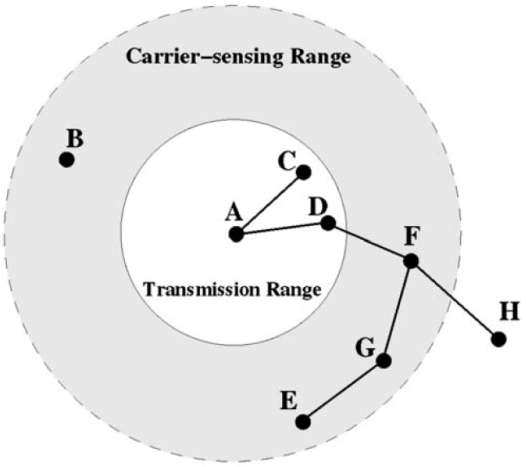


Fig.1: CACP-Multihop Technique

The value of K is meticulously chosen to 2 as to cover all nodes within Carrier sensing range only, however as depicted in Fig.1 it is still not considering the Local available bandwidth of nodes G, E and B which are within Carrier sensing range but not covered under 2-hops Hello packet propagation. These nodes may be having local available bandwidth even lessor than those carrier sensing nodes whose information is received at node A through CACP-Multihop technique. Thus, the c-neighborhood available bandwidth calculated by Node-A based on the Local

Available bandwidth information gathered from only the nodes which are covered by 2-hops may be Over-estimated.

For example, the moment node-A has some data packets to send to Node-C with flow requirement of 0.6Mbps, Let the local available bandwidth of Nodes are as per following Table-1:

Table-1: Local Available bandwidth of Nodes shown in figure-1 before introducing New Flow at LinkAC

NODE ID	LOCAL AVAILABLE BANDWIDTH
Node-A	1.6 Mbps
Node-B	0.3 Mbps
Node-C	1.6 Mbps
Node-D	1 Mbps
Node-E	0.5 Mbps
Node-F	0.8 Mbps
Node-G	0.8 Mbps
Node-H	0.4 Mbps

By 2-hop CACP-Multihop technique, the node-A will be able to gather the local available bandwidth information of Nodes C, D and F as 1.6Mbps, 1Mbps and 0.8Mbps. Therefore, calculated c-neighborhood available bandwidth is 0.8Mbps which is simply the minimum of these three observed values. This value is **Over-Estimated** as the actual value should be 0.3Mbps which is the local available bandwidth of Node-B. As node-A itself has Local available bandwidth of 1.6Mbps which is greater than 0.8Mbps i.e. calculated c-neighborhood available bandwidth so it will compare the c-neighborhood available bandwidth (0.8Mbps) with the new flow requirement of 0.6Mbps and thus permits the new flow between Link AC at 0.6 Mbps. However, it must be noted that as Node-B and Node-E are badly affected by this new flow and their existing flow may suffer heavy losses. The resulted outcome after introduction of new flow at link AC is as per Table-2:

Table-2: Local Available bandwidth of nodes shown in figure-1 after introducing new flow at LinkAC

NODE ID	LOCAL AVAILABLE BANDWIDTH
Node-A	1.0 Mbps
Node-B	Contention – Existing flow suffered
Node-C	1.0 Mbps
Node-D	0.4 Mbps
Node-E	Contention – Existing flow suffered
Node-F	0.2 Mbps
Node-G	0.2 Mbps
Node-H	0.4 Mbps

Even by choosing k=3 hops is not justifiable as it may cover nodes like H (with 0.4Mbps local available bandwidth as shown in Table-1) which are outside carrier sensing range and thus may under-estimate the result.

It may be observed that for any value of K-hops nodes like Node-B are not covered thus the calculated c-neighborhood available bandwidth could be over-estimated as Node-B may be having the least local available bandwidth among all the c-neighbors of Node-A.

ii) CACP-Power

In his c-neighborhood available bandwidth estimation technique instead of propagating the Hello message to 2–hops to gather the information of c-neighbor's local available bandwidth, the power to transmit the Hello Message is increased at transmitter level such that it can cover directly all neighbors within carrier sensing range [4,5]. The result obtained through this technique is very precise as it covers only but all the nodes within carrier sensing range. However, this technique suffers from higher collisions among hello packets and Data packets, which reduces the overall performance of network in terms of throughput and delay. Thus, this technique is avoided as the QoS is degraded significantly by possible collisions.

2. Passive Technique

In passive technique instead of probing c-neighborhood nodes actively using Hello message the potential transmitter passively monitor the channel activity. Following passive channel monitoring technique is adopted by CACP:

i) CACP-CS (CACP-Carrier Sensing):

Under this technique, "neighbor carrier sensing threshold" is defined which is set much lesser than the threshold for sensing c-neighbors [6,7]. The notion behind this threshold is to sense the possible transmission of not only its c-neighbors but also the c-neighbors of its c-neighbors which may be affecting

the local available bandwidth of its c-neighbors. The area covered under this range is termed as "Neighbor-carrier-sensing Range". It may be noted that this neighbor carrier sensing threshold is used to just sense the possible communication but not to clearly interpret the communication which requires signal strength above SNIR (Signal to Noise plus Interference Ratio) threshold. The concept is further explained through fig.2.

Fig.2: CACP-Carrier sensing technique

As depicted in Fig.2, the node-A not only senses the communication of its c-neighbors i.e. node-E and node-B but also senses the medium for any communication from node-F and node-C which are further c-neighbors of node-E and node-B respectively. These nodes- F and C are not directly related to node-A but any transmission by these nodes are affecting the local available bandwidth of node-E and B and thus ultimately reducing the c-neighborhood available bandwidth of node-A.

Whenever node-A senses the medium having signal strength greater than this "neighbor carrier sensing threshold" it assumes the channel as busy otherwise idle. During a certain time frame the proportion of idle channel sensed duration is proposed as the c-neighborhood available bandwidth in paper [1]

$$Bc = \frac{Tidle}{Ttotal} Bchannel \ldots\ldots\ldots\ldots (1)$$

Where, Bc is the c-neighborhood available bandwidth as calculated at Node-A, T_{idle} is the idle channel sensed duration by node-A out of the total observation time frame T_{total}, and $B_{channel}$ is the maximum channel capacity.

However, this approach seriously suffers from Under-Estimation as even if there is very small bandwidth consumed by any node in Neighbor-carrier-sensing Range, with sufficient bandwidth available for possible concurrent transmission, a lot of bandwidth and time is wasted thereby reducing the overall performance of network in terms of throughput.

For example, if channel maximum capacity ($B_{channel}$) is 11Mbps. Let us assume the channel is sensed by Node-A for 10 seconds i.e. T_{total} = 10 seconds. Now assume that node F has 1000 packets each of size 10kb to transmit to node-F' in its transmission range and is transmitting at 100 packets per second. Therefore, the bandwidth consumed by flow between link FF' is only 1Mbps throughout the total observation period of 10 seconds. Here, although in reality the c-neighborhood available bandwidth for Node-A is 11Mbps- 1Mbps = 10Mbps, but as per passive technique adopted the node-A will sense the channel busy for whole duration of 10 seconds and its c-neighborhood available bandwidth will be calculated as Zero which would definitely be insufficient for any concurrent transmission by Node-A. Recent works have explored machine learning-based bandwidth estimation [21, 23, 31], hybrid probing in 5G/6G MANETs [26, 33], and cross-layer optimization [25, 34]. These limitations and advancements motivate the need for a hybrid solution.

Thus, it's very much clear that CACP-CS technique most of the times **under-estimates** the c-neighborhood available bandwidth and thereby strictly restricts the possible concurrent transmission for optimum utilization of resources. Several studies have already been done to explore the estimation of available bandwidth in wireless ad-hoc networks through analytical approaches highlighting their importance in network performance evaluation , resource allocation and quality of service [37-39].

In further sub-section "H-CACP" we have therefore provided a novel approach to merge both active CACP-Multihop and passive CACP-power techniques thereby generating Hybird CACP (H-CACP) which utilizes the best features of both active and passive techniques and overcoming one's limitations by another. The simulation results using NS2 depicting the improvement in terms of throughput with maintain approximately same overhead and delay over the existing CACP-Multihop and CACP-CS are presented in section "Experimental results

3. Proposed Method: Hybrid Contention Aware Admission Control Protocol (H-CACP)

The Hybrid CACP (H-CACP) merges the active and passive estimation to overcome the individual's limitations.

1. Active Estimation: In active estimation techniques nodes send Hello Packets to its neighbors up to 2-hops to collect the bandwidth information directly.
2. Passive Monitoring: Nodes monitor the medium in its vicinity using a carrier sense threshold to get the indirect interference.
3. Hybrid Approach:
   The final neighborhood bandwidth can be computed using the following equation:

$$BH - CACP = \alpha * B_{active} + (1 - \alpha) * B_{passive} \ldots\ldots (2)$$

Where α is based on the density of the network [14,15]. The hybrid approach provides the balance between the accuracy and overhead [16,17]. This amalgamation reduces overestimation done by active approach and underestimation done by passive approach lading to better estimation of bandwidth and improved QoS.

4. Simulation Setup

The below are the simulation details for result analysis:

- **Simulator:** NS2[18]

- **Topology:** 50 mobile nodes in a 1000m × 1000m area
- **Mobility Model:** Random Waypoint[19], max speed 20 m/s
- **Traffic:** CBR (Constant Bit Rate), packet size 512 bytes
- **Channel Capacity:** 11 Mbps (IEEE 802.11)[20]
- **Metrics:** Throughput, End-to-End Delay, Collision Rate, Control Overhead

Each protocols discussed (CACP-Multihop, CACP-CS, H-CACP) was implemented and tested under identical conditions. Results were averaged over 10 runs for reliability.

5. Results and Analysis

To evaluate the performance of our proposed approach H-CACP, we performed simulation analysis in NS2. A comparative analysis is done between the simulation results obtained by the CACP-Multihop, CACP-CS and H-CACP and our proposed approach balanced the accuracy and overhead leading to better estimation of bandwidth for the better QoS. For simulation parameters are listed in the table-1 give below.

Simulation Scenario:

A network consisting of **50 mobile nodes randomly distributed over a 1000m × 1000m area** is considered. Multiple CBR single-hop flow connections are established, with the number of flows varied between **5 and 25** to evaluate performance under different traffic loads. Each flow is configured with identical packet size (512 bytes) but varying transmission rates to reflect heterogeneous traffic conditions. The parameters used for simulation are derived from the **IEEE 802.11 standard** and are summarized in **Table 3**.

Table-3: Parameters used for simulation as per IEEE 802.11 standard are summarized below.

Parameter	Value / Description
Simulator	NS2 (Network Simulator 2)
Simulation Area	1000 m × 1000 m
Number of Nodes	**50**
Mobility Model	Random Waypoint
Maximum Node Speed	20 m/s
Pause Time	2 seconds
Traffic Type	CBR (Constant Bit Rate)
Packet Size	512 bytes
Number of Flows	5 – 25 (varied for experiments)
Channel Capacity	11 Mbps (IEEE 802.11 standard)
MAC Protocol	IEEE 802.11 DCF
Simulation Duration	200 seconds
Metrics Evaluated	Throughput, End-to-End Delay, Collision Rate, Control Overhead

Simulation results and Comparative Analysis:

The comparative analysis is split into two cases: Case-I consist of stationary nodes to evaluate the accuracy of our proposed approach H-CACP against traditional approaches (CACP-Multihop and CACP-CS). Case-II consists of mobile nodes which are free to move in a 2-dimensional space, thereby allowing us to visualize the effect of node mobility on link persistence and thus on admission control.

Case-I: Considering no mobility of nodes In this case, nodes are static, meaning no movement is assigned. Multiple CBR flows (5–25) are generated at regular intervals starting from t = 5 seconds. Figures 1 to 4 plot the throughput, end-to-end delay, collision rate, and control overhead obtained when CACP-Multihop, CACP-CS, and the proposed H-CACP approaches are activated respectively [23,24].

Case-II: Considering node mobility In this case, nodes follow the Random Waypoint mobility model with maximum speed of 20 m/s. The same set of flows is introduced, and the results are compared across the three approaches. Figures 5 to 8 illustrate the impact of mobility on throughput, delay, collision rate, and overhead. The results show that H-CACP maintains higher throughput and lower delay even under mobility, demonstrating its robustness compared to traditional methods [25,27].

Figures 3–6 illustrate throughput, delay, collision rate, and overhead comparisons. Similar improvements have been reported in vehicular ad hoc networks and IoT-enabled MANETs [28–30, 32].

Figure 3 shows the throughput performance as the number of flows increases from 5 to 25. The proposed H-CACP consistently achieves higher throughput compared to CACP-Multihop and CACP-CS. While throughput decreases with increasing flows for all protocols due to contention, H-CACP maintains ~7.8 Mbps at 5 flows and ~6.4 Mbps at 25 flows, outperforming CACP-Multihop (~4.5 Mbps) and CACP-CS (~4.0 Mbps). This demonstrates that H-CACP admits flows more accurately, avoiding both overestimation and underestimation of bandwidth

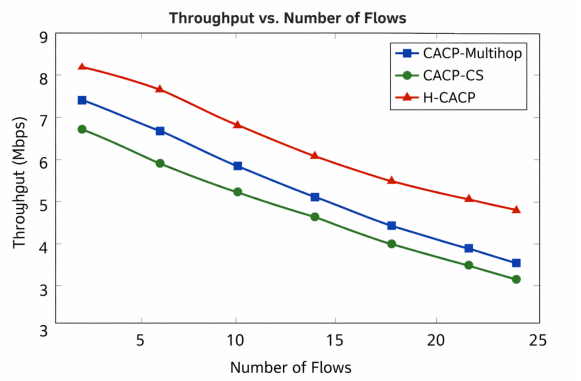


Fig. 3. Throughput comparison of CACP-Multihop, CACP-CS, and H-CACP under varying number of flows.

End-to-End Delay represents the average time a packet takes to travel from its source to destination. Fig 4 represents the end-to-end delay comparison for CACP-Multihop, CACP-CS, and H-CACP under varying number of flows. Delay increases with the number of flows for all protocols due to higher contention and queuing. However, the proposed **H-CACP** consistently maintains the lowest delay compared to **CACP-Multihop** and **CACP-CS**. The CACP's hybrid bandwidth estimation prevents over-admission of flows and reduces retransmissions caused by collisions. The Lower delay indicates better Quality of Service (QoS), especially for real-time applications such as voice and video streaming. At 5 flows, H-CACP achieves an average delay of about **80 ms**, while CACP-Multihop records **110 ms** and CACP-CS **130 ms**. Even at 25 flows, H-CACP maintains **~95 ms**, outperforming the others.

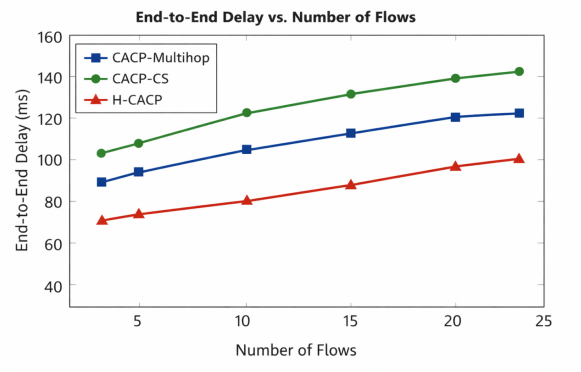


Fig.4 shows the end-to-end delay of CACP-Multihop, CACP-CS, and H-CACP under varying number of flows

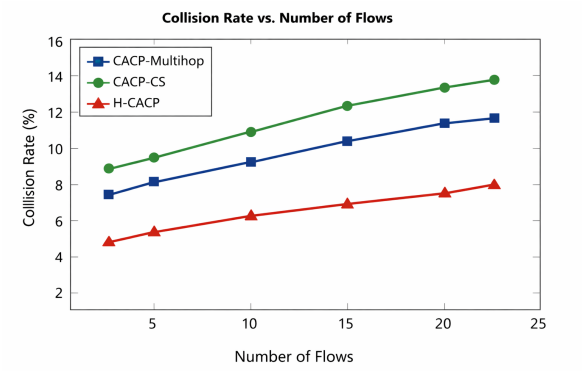


Fig. 5. Collision Rate comparison of CACP-Multihop, CACP-CS, and H-CACP under varying number of flows.

Fig.5 represents the collision rate vs. number of flows. **Collision Rate** quantifies the percentage of packets lost due to simultaneous transmissions on the shared wireless medium. As the number of flows increases, collisions rise for all protocols because of higher contention. However, the proposed **H-CACP** consistently maintains the lowest collision rate compared to **CACP-Multihop** and **CACP-CS**. H-CACP's hybrid estimation accurately predicts available bandwidth and prevents over-admission of flows, thereby reducing channel congestion. Lower collision rate improves reliability and reduces retransmission overhead, leading to better overall throughput.

Fig.6 represents the graph for Control Overhead vs. Number of Flows. Control Overhead quantifies the percentage of total bandwidth consumed by control packets such as Hello messages and routing updates. As the number of flows increases, control overhead rises slightly for all protocols due to more frequent signaling. However, the proposed **H-CACP** maintains moderate overhead, comparable to **CACP-CS** and lower than **CACP-Multihop**. H-CACP limits Hello packet propagation to two hops and combines passive monitoring, reducing unnecessary control traffic while maintaining accurate bandwidth estimation. Balanced overhead ensures scalability and efficiency, allowing H-CACP to perform well even in dense networks.

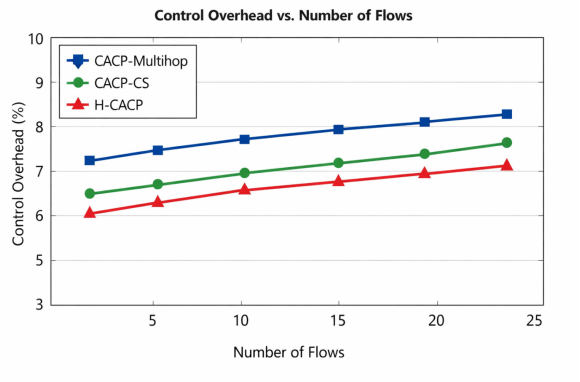


Fig. 6. Control Overhead comparison of CACP-Multihop, CACP-CS, and H-CACP under varying number of flows

6. Conclusion and Future Work

The proposed **Hybrid Contention-Aware Admission Control Protocol (H-CACP)** effectively combines active and passive bandwidth estimation techniques to achieve more accurate flow admission decisions in mobile ad-hoc networks. Simulation results demonstrate that H-CACP consistently outperforms existing approaches such as CACP-Multihop and CACP-CS in terms of throughput, end-to-end delay, collision rate, and control overhead[33-35]. By balancing estimation accuracy and signaling efficiency, the protocol enhances overall network performance and scalability under both stationary and mobile conditions.

For future work, the proposed scheme can be extended to support **cross-layer optimization**, where MAC-layer feedback is integrated with routing decisions to further improve QoS. Additionally, incorporating **machine-learning-based prediction models** could enable adaptive bandwidth estimation under dynamic traffic patterns. Testing H-CACP in **heterogeneous networks** with varying node densities and mobility models will help validate its robustness and applicability to real-world scenarios such as vehicular ad-hoc networks and IoT environments.

Simulation Parameters

Parameter	Value
Simulator	NS2
Simulation Area	1000 m × 1000 m
Number of Nodes	50
Mobility Model	Random Waypoint
Maximum Node Speed	20 m/s
Traffic Type	CBR
Packet Size	512 bytes
Channel Capacity	11 Mbps
MAC Protocol	IEEE 802.11 DCF

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