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September 13, 2018

IMPROVING DETERMINISM FOR WIRELESS: SETTING DYNAMIC CLEAR CHANNEL ASSESSMENT THRESHOLD IN LOW-POWER AND LOSSY NETWORKS

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ABSTRACT

Techniques are described herein for a mechanism to determine Clear Channel Assessment (CCA) thresholds in the scope of link neighbors in low power and lossy wireless networks. Without adding too much extra traffic, a dynamic, newly designed CCA threshold is unique for each link neighbor and helps to improve the wireless network performance.

DETAILED DESCRIPTION

In wireless mesh networks, when an entity starts a packet transmission, ideally it needs awareness of the radiation environment if there is active radio congestion. Radio congestion brings heavy drawbacks to low power and lossy wireless networks, such as transmission error, traffic throughput downgrade, etc. Detecting this radio congestion is challenging in current wireless mesh network implementations: the entity applies a simple method of Clear Channel Assessment (CCA) in accordance with its radio-frequency (RF) chipset capability for radio congestion detection in the following manners:

1. The entity enables an interrupt by setting the fixed CCA threshold at the start of transmission. This approach relies on the RF chipset's support of such an interrupt.

2. The entity reads the received signal strength indication (RSSI) and compares the RSSI with the fixed CCA threshold. This approach relies on a software solution that, if the RSSI reading overlaps the CCA threshold, determines a radio congestion situation is active which causes a drop of the transmission at that time. A back-off window is designed, that allows entity to retry transmission.

The methods described above can solve radio congestion passively because they apply the fixed CCA threshold and provide appropriate time slots for a potentially successful re-transmission. However, the fixed CCA threshold applicable to all entities in different circumstances may be inappropriate.

The fixed CCA threshold brings performance related issues in wireless mesh networks, because the number of link neighbors can be huge, the radio link statistics can be varied, and irrelative signals may make an entity respond to radio congestion incorrectly. On one hand, a certain signal strength may be weak for one entity that is not harmonic, but the same signal may cause collisions for others. On the other hand, a signal that is considered to be harmonic for one entity, but would be less critical for others, for instance, the Power Outage Notification (PON) or Power Recovery Notification (PRN) message, needs to be allowed in a multi-hops hierarchy network if the radio congestion source is from upper layer entities. Overall, the fixed CCA threshold may result in throughput downgrading due to the mishandling of radio congestion.

The techniques described herein may be illustrated by two examples of the issues to be solved. In order to simplify the explanation, the examples assume the CCA threshold is only determined by the RSSI.

Example 1. As shown in Figure 1 below, CGE A, B, C, D are in link neighbors, communicating in unicast. In some circumstances, CGE A, B, C are trying to transmit a packet to CGE D. All entities have the same pre-configured CCA threshold T. Suppose CGE B first sends a packet to CGE D on channel α, CGE A and C try sending packets at the same time, they can hear CGE B's signal on the same channel α.

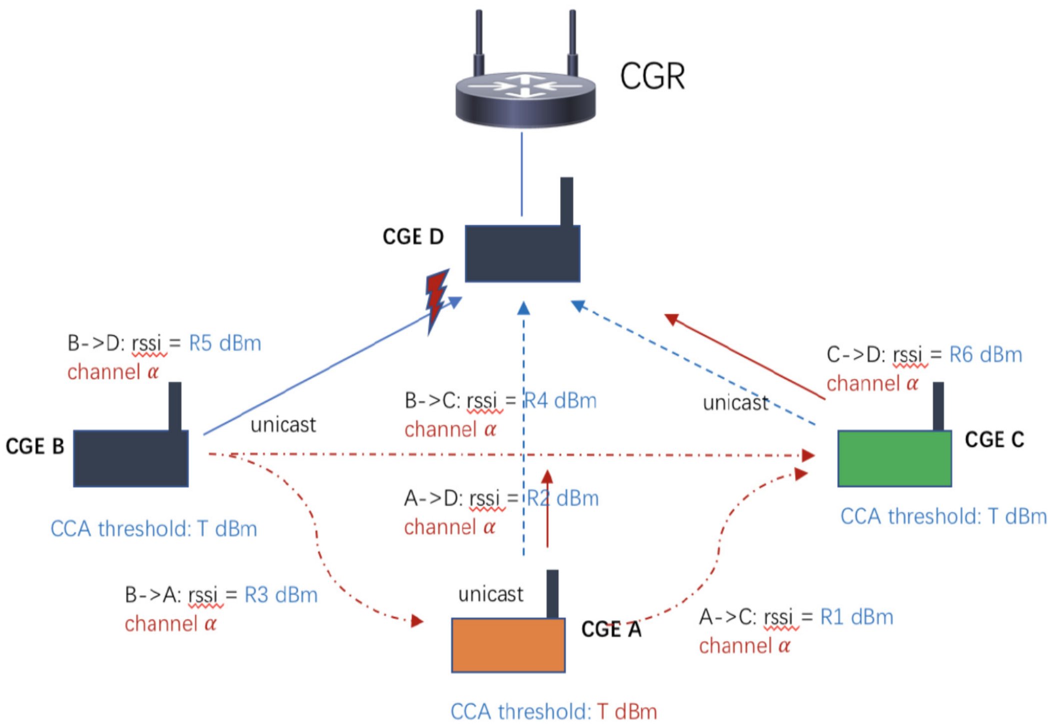

Figure 1

The following table describes the RSSI value of each signal path. Note: "->" indicates the traffic direction, "<" means "less than", and ">>" means "far greater than"

A -> C	A -> D	B -> A	B -> C	B -> D	C -> D
R1 < T	R2 >> T	R3 < T	R4 < T	R5 >> T	R6 >> T

Table 1

If CCA threshold T is set inappropriately, as described above, assuming that the radio link path is symmetrical, it will allow each of CGE A, B, C to send a packet to CGE D simultaneously, which causes bit errors.

Example 2. Power Outage Notification (PON) and Power Recovery Notification (PRN) are broadcast messages in wireless mesh networks. The fixed CCA threshold will also affect their transmission. Consider an example illustrated as shown in Figure 2 below.

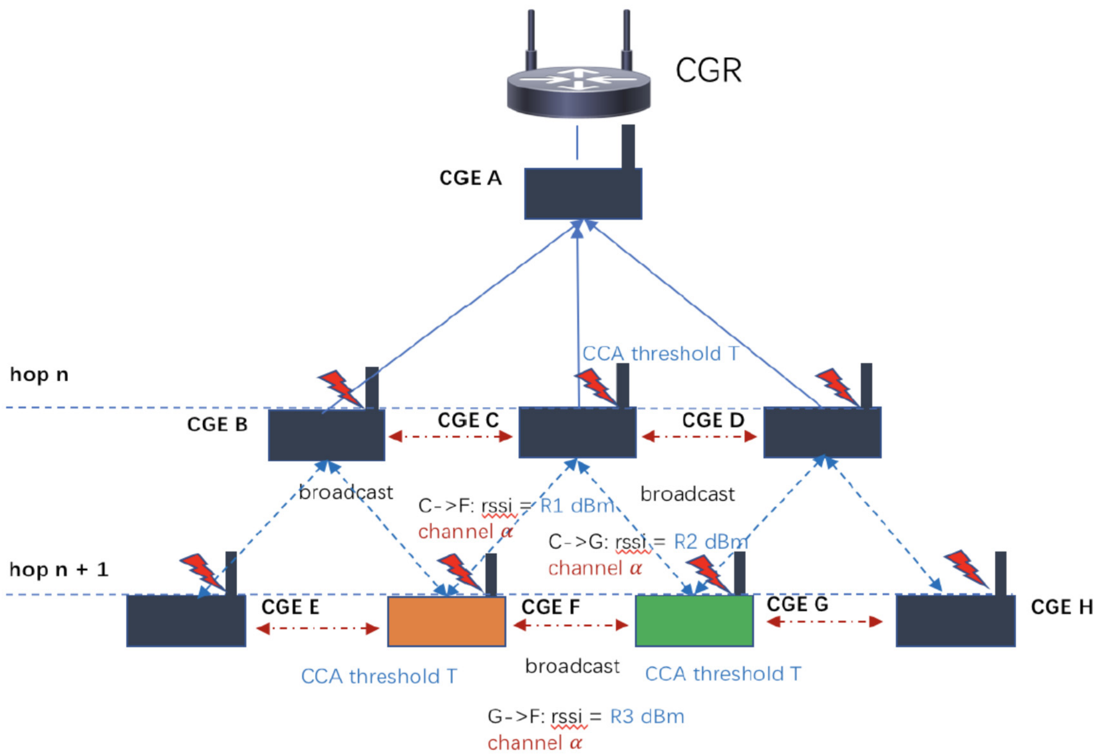

Figure 2

In this example, all entities in hop n and hop n + 1 are in a power outage state. Possibly, CGE C and G may trigger the PON simultaneously in broadcast. Suppose CGE C is transmitting slightly ahead of CGE G, which causes CGE G to hear CGE C on channel α. The following table describes the RSSI value of each signal path:

C -> F	C -> G	G -> F
R1 < T	R2 < T	R3

Table 2

When R2 < T, CGE G will be allowed to send broadcast packets. If R3 is large enough, it will cause bit errors in a broadcast packet sent from CGE C to CGE F.

Consider another special case illustrated in Figure 3 below.

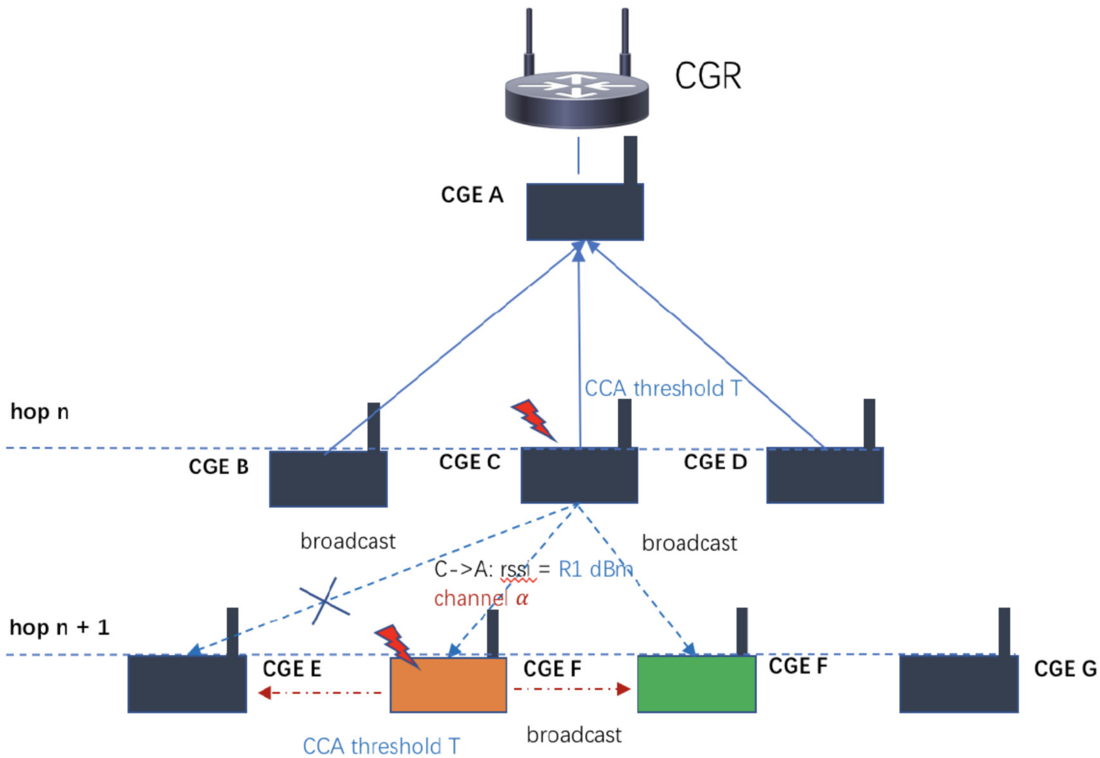

Figure 3

In this case, suppose CGE C starts sending packets successfully (no CCA). When CGE F starts sending packets later, it might suffer CCA because CGE C is occupying broadcast channel α and R1 >> T. In such circumstances, CGE F has to start to back-off. Unfortunately, it is possible that there will not be sufficient power, and the PON for CGE F will be lost.

However, while CGE E is working normally, it is not CGE C's link neighbor (*i.e.*, they cannot be heard by each other). In such case, CGE F can send broadcast PON even though R1 >> T, then CGE E can receive PON from CGE F and can help relay the packet. The CCA threshold can be less significant with a lower threshold, or even be disabled, when dealing in such cases, so that every entity can try the best to send.

We understand the fixed CCA threshold is not suitable in general. To make wireless mesh networks smarter and more efficient, the techniques described herein provide a novel mechanism of calculating a dynamic CCA threshold for each link neighbor's transmission. This technique will improve the efficiency and decrease the possibility of mishandling of CCA caused by the fixed threshold. According to this solution, there is not much extra traffic added, but it allows the single entity to have an overview of the radio congestion in the scope of its link neighbors.

The techniques described here introduce a novel mechanism to determine the CCA threshold in the scope of link neighbors and apply dynamic settings in both unicast and broadcast transmissions. This newly designed dynamic CCA threshold is unique for each link neighbor.

For the purposes of this mechanism, we assume that the environment does not contribute any RF performance changes. For unicast transmissions, an entity applies each CCA threshold mapping to its destination but related to its link neighbors as well. For broadcast transmissions, a common CCA threshold is determined by all link neighbors. Each entity maintains its own CCA threshold map of link neighbors. The CCA threshold can be calculated in a flooding manner and be stable in the end. In these examples, there is defined refresh period P for the task.

In the following description, further details of how to determine the CCA threshold for unicast and broadcast transmissions in the wireless mesh network are provided. To describe the mechanism, an example scenario including five entities (CGE A, B, C, D, E) is shown in Figure 4 below.

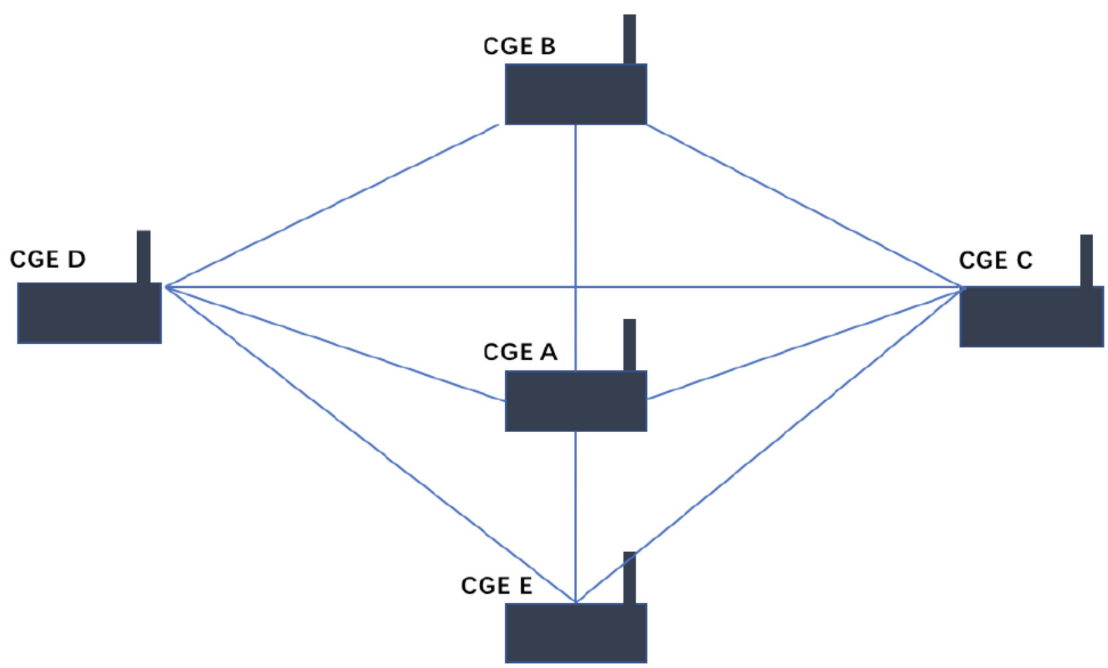

Figure 4

Component 1: each entity starts working with a default CCA threshold t_{def}

Component 2: each entity e_i (i belongs [0, k]) maintains the flexible CCA threshold set $T_i = \{t_{i,0}, t_{i,1}, \ldots, t_{i,k}\}$ corresponding to its link neighbors set $N_i = \{n_0, n_1, \ldots, n_k\}$

Component 3: each entity e_i maintains the RSSI set $R_i = \{r_{i,0}, r_{i,1}, \ldots, r_{i,k}\}$ corresponding to its link neighbors set N_i

Component 4: each entity e_i maintains the Last Heard set $H_i = \{h_{i,0}, h_{i,1}, \ldots, h_{i,k}\}$ corresponding to its link neighbors set N_i

Component 5: each entity e_i maintains the CCA retry set $C_i = \{c_{i,0}, c_{i,1}, \ldots, c_{i,k}\}$ corresponding to its link neighbors set N_i

Component 6: when traffic needs to send from entity e_i to e_j, fetches their common sets: neighbor set N_{ij}, RSSI set R_{ij}, Last Heard set H_{ij}, and CCA retry set C_{ij}

Component 7: the updated unique CCA threshold $t_{i,j} = \min(R_{ij}) + d_{ij}$ where min means minimum value and d_{ij} is a factor determined by: (1) radio noise level L, and (2) common set H_{ij} and C_{ij}, as $d_{ij} \rightarrow L + w_{ij} * (H_{ij}, C_{ij})$, w_{ij} is the weights for H_{ij} and C_{ij}

UNICAST TRANSMISSIONS

In regard to unicast transmissions, the following description details how a dynamic CCA threshold is determined by an example of network formatting. In this example, let L = -110 dB network is started with two entities as shown in Figure 5 below.

Figure 5

Step 1: CGE A and B are link neighbors, respectively, and they are each set with a default CCA threshold t_{def}, shown in Table 3.

CGE	Link Neighbor	Last Heard	RSSIF	CCA Retry	CCA Threshold
A	B	$h_{0,1}$	$r_{0,1}$	$c_{0,1}$	t_{def}
CGE	Link Neighbor	Last Heard	RSSIF	CCA Retry	CCA Threshold
B	A	$h_{1,0}$	$r_{1,0}$	$c_{1,0}$	t_{def}

Table 3

Step 2: A new CGE C joins the network, they are link neighbors with each other as shown in Figure 6 below.

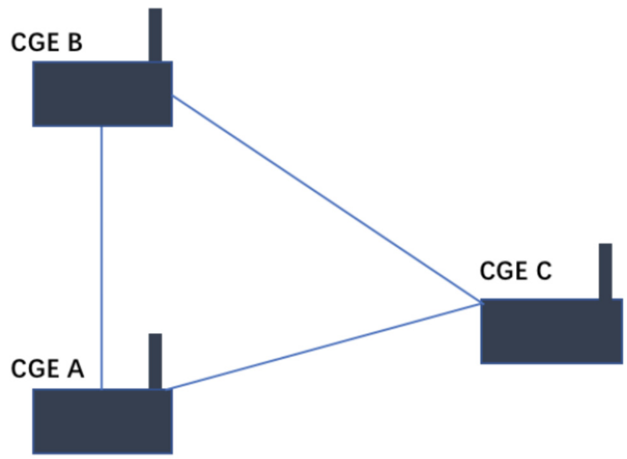

Figure 6

In this step, $t_{0,1}$ and $t_{1,0}$ will be determined, others are set to t_{def}, as shown in Table 5.

CGE	Link Neighbor	Last Heard	RSSIF	CCA Retry	CCA Threshold
A	B	$h_{0,1}$	$r_{0,1}$	$c_{0,1}$	$t_{0,1}$
	C	$h_{0,2}$	$r_{0,2}$	$c_{0,2}$	t_{def}
CGE	Link Neighbor	Last Heard	RSSIF	CCA Retry	CCA Threshold
B	A	$h_{1,0}$	$r_{1,0}$	$c_{1,0}$	$t_{1,0}$
	C	$h_{1,2}$	$r_{1,2}$	$c_{1,2}$	t_{def}
CGE	Link Neighbor	Last Heard	RSSIF	CCA Retry	CCA Threshold
C	A	$h_{2,0}$	$r_{2,0}$	$c_{2,0}$	t_{def}
	B	$h_{2,1}$	$r_{2,1}$	$c_{2,1}$	t_{def}

Table 5

$t_{0,1} = \min(\{r_{0,2}, r_{1,2}\}) + d_{0,1}$ and $t_{1,0} = \min(\{r_{0,2}, r_{1,2}\}) + d_{1,0}$

Step 3: A new CGE D joins the network, they are link neighbors with each other as shown in Figure 7 below.

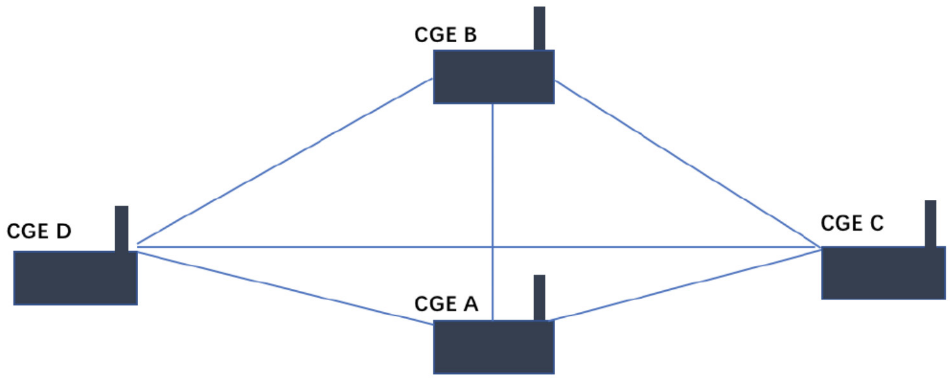

Figure 7

In this step, $t_{0,1}$, $t_{0,2}$, $t_{1,0}$, $t_{1,2}$, $t_{2,0}$, $t_{2,1}$ will be determined, others are set to t_{def}, as shown in Table 6.

CGE	Link Neighbor	Last Heard	RSSIF	CCA Retry	CCA Threshold
A	B	$h_{0,1}$	$r_{0,1}$	$c_{0,1}$	$t_{0,1}$
	C	$h_{0,2}$	$r_{0,2}$	$c_{0,2}$	$t_{0,2}$
	D	$h_{0,3}$	$r_{0,3}$	$c_{0,3}$	t_{def}
CGE	Link Neighbor	Last Heard	RSSIF	CCA Retry	CCA Threshold
B	A	$h_{1,0}$	$r_{1,0}$	$c_{1,0}$	$t_{1,0}$
	C	$h_{1,2}$	$r_{1,2}$	$c_{1,2}$	$t_{1,2}$
	D	$h_{1,3}$	$r_{1,3}$	$c_{1,3}$	t_{def}
CGE	Link Neighbor	Last Heard	RSSIF	CCA Retry	CCA Threshold
C	A	$h_{2,0}$	$r_{2,0}$	$c_{2,0}$	$t_{2,0}$
	B	$h_{2,1}$	$r_{2,1}$	$c_{2,1}$	$t_{2,1}$
	D	$h_{2,3}$	$r_{2,3}$	$c_{2,3}$	t_{def}
CGE	Link Neighbor	Last Heard	RSSIF	CCA Retry	CCA Threshold
D	A	$h_{3,0}$	$r_{3,0}$	$c_{3,0}$	t_{def}
	B	$h_{3,1}$	$r_{3,1}$	$c_{3,1}$	t_{def}
	C	$h_{3,2}$	$r_{3,2}$	$c_{3,2}$	t_{def}

Table 6

$t_{0,1} = \min(\{r_{0,2}, r_{0,3}, r_{1,2}, r_{1,3}\}) + d_{0,1}$

$t_{0,2} = \min(\{r_{0,1}, r_{0,3}, r_{2,1}, r_{2,3}\}) + d_{0,2}$

$t_{1,0} = \min(\{r_{1,2}, r_{1,3}, r_{0,2}, r_{0,3}\}) + d_{1,0}$

$t_{1,2} = \min(\{r_{1,0}, r_{1,3}, r_{0,2}, r_{0,3}\}) + d_{1,2}$

$t_{2,0} = \min(\{r_{2,1}, r_{2,3}, r_{0,1}, r_{0,3}\}) + d_{2,0}$

$t_{2,1} = \min(\{r_{2,1}, r_{2,3}, r_{1,0}, r_{1,3}\}) + d_{2,1}$

Step 4: A new CGE E joins the network, it is neighbor of A, C and D but not with B as show in Figure 8 below.

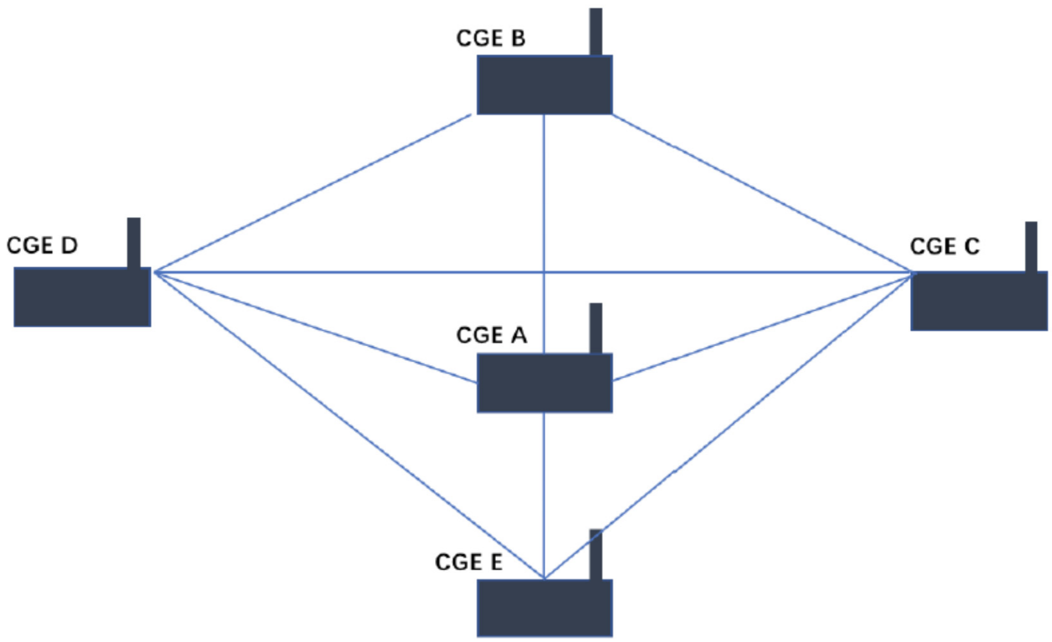

Figure 8

In this step, $t_{0,1}$, $t_{0,2}$, $t_{0,3}$, $t_{1,0}$, $t_{1,2}$, $t_{1,3}$, $t_{2,0}$, $t_{2,1}$, $t_{2,3}$, $t_{3,0}$, $t_{3,1}$, $t_{3,2}$ will be determined, others are set to t_{def}, as shown in Table 7.

CGE	Link Neighbor	Last Heard	RSSIF	CCA Retry	CCA Threshold
A	B	$h_{0,1}$	$r_{0,1}$	$c_{0,1}$	$t_{0,1}$
	C	$h_{0,2}$	$r_{0,2}$	$c_{0,2}$	$t_{0,2}$
	D	$h_{0,3}$	$r_{0,3}$	$c_{0,3}$	$t_{0,3}$
	E	$h_{0,4}$	$r_{0,4}$	$c_{0,4}$	t_{def}
CGE	Link Neighbor	Last Heard	RSSIF	CCA Retry	CCA Threshold
B	A	$h_{1,0}$	$r_{1,0}$	$c_{1,0}$	$t_{1,0}$
	C	$h_{1,2}$	$r_{1,2}$	$c_{1,2}$	$t_{1,2}$
	D	$h_{1,3}$	$r_{1,3}$	$c_{1,3}$	$t_{1,3}$
	E	$h_{1,4}$	$r_{1,4}$	$c_{1,4}$	t_{def}
CGE	Link Neighbor	Last Heard	RSSIF	CCA Retry	CCA Threshold
C	A	$h_{2,0}$	$r_{2,0}$	$c_{2,0}$	$t_{2,0}$
	B	$h_{2,1}$	$r_{2,1}$	$c_{2,1}$	$t_{2,1}$
	D	$h_{2,3}$	$r_{2,3}$	$c_{2,3}$	$t_{2,3}$
	E	$h_{2,4}$	$r_{2,4}$	$c_{2,4}$	t_{def}
CGE	Link Neighbor	Last Heard	RSSIF	CCA Retry	CCA Threshold
D	A	$h_{3,0}$	$r_{3,0}$	$c_{3,0}$	$t_{3,0}$
	B	$h_{3,1}$	$r_{3,1}$	$c_{3,1}$	$t_{3,1}$
	C	$h_{3,2}$	$r_{3,2}$	$c_{3,2}$	$t_{3,2}$
	E	$h_{3,4}$	$r_{3,4}$	$c_{3,4}$	t_{def}
CGE	Link Neighbor	Last Heard	RSSIF	CCA Retry	CCA Threshold
E	A	$h_{4,0}$	$r_{4,0}$	$c_{4,0}$	t_{def}
	B	$h_{4,1}$	$r_{4,1}$	$c_{4,1}$	t_{def}
	C	$h_{4,2}$	$r_{4,2}$	$c_{4,2}$	t_{def}
	D	$h_{4,3}$	$r_{4,3}$	$c_{4,3}$	t_{def}

Table 7

$$t_{0,1} = \min(\{r_{0,2}, r_{0,3}, r_{0,4}, r_{1,2}, r_{1,3}, r_{1,4}\}) + d_{0,1}$$

$$t_{0,2} = \min(\{r_{0,1}, r_{0,3}, r_{0,4}, r_{2,1}, r_{2,3}, r_{2,4}\}) + d_{0,2}$$

$$t_{0,3} = \min(\{r_{0,1}, r_{0,2}, r_{0,4}, r_{3,1}, r_{3,2}, r_{3,4}\}) + d_{0,3}$$

$$t_{1,0} = \min(\{r_{1,2}, r_{1,3}, r_{1,4}, r_{0,2}, r_{0,3}, r_{0,4}\}) + d_{1,0}$$

$$t_{1,2} = \min(\{r_{1,0}, r_{1,3}, r_{1,4}, r_{2,0}, r_{2,3}, r_{2,4}\}) + d_{1,2}$$

$$t_{1,3} = \min(\{r_{1,0}, r_{1,2}, r_{1,4}, r_{3,0}, r_{3,2}, r_{3,4}\}) + d_{1,3}$$

$$t_{2,0} = \min(\{r_{2,1}, r_{2,3}, r_{2,4}, r_{0,1}, r_{0,3}, r_{0,4}\}) + d_{2,0}$$

$$t_{2,1} = \min(\{r_{2,0}, r_{2,3}, r_{2,4}, r_{1,0}, r_{1,3}, r_{1,4}\}) + d_{2,1}$$

$$t_{2,3} = \min(\{r_{2,0}, r_{2,1}, r_{2,4}, r_{3,0}, r_{3,1}, r_{3,4}\}) + d_{2,3}$$

$$t_{3,0} = \min(\{r_{3,1}, r_{3,2}, r_{3,4}, r_{0,1}, r_{0,2}, r_{0,4}\}) + d_{3,0}$$

$t_{3,1} = \min(\{r_{3,0}, r_{3,2}, r_{3,4}, r_{1,0}, r_{1,2}, r_{1,4}\}) + d_{3,1}$

$t_{3,2} = \min(\{r_{3,0}, r_{3,1}, r_{3,4}, r_{1,0}, r_{2,1}, r_{2,4}\}) + d_{3,2}$

Step 5: following Step 4, after period P, all thresholds will be determined as shown in Table 8.

CGE	Link Neighbor	Last Heard	RSSIF	CCA Retry	CCA Threshold
A	B	$h_{0,1}$	$r_{0,1}$	$c_{0,1}$	$t_{0,1}$
	C	$h_{0,2}$	$r_{0,2}$	$c_{0,2}$	$t_{0,2}$
	D	$h_{0,3}$	$r_{0,3}$	$c_{0,3}$	$t_{0,3}$
	E	$h_{0,4}$	$r_{0,4}$	$c_{0,4}$	$t_{0,4}$
CGE	Link Neighbor	Last Heard	RSSIF	CCA Retry	CCA Threshold
B	A	$h_{1,0}$	$r_{1,0}$	$c_{1,0}$	$t_{1,0}$
	C	$h_{1,2}$	$r_{1,2}$	$c_{1,2}$	$t_{1,2}$
	D	$h_{1,3}$	$r_{1,3}$	$c_{1,3}$	$t_{1,3}$
	E	$h_{1,4}$	$r_{1,4}$	$c_{1,4}$	$t_{1,4}$
CGE	Link Neighbor	Last Heard	RSSIF	CCA Retry	CCA Threshold
C	A	$h_{2,0}$	$r_{2,0}$	$c_{2,0}$	$t_{2,0}$
	B	$h_{2,1}$	$r_{2,1}$	$c_{2,1}$	$t_{2,1}$
	D	$h_{2,3}$	$r_{2,3}$	$c_{2,3}$	$t_{2,3}$
	E	$h_{2,4}$	$r_{2,4}$	$c_{2,4}$	$t_{2,4}$
CGE	Link Neighbor	Last Heard	RSSIF	CCA Retry	CCA Threshold
D	A	$h_{3,0}$	$r_{3,0}$	$c_{3,0}$	$t_{3,0}$
	B	$h_{3,1}$	$r_{3,1}$	$c_{3,1}$	$t_{3,1}$
	C	$h_{3,2}$	$r_{3,2}$	$c_{3,2}$	$t_{3,2}$
	E	$h_{3,4}$	$r_{3,4}$	$c_{3,4}$	$t_{3,4}$
CGE	Link Neighbor	Last Heard	RSSIF	CCA Retry	CCA Threshold
E	A	$h_{4,0}$	$r_{4,0}$	$c_{4,0}$	$t_{4,0}$
	B	$h_{4,1}$	$r_{4,1}$	$c_{4,1}$	$t_{4,1}$
	C	$h_{4,2}$	$r_{4,2}$	$c_{4,2}$	$t_{4,2}$
	D	$h_{4,3}$	$r_{4,3}$	$c_{4,3}$	$t_{4,3}$

Table 8

$t_{0,1} = \min(\{r_{0,2}, r_{0,3}, r_{0,4}, r_{1,2}, r_{1,3}, r_{1,4}\}) + d_{0,1}$

$t_{0,2} = \min(\{r_{0,1}, r_{0,3}, r_{0,4}, r_{2,1}, r_{2,3}, r_{2,4}\}) + d_{0,2}$

$t_{0,3} = \min(\{r_{0,1}, r_{0,2}, r_{0,4}, r_{3,1}, r_{3,2}, r_{3,4}\}) + d_{0,3}$

$t_{0,4} = \min(\{r_{0,1}, r_{0,2}, r_{0,3}, r_{4,1}, r_{4,2}, r_{4,3}\}) + d_{0,4}$

$t_{1,0} = \min(\{r_{1,2}, r_{1,3}, r_{1,4}, r_{0,2}, r_{0,3}, r_{0,4}\}) + d_{1,0}$

$t_{1,2} = \min(\{r_{1,0}, r_{1,3}, r_{1,4}, r_{2,0}, r_{2,3}, r_{2,4}\}) + d_{1,2}$

$t_{1,3} = \min(\{r_{1,0}, r_{1,2}, r_{1,4}, r_{3,0}, r_{3,2}, r_{3,4}\}) + d_{1,3}$

$t_{1,4} = \min(\{r_{0,1}, r_{0,2}, r_{0,3}, r_{4,0}, r_{4,2}, r_{4,3}\}) + d_{1,4}$

$t_{2,0} = \min(\{r_{2,1}, r_{2,3}, r_{2,4}, r_{0,1}, r_{0,3}, r_{0,4}\}) + d_{2,0}$

$t_{2,1} = \min(\{r_{2,0}, r_{2,3}, r_{2,4}, r_{1,0}, r_{1,3}, r_{1,4}\}) + d_{2,1}$

$t_{2,3} = \min(\{r_{2,0}, r_{2,1}, r_{2,4}, r_{3,0}, r_{3,1}, r_{3,4}\}) + d_{2,3}$

$t_{2,4} = \min(\{r_{2,0}, r_{2,1}, r_{2,4}, r_{4,0}, r_{4,1}, r_{4,3}\}) + d_{2,4}$

$t_{3,0} = \min(\{r_{3,1}, r_{3,2}, r_{3,4}, r_{0,1}, r_{0,2}, r_{0,4}\}) + d_{3,0}$

$t_{3,1} = \min(\{r_{3,0}, r_{3,2}, r_{3,4}, r_{1,0}, r_{1,2}, r_{1,4}\}) + d_{3,1}$

$t_{3,2} = \min(\{r_{3,0}, r_{3,1}, r_{3,4}, r_{1,0}, r_{2,1}, r_{2,4}\}) + d_{3,2}$

$t_{3,4} = \min(\{r_{3,0}, r_{3,1}, r_{3,2}, r_{4,0}, r_{4,1}, r_{4,2}\}) + d_{3,4}$

$t_{4,0} = \min(\{r_{4,1}, r_{4,2}, r_{4,4}, r_{0,1}, r_{0,2}, r_{0,3}\}) + d_{4,0}$

$t_{4,1} = \min(\{r_{4,0}, r_{4,2}, r_{4,3}, r_{1,0}, r_{1,2}, r_{1,3}\}) + d_{4,1}$

$t_{4,2} = \min(\{r_{4,0}, r_{4,1}, r_{4,3}, r_{2,0}, r_{2,1}, r_{2,3}\}) + d_{4,2}$

$t_{4,3} = \min(\{r_{4,0}, r_{4,1}, r_{4,2}, r_{3,0}, r_{3,1}, r_{3,2}\}) + d_{4,3}$

BROADCAST TRANSMISSIONS

In regard to broadcast transmissions, when there is a unicast CCA threshold ready, the broadcast CCA threshold can be the corresponding minimum value of T.

It is understood that the far end server has the overall snapshot of the network. As a result, all link neighbors' information can be collected and computing may be executed there. The entity just needs to receive the determined result and change the CCA threshold accordingly. With such a solution, it is more accurate to set the deterministic CCA threshold for both unicast and broadcast transmissions which helps to improve the system performance.