Wireless Multihop Networks with Network Coding Communication Using Collision Detection of Control Messages

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***Abstract*—In some wireless network applications using bidirectional wireless multihop transmissions of sequences of data messages, intermediate wireless nodes hold temporarily data messages in both directions with high probability. Network coding methods have been proposed for reduction of forwarding and end-to-end transmission delays and for increase of end-to-end data message throughput. However, for collision-free transmissions, 2-hop neighbor intermediate nodes are required to be suspended during a data message transmission. Some extended Request To Send/Clear To Send (RTS/CTS) controls have been proposed for network coding support; however, for avoidance of collisions between control messages, longer transmission delay is inevitable. This paper proposes a novel RTS/CTS control method for supporting network coding in bidirectional data message transmission. Here, the CTS and ACK control messages are transmitted with the usual Short Inter Frame Space ($SIFS$) interval and their correct simultaneous transmissions are detected by their collisions. In simulation experiments, 30.1% higher end-to-end throughput of data messages is achieved by the proposed RTS/CTS control in comparison with conventional methods.**

Keywords–Wireless Multihop Transmissions; Bidirectional Communications; Collision Avoidance; RTS/CTS Control.

I. INTRODUCTION

In wireless multihop networks, such as wireless ad-hoc networks, wireless mesh networks and wireless sensor networks consisting of numerous mobile and/or stationary wireless nodes with wireless transmission/reception devices, data messages are transmitted along a wireless multihop transmission route. It is a sequence of neighboring nodes, which forwards data messages from their previous-hop node to their next-hop node. Advantages of wireless multihop transmissions are reduction of end-to-end transmission delay by avoidance of collisions of wireless signals simultaneously transmitted by multiple nodes, reduction of required transmission power consumption in each node and improvement of data message reachability in wide-area and large-scale networks with a large number of nodes. Transmissions of data messages are realized by cooperation of all the intermediate nodes included in a route $||N_0 \dots N_n\rangle\rangle$ from a source node N_0 to a destination node N_n. Each intermediate node N_i $(1 \leq i \leq n-1)$ receives data messages from its previous-hop intermediate node N_{i-1} and forwards them to its next-hop intermediate node N_{i+1}.

In transmissions of a sequence of data messages, collisions between successively transmitted data messages might degrade their performance, i.e., such collisions cause longer end-to-end transmission delay and lower end-to-end throughput. Since most wireless LAN protocols, such as IEEE802.11, support Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [7], neighbor intermediate nodes N_i and N_{i+1} do not transmit data messages simultaneously. However, N_{i-1} and N_{i+1} might transmit data messages simultaneously since N_{i-1} is out of the wireless signal transmission range of N_{i+1} and vice versa. Though their next-hop nodes N_i and N_{i+2} are different, a collision of data messages can occur at N_i since N_i is included in wireless signal transmission ranges of not only N_{i-1} but also N_{i+1}, as shown in Figure 1. Hence, data messages transmitted by not only N_{i-1} but also N_{i+1} reach N_i and the collision can occur at N_i. Retransmissions of data messages due to such collisions by the hidden-terminal problem at intermediate wireless nodes and transmission intervals for contentions, i.e., for avoidance of collisions caused by 1-hop and/or 2-hop neighbor intermediate nodes cause longer transmission delay for forwarding of data messages in each intermediate node. This makes end-to-end transmission delay of data messages longer. Hence, the source node should reduce its transmission rate of data messages. However, lower end-to-end throughput of data messages should be accepted.

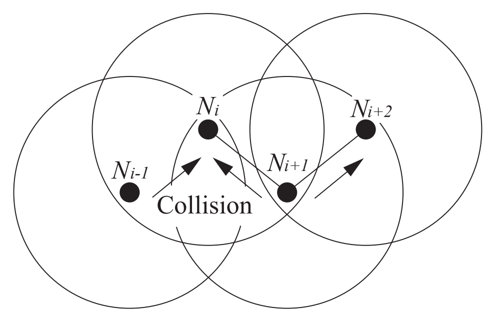

Figure 1. Collision of Successively Transmitted Data Messages due to the Hidden-Terminal Problem in Wireless Multihop Networks.

In Peer-to-Peer (P2P) type network applications in which multimedia data such as voice, picture and video data is transmitted bi-directionally, sequences of data messages are transmitted concurrently in both directions along a wireless multihop transmission route between two terminal wireless nodes, N_0 and N_n. Here, it is expected that collisions of data messages transmitted in the same and/or the opposite directions occur much more frequently than the cases of uni-directional transmissions of a sequence of data messages. For improvement of performance of bi-directional transmissions, the introduction of network coding communication has been

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proposed [2]. As shown in Figure 2, an intermediate node N_i broadcasts a network coded data message m_e for transmission of data messages m_f from N_{i-1} and m_b from N_{i+1}, e.g., $m_e := m_f \oplus m_b$. On receipt of m_e, N_{i-1} and N_{i+1} induce m_b and m_f by using m_e broadcasted by N_i and m_f and m_b buffered in N_{i-1} and N_{i+1}, respectively, e.g., $m_b = m_e \oplus m_f$ in N_{i-1} and $m_f = m_e \oplus m_b$ in N_{i+1}. By using this network coding communication, fewer messages are transmitted than the usual combination of two one-to-one data message transmissions from N_i to N_{i-1} and from N_i to N_{i+1}. In addition, by reducing the number of transmitted data messages, the opportunities of collisions among data messages and/or control messages, such as ACK control messages, are reduced. Hence, end-to-end performance such as transmission delay and throughput of data messages is expected to be improved.

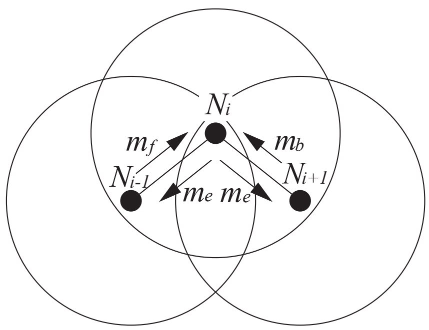

Figure 2. Network Coding Communication in Wireless Multihop Networks.

However, collisions between data and/or control messages caused by bi-directional transmissions of sequences of data messages might cause reduction of transmission performance. Hence, the RTS/CTS control should be introduced for collision avoidance, which should be modified for network coding communication since the original one is designed for ad-hoc communication and uni-directional wireless multihop transmission of data messages. This paper proposes a novel extended RTS/CTS control for network coding communication which improves end-to-end transmission performance.

In Section II, we explain related works. Our proposed novel RTS/CTS control method for network coding communication is proposed in Section III. Performance improvement by our proposal is evaluated in Section IV. Finally, we conclude in Section V.

II. RELATED WORK

This section explains conventional methods to exchange control messages such as RTS, CTS and ACK for collision avoidance in network coding communication in wireless multihop networks. Some of them are designed for wireless multihop networks and the others are designed for wireless ad-hoc networks, i.e., for supporting 1-hop data message exchanges between neighbor wireless nodes. However, for comparison with our proposal, they are explained as being used for data message transmissions along a wireless multihop transmissions. That is, as being network coding communication methods among successive intermediate nodes, N_{i-1}, N_i and N_{i+1}. Hence, N_i has two data messages, one is received from N_{i-1} and is about to be forwarded to N_{i+1} and the other is received from N_{i+1} and is about to be forwarded to N_{i-1}, configures a network encoded data message by using these data messages and then broadcasts the network encoded message to its wireless transmission area including both N_{i-1} and N_{i+1}.

COPE [2] and IFNCPA (Inter-Flow Network Coding with Passive ACK) [4] propose methods to exchange ACK control messages in network coding communication. If both N_{i-1} and N_{i+1} send back ACK control messages to N_i with a $SIFS$ interval after receipt of network coded data message broadcasted from N_i in accordance with a wireless LAN protocol IEEE 802.11, a collision between these two ACK control messages occurs at N_i and N_i fails to receive these ACK control messages. Hence, N_i cannot detect the correct receipts of the network coded data message in N_{i-1} and N_{i+1}. In order to avoid collisions between the ACK control messages transmitted simultaneously, COPE proposes a method in which an ACK control message for receipt of the network coded data message is piggybacked to the next data message transmitted by N_{i-1} and N_{i+1}, as shown in Figure 3. COPE was originally designed not for wireless multihop communication but for wireless ad-hoc communication. Since N_{i-1} and N_{i+1} independently require to transmit their next data message, collisions of the piggybacked ACK control messages are expected to be avoided; however, the intervals of the ACK control messages after receipt of the network coded data message depend on the applications in N_{i-1} and N_{i+1}. The network coded data message tends to be retransmitted frequently.

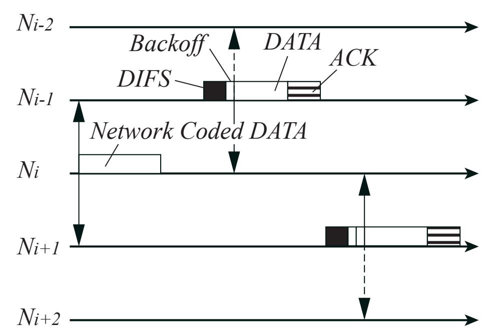

Figure 3. ACK Control Message Piggybacked to Data Message in COPE.

IFNCPA is based on the same idea in COPE but is designed for wireless multihop communication. On receipt of the network coded data message broadcasted from an intermediate node N_i, both of its neighbor intermediate nodes N_{i-1} and N_{i+1} extract the data messages to be received. Since all three wireless nodes are in a route, both N_{i-1} and N_{i+1} are required to forward data messages received from N_i. Thus, after a DCF Inter Frame Space ($DIFS$) interval and their random backoffs for collision avoidance, N_{i-1} and N_{i+1} forward the received data message to their neighbor intermediate nodes N_{i-2} and N_{i+2}, respectively. Since N_i is included in wireless transmission ranges of both N_{i-1} and N_{i+1}, it can overhear these data messages which play the role of passive ACK control messages for the network coded data message broadcasted by N_i. Different from the ACK control messages piggybacked to the next data messages in COPE, the passive ACK control messages in IFNCPA are surely transmitted after an estimated interval since the data messages are surely forwarded, as shown in Figure 4. This solves the retransmission problem in COPE. However, it is highly possible for N_{i-1} and N_{i+1} to forward the data messages simultaneously since N_{i-1} and N_{i+1} are hidden terminals for N_i. As a result, these forwarded data messages might collide at N_i. This means a failure of passive ACK control message transmissions to N_i. Hence, for network coding communication, the RTS/CTS control is mandatory for collision avoidance between the ACK control messages.

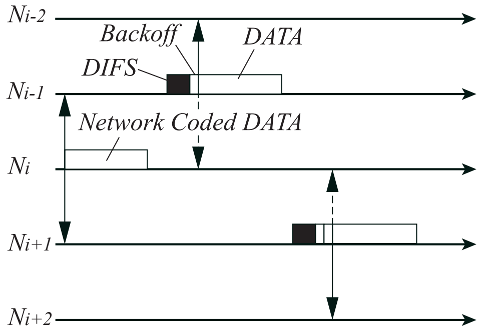

Figure 4. Pseudo ACK by Overhearing of Forwarded Data Message in IFNCPA.

In transmissions of data messages along a route, for avoidance of collisions caused between 1-hop neighbor intermediate nodes, i.e., between exposed ones, and between 2-hop neighbor intermediate nodes, i.e., between hidden ones, data and control message transmissions by 1-hop and 2-hop neighbor nodes, N_{i-2}, N_{i-1}, N_{i+1} and N_{i+2} should be suspended for data message transmissions by N_i. Thus, the introduction of the RTS/CTS control is inevitable. In the usual RTS/CTS control for a data message transmission from N_i to N_{i+1}, N_i broadcasts an RTS control message which reaches both N_{i-1} and N_{i+1} and then N_{i+1} broadcasts a CTS control message which reaches both N_i and N_{i+2}. Even if N_{i-1} receives an RTS control message from N_{i-2}, N_{i-1} never sends back a CTS control message. Therefore, a data message from N_i never collides with another data message transmitted along the route. However, in network coding communication, N_i transmits data messages to both N_{i-1} and N_{i+1} by broadcasting the network coded data message. So, the RTS control message transmission from N_{i-2} should also be avoided. This means that the transmission of the CTS control message is required not only for N_{i+1} but also for N_{i-1}. For collision-free transmissions of network coded data messages, it is required for N_i to receive the CTS control messages from both N_{i-1} and N_{i+1}. In the original RTS/CTS control in wireless LAN protocols such as IEEE 802.11, a CTS control message is broadcasted with the $SIFS$ interval after receipt of the broadcasted RTS control message. Hence, CTS control messages from N_{i-1} and N_{i+1} surely collide at N_i in network coding communication.

In CSMA with RTS/CTS [5] and NC-MAC [1], the order information of the transmissions of CTS control messages is included in an RTS control message. As shown in Figure 5, according to the order the information is piggybacked onto the RTS control message from N_i, one of N_{i-1} and N_{i+1} broadcasts a CTS control message with the $SIFS$ interval after receipt of the RTS control message and the other broadcasts a CTS control message with an interval enough for avoidance of a collision between the CTS control messages at N_i. This method is also applied to avoid collisions between the ACK control messages transmitted to N_i by N_{i-1} and N_{i+1} after receipt of a network coded data message from N_i. Though, different from the CTS control messages broadcasted by N_{i-1} and N_{i+1}, the ACK control messages are unicasted to N_i by N_{i-1} and N_{i+1}, these are transmitted simultaneously, which causes a collision at N_i. Hence, the order information of the ACK messages is included in the network coded data message. This method works well for avoidance of collisions of the CTS and ACK control messages at N_i; however, the required time duration for a transmission of a network coded data message causes a longer data message transmission delay and lower end-to-end throughput of data messages.

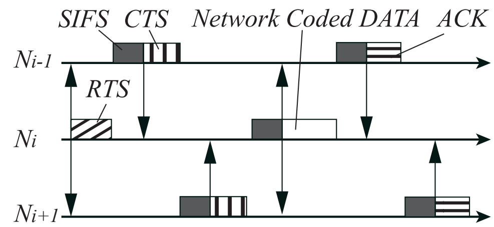

Figure 5. Collision Avoidance of CTS and ACK Control Messages in NC-MAC.

Adaptive Round-Robbin Acknowledge and Retransmit (ARAR) [3] is a method for a multicast data message transmission in a wireless ad-hoc network. A sender node N_s broadcasts an RTS control message to all its neighbor nodes in its wireless transmission range. After a $SIFS$ interval, all the receiver nodes which successfully receive the RTS control message send back a CTS control message to N_s. If multiple receiver nodes simultaneously send back the CTS control messages to N_s, these collide at N_s and N_s cannot receive these CTS control messages correctly, as shown in Figure 6. Hence, N_s cannot determine which receiver wireless nodes received the RTS control message correctly. However, N_s identifies the following three cases: (1) no receiver nodes correctly received the RTS control message if no CTS control message is sent back to N_s. (2) only 1 receiver node correctly received the RTS control message if only 1 CTS control message is transmitted and received by N_s correctly, i.e., without collisions. (3) multiple receiver nodes correctly received the RTS control message if multiple CTS control messages are transmitted and collide at N_s. Our proposal for performance improved network coding communication is based on this 3-cases identification in ARAR.

III. PROPOSAL

We suppose wireless multihop networks with bi-directional and concurrent transmissions of sequences of data messages along a wireless multihop transmission route between two

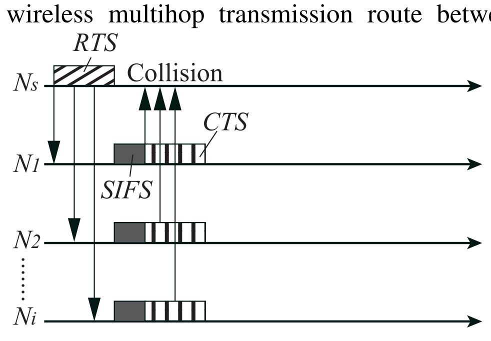

Figure 6. Collision of $CTSs$ in ARAR.

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terminal wireless nodes. Here, most of the intermediate wireless nodes temporarily hold data messages in transmission for both directions in their buffer. This is because data message transmissions between two successive intermediate nodes are based on the half-duplex communication. Hence, there are so many opportunities to apply the network coding communication in which each intermediate node encodes data messages transmitted in different directions into one combined data message and broadcasts it to transmit it to its neighbor intermediate nodes in both directions that the end-to-end transmission performance such as end-to-end transmission delay and end-to-end throughput is expected to be improved. However, as discussed in the previous section, a sequence of data messages transmitted along a route tends to collide at intermediate nodes due to exposed and hidden node problems. Especially, it is more difficult to avoid and/or reduce collisions in bi-directional and concurrent transmissions of data messages along a route. Hence, collision avoidance methods such as the RTS/CTS control should be introduced. On the other hand, since an intermediate node broadcasts a network coded data messages to transmit original data messages to both directions to its two successive intermediate nodes in both directions different from the original one-way transmissions, an extended RTS/CTS control is required to be designed. Though some methods for the RTS/CTS control in network coding communication have been proposed as in the previous section; however, their additional overhead is unignorable. Thus, the advantage of the network coding communication is tremendously reduced.

In order to solve this problem, this paper proposes a novel extended RTS/CTS control and transmissions of ACK control messages for network coding wireless multihop transmissions based on ARAR supporting multicast transmissions of data messages in wireless ad-hoc networks. As shown in Figure 7, in order for an intermediate node N_i to broadcast a network coded data message m_e of data messages m_f and m_b received from N_{i-1} and N_{i+1}, respectively, N_i broadcasts an RTS control message destined to N_{i-1} and N_{i+1} to all its neighbor nodes within its wireless signal transmission range. On receipt of the RTS control message, N_{i-1} and/or N_{i+1} broadcast CTS control messages destined to N_i to all their neighbor wireless nodes within their wireless signal transmission ranges after a $SIFS$ interval if it is possible for N_{i-1} and/or N_{i+1} to receive a data message from N_i, i.e., N_{i-1} and/or N_{i+1} have not yet received RTS or CTS control messages from their neighbor wireless nodes. Neither N_{i-1} nor N_{i+1} is transmitting a data message since it is possible for N_i to transmit the RTS control message; this means that N_i has not received an RTS control message from N_{i-1} and/or N_{i+1}.

Among the neighbor nodes of N_i, which have received the RTS control message from N_i, it is possible only for N_{i-1} and N_{i+1} to broadcast CTS control messages. Hence, there are only the following 4 cases for N_i on receipts of CTS control messages (Figure 7):

- Both N_{i-1} and N_{i+1} broadcast CTS control messages and N_i detects a collision of them.
- Only N_{i-1} broadcasts a CTS control message and N_i receives it.
- Only N_{i+1} broadcasts a CTS control message and N_i receives it.
- Neither N_{i-1} nor N_{i+1} broadcasts a CTS control message and N_i receives no CTS control messages.

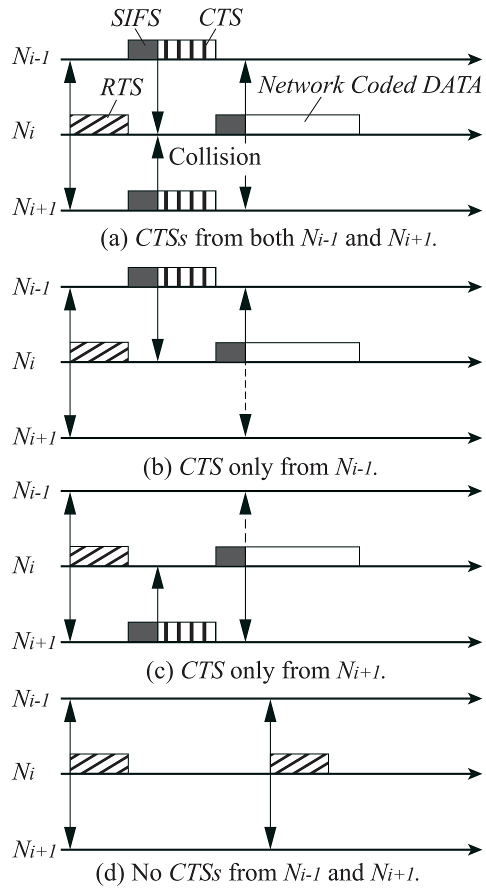

Figure 7. Acceptance of CTS by Collision Detection.

If both N_{i-1} and N_{i+1} broadcast CTS control messages, these CTS messages collide at N_i since both of them are transmitted with the same $SIFS$ interval after receipts of the RTS control message from N_i. However, since it is impossible for N_i to detect a collision in all the other 3 cases, by detection of a collision N_i determines that the collision is caused by the concurrently transmitted CTS control messages from N_{i-1} and N_{i+1}. That is, N_i finds that both N_{i-1} and N_{i+1} notify N_i of their possibility for receipt of a forthcoming data message by transmissions of their CTS control messages and broadcasts a network coded data message m_e of m_f and m_b.

If either N_{i-1} or N_{i+1} broadcasts a CTS control message in response to the RTS control message from N_i, N_i receives the CTS control message without a collision. Thus, N_i finds that only one of the successive intermediate nodes in a route broadcasts the CTS control message, which means that only the sender intermediate node is ready for receipt of a data message from N_i and the other is currently impossible to receive it. Then, N_i broadcasts the network coded data message or the original data message to the successive intermediate node broadcasting the CTS control message. The data message is expected to be received correctly by the receiver node. In addition, no collisions are caused at the successive intermediate node of N_i, which does not broadcast a CTS control message since it does not broadcast it due to not to be a sender or a receiver node but a receipt of an RTS or a CTS control message from its neighbor node other than N_i. Otherwise, both N_{i-1} and N_{i+1} has already been received RTS and/or CTS control messages from their neighbor nodes and are not possible to receive data messages from N_i. N_i tries to rebroadcast an RTS control message after a $DIFS$ interval.

Same as CTS control messages, ACK control messages for a network coded data message broadcasted by N_i are broadcasted by N_{i-1} and N_{i+1} and their collisions are treated. After detection of a collision between the CTS control messages from N_{i-1} and N_{i+1}, N_i broadcasts a network coded data message m destined to N_{i-1} and N_{i+1} with a $SIFS$ interval. On receipt of the network coded data message m, N_{i-1} and/or N_{i+1} transmit ACK control messages to N_i after a $SIFS$ interval if N_{i-1} and/or N_{i+1} receive the network coded data message correctly. Among the neighbor nodes of N_i, which have received the RTS control message from N_i, it is possible only for N_{i-1} and N_{i+1} to transmit ACK control messages. Hence, there are only the following 4 cases for N_i on receipts of ACK control messages (Figure 8):

- Both N_{i-1} and N_{i+1} transmit ACK control messages and N_i detects a collision of them.
- Only N_{i-1} transmits an ACK control message and N_i receives it.
- Only N_{i+1} transmits an ACK control message and N_i receives it.
- Neither N_{i-1} nor N_{i+1} transmits an ACK control message and N_i receives no ACK control messages.

If both N_{i-1} and N_{i+1} transmit ACK control messages, these ACK messages collide at N_i since both of them are transmitted with the same $SIFS$ interval after receipts of the network coded data message from N_i. However, since it is impossible for N_i to detect a collision in all the other 3 cases, by detection of a collision N_i determines that the collision is caused by the concurrently transmitted ACK control messages from N_{i-1} and N_{i+1}. That is, N_i finds that both N_{i-1} and N_{i+1} notify N_i of their receipt of the network coded data message by transmissions of their ACK control messages.

If either N_{i-1} or N_{i+1} transmits an ACK control message in response to the network coded data message from N_i, N_i receives the ACK control message without a collision. Thus, N_i finds that only one of the successive intermediate nodes in a route transmits the ACK control message, which means that only the sender intermediate node received the network coded data message from N_i and the other failed to receive it. Then, N_i tries to retransmit a data message destined to the successive intermediate node from which N_i does not receive an ACK control message. In this case, it is possible for N_i to transmit either only the original message failed to transmit to the node or another network coded data message for the original message failed to transmit to the node and another buffered data message destined to the other successive intermediate node of N_i. For performance improvement point of view, the latter, i.e., a network coded data message is desirable to be transmitted. Otherwise, both N_{i-1} and N_{i+1} has already been received RTS and/or CTS control messages from their neighbor nodes and are not possible to receive data messages from N_i. N_i tries to rebroadcast an RTS control message after a $DIFS$ interval.

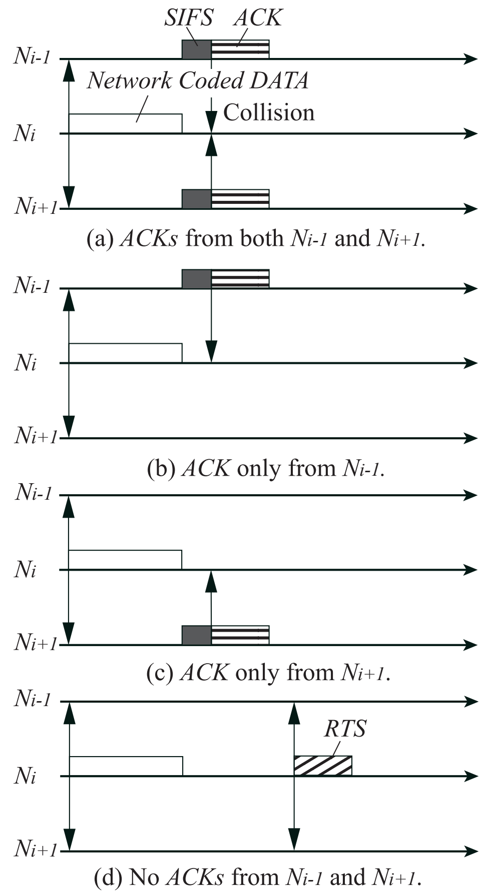

Figure 8. Acceptance of ACK by Collision Detection.

In the proposed method, the concurrent transmissions of CTS control messages transmitted by N_{i-1} and N_{i+1} are recognized by N_i by the collision of the messages at N_i. The collision is detected not only by N_i but also all the nodes included in both of the wireless signal transmission ranges of N_{i-1} and N_{i+1}. The nodes included in the wireless signal transmission range of N_i receive the RTS control message from N_i and is notified of the transmission request for a network coded data message by N_i and the NAV which represents the interval when the neighbor nodes suspend to initiate a data message transmission and keep silent. However, the nodes out of the wireless signal transmission range of N_i and detect the collision of the CTS control messages cannot achieve the NAV. Hence, it is possible for such nodes to broadcast an RTS or a CTS control message to initiate a transmission or a receipt of a data message though N_{i-1} and N_{i+1} are included in the wireless signal transmission range of the nodes as shown in Figure 9. The probability of occurrences of collisions at N_{i-1} and/or N_{i+1} caused by a data or a control message depends on the distances between successive intermediate nodes N_{i-1}, N_i and N_{i+1}, i.e., the lengths of communication links $\langle N_{i-1}N_i \rangle$ and $\langle N_i N_{i+1} \rangle$, their angle and transmission request ratio of data messages along the route.

IV. EVALUATION

This paper proposes a novel RTS/CTS control for collision avoidance in bi-directional wireless multihop transmissions of sequences of data messages supporting P2P type multimedia network applications. In order to evaluate the

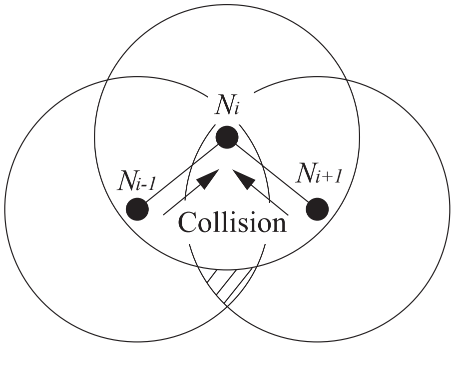

Figure 9. NAV Unacceptable Areas due to Collision of CTS Messages.

advantage of the proposed method, which allow two successive intermediate wireless nodes to broadcast CTS control messages and to transmit ACK control messages concurrently with the same $SIFS$ interval after receipts of a broadcasted RTS control message and a network coded data message from N_i, this section evaluates end-to-end throughput of data messages in simulation experiments.

Here, two terminal nodes and all the intermediate nodes are located with 100m spaces. All the nodes communicate with a 101m wireless signal transmission range by IEEE 802.11b wireless LAN protocol. Hence, in this simulation, only collisions of control and/or data messages along the route are considered. That is, there are no other routes. Appropriate routing tables are assumed to be set in advance in all the nodes. Length of routes are 2–19 hops, i.e., there are 1–18 intermediate nodes in a route and sequences of data messages are transmitted in both direction between the two terminal nodes. End-to-end throughput of data messages are evaluated in the proposed method in comparison with a naive wireless multihop transmission with the original RTS/CTS control and without network coding communication and NC-MAC where the transmission order of CTS and ACK control messages are indicated by the intermediate node broadcasting a network coded data message (See Section 2). All the related protocols are implemented on ns-3 simulator [6].

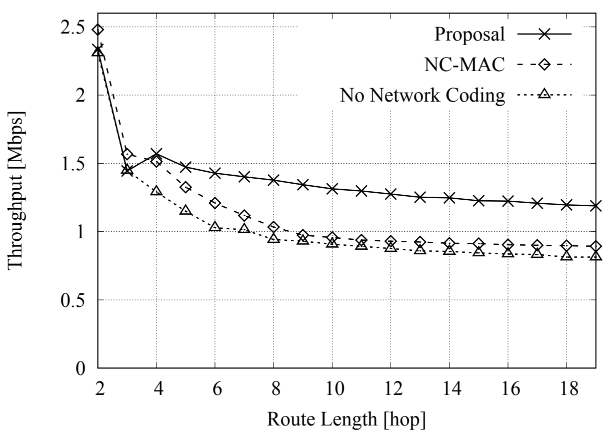

Figure 10. End-to-End Throughput of Data Message.

Figure 10 shows the results of the simulation experiments. The horizontal axis represents the length of routes and the vertical axis represents the average end-to-end throughput of data messages.

First, the end-to-end throughput of data messages in NC-MAC is averagely 11.5% higher than the naive transmissions with the usual RTS/CTS control and without network coding communication. In cases of more than 9-hop routes, the performance improvement is almost the same as 7.8%. Anyway, it is clear that the advantage of network coding communication and avoidance of collisions between data and control messages is reasonable. However, as mentioned in Section 2, 6-phase transmissions, i.e., RTS, CTS, CTS, network coded data message, ACK, ACK are required in NC-MAC and 8-phasetransmissions, i.e., RTS, CTS, original data message, ACK, RTS, CTS, original data message, ACK are required in the naive approach.

Next, in the comparison between our proposed method and NC-MAC, NC-MAC is superior to the proposed method in routes with less than 4 hops. However, in routes with more than 4 hops, the proposed method performs much better than NC-MAC. This is because the proposed method requires only 4-phase transmissions RTS, CTS, network coded data message, ACK by introduction of collision detection for receipt of concurrently transmitted CTS and ACK control messages. Totally, the proposed method achieves 30.1% and 42.2% higher end-to-end throughput of data messages than NC-MAC and the original RTS/CTS control without network coding communication, respectively.

V. Conclusion

This paper has proposed a novel RTS/CTS control for collision avoidance in network coding communication for bi-directional concurrent transmissions of sequences of data messages in wireless multihop networks. Here, receipt of CTS and ACK control messages from two successive intermediate nodes are recognized by an intermediate node transmitting a network coded data message by their collision. The results of simulation experiments show that the proposed method achieves more than 30% higher end-to-end throughput of data messages. For higher performance, the authors is designing a more cooperative protocol for network coding communication to have more opportunities to apply the network coding transmissions of both directional data messages.

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