Performance Evaluation of TDMA Based Wireless Network Coding Prototype System

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***Abstract*— This paper presents the feasibility of a wireless network coding prototype system based on time division multiple access using the global positioning system to facilitate the synchronization of wireless nodes. We evaluate the system throughput of a system where wireless network coding and data aggregation are jointly applied in a saturated traffic environment based on Ethernet including 1,518 and 218 bytes data lengths assuming web browsing and VoIP applications. Experimental results show that wireless network coding with aggregation improves the system throughput by approximately 1.85-fold compared to a system without wireless network coding or aggregation.**

Keywords- wireless network coding, multihop, TDMA, GPS

I. INTRODUCTION

Wireless multihop systems have received a great deal of attention recently due to their capability for easy expandability of wireless service areas. Wireless multihop systems where packets are relayed between wireless nodes located at separate locations enable wireless communications between the sub-networks at those locations as shown in Fig. 1. The systems are expected to resolve the digital divide problem. They are also expected to function as backup networks for areas where wired networks are destroyed due to serious disasters.

Wireless multihop systems consume the same number of frequency channels as the number of wireless links (hops) in order to avoid imparting or incurring interference from other links. However, there has been a shortage in the available frequency bandwidth recently because many new wireless systems require a wide frequency bandwidth. In addition, the number of users using those wireless systems is increasing. Therefore, it is difficult for wireless multihop systems to have multiple frequency channels. Higher frequency utilization efficiency in wireless multihop systems must be achieved to meet the demand for wireless broadband services even when only one channel can be used.

Wireless network coding (WNC) is one of the most promising techniques to achieve higher frequency utilization efficiency in wireless multihop systems [1-8]. The basic idea of WNC for a bidirectional two-hop wireless network in an Alice and Bob topology [2] is that the relay node (RN) superposes two bidirectional relay signals received from the Alice node (AN) and Bob node (BN) and broadcasts them to both the BN and AN simultaneously. This reduces the number of required

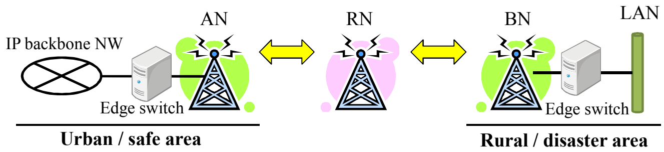
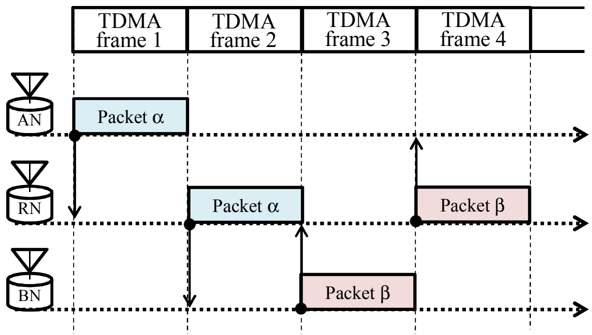
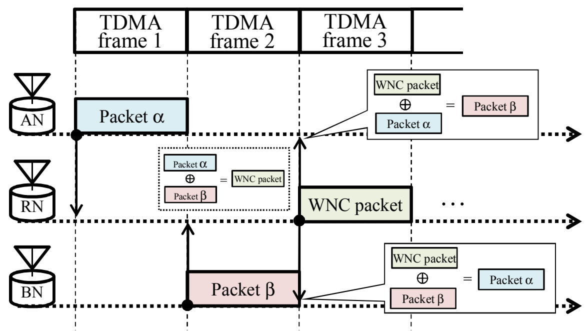


Figure 1. Application image.



(a) Non-WNC systems.



(b) WNC systems.

Figure 2. TDMA based systems with frame assignment for bidirectional communications for (a) non-WNC systems and (b) WNC systems.

transmissions in the two-hop wireless network for bidirectional communications. WNC can be applied to distributed control based systems such as carrier sense multiple access (CSMA) or centralized control based systems such as time division multiple access (TDMA). CSMA based WNC systems were well investigated from the aspects of implementation and analysis based on computer simulations [4-8]. However, CSMA based systems cannot always obtain a benefit from WNC because the RN in CSMA based systems does not

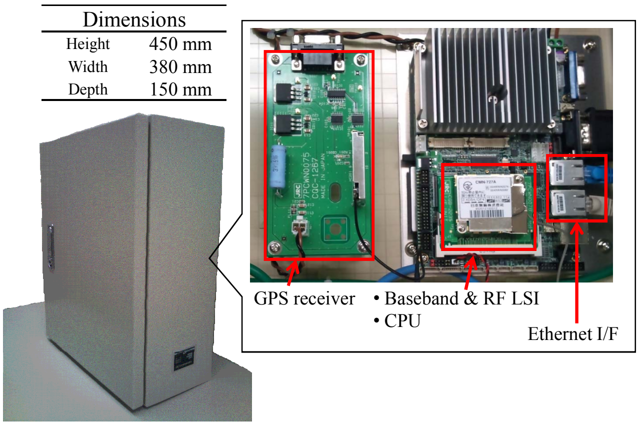


Figure 3. Outlook of prototype.

Table I. Specifications

PHY Layer Specifications	
Carrier frequency band	5.15 ~ 5.35, 5.47 ~ 5.725 GHz
Frequency bandwidth	20 MHz
Modulation	OFDM (64QAM, 16QAM, QPSK, BPSK)
FEC	Convolutional code (K = 7) (R = 1/2, 2/3, 3/4) Soft decision Viterbi decoder
FFT point	64
MAC Layer Specifications	
Access control	Pre-assign type TDMA
Criteria of time synchronization	GPS
Maximum payload size	2,290 bytes

always hold both packets received from the AN and BN when the RN obtains a transmission opportunity.

On the contrary, TDMA based systems can always obtain a benefit from WNC because all nodes can be assigned a transmission opportunity in turn. Thus, we focus on WNC in TDMA based systems in terms of the maximum achievable throughput. When WNC is applied to TDMA based systems, the number of time slots necessary for bidirectional communications is reduced from 4 to 3 as shown in Fig. 2. Therefore, WNC can gain a 4/3-fold higher system throughput without increasing the frequency bandwidth.

In this paper we introduce the developed WNC prototype system utilizing the global positioning system (GPS) to facilitate the time synchronization of wireless nodes. In addition, we present experimental results on the throughput performance of the prototype system in order to confirm the feasibility and throughput improvement of WNC based on the TDMA system.

II. PROTOTYPE SPECIFICATIONS

A. Overview

Fig. 3 shows an outlook of a wireless node of the prototype system. The prototype system consists of three wireless nodes: the AN, RN, and BN. The wireless node shown in Fig. 3 can be used as either the AN, RN, or BN. The wireless node is encased in a water and dust proof chassis since the system is to be used outdoors. The AN and BN have Ethernet interfaces so

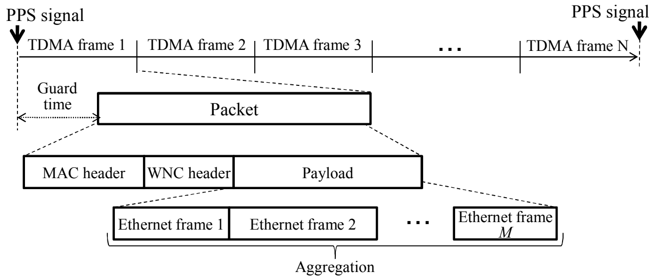


Figure 4. Frame structure of prototype.

that they can connect to their respective networks through Ethernet. The RN does not have a network connection to the other networks. The AN and BN communicate with each other over the air in order to exchange the Ethernet frame input from the interfaces. The WNC functionality is implemented in the RN. In addition, an aggregation function is implemented in both the AN and BN in order to improve the system throughput. We describe the aggregation scheme in Section III B.

B. PHY Specifications

The PHY layer adopts 5-GHz wireless LAN based orthogonal frequency division multiplexing (OFDM) modulation. It provides a 54-Mbps transmission mode with 64QAM (R = 3/4) as the maximum data rate.

C. MAC Frame Structure

Time synchronization is achieved by utilizing a pulse per second (PPS) signal received from the GPS in 1 s cycles. Each wireless node equally divides the 1 s cycle into N TDMA frames. In order to achieve easy time synchronization with GPS, this prototype system adopts a pre-assigned type of TDMA. The difference between the PPS estimated by different GPS modules that are located separately is 100 ns at maximum [9]. The difference between the timers of different GPS satellites is less than 100 ns [10]. Therefore, the maximum estimation error for the PPS estimated at each wireless node is calculated to be 200 ns. We consider that GPS is sufficient to synchronize wireless nodes since the prototype system employs a guard time of 500 µs. Each wireless node transmits its packets according to the TDMA frame assignment pattern that is preliminarily determined as shown in Fig. 2 (b).

At TDMA frame 1

- The AN transmits its α packet to the RN.
- The RN receives and stores the packet in the buffer.

At TDMA frame 2

- The BN transmits its β packet to the RN.
- The RN receives and stores the packet in the buffer.

At TDMA frame 3

- The RN generates the WNC packet encoding the stored packets and broadcasts it to the AN and BN.
- The AN decodes the received WNC packet using its own α packet transmitted in TDMA frame 1 to obtain the packet from the BN.
- The BN decodes the received WNC packet using its own β packet transmitted in TDMA frame 2 to obtain the packet from the AN.

After TDMA frame 3, the cycle of these three frames is repeated.

Fig. 4 shows the frame structure used in this prototype system. In each TDMA frame, one packet is transmitted. The packet consists of a MAC header, WNC header, and the payload. The WNC header indicates the IDs of the payloads contained in the packet. The payload is an Ethernet frame that consists of an Ethernet header and a data component. If aggregation is applied, the payload can contain a number of Ethernet frames.

III. FUNCTIONS IMPLEMENTED IN PROTOTYPE

A. Wireless Network Coding

In most previous studies, exclusive OR (XOR) is used as the wireless network coding scheme [2, 4-8]. Therefore, we implemented XOR as the WNC scheme for this prototype system in order to verify the feasibility.

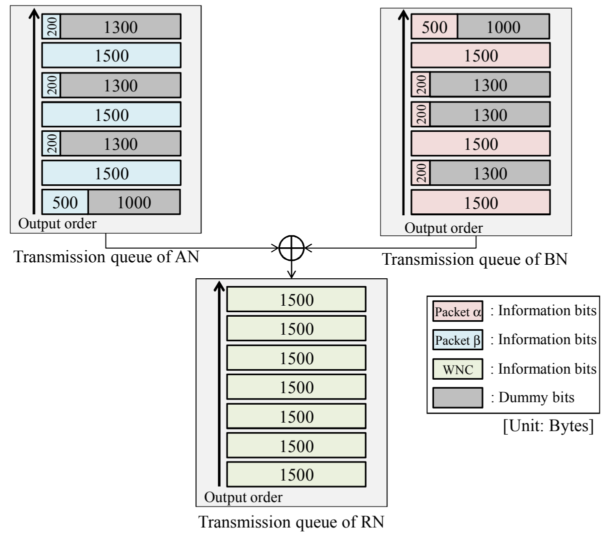
The AN and BN transmit α and β packets, respectively, and store the transmitted payload with the payload ID in their transmitted buffers for XOR decoding. The RN receives the α and β packets in TDMA frames 1 and 2, respectively, and uses the cyclic redundancy check (CRC) to verify whether or not the received packets α and β are correct. If the CRC results show that the packet is not correct, the RN discards the packet in order to prevent error propagation. Only when the CRC results shows that the packet is correct, the RN stores the payloads of the received α and β packets in relay buffers α and β, respectively.

In TDMA frame 3, the RN checks both relay buffers to see whether any payload remains in the buffers. If there are payloads in both relay buffers, the RN executes XOR for the first payload in each buffer to generate a WNC packet and broadcasts it to both the AN and BN. If only one buffer contains a payload, the RN transmits the first payload in the non-empty buffer. If there is no packet in either buffer, the RN skips the assigned TDMA frame.

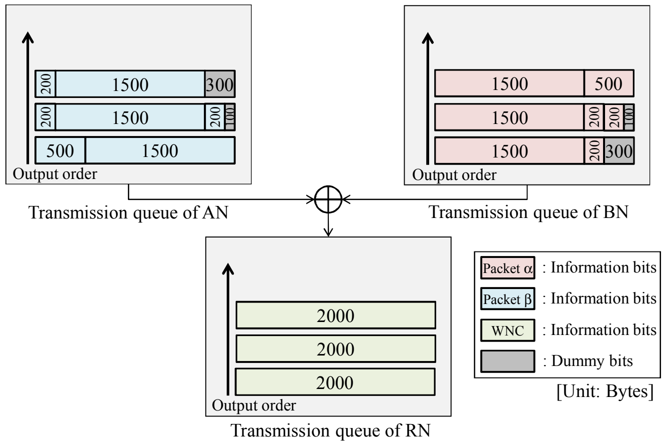
The payload ID and the number of Ethernet frames contained in the WNC packet are stored in the WNC header. The WNC encodes only the payload part of the α and β packets. The MAC header and WNC header are not XOR encoded because the AN and BN refer to the payload ID in order to select the corresponding transmitted payload from their transmitted buffers for XOR decoding. The AN and BN extract the required β and α packets by operating XOR with the selected payload.

B. Aggregation

We assume that this system will be used as an entrance network. Therefore, a number of terminals are connected to the AN and BN. In a real situation, users use a variety of applications, e.g., web browsing, VoIP, and video streaming. Thus, the traffic that the AN and BN transmit includes Ethernet frames with a variety of data lengths. If the lengths of a pair of packets for WNC are different, the shorter packet must be padded with dummy bits so that the length of the padded packet is as long as the longer packet because bit-by-bit XOR is employed. Thus, the generated WNC packet has



(a) Without aggregation.



(b) With aggregation.

Figure 5. Transmission queues for AN and BN with and without aggregation.

the same length as the longer packet. Dummy bits do not contribute to the information transmission. Therefore, the shorter packet in the traffic degrades the system throughput of WNC systems.

In order to reduce the number of dummy bits included in WNC packets, we implement an aggregation scheme for the Ethernet frames in the prototype system. In this aggregation scheme, the AN and BN aggregate Ethernet frames kept in their transmission queues that are input from the Ethernet I/F and output as one payload. The aggregate payload consists of various lengths of Ethernet frames. Thus, the lengths of aggregate payloads are expected to be similar due to the statistic multiplexing effect. In other words, the number of dummy bits for padding the shorter packet in the WNC packet is expected to be small. Thus, the system throughput can be improved by using the aggregation scheme.

Although the aggregation schemes for WNC systems are generally executed at the RN [7, 8], the prototype system carries out the aggregation scheme at the AN and BN. This is because, in the prototype system, the same numbers of TDMA frames with equal length are assigned to each wireless node due to the pre-assigned type of TDMA. The TDMA frame

Table II. Experimental Parameters

Transmission mode	54 Mbps
Maximum payload size, L_{max}	2.172 bytes
Propagation environment	AWGN (cable connected)
Traffic model	Saturated traffic with 1,518 and 218 bytes Ethernet frame lengths (Probability of each occurrence: 50 %)

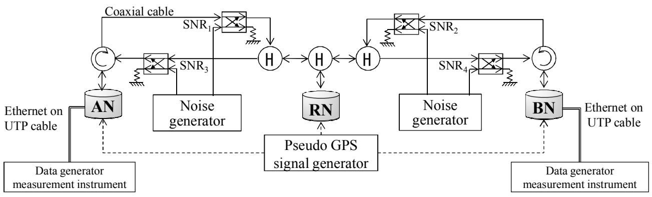


Figure 6. Experimental configuration.

length needs to suit the longest packet of the traffic. Therefore, the other aspect of aggregation at the AN and BN is to improve the TDMA frame efficiency.

Fig. 5 shows an example of the transmission queues of the AN, BN, and RN in the WNC systems with and without aggregation. The aggregation scheme aggregates as many Ethernet frames as possible in the transmission queue under the condition that the aggregate payload is within the preset limit of the payload size of L_{max}. The fragmenting and reordering of Ethernet frames are not implemented in this prototype for the sake of signal processing simplicity. Let us set L_{max} to 2,000 for example. In the transmission queue of the AN without aggregation, the total length of the first 2 payloads equals 2,000 bytes. Therefore, the number of aggregated Ethernet frames for the first AN aggregate payload is 2 with no padding. In the transmission queue of the BN without aggregation, the total length of the first 2 payloads equals 1,700 while the first 3 payloads equals 3,200, which is beyond the limit. Therefore, the number of aggregated Ethernet frames for the first BN aggregate payload is 2 with 300 bytes of padding. The same calculation is repeated for the remaining payloads. As a result, after the aggregation scheme, the number of dummy bits is reduced to 800 bytes in total while that without aggregation is 9,800 bytes as shown in Fig. 5. Thus, the aggregation scheme is effective in improving the system throughput.

IV. Experiment Results

A. Packet Error Rate Performance

We evaluated the packet error rate between the AN and BN via the RN when WNC is applied in order to confirm the PHY layer performance. Fig. 6 shows the experimental configuration. We evaluated the performance when the wireless nodes are connected by coaxial cables. Additive white Gaussian noise (AWGN) is added to all the links using the external noise generators shown in Fig. 5. The signal-to-noise ratios (SNRs) of all the links are set to the same value, i.e., $SNR_1 = SNR_2 = SNR_3 = SNR_4$. Since this experiment is conducted indoors, the prototype cannot receive PPS signal from the GPS. Therefore, we used a pseudo-GPS signal generator instead of the real GPS. The payload size is set to 1,518 bytes, which is the maximum transfer unit (MTU) of Ethernet with an Ethernet header [11].

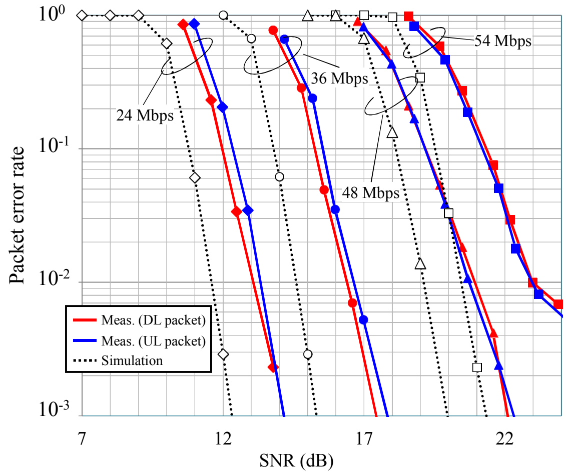


Figure 7. Packet error rate.

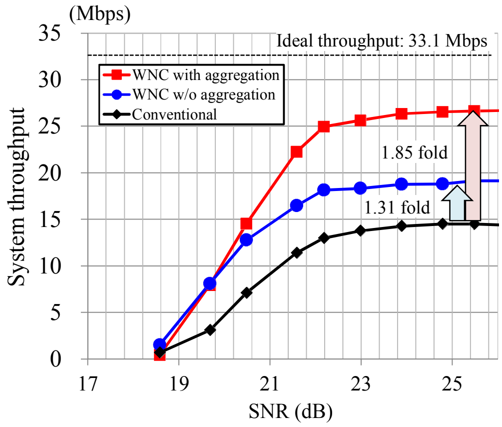


Figure 8. System throughput for 54-Mbps mode.

Fig. 7 shows the packet error rate (PER) performance against the SNRs for the transmission modes of 54-Mbps, 48-Mbps, 36-Mbps, and 24-Mbps. The dotted lines represent the simulation results. The time synchronization between wireless nodes, and the time and frequency offsets between the transmitter and receiver sides are ideal in the simulations. The solid lines represent the measurement results. The red and blue lines for the experimental results represent the performances for the α and β packets, respectively. They yield almost the same performance since the SNRs of all the links are set to the same value. The experimental results show a degradation within 2.5 dB at maximum compared to the simulation results when we compare the required SNR to achieve the PER < 10^{-2}. The degradation in the required SNR is reasonable considering hardware imperfections. Thus, we confirm that the PHY layer works satisfactorily.

B. System Throughput Performance

The system throughput is defined as the average number of effective information bits received by the AN and BN during one cycle of bidirectional communications divided by the sum of the wireless burst length for the one cycle. The experimental conditions are given in Table II. We used a saturated traffic condition that include Ethernet frames with lengths of 1,518 bytes and 218 bytes assuming web browsing and G.711 VoIP [12] as the applications on Ethernet. The occurrence probability for each is 50%. The maximum

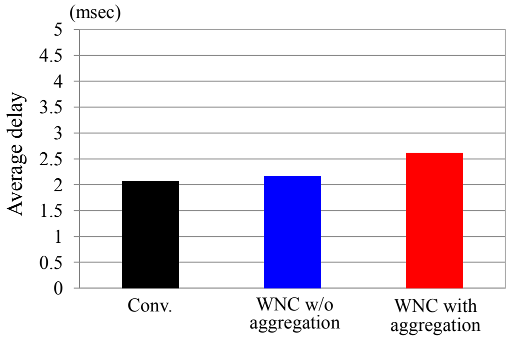


Figure 9. Average delay for 54-Mbps mode.

payload size that can be set for this prototype is 2,290. When we aggregate payloads to the densest possible in the range, the aggregate payload length becomes 2,172 bytes, which contains one web browsing and four VoIP Ethernet frames. Therefore, we set the payload size, $L_{\max}$, to 2,172 in order to achieve the most efficient TDMA frame length. In the case of non-aggregation, the payload is set to 1,518 bytes for the same reason.

Fig. 8 shows the measured system throughput performance of for the 54-Mbps transmission mode. The system throughput of each scheme increases as the SNR increases since the PER also improves as the SNR increases. When we compare the performance at SNR = 25 dB, WNC improves the system throughput by 1.31 fold compared to the conventional scheme, which employs neither WNC nor aggregation. Based on these results, we confirm that WNC uses fewer TDMA frames to communicate the same number of information bits as that for the conventional scheme.

WNC with aggregation increases the system throughput further. The ideal throughput is 33.1 Mbps when we assume that all the payloads are 2,290 bytes long without any dummy bits. Although WNC with aggregation can decrease the number of dummy bits to improve the system throughput compared to WNC only, it cannot remove all the dummy bits. Therefore, WNC with aggregation becomes degraded compared to the ideal throughput. However, WNC with aggregation increases the system throughput by 1.85 fold compared to the conventional scheme. Thus, we find that WNC with aggregation is effective in improving the system throughput of bidirectional two-hop wireless relay networks.

C. Delay Performance

We evaluate here the delay performance. Fig. 9 shows the one-way average delay per Ethernet frame received by the BN when the offered traffic is not saturated at SNR = 25 dB. WNC without aggregation exhibits worse performance than the conventional scheme. This is because the conventional scheme achieves one-way communications with a minimum of two TDMA frames while WNC requires at least three TDMA frames. The addition of aggregation to WNC further degrades the delay performance since WNC with aggregation requires a longer TDMA frame than that for WNC without aggregation. However, the recommended delay for VoIP applications that satisfies most users in is less than 150 ms [13]. The total delay including the vocoder processing delay, backbone network delay, and buffering delay for de-jittering is estimated to be 138 ms [14]. Since we assume that WNC systems are used as the entrance network to backbone networks, the allowable delay for WNC systems as an entrance network is 12 ms. WNC with aggregation incurs an average delay of approximately 2.6 ms. Therefore, the average delay of WNC with aggregation satisfies the user demand when used as an entrance network.

V. CONCLUSION

We developed and evaluated a wireless network coding prototype system based on TDMA using GPS for time synchronization. Based on the experimental results, we confirmed that WNC achieves sufficient system throughput for bidirectional two-hop wireless relay networks in a traffic scenario where Ethernet frames with the lengths of 218 and 1,518 bytes are generated with equal probability. In addition, WNC with aggregation further improves the system throughput by 1.85 fold compared to that for the conventional system while its average delay performance satisfies the user criteria for VoIP application. This verifies the feasibility of wireless network coding systems with an aggregation scheme.

VI. ACKNOWLEDGMENT

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