Research Article

A Cross-Layer Cooperation Mechanism of Wireless Networks Based on Game Theory

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To meet the wireless network congestion control problem, we give a definition of congestion degree classification and propose a mechanism of directed cooperative path net, guided by the wireless network’s cross-layer design methods and node cooperation principles. Considering the virtual collision and “starved” phenomenon in congested networks, the QRD mechanism and channel competition mechanism QPCG are proposed, with introducing the game theory into the cross-layer design. Simulation results showed that directed cooperative path nets could effectively improve network resource utilization and network transmission performance in congested network. And the QRD and QPCG mechanism could effectively reduce the probability of “starved” phenomenon and increased the wireless network throughput with reducing the packet loss rate.

1. Introduction

With the development of wireless networks, cross-layer design and node cooperation have become key technologies of wireless network communication. Cross-layer design has broken the conventional layered concept to coordinate parameters between different layers with considering the influence of wireless communication transmission layers, so it could ensure the overall performance of wireless network communication [1–3]. Through node cooperation, the cooperative communication (CC) provides more network performance gain for the wireless networks [4–6]. It is valuable to combine cross-layer design with node cooperation, to improve the transmission quality of wireless networks. By introducing game theory (GT) into the cross-layer design and node cooperation, the parameters in different layers can be effectively used to formulate wireless network bidding functions. Besides, combined with the resource scheduling mechanism of node cooperation [7], the Nash equilibrium strategy of wireless networks can be constituted to obtain overall performance gain of the wireless networks [8].

Currently, the node cooperation mechanism (NCM), based on GT and cross-layer design, has achieved certain results, in terms of node energy consumption, transmission quality, and protocol optimization. Combined with CC protocol, [9] studied the key problems of relay selection schemes and analyzed the application prospect of GT and adaptive learning techniques in network resources’ allocation. Reference [10] proposed a selfish node punishment strategy, which is a NCM based on GT and effectively overcomes the nodes’ selfishness, to increase the probability of nodes’ cooperation. Based on GT, [11] presented a network nodes’ collusion strategy and took a comprehensive consideration of network layer information and data link layer information, to realize cooperative transmission and ensure the nodes’ best interests. Combined with the GT, [12] proposed a method of wireless network nodes’ independent control of data transmission channel. This method is equivalent to a distributed transmission system on the function and effectively enhances network throughput in aspect of distributed multiple antenna system diversity. In the consistent random backoff (CRB) scheme of [13], a contention window (CW) size at each backoff stage is determined by hashing the session identifier and the talk spurt index, so as to reduce the channel access delay jitter. Based on cross-layer design and energy-harvesting mechanism, [14] proposed a secure routing protocol. In this protocol, parameters are exchanged between different layers to ensure efficient use of energy. Through
comprehensive consideration of relevant data in physical layer and MAC sublayer, [15] applied cross-layer concept to realize nodes' cooperative transmission and improve nodes' power consumption. The CL-MAC protocol in [16], as a novel cross-layer MAC protocol, can effectively handle the wireless network's communication mode of multiple packets, multiple-hops, and multiple flows and reduce nodes' load pressure. Through each layer’s comprehensive information, CL-MAC protocol can reflect the current network situation and provide a dynamic scheduling mechanism to reduce the end-to-end delay and finally improve the delivery rate and reduce the average energy consumption. As for the unfairness of channel occupation in multimedia wireless networks, [17] gave a node cooperation strategy of weighted fairness. Through adding a label field in the RTS/CTS frame, the fairness problem of multimedia stream is solved effectively.

In this paper, we combined cross-layer design and node cooperation through GT and proposed a mechanism of cross-layer cooperation communication based on game concept. By this mechanism application, the resource competition and cooperation of wireless network cross-layer design achieve an overall optimal effect.

2. The Mechanisms of QRD and QPCG Based on GT

2.1. QRD Mechanism. In the 802.11e EDCA protocol, there are multiple sending queues in one node. When sending the packets of multiple queues, nodes need to transmit with considering queues’ priority, to avoid the virtual collision problem. But when the collision occurs frequently, “starved” phenomenon will occur to lower priority data flows, at the same time the wireless network is congested. The fairness of queue scheduling mechanism should also be taken into consideration. In accordance with the existing strategy of proportional fairness, [18] proposed a queue-length scheduling mechanism $S_{intra-node}$ to solve the single queue problems and frequent information exchanging problem in the proportional fairness solutions. This fairness is just in terms of the queue length, where the weight proportion selection lacks adaptability to the wireless network time-varying property.

Based on the queue length and the current transmission rate, a fair queue dispatch mechanism, Queue and Rate Dispatch (QRD), is proposed. QRD mechanism not only considers the nodes’ current length of each transmission queue, but also considers the influence of previous and successor nodes transmitted. The main idea of QRD mechanism is that, within any time period, queue backlog ratio is reflected as the queue’s load level of this specific time period. The queue backlog represents the ratio of the queue’s average sent throughput and average receipt throughput in a certain time period. When the queue backlog is greater than 1, it means that the queue’s load level is decreasing constantly; otherwise, the load level is increasing.

The queue’s backlog ratio is defined as the ratio value $R$ of the average, sent throughput $r_T(t,0,t)$ and the average receipt throughput $r_A(t,0,t)$ within time period $t_0$ to $t$, as follows, and function $R$ is regarded as the bidding function of multiple queues’ packet sending within one node:

$$ R = \frac{R_T}{R_A} = \frac{r_T(t_0,t)}{\sum_{i=1}^{N_J(t_0,t)} \omega_i} = \frac{r_A(t_0,t)}{\sum_{j=1}^{N_J(t_0,t)} \omega_j}, \quad (1) $$

where $R_T$ means the standardized average sent throughput and $R_A$ means the standardized average receipt throughput. $\omega_i$ represents the channel obtaining weight of each sent packet, and $\omega_j$ represents the channel obtaining weight of each receipt packet.

For the queue’s sent packets, $T_i(t)$ is the time to finish transmitting packet $i$. $t_{q_i}$ is the time when packet $i$ receives the ACK, $t_{q_i}$ is the time when packet $i$ reaches the queue’s head, $L_i$ is the length of packet $i$, and $B_i$ is the sending rate of packet $i$:

$$ T_i(t) = t_{ai} - t_{q_i} + \frac{L_i}{B_i}. \quad (2) $$

Within the time period $t_0$ to $t$, the average throughput of a queue’s sent packets is

$$ r_T(t_0,t) = \frac{N_i(t_0,t)}{T_i(t_0,t)} = \frac{\sum_{m=1}^{N_i(t_0,t)} T_i(t_m)}{N_i(t_0,t)} = \frac{G_i}{K_i}, \quad (3) $$

where $N_i(t_0,t)$ means the queue’s sent packet amount within time period $t_0$ to $t$ and $L_i$ means the average length of the queue’s sent packets. $T_i(t_0,t)$ is the average transmission time of each packet within time period $t_0$ to $t$.

For a queue’s reception packets, $A_j(t)$ is the consuming time that the queue takes to receive packet $j$. $T_j$ is the length of time that it takes to transmit the sending request packet from the precursor to current node and the corresponding acknowledgement packet from current node to its precursor. So, parameter $T_j$ is the time length of the round-trip between current node and its precursor. And before receiving packets, the first packet transmitting from precursor takes the time of 1/2 $T_j$; therefore, the waiting time before valid data receiving is 3/2 $T_j$. $L_j$ is the length of packet $j$, and $B_j$ means the receiving rate of packet $j$. Then the computation formula of $A_j(t)$ is shown as follows:

$$ A_j(t) = \frac{3}{2} T_j + \frac{L_j}{B_j}. \quad (4) $$

In the time period $t_0$ to $t$, the average throughput of a queue’s reception packet is

$$ r_A(t_0,t) = \frac{N_j(t_0,t)}{A_j(t_0,t)} = \frac{\sum_{m=1}^{N_j(t_0,t)} A_j(t_m)}{N_j(t_0,t)} = \frac{G_j}{K_j}, \quad (5) $$

where $N_j(t_0,t)$ means the queue’s receipt packet amount within time period $t_0$ to $t$ and $L_j$ means the average length of
the queue’s receipt packets. \( \bar{A}_j(t_0, t) \) is the average receiving time of each packet within time period \( t_0 \) to \( t \).

As in formula (1), the standardized sent throughput and receipt throughput can well reflect the relationship between packet’s channel occupation priority and the queue’s throughput, thus providing a fair packet sending mechanism. According to the analysis above and the queue backlog definition, nodes’ queue scheduling mechanism QRD is composed of the following events.

1) **Scheduling Rules.** To ensure a fair packet transmission chance for each queue in the same node, QRD mechanism only needs to minimize the differences of each queue’s R value, and R value should be as small as possible. So, the queue with a minimum R value is transmitted firstly. If multiple nodes own the same R value, QRD mechanism will choose a queue of the minimum priority to prevent the lower priority data stream from being “starved.”

2) **Updating Rules.** After packets’ transmission, R value needs to be updated. According to the computing formula of \( \bar{T}_i(t_0, t) \) and \( \bar{A}_j(t_0, t) \), we set \( G_i = G_i + T_i(t) \), \( K_i = K_i + 1 \), \( G_j = G_j + A_j(t) \), and \( K_j = K_j + 1 \) and then they are substituted into the formula.

When frequent collision occurs to the multiple queues’ packet sending inside one node, QRD mechanism will abandon the inherent strategy of sending by priority; instead, it will comprehensively consider the relationship between current node with its precursor and subsequent nodes to formulate bidding function, thus competing for the packets’ sending order. During the wireless network congestion processing, QRD mechanism is specific for the time-varying property of wireless network and owns better dynamic adaptability, which is because the value of bidding function R changes with queues’ variation status inside each node. So the QRD mechanism effectively improves the fairness of queue scheduling mechanism and avoids the “starvation” phenomenon of low-priority data stream. For this scheduling mechanism, both the time complexity and space complexity of R value are linear, thus adapting to the low computing capacity and low power consumption of wireless network nodes.

2.2. QPCG Mechanism. The channel competition mechanism QPCG (Queue Transmission Path of Channel Game) is an incompletely cooperative game communication mechanism, which is based on queue length and channel competition weights. Our ideas of incompletely cooperative game refers to the concept in [19, 20]. The reason we call it an incomplete cooperation is that the mechanism considers both the wireless network nodes’ noncooperative selfishness and the positive collaboration when without cooperation protocol. Because of the selfish nodes’ noncooperation, the incomplete cooperation game solution is also the one of noncooperative game mechanism, called Nash equilibrium concept. The incomplete cooperation game and Nash equilibrium solution in [19, 20] are mainly specific for 802.11 DCF, and its game competition condition is node number. The channel competition mechanism QPCG proposed in this paper not only considers the influence of node number on game competition, but also considers the impact of data transmission priority and the queue length. When considering selfish nodes’ priority, we standardize the influence of priority on the selfishness to highlight the cooperation property. The following is an analysis of the main idea of channel competition mechanism QPCG; an illustration of the Nash equilibrium solution property is presented as well. QPCG is divided into two stages of game’s delay time initializing and mechanism state updating.

1) **Set the Game’s Delay Time** \( T_{QPCG} \): According to the weight \( \omega_i \) and the length \( L_i \) of current packet in node \( i \), the game’s delay time \( T_{QPCG} \) is calculated as follows:

\[
T_{QPCG} = \text{Delay}_{Time} \times \alpha \times \frac{P_\omega}{P_L},
\]

\[
P_\omega = \frac{\omega_i}{\sum_{j=1}^{N} \omega_j},
\]

\[
P_L = \frac{L_i}{\sum_{k=1}^{M} L_k}.
\]

In accordance with the Nash equilibrium concept, the explanation of each parameter is described as follows.

Parameter \( \text{Delay}_{Time} \) represents waiting time of current channel competition, which is changing with the channel competition degree. Assuming that fierce competition happened among \( n \) data flows, the average transmission time of one data stream is \( T_i \). Then the delay game time of the \( n \) data streams can be, respectively, set as \( \text{Delay}_{Time} + kT_i \), where \( k = 1, 2, \ldots, n \). With the \( \text{Delay}_{Time} \) value growing, the transmission state of both high-priority data stream and low-priority data stream can be coordinated; the problem of intense channel competition can be effectively solved as well. The value of parameter \( \text{Delay}_{Time} \) does not depend on the priority weight \( \omega_i \), so it overcomes the node’s selfishness property during transmitting, and reflects the cooperation property of QPCG mechanism. Through this cooperation property, the wireless network throughput is improved.

The initialization value of parameter \( \alpha \) is set as the sent packet weight \( \omega \). In intensely competitive circumstances, parameter \( \alpha \) can be set with a random value in \([\min \omega_i, \max \omega_i]\), which means the value of parameter \( \alpha \) is uniformly distributed on the interval from \( \min \omega_i \) to \( \max \omega_i \), and it precisely reflects the fairness of QPCG mechanism. It reflects the same priority nodes’ cooperation characteristics. The uniform distribution which is on the interval from maximum weight to minimum weight can avoid the same weighted packets’ virtual collision as well.

Parameter \( P_\omega \) means the weight proportion of node \( i \) of all sent packets’ weights; Parameter \( P_L \) represents the length proportion of node \( i \) of all sent packets’ length. The nodes’ current transmission weights and transmission queue length are selected as the competition parameters of \( P_\omega \) and \( P_L \). The channel occupation expectation of node \( i \) will increase along with the priority of node \( i \) (weight \( \omega_i \)), which reflects the noncooperation and selfishness of channel competition mechanism QPCG. Whereas, either \( P_\omega \) or \( P_L \) is a ratio function, and the latency time is reflected by the function of \( P_\omega/P_L \). So it is equivalent to standardize the weight and
sent packet length of node \( i \), corresponding to decreasing its noncooperation and selfishness properties, thus effectively reflecting the fairness of channel competition mechanism QPCG. When the value of \( P_o/P_e \) is smaller, corresponding to a smaller weight proportion and a larger packet length proportion of node \( i \), the game’s delayed time \( T_{QPCG} \) is instead smaller, so that packets of a minor priority will be transmitted in advance. Such competition mechanism effectively avoids minor priority data steam being “starved” under a fierce competition circumstance. Above analysis can fully embody the fairness property of channel competition mechanism QPCG.

(2) Update the State of Mechanism QPCG. During the initialization process of parameter \( T_{QPCG} \), \( P_o/P_e \) will effectively reduce virtual collision, but it still cannot completely prevent the packet collision during the process of wireless network nodes’ competition. If we recalculate the \( T_{QPCG} \) value after each collision, there is no doubt that the implementation complexity of the node transmission protocol will be increased. If the channel competition is not intense and the virtual collision is occasional, the back-off collision time interval can be updated as follows:

\[
T_{QPCG} = \{1 + \text{random} \left[ \min P_w, \text{Counter} \times \max P_w \right] \} \times T_0,
\]

where Counter is a parameter of game collision status and its initial value is 0. After a collision, Counter = Counter + 1. \( T_0 \) is the value of \( T_{QPCG} \) after the first collision. With base value of \( T_0 \), \( T_{QPCG} \) value increases properly, which not only effectively avoids the small-scale virtual collision, but also reduces the implementation complexity of node transmission protocol.

Under the condition that the channel competition is intense, QPCG channel competition mechanism not only considers current node's status, but also comprehensively considers the situation of its precursor and subsequent nodes. By balancing the relationship between the transmission data priority and the queue packet length in each node, the fair and effective bidding function \( T_{QPCG} \) is established to effectively avoid the virtual collision phenomenon of packet sending, which is caused by equal priority weights. Through the analysis of each parameter of the bidding function \( T_{QPCG} \), we can conclude that QPCG mechanism not only contains wireless network nodes’ selfishness and competition properties, but also emphasizes the cooperation property of different nodes, which reflects the noncooperative game concept and Nash equilibrium ideas.

3. The Model Establishment of Cross-Layer CC

When applying cross-layered concept to solve wireless network congestion problems, we should first monitor the information of congested nodes or channels [21], synthesize the feedback information of each layer [22], and then achieve the purpose of cross-layered processing of the wireless network congestion with a joint optimization [23]. The congestion degree function calculation achieves a meticulous classification of congestion degree, and depending on the specific congestion degree, we take a corresponding congestion control mechanism or pretreatment mechanism, so as to avoid more serious wireless network congestion phenomenon and eventually achieve an improvement of wireless network transmission quality.

3.1. Congestion Degree Division Based on Cross-Layer Design.

Because of the complicated cause of wireless network congestion, it is necessary to synthesize congestion formulation reasons. In this paper, we consider congestion reasons from three aspects (node, link, and channel). According to the congestion degree function \( f_{CCM} \) (Comprehensive Congestion Metrics), we divide the congestion degree so that the congestion processing is targeted and dynamically adaptive. The \( f_{CCM} \) function is described below:

\[
f_{CCM} = W_1 \sum D_{LONL} (i) + W_2 \sum D_{LOLL} (i, j)
\]

\[
+ W_3 \sum D_{LOCI} (i),
\]

where \( W_1, W_2, \) and \( W_3 \), respectively mean the weight of node load, link load, and channel interference causing congestion, and \( W_1 + W_2 + W_3 = 1 \). \( D_{LONL} (i) \) (the level of node load) is to quantify the severity of nodes’ congestion. \( D_{LOLL} (i, j) \) (the level of link load) is to value the severity of links’ congestion. \( D_{LOCI} (i) \) (the level of channel interference) is to quantify the severity of channels’ congestion.

According to the transmission rate, expected transmission time (ETT), and expected transmission times (ETX), we can quantify the levels of node load, link load, and channel interference.

Any node’s load is related with the previous nodes and the next node. The load degree of node \( i \) can be described by its transmission queue length. As shown in Figure 1, node \( i \) is the previous-hop of node \( i + 1 \) as well as the next-hop of several nodes. Under the condition of stable channel, node \( i \) will constantly transmit data information to next-hops, the same time it continuously receives data from previous-hops. When the overall receiving rate is far higher than sending, it will cause congestion of the transmission path. Nodes’ overload certainly will affect the transmission quality of relevant links. In the wireless network, the link sharing is unavoidable. A sharp increase of shared links certainly will lead to wireless network’s congestion. When the channel is unstable and the channel interference is strong, wireless network congestion phenomenon will happen.

Nodes’ load is influenced by waiting queues’ length and packets’ sending and receiving rate, so nodes’ accumulated load degree could be used to measure the congestion degree of all nodes on the whole transmission path:

\[
D_{LONL} (i) = \frac{Q_i + \sum b_j \cdot ETT_j - \alpha \sum b_m \cdot ETT_m \cdot ETX_p}{b_j},
\]

where \( Q \) means length of the queues that are waiting to be transmitted in node \( i \), \( b_j \) is the sending rate of nodes that are previous-hops of node \( i \), which also means the receiving rate of node \( i \). \( \alpha \) is a potential factor which means the potential next-hops’ influence on the congestion degree. Its value is 0 or 1. \( b_m \) is the receiving rate of potential nodes that are next-hops of node \( i \), which also means the potential sending rate of node \( i \). \( b_j \) means the sending rate of node \( i \) in the current transmission path.
Even though both the sending rate and receiving rate can be adjusted but the sending rate is changing over time, so it will bring about a big difference. Assume that the nodes' sending speed limit is $B_i$; the limit formula is described below:

$$\lim_{b_i \to B_i} \frac{Q_i + \sum b_j \cdot ETT_j - \alpha \cdot \sum b_m \cdot ETX_m \cdot ETX_i = M}{\sum b_j \cdot ETT_j \to N}$$  \hspace{1cm} (10)$$

Even if the rate limit of node $i$ is close to $B_i$, but, when the previous-hop node set of node $i$ is under heavy load which means a pretty big value of $N$, the above limitation formula may approach a high value of $M$ which is certainly much larger than $ETT_i$. Then, no matter how to adjust the sending rate or whether the potential factor $\alpha$ plays a role, it inevitably leads to congestion.

For the link load level $D_{LOLL}(i,j)$, it can be measured by the links' load transmission capacity:

$$D_{LOLL}(i,j) = \frac{Q_{ij}}{B_i - \sum_{k \in N_i} B_{jk} \cdot ETX_{ij}},$$  \hspace{1cm} (11)$$

where $Q_{ij}$ is the amount of information to be transmitted from node $i$ to node $j$. $B_i$ means the total transmission rate of node $i$. $B_{jk}$ means an actual shunt transmission rate after linking with node $i$. $ETX_{ij}$ is the expected transmission times from node $i$ to node $j$. $N_i$ is the next-hop node set of node $i$ except node $j$. When $\sum_{k \in N_i} B_{jk}$ is approaching larger and the links are overloaded, then it will cause congestion. To avoid an unrecoverable congestion, we provide that when $B_i - \sum_{k \in N_i} B_{jk} = 2B_0$, where $B_0$ is the minimum transmission rate of node $i$, congestion control must be taken. Meanwhile, the $D_{LOLL}(i,j)$ can be defined as links' load threshold.

The channel interference degree is described by $D_{LOCI}(i)$ as follows:

$$D_{LOCI}(i) = T_{CST}(i) + \max_{k \in N_i} \left\{ \frac{r}{d_k} \cdot T_{LCIT}(k) \right\},$$  \hspace{1cm} (12)$$

where $T_{CST}(i)$ means channel switching time, $T_{LCIT}(k)$ means link channel interference time, $\gamma$ is channel interference factor, $d_j$ is interference distance of each interference link, and $N_k$ is a link set which use channel $i$, $T_{LCIT}(k) = \sum_{k \in N_i} ETT_j$. The constant increasing of $D_{LOCI}(i)$ inevitably causes excessive cochannel interference on the link. When the channel interference degree reaches a certain limit degree of $Z$, it may lead to serious network congestion. To avoid the above phenomenon, we set that when channel interference degree $D_{LOCI}(0) < Z$, congestion process must be taken. Meanwhile, $D_{LOCI}(0)$ can be regarded as channel interference tolerance.

3.2. The Cross-Layer Cooperative Congestion Processing Model Based on GT. Through the congestion degree division, the wireless network congestion is processed with a specific mechanism, thus achieving a targeted dynamic adaptive system of the wireless network congestion. The main processing flow is shown in Figure 2. First of all, the wireless network uses cross-layer technology to monitor the channel information of physical layer, sending/receiving rate information of link layer's MAC sublayer and the buffer queue information of the network layer and then apply the congestion measurement function to get a comprehensive evaluation which is used to judge block and find the main causes of congestion.

(1) When the congestion is caused by nodes' overload, we should use formula $D_{LOLL}(i)$ to determine whether the congestion could be controlled by adjusting nodes' sending/receiving rate. If it can be processed by rate adjusting, then apply the rate adjusting mechanism or the mechanism QRD; otherwise we should find cooperative nodes to realize cooperative transmission.

(2) When the congestion is caused by links' heavy load, we should determine whether the load has reached the link load's threshold defined in formula $D_{LOLL}(i,j)$; if not, then the QRD mechanism should be adopted first to process the congestion; otherwise it needs to seek for cooperative nodes to realize cooperative transmission.

(3) When the congestion is caused by excessively strong channel interference, first what we should do is to determine whether it has exceeded the tolerance range of channel interference. If it is within the tolerance range, the congestion can be processed through channel competition mechanism QPCG; otherwise it needs to find cooperative nodes to realize node cooperation transmission.

(4) When the congestion reasons cannot be simply classified into one class, which means two or three congestion reasons exist at the same time, the congestion should be controlled according to the following order:
first to deal with the effects of excessive channel interference on network transmission; then, process the effects of excessive node load on network transmission; and last, process the effects of excessive link load on network transmission. Why we follow such processing flow is because only after the channel interference degree decreasing, can improve nodes’ average sending/receiving rate, so as to reduce the load pressure of a single node and eventually reduce the link load pressure.

So, when the congestion reaches a certain extent, it needs to seek for cooperative nodes to realize nodes’ cooperation processing. If cooperative nodes cannot be found within a certain region, then set a time trigger in the congested node to monitor a time period’s information including channel information of physical layer, sending/receiving rate information of MAC sublayer in link layer and buffer queue information of network layer. If in a time period, the corresponding information is weakening, then we should reuse the congestion metric function to classify congestion degree; otherwise, we need to reestablish a transmission path. If several cooperative nodes have been found, we should establish the directed cooperative path net through trust level and AFCR algorithm, then we should seek for an optimal cooperative path in the directed cooperative path net to realize cooperative transmission. The targeted congestion processing can eventually realize an improvement of wireless network transmission quality.

When congestion reached a certain degree, it is necessary to establish a directed cooperative path net to solve the congestion. The main idea of directed cooperative path net is described as follows. In Figure 3, when node \( C \) is congested, or load of transmission path \( BC \) is excessive, or the channel interference is too strong, then a directed cooperative path...
net around node \( C \) is established. Under the protection of the directed cooperative path net, node \( C \) no longer accepts transmission request of any node until the load pressure of node \( C \) reduces to rating value. If node \( B \) wants to send information to node \( C \), it should choose other transmission paths in the directed cooperative path net to realize a load shunt for node \( C \).

The establishment steps of directed cooperative path net are shown as follows.

1. **Select Credible Nodes of the Directed Cooperative Path Net.** Node \( C \) will broadcast cooperation request to its neighbor nodes within its radiation scope. If received from cooperative nodes, the cooperative set \( CS = \{ B, F, C, H, I, J, K, L, M, D \} \) can be formed. Each node in \( CS \) will be marketed as trusted node, and the credibility value is set in the routing selection process. In the set of \( CS \), node \( B \) and node \( D \) are, respectively, regarded as source node and destination node.

2. **Establish Directed Cooperative Path Net.** According to the AFCR [24] algorithm, the rest nodes within one-hop are clustered. Before AFCR algorithm, it needs to initialize each node’s weight according to the formula of CMM and immediately send the initialization information of one-round clustering to all nodes in \( CS \); then each node forms a temporary table of neighbor nodes and set a clustering timer. In the execution process of AFCR algorithm, we select nodes of larger weight as the cluster head. After every node in \( CS \) finishing route selection, each node needs to save a temporary table of adjacent nodes, a temporary table of cluster heads and a temporary table of cluster members. The clustered nodes conduct wireless communication through route establishment, route selection, and route maintenance.

3. **Create Optimal Path in the Directed Cooperative Path Net.** During the route selection process, each node needs to initialize the credibility value based on formula CMM and the credibility value is \( 1/f_{CMM} \); then the accumulated credibility is used to realize optimal route selection. If several nodes in \( CS \) do not exist in the final directed cooperative path net, such as node \( M \), then we set a value of \( 1/D_{LONL}(M) \) as the credibility of \( M \). Provided that path \( BFGH \) is created as an optimal transmission path, while each node in the path needs to shunt loading for node \( C \) in a certain period, which certainly will increase load pressure, this moment the data transmission should apply QRD mechanism and QPCG mechanism to effectively avoid virtual collision and “starvation” phenomenon. We also stipulate that the credible nodes choose nodes of higher credibility as next-hops after receiving routing request. For instance, after node \( I \) receiving the routing broadcast, it will accord to the credibility value to choose node \( J \) as next-hop, not node \( C \).

The directed cooperative path net around a congested node can effectively protect the congested node and prevent its load increasing and channel interfering. And the credibility concept introduction can realize a targeted route selection, which not only reduces the node’s load pressure, but also decreases the link load pressure and channel interference. Thereby, the NCM greatly improves the utilization rate of network resources, and finally achieves the purpose of improving entire network service quality.

### 4. Performance Analysis

In this paper, we choose GloMoSim [25] as simulation tool and the simulation is based on 802.11 protocol. In the simulation experiment, under the simulation environment of gradual congestion phenomenon and the ever-changing congestion degree and congestion reasons, we compare the network transmission quality of no congestion process, single rate control mechanism, and the adopting different congestion mechanism based on different congestion degree. The simulation scope is \( 600 \times 600 \); we distribute 30 simulation nodes in the manner of uniform as simulation scene, as shown in Figure 4. When constructing different number of CBR, we stimulate that it sends a packet every 10 milliseconds, which size is 1024 Bytes. And then we compare the changes over time of the whole network throughput and the packet delivery ratio in each case.

Firstly, we conduct a simulation of directed cooperative path net which is based on congestion degree division to verify the effectiveness of congestion degree division mechanism and cross-layer cooperation congestion processing.

When the wireless network load is gradually increasing, Figure 5 shows the total throughput variation trend of 4 different congestion processing mechanisms. With the CBR number increasing from 3 to 10, the network total throughput is also constantly increasing. But, there exists obvious difference between different congestion processing mechanisms. Clearly, in the current simulation environment, for the first three mechanisms, except directed cooperative path net mechanism, the total throughput begins declining after reaching a peak, which indicates that, under this three mechanisms, the network will be congested after its load pressure reaching a certain extent, thus causing a declination to the total network throughput. But when applying the directed
cooperative path net, because of its effect of congestion degree division, the total throughput obviously improves.

In the case of CBR number increasing from 3 to 10, which means the wireless network load is increasing, Figure 6 shows the wireless network average end-to-end throughput variation trend of 4 different congestion processing mechanisms. Obviously, under the condition of equal initial average end-to-end throughput, when applying the directed cooperative path net mechanism, the average end-to-end throughput declines more modest, which means the average end-to-end throughput is improved obviously.

Then, we apply QRD mechanism and QPCG mechanism in the directed cooperative path net and contrast the processing effect of wireless network congestion.

In the case of wireless network load increasing, Figure 7 shows the wireless network’s total throughput variation trend. With the CBR number increasing from 3 to 10, three different congestion processing mechanisms bring obviously different impact to the total throughput. Under the condition of without any processing mechanism, a sharp decline point is the total throughput peak, which indicates that serious congestion has occurred to the wireless network. But for the game cross-layer CC based congestion processing, this simulation has not yet appeared congested trend, and the network’s total throughput has displayed an obvious increasing tendency, which indicates that the congestion processing mechanism based on game cross-layer CC can tolerate immense network load pressure.

In the case of network load increasing, Figure 8 shows the wireless network’s average packet delivery rate variation trend. With the CBR number increasing from 3 to 10, compared to no processing mechanism and a single cooperative mechanism, game cross-layer CC mechanism has the most gentle declination tendency of the average packet delivery rate. With the CBR number increasing, the
congestion classification function of game cross-layer cooperation communication mechanism can adaptively control the congestion according to the current wireless network environment thus to maintain a relatively stable transmission quality of wireless networks.

5. Conclusions

With considering GT, cross-layer design, and CC, this paper gave a concept of directed cooperative path net, for wireless network congestion processing. With the congestion degree division, we realize a targeted processing of wireless network congestion. During wireless network congestion processing, the applications of QRD and channel competition mechanism QPCG can effectively enhance the fairness of the wireless network resource competition, improve the resource utilization of wireless network, and increase the wireless network transmission. Simulation comparison shows that the integration of game concept into cross-layer cooperation can improve the wireless network throughput, reduce the packet loss rate, increase the utilization rate of spare nodes, and decrease the risk of “starved” phenomenon. Combined with the cross-layer concept and GT, the applications of QRD and channel competition mechanism QPCG can improve the blindness of wireless networks, thus effectively improving the transmission quality of wireless networks.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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