

Collision Reduction for Heterogeneous Wireless Sensor Networks

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Abstract—This paper introduces an approach of media access control for reducing collisions in a heterogeneous wireless sensor network, which contains different types of sensor nodes so a sensor fusion technique can be barely applied. Data packets sent to a designated node can cause serious collision due to a funneling effect of network traffic. At lightly loaded networks, our approach uses traditional random media access, but it dynamically divides collision domains at heavy traffic to allow contending nodes fair opportunity to acquire the media. We have conducted extensive simulation to demonstrate the effectiveness of the approach.

Index Terms—Media access control, sensor network, wireless communication, funnel effect, division of collision domain.

I. INTRODUCTION

The recent advances in wireless communications and wireless networks have led to many potential applications in different fields due to their versatile list of applications [5]. Consisting of small embedded sensors equipped with RF transceivers, sensors and micro-controllers, sensor nodes are interconnected by wireless communication channels and provide distributed sensing storage computation and communication services. The sensors collect information from their surrounding areas and report it to the remote user. Wireless sensor networks have broad applications in fields like vehicle tracking, biological detection, security devices, machine failure diagnosis, remote environment monitoring, and military monitoring [7], [13], [23]. While the sensor networks normally operate in low load conditions, the sensors are activated abruptly and need to send a large amount of data to a user simultaneously. In the case, the high volume of data may collide and result in the loss of useful data [23]. It is highly desirable to reduce the collision that can be caused in the wireless sensor networks to increase the throughput of the network and ensure timely delivery of the information. Hence the main aim in the design of wireless sensor networks is to increase the network efficiency by reducing the collision.

In a homogeneous sensor network, all the sensor nodes deployed in a region are identical in a way that they have the same capability in terms of communication, reliability, lifetime and throughput [19]. This network mainly uses low data rate and can optimize the volume of data using sensor fusion techniques. On the other hand a heterogeneous sensor network contains sensors of different types with different communication and sensing capabilities that provides more

network performance and optimizes the cost of the deployed sensor network [8], [11], [12], [18], [25]. A mixture of different sensor nodes deployed together in a region collects information from the region and constitutes a heterogeneous sensor networks. Since the data is collected from different sensor nodes, the packet aggregation or fusion that occurs at the receiver may not be perfect [1], [17]. Hence there always lies a tradeoff between the deployment of heterogeneous sensor networks and the data aggregation at the receiver [6], [15], [20].

There is substantial research to reduce the length of collision and avoid implicit problems in wireless communication such as a hidden-terminal problem and an exposed-terminal problem. Because a sensor network uses low data rate, its MAC implementation has substantial impacts on system complexity, performance, power consumption, cost, and scalability. In MACA (Multiple Access with Collision Avoidance) protocol [14] and CSMA/CA protocol [4], a sender initiates a four-way handshake by sending a small control RTS (Request To Send) packet, and a receiver responds with another control packet, CTS (Clear To Send). In MACA-BI (Multiple Access with Collision Avoidance By Invitation) protocol [21], [22], a receiver initiates a three-way handshake by sending an RTR (Ready To Receive) control packet, which reduces the overhead of an extra control packet and the delay. It is also reported that this protocol more efficiently reduces the collision of the control packets than the MACA [9], [10].

The performance of the random multiple access protocols can be improved by two strategies: carrier sense multiple access [16] and collision resolution scheme [3], [24]. A contention tree algorithm [2] explains one of the collision resolution schemes, where a large number of transmitters try to access the common slotted channel and have the capability to obtain the feedback either immediately or with a certain amount of delay. The tree in this algorithm has a nodal degree of any constant size, prevalently binary, and consecutive contention slots are grouped into a contention frame.

II. CONTENTION REDUCTION IN SENSOR NETWORKS

In this paper, we propose a new collision reduction algorithm especially for heterogeneous wireless sensor networks where data messages upon a collection request are synchronized and form a funnel effect at a sink node. Based on the

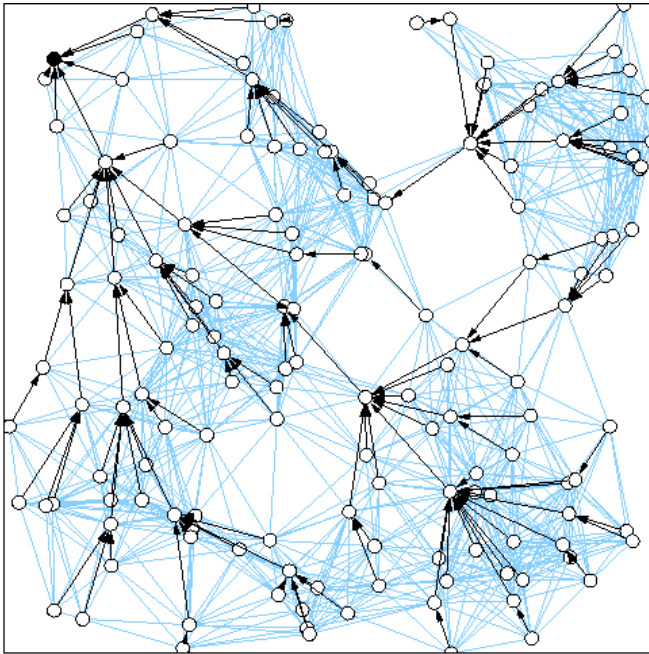


Fig. 1. Sensor network form a funnel effect, where a sink node is the black node on the left-upper corner and sensing nodes are white. Gray lines indicate neighborhood between two nodes upon their transmission power, and routing decision is indicated by black arrows based on a minimal number of hops and distances. (Illustrated by aml2fig)

contention tree, this approach dynamically divides the collision domain so as to improve the efficiency of the heterogeneous sensor networks by reducing the collision among the nodes.

Fig. 1 shows a typical sensor network topology with an optimal sink tree indicated by arrows. Although distributed routing algorithms in ad hoc networks may not match to the optimal sink tree, they calculate sub-optimal routing decisions similar to the figure. The sink node in the network periodically broadcasts a request to all nodes to collect the sensed data, and each sensing node sends the messages to the sink node almost at the same time through the sink tree. The use of low bandwidth in sensor networks causes the messages to be buffered at forwarding nodes due to the high ratio of packet collision and the amount of packets routed through the forwarding nodes. As a result, the messages funnels through the sink node as well as the forwarding nodes for each request.

In a typical multi-hop wireless sensor network architecture, the sink node operates as a gateway sensor node containing dual network interfaces: one for connecting to the sensor networks, and the other for allowing a user to access to the sensor network, mainly via Internet-based public networks. Upon receiving a collection request from the user, the gateway node broadcasts the request to all sensor nodes in the network and a number of response messages are expected to funnel through the gateway node. Many existing media access control protocols assume the randomness of data readiness among nodes and optimizes their efficiency and fairness based on the randomness. However, in massive sensor networks the expectation can be utilized to improve the network performance, in

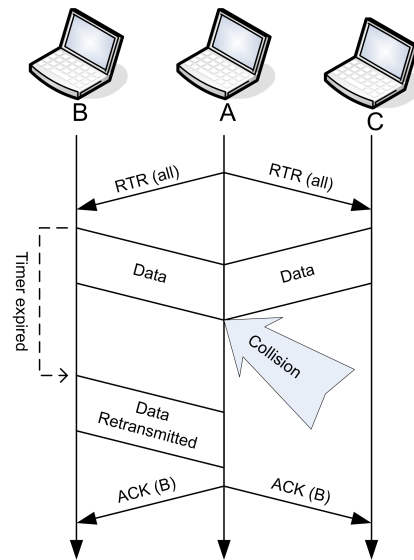


Fig. 2. 3-way handshaking. Sending nodes, *B* and *C*, detect a collision by recognizing the absence of acknowledgement and one of them, *B*, successfully retransmits its packet after a backoff delay. The other node, *C*, recognizes the successful transmission by overhearing an ACK to the other node.

that sensor nodes including the sink node anticipate a stream of messages after they forward the broadcast request message. A receiving node locally broadcasts (localcasts) a MAC control packet, says ready-to-receive (RTR), to all neighbor nodes. There could be more than one node trying to send its data to the receiving node at the same time, resulting in collision at the collision domain of the receiving node. Actually, there are a large number of packets waiting to be forwarded to the receiving node shortly after the request was broadcasted. The contention period considerably extends until the congested node funnels packets from all nodes under its partial sink tree. To shorten the contention period, this paper proposes to divide the collision domain by encoding a valid address range in an RTR frame when there is a collision. In this way, only a particular set of neighbor nodes are allowed to transmit data when their addresses match with the encoded address range. However, we propose one packet to be transmitted successfully for each collision to maintain the compatibility with existing random-based MAC protocols. This will give a chance to a small number of nodes for resolving the contention using binary exponential backoff mechanism, but reduce the collision probability without incrementing the backoff counter too much in the case of heavy load network involved with a large number of neighbor nodes.

If there is any further collision at a receiving node, it further divides the collision domain by reducing the valid address range in an RTR control frame that reduces the number of neighbor node capable of sending data. The collision domain is recursively divided as long as the encoded address field in an RTR frame allows. The size of the encoded address field may be smaller than the actual MAC address field to restrict the maximum level of domain division, in which the encoded valid address may not able to pinpoint individual

transmitting node. Note that the size of a typical MAC address is 6 octets, or 48 bits, but it could be wasteful to divide the collision domain up to 48 levels in any sink tree, or subtree. To overcome the overhead and vagueness, this method is designed to work with a typical distributed coordination using binary exponential backoff in a case of collision by allowing one successful transmission before dividing the domain. To implement the address range, an RTR control frame contains two fields: receiver's encoded address and mask. Using binary AND operations with the encoded address and mask, we can effectively determine whether a node is in a selected set of node and able to transmit its data. For example, assume that A is a MAC address of a node that receives an RTR frame containing R and M indicating the receiver's encoded address and mask, respectively. The following condition indicates the node A in the selected range:

$$(\text{encode}(A) \wedge M) = (R \wedge M), \quad (1)$$

where $\wedge$ is a bitwise *and*-operator. Likewise, the receiving node can verify the validity of an incoming frame using the condition with transmitter's address for A .

Due to a number of nodes deployed in a network there could be collision among frames at a node. If a node detects a collision among its neighbor nodes, it will wait for one successful transmission as shown in Fig. 2 and dynamically change the encoded address range and mask for a next RTR control frame to halve the number of the nodes for transmission. To be fair, the node may choose the range and mask for selecting a group of nodes that did not successfully acquire the channel for the last successful receiving. We have chosen to wait for one successful transmission so that there is no overhead in continuously dividing the collision domain. At this stage, one of the three possible situations could arise:

- 1) Neighbor nodes have no frame to transmit after dividing the collision domain. In this case the node rejoins the divided collision domains for the next RTR frame.
- 2) There is a successful transmission. In this case, move to the next collision domain that has not been handled previously.
- 3) There is further collision among the neighbor nodes in the new domain. In this case, the node waits for one successful transmission and change the range address and mask for the next RTR frame for dividing the collision domain further. This process continues until all frames from the domain are received without collision up to the maximum level of division allowed.

This approach can be viewed as a breadth-first traversal of a binary tree, representing a group of nodes allowed to transmit data as shown in Fig. 3, where the encoded address range is limited to 4-bit for simplicity. For random shuffling of collision domains, any don't-care x is selected randomly to build a subtree and a child replaces the x of its parent by either 0 or 1. The random shuffle allows a number of transmitting nodes to be divided arbitrarily regardless of their address pattern, so that the group testing tree is probabilistically well-balanced

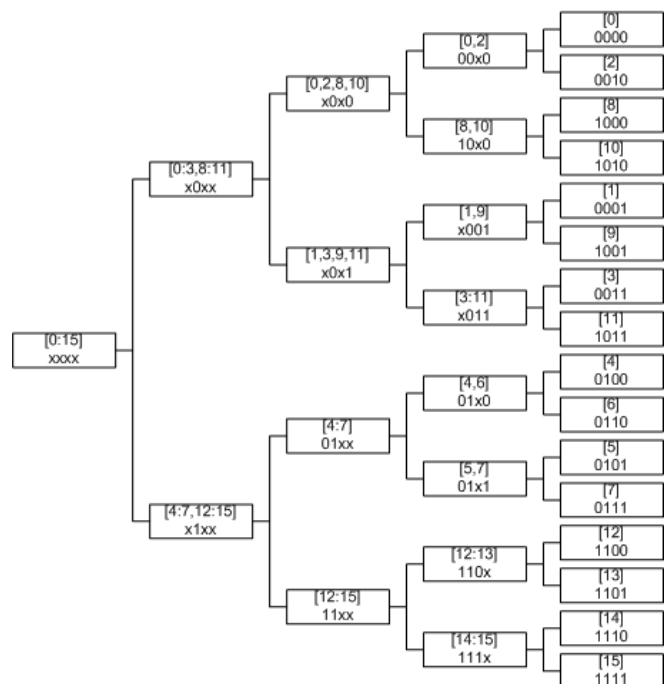


Fig. 3. An example of binary traversal tree with 4-bit encoded address and mask. The first line of each box indicates a group of nodes represented by a tree rooted at the box. The second line is the binary address where x means a don't-care.

and the depth of group testing is minimized. Note that the don't-care can be easily implemented using a pair of address and mask as described previously. The traversal algorithm can be clearly expressed using a FIFO queue for storing a pair of address and mask. The address and mask are set to zeros initially, or are retrieved from the queue. When the algorithm completes a round of group testing, the queue becomes empty so that the address and mask are to be set to zeros again.

A node periodically transmits an RTR control frame with the address and mask. If two or more neighbor nodes send their data frames upon the RTR frame, they are collided at the receiving node. The sending nodes also recognize the collision by absence of acknowledge frame, they initiate the binary exponential backoff process and one of them makes a success recognized by an acknowledge from the receiving node. The receiving node now divides the collision domain by calculating a new pair of address and mask. The node randomly selected a bit position of the mask with an OFF-value. The new mask is computed by setting the bit position of the mask and two new addresses are obtained by clearing the bit position and setting the bit position of the address alternatively. The two pairs of address and mask are pushed into the queue. This procedure at the receiving node is described in Fig. 4.

Assume that there is one node to transmit for each leaf in the binary tree of Fig. 3. The algorithm would generate the following sequence of RTR control frames and receive data as in the following table:

```

begin
  while true do
    if queue is empty then
       $a \leftarrow 0$ ;
       $m \leftarrow 0$ ;
    else
      dequeue( $a, m$ );
      Send an RTR with  $a$  and  $m$ ;
    if collision then
      Wait for a successful frame;
       $a_x \leftarrow$  the TX address of the frame;
      Randomly select an OFF-bit of  $m$ ;
       $m_2 \leftarrow$  set the selected bit of  $m$ ;
       $a_1 \leftarrow$  clear the selected bit of  $a$ ;
       $a_2 \leftarrow$  set the selected bit from  $a$ ;
      if ( $encode(a_x) \wedge m_2$ ) = ( $a_2 \wedge m_2$ ) then
        enqueue( $a_1, m_2$ );
        enqueue( $a_2, m_2$ );
      else
        enqueue( $a_2, m_2$ );
        enqueue( $a_1, m_2$ );
    end
  end
end

```

Fig. 4. Traverse the domain tree

Seq.	RTR address/mask	Collision	Node of success
1	0000/0000	Y	0011 (3)
2	0100/0100	Y	1101 (13)
3	0000/0100	Y	1001 (9)
4	0100/1100	Y	0110 (6)
5	1100/1100	Y	1100 (12)
6	0000/0101	Y	0010 (2)
7	0001/0101	Y	1011 (11)
8	0101/1101	Y	0101 (5)
9	0100/1101	N	0100 (4)
10	1110/1110	Y	1110 (14)
11	1100/1110	N	—
12	1000/1101	Y	1010 (10)
13	0000/1101	N	0000 (0)
14	0001/0111	N	0001 (1)
15	0011/0111	N	—
16	0111/1111	N	0111 (7)
17	0101/1111	N	—
18	1111/1111	N	1111 (15)
19	1110/1111	N	—
20	1000/1111	N	1000 (8)
21	1010/1111	N	—

The third column of the table indicates whether there is a collision or not with the given address range. The fourth column is an encoded address of a node that makes a success of transmission. If there is a collision, the node is selected from the binary exponential backoff process. Otherwise, the node is identified immediately after the RTR frame without applying the binary exponential backoff process. There are 5 idle RTRs which were not responded with any data frame. Some of idle RTRs can be avoided with minor revision of the traversal algorithm. For example, the address of the 11th RTR is 110x. This implicant covers nodes 1100(12) and 1101(13)

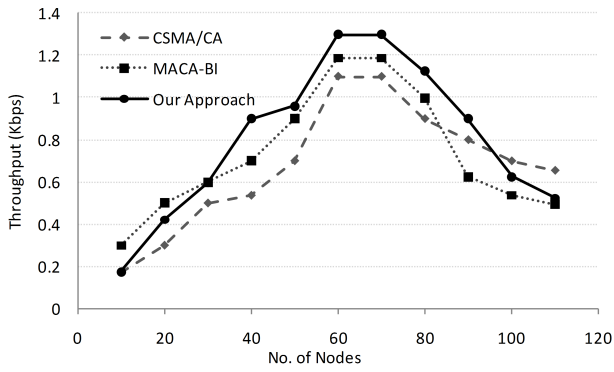
which already made success transmission from the higher level of the traversal tree at Seq 2 and 5, so this RTR is surely idle. If a node traversing the tree has a capability of recording the success of data transmission, it can avoid all idle RTR frames in the example.

III. PERFORMANCE

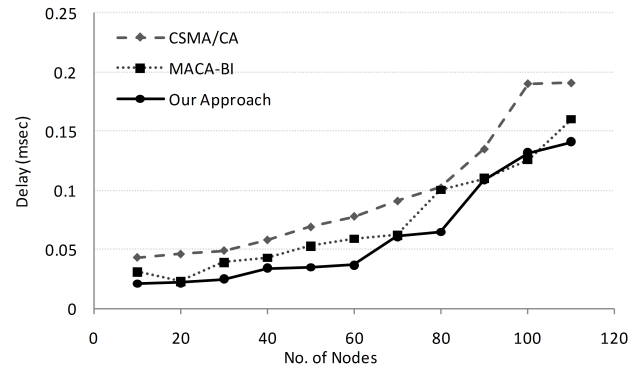
The performance of the proposed algorithm has been evaluated by extensive simulation using Ns-2 and Mannasim network simulators. Simulations were conducted for three media access control protocols: IEEE 802.11 CSMA/CA, MACA-BI and our approach. Comparing algorithms for massive sensor network, or heavy funneled network loads, we have focused our attention to the performance of the sink node that is the major area to which all nodes of the network send their data and it is supposed to carry a very high density of data traffic. The transmission range of each node is assumed as 200m in a square area whose length is 1,000m. The number of nodes is varied from 10 to 110 to generate different network loads and topology. One of the nodes is elected as a sink node that is connected to a server through wired channel. The server periodically sends a collection request to the sink node that wirelessly broadcasts the request to all nodes in the network and each node sends a reply message to the sink node that forwards them to the server in turn. Ad-hoc on-demand distance vector (AODV) routing protocol was adopted for route packets through the multihop ad-hoc network.

Fig. 5(a) shows the throughput at a sink node by incrementing the number of nodes by 10. It is observed that the throughput of our approach is similar to the one of CSMA/CA at a low network load (10 nodes) because the division of collision domain does not frequently happen at the low load. Increasing the number of nodes or increasing the network load at the sink node, the throughput of our approach is rapidly improved and matches to the one of MACA-BI (30 nodes) where the random media-access opted by CSMA/CA may not be adequate for the number of packets. Our approach starts to outperform the other methods for more than 30 nodes and reaches to the highest peak throughput among those three methods at which it improved 10% to 18% of the throughput from other methods. Note that the CSMA/CA yields lower throughput than other methods because of its overhead in the four way handshake process. Our approach gives probabilistically fair opportunity to all nodes ready to transmit the data because only a sub-set of nodes are eligible for data transmission on receiving an RTR frame at heavier network load. Thus it increases the probability of each node to access the channel without collision. As a whole, all neighbor nodes will be given fair chance to access the channel by the subsequent RTR.

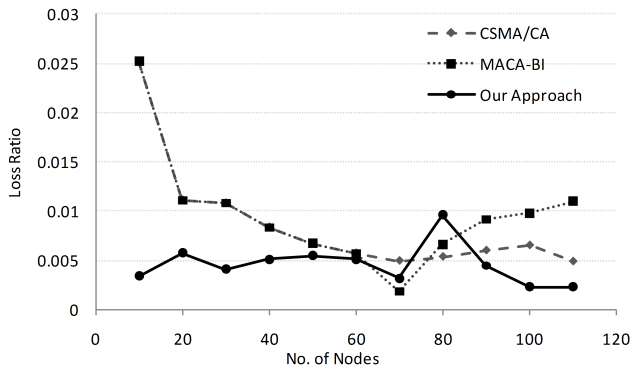
The average end-to-end delay depending on the number of nodes is shown in Fig. 5(b). The average delays increases linearly for a small number of nodes, but rises rapidly at a larger number of nodes, especially after the number of nodes at the peak throughput, i.e. more than 60 nodes. In the simulation, each node generates same amount of data traffic



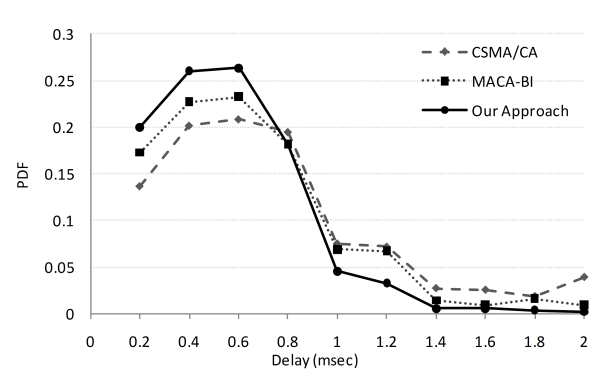
(a) Throughput at a sink node in Kbps on the number of nodes.



(b) Average packet delay in msec on the number of nodes



(c) Packet loss rate



(d) Distribution of packet at the peak throughput.

Fig. 5. Simulation results

regardless of the total number of nodes in the network so the more nodes will result in the more network load. The sharp rise of the delay at the high network load is generally consistent to the theories of queuing network and media access control [16]. It can be observed that the CSMA/CA media access control is not optimal for the data collecting sensor networks over all ranges of network loads. At lower network load, the four-way handshaking causes additional delay, and the random access of the CSMA/CA increases the collision at higher load. Our approach yields shorter delay than the other methods over all ranges of network loads. This validates the fact that our method divides the collision domain in a balanced manner and reduces the occurrence of collisions regardless of the load conditions in the network. When a node sends an RTR frame with specific address range, only eligible nodes transmit their data frame, but the other nodes are silently waiting for a next round. The chances of data collision is lowered because a reduced number of nodes try to send the data to the receiver at higher network load. Avoiding the unneeded collision has several impacts on reducing the delay. The first reason is that the sending nodes need not double their backoff counter. A node with a smaller backoff counter tries retransmission after shorter waiting time. The other reason is that the collision detection itself takes time to recognize the absence of acknowledgement.

In Fig. 5(c), the packet loss rate was compared among CSMA/CA, MACA-BI and our approach. At a smaller number of nodes, resulting low network load, MACA-BI exhibits very high packet loss. As know of the authors, there is rare research on the network performance of MACA-BI, especially the dependence of the packet loss on network loads. It is difficult to analyze the reason of the high packet loss in MACA-BI and its dependence. However, it is conjectured that the frequency of RTR control frames has significant impact on the packet loss. When the network load increases, the packet loss of our approach remains lower than the traditional CSMA/CA and MACA-BI. It is observed that our approach loses, or drops, much less packets than the other methods over all ranges of loads in general. At 80 nodes, our approach drops more packets than the other methods, which is believed as the variation of the random simulations.

The distribution of the delays are given in Figure 5(d) at the peak load. From the figure, we can observe packet delay variations (PDV) that measures the variability of the total delay encountered by packets. Our approach shows the maximum PDV as 1.4 msec, compared to 1.8 msec and 2 msec for the other methods. The modes of PDV for all methods are 0.6 msec. However, our approach yields the smallest delay variation among all methods, in that more than 72% packets are experienced less than 0.6 msec in our approach but 54%

or 63% packets of the other methods are less than 0.6 msec.

IV. CONCLUSION

This paper proposed a new media access control protocol reduce the probability of collision in data collection networks such as wireless sensor networks. When there is a difficulty in compressing collected data, there is significant congestion or funneling effect. The proposed approach can reduce the chance of contention by dynamically dividing collision domain in such a funneling phenomena. This approach has been validated by extensive network simulation and comparative study with IEEE 802.11 CSMA/CA and MACA-BI. The approach yielded superior network performance in the maximum throughput, packet delay, and packet delay variation.

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