Wireless Packet Collision Detection Using Self-Interference Canceller

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***Abstract*—The paper considers wireless collision detection at the transmitter for wireless local area network systems. One of the major challenges to achieve such collision detection is the self-interference of very high power, which decrease the effective quantization level for the collision packet to be detected. In order to cope with the interference, we employ a self-interference canceller for each receiving antenna and combine the outputs of the cancelers with maximal ratio combining. Moreover, we utilize the correlation between the combiner output and the preamble of the packet for the detection of the existence of the collision packets. Performance of the proposed scheme is demonstrated via computer simulations.**

I. Introduction

Recently, a lot of things including smart phones, game consoles, and home electronics can access to wireless LANs (Local Area Networks), and thus the realization of the wireless LANs which can utilize radio resources more efficiency is desired. So far, considerable studies have been made from physical layer aspects to improvement the transmission performance, however, improvement of the performance from more higher layer will be crucial, because overall performance of the communications systems are often dominantly determined by that of higher layer.

CSMA/CD (Carrier Sense Multiple Access with Collision Detection) is a protocol widely used in wired LAN systems. In CSMA/CD, sending node detects packet collision by observing the channel during the transmission. The sending node stops the transmission immediately if it detects the collision in order not to waste the channel with the damaged packet by the collision. On the other hand, CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) is widely used in wireless LAN systems. Unlike CSMA/CD, this protocol is designed not to detect the packet collision but to avoid it. This is because the wireless packet collision detection has been rather difficult task due to the feature of the wireless channels and the transmitted signals.

Recently, a wireless packet collision detection method using the structure of the short preamble of IEEE 802.11 based wireless LANs has been proposed [1], and it is shown that the throughput can be considerably improved with the method [2]. In the method, taking advantages of the fact that the short preamble of IEEE 802.11a/n/g based systems is generated by using only a part of subcarriers, a node transmitting preamble signal receives the radio signals at the same time, and performs the fast Fourier transform (FFT). By checking the signal power on the subcarriers, which are not used by the preamble, the sending node can detect the collision with his preamble. In [1], orthogonal polarization antennas are also used for the transmission and the reception at the sending node, in order to decrease the impact of his own transmitted signal (self-interference) at the receiving side, and it has been reported that the isolation of 40 dB can be achieved even if the distance between the transmission and reception antennas is the half of the carrier wavelength [1]. Moreover, in [3], a simple collision detection method by using feature extraction of the waveform with collisions, and the validity of the method is demonstrated via experiments.

In this paper, we propose wireless packet collision detection methods by applying the idea of the coupling wave canceller originally proposed for full-duplex radio relay stations [4]. In the proposed method, a sending terminal detects the collision caused by packets being transmitted from other node by using the received signal during his transmission. Unlike the method in [1], the proposed methods can detect the collision during the transmission of data signals. In general, the received power of his own transmitted signal, namely, self-interference is far greater than that of the collision packet to be detected. Hence, how to suppress the self-interference is one of the key issues for the realization of the wireless packet collision detection. In the proposed method, sending node cancels the components of self-interference from the received signal by using an adaptive filter, whose input is the transmitted signal of the sending node, and detects the collision by observing the change of the canceller output instantaneous power. Moreover, in order to cope with higher self-interference power, we introduce a receiving antenna array having a self-interference canceller at each element, and maximum ratio combining is performed for the signals after the self-interference cancellation. The packet collision detection is achieved by evaluating the combiner output instantaneous power. Furthermore, since a common preamble is used in every packet in wireless LAN systems based on IEEE802.11a/g/n, we utilize the preamble to improve the collision detection performance. To be more specific, we propose to use the correlation between the canceller output or

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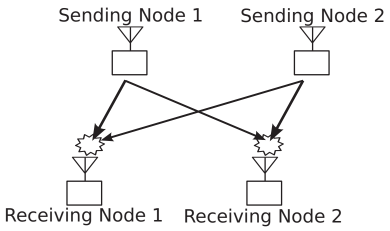

Fig. 1. Packet Collision Scenario 1

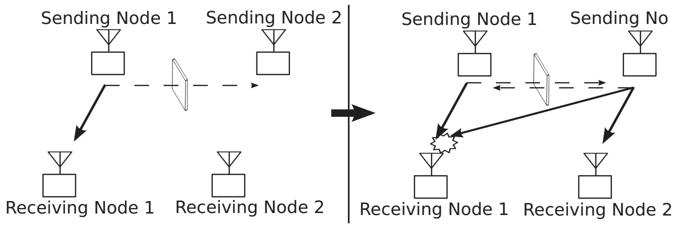

Fig. 2. Packet Collision Scenario 2

the combiner output and the preamble for the detection of the packet collision. We confirm the performance of the proposed methods by numerical simulations taking the impact of the finite quantization level into considerations.

II. Scenarios of Wireless Packet Collision in Wireless LAN Systems

Possible scenarios of wireless packet collisions in wireless LAN systems based on CSMA/CA protocol will be the following two cases. One case is that two sending nodes judge the channel to be idle based on the carrier sensing, and start transmission almost simultaneously, which is shown in Fig. 1. On the other hand, another possible case is depicted in Fig. 2, where Sending Node 1 is transmitting packets to Receiving Node 1, while the packets are not detected at the Sending Node 2 since the received signal power at the node might be lower than the carrier sense level because of, say, the wall between Sending Node 1 and Sending Node 2 (that is, the hidden terminal problem). Since Sending Node 2 will start signal transmission, the transmitted packets cause collisions at Receiving Node 1, if the channel gain between Sending Node 2 and Receiving Node 1 is much greater than that between Sending Node 2 and Sending Node 1.

In this paper, we consider the packet collision of the later scenario, and propose wireless packet collision detection methods at Sending Node 1 of the scenario 2. Although it is true that the packet collision at Sending Node 1 does not necessarily means the packet collisions at Receiving Node 1, which actually determine success of the transmission from Sending Node 1 to Receiving Node 1, Sending Node 1 can judge that a harmful packet collision happens at Receiving Node 1, if Sending Node 1 detects a packet collision and it does not receive any ACK from Receiving Node 1. If Sending Node 1 can tell the packet loss is caused not by fading or other reasons but by the packet collision, then the information could

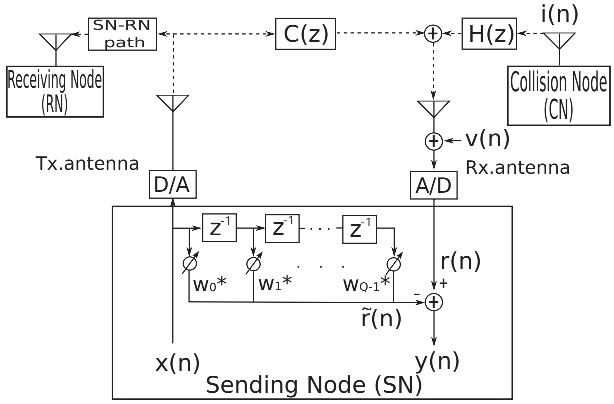

Fig. 3. System configuration with single receiving antenna

be used in the MAC layer protocol for the determination of the optimum retransmission strategy. The issues of the MAC layer protocol with knowledge of the collision at the transmitter will be discussed in our future studies.

In the packet collision scenario 2, the received signal power of the collision packet to be detected at Sending Node 1 will be much smaller than that of the self-interference. For example, let us assume the distance between the Sending Node 1 and Sending Node 2 to be 60 m, and the distance between the transmit antenna and the receive antenna for the collision detection of the Sending Node 1 to be 6 cm. If we assume the path loss exponent to be 2, then the received power of the self-interference will be 60 dB higher than that of the collision packet to be detected. Moreover, if we assume the detection of the collision packet with the received power less than the carrier sense level, the received power of the self-interference will be at least 70 dB higher than that of the collision packet, since the carrier sense level and the maximum transmit power of IEEE802.11a are -62 dBm and 10 dBm, respectively. Since it has been reported in [1] and [2] that the employment of the orthogonal polarization antennas for the transmit and receive antennas can achieve about 40 dB isolation of the self-interference, the proposed method based on the digital signal processing is required to detect the collision packet with the received power at least 30 dB smaller than that of the self-interference.

III. Proposed Wireless Packet Collision Detection Method

In this section, we propose three different packet collision detection schemes in terms of the configuration or the signal used for the collision detection.

A. Proposed method 1: packet collision detection using canceller output power

The system configuration of the first method (*proposed method 1*) is shown in Fig. 3, where sending node (SN) detects the collision during his transmission. Receiving node (RN) is the destination node of SN and collision node (CN) causes the collision by sending packets at some point during

SN's transmission. In the configuration, both the transmit (Tx.) and the receive (Rx.) antennas of SN are assumed to have a single element. Taking advantages of the fact that the self-interference is composed by the SN's own past transmitted signal, an adaptive filter having Q taps, whose input is the SN's transmitted signal, is employed in SN, and the output of the filter is subtracted from that of the Rx. antenna in order to cancel the self-interference.

Let $\{c_0,\dots,c_{K-1}\}$ and $\{h_0,\dots,h_{L-1}\}$ be impulse responses of the channel between Tx. and Rx. antennas of SN, and between Tx. antenna of CN to Rx. antenna of SN, respectively. The transfer functions of the corresponding channels are given by

$$C(z)=\sum_{k=0}^{K-1} c_k z^{-k}, \tag{1}$$

and

$$H(z)=\sum_{l=0}^{L-1} h_l z^{-l}, \tag{2}$$

where K and L denote lengths of the impulse responses.

The transmitted signal at time n from SN $x(n)$ is assumed to be zero mean and variance σ_x^2, and $v(n)$ is the zero mean additive white noise at Rx. antenna of SN with variance σ_v^2. Moreover, $i(n)$ is the transmitted signal of CN with zero mean and variance σ_i^2. Then, the received signal at Rx. antenna of SN $r(n)$ is written as

$$r(n)=\sum_{k=0}^{K-1} c_k x(n-k)+\sum_{l=0}^{L-1} h_l i(n-l)+v(n). \tag{3}$$

Defining the weight of the adaptive filter as $\{w_0,\dots,w_{Q-1}\}$, the output of the adaptive filter is given by

$$\tilde{r}(n)=\sum_{q=0}^{Q-1} w_q^* x(n-q). \tag{4}$$

Thus, the canceller output signal $y(n) = r(n) - \tilde{r}(n)$ is obtained as

$$\begin{aligned} y(n)=&\sum_{k=0}^{K-1} c_k x(n-k)-\sum_{q=0}^{Q-1} w_q^* x(n-q)\\ &+\sum_{l=0}^{L-1} h_l i(n-l)+v(n). \end{aligned} \tag{5}$$

From (5), we can see that, if $Q \geq K$ holds and

$$w_q=\begin{cases} c_q^*, & (q=0,\dots,K-1)\\ 0, & (q=K,\dots,Q-1) \end{cases} \tag{6}$$

are satisfied, then the components of self-interference are completely eliminated[1].

[1] It should be noted here that we have been ignoring the impact of the quantization noise, which is inevitable in the analog-to-digital (AD) conversion. We will consider the impact later.

Defining the transmitted signal vector and the weight vector as $\boldsymbol{x}(n)=(x(n),\dots,x(n-Q+1))^{\mathrm{T}}, \boldsymbol{w}=(w_0,\dots,w_{Q-1})^{\mathrm{T}}$, respectively, the cost function to determine the weight of adaptive filter based on MMSE criterion is given by

$$\begin{aligned} J&=E[|y(n)|^2]\\ &=E[|r(n)|^2]-\boldsymbol{p}^{\mathrm{H}}\boldsymbol{w}-\boldsymbol{w}^{\mathrm{H}}\boldsymbol{p}+\boldsymbol{w}^{\mathrm{H}}\boldsymbol{R}_x\boldsymbol{w}, \end{aligned} \tag{7}$$

where

$$\boldsymbol{p}=E[r(n)\boldsymbol{x}(n)], \tag{8}$$

$$\boldsymbol{R}_x=E[\boldsymbol{x}(n)\boldsymbol{x}(n)^{\mathrm{H}}]=\sigma_x^2\boldsymbol{I}_Q, \tag{9}$$

and $\boldsymbol{I}_Q$ is a $Q \times Q$ identity matrix. The optimum adaptive filter weight is obtained as

$$\boldsymbol{w}=\boldsymbol{R}_x^{-1}\boldsymbol{p}=\frac{1}{\sigma_x^2}\boldsymbol{p}. \tag{10}$$

Since cross-correlation vector $\boldsymbol{p}$ is unknown in general, we replace $\boldsymbol{p}$ with a sample cross-correlation vector obtained by using the update rule of

$$\boldsymbol{p}(n)=\lambda\boldsymbol{p}(n-1)+(1-\lambda)r(n)\boldsymbol{x}(n), \tag{11}$$

where λ $(0<\lambda<1)$ is a forgetting factor. Thus, the weight update rule is given by

$$\boldsymbol{w}(n)=\frac{1}{\sigma_x^2}\boldsymbol{p}(n). \tag{12}$$

Assuming $Q \geq K$ and the perfect self-interference cancellation, the canceller output power is given by

$$E[|y(n)|^2]=\begin{cases} \sigma_v^2, \text{(before collision)}\\ \sigma_i^2\sum_{l=0}^{L-1}|h_l|^2+\sigma_v^2, \text{(after collision)}. \end{cases} \tag{13}$$

That is to say, the canceller output power is equal to noise power before the packet collision, and it increases by the power of collision packet $\sigma_i^2\sum_{l=0}^{L-1}|h_l|^2$ after the collision. The proposed method 1 utilizes this increment of the canceller output power to detect the collisions.

In actual implementations of the packet collision detection method, we have to consider the impact of the quantization bit of the A/D converter at the receiver, because the collision signal might be smaller than a unit quantization step after the attenuation of the received signal to avoid the saturation because of the very high power of the self-interference. In order to cope with the problem, we propose two different approaches in what follows.

B. Proposed method 2: packet collision detection using combining signal power

In the proposed method 2, in order to improve the collision detection performance of the method 1, we introduce a receiving adaptive antenna array in SN aiming at the improvement of the SNR by the array combining. The system configuration is shown in Fig. 4. In the configuration, Rx. antenna of SN is an antenna array with M elements, and each antenna element has the Q-tap adaptive filter for the self-interference cancellation. Defining $\{c_m^0,\dots,c_m^{K-1}\}$ and $\{h_m^0,\dots,h_m^{L-1}\}$ as impulse

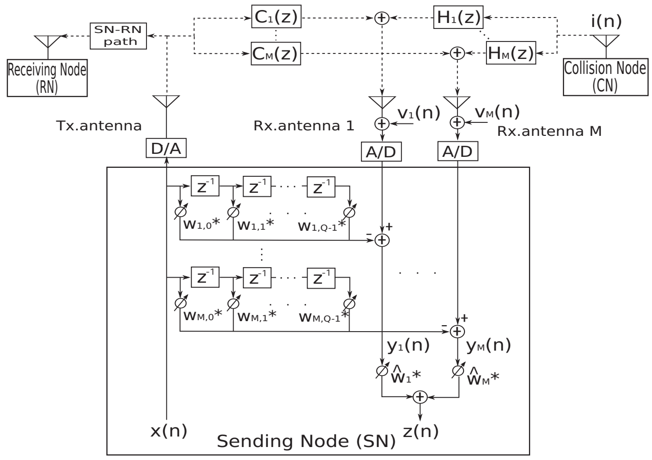

Fig. 4. System configuration with receiving antenna array

responses of the channels between Tx. antenna and the m-th Rx. antenna of SN, and between Tx. antenna of CN and the m-th Rx. antenna, respectively. The corresponding transfer functions are written as

$$C_m(z) = \sum_{k=0}^{K-1} c_m^k z^{-k},\ (m = 1, \ldots, M), \tag{14}$$

$$H_m(z) = \sum_{l=0}^{L-1} h_m^l z^{-l},\ (m = 1, \ldots, M), \tag{15}$$

The additive white noise at the m-th Rx. antenna of SN $v_m(n)$ is zero mean and variance σ_v^2. We Define weight of the adaptive filter at the m-th antenna element as $\{w_m^0, \ldots, w_m^{Q-1}\}$. The output signal of the m-th Rx. antenna after the self-interference cancellation $y_m(n)$ is obtained as

$$\begin{aligned} y_m(n) = &\sum_{k=0}^{K-1} c_m^k x(n-k) - \sum_{q=0}^{Q-1} w_m^{q\,*} x(n-q) \\ &+ \sum_{l=0}^{L-1} h_m^l i(n-l) + v_m(n). \end{aligned} \tag{16}$$

By denoting the weight for combining canceller output signals (i.e., array weight) as $\{\hat{w}_1, \ldots, \hat{w}_M\}$, the combiner output signal $z(n)$ is given by

$$z(n) = \hat{\boldsymbol{w}}^{\mathrm{H}} \boldsymbol{y}(n), \tag{17}$$

where $\boldsymbol{y}(n) = [y_1(n) \cdots y_M(n)]^{\mathrm{T}}$ and $\hat{\boldsymbol{w}} = [\hat{w}_1 \cdots \hat{w}_M]^{\mathrm{T}}$.

In the proposed method 2, the weights of both the adaptive filters and the adaptive array have to be controlled. Here, we introduce two-step procedure to control them. In the first step, for each antenna element, we control the weight of corresponding adaptive filter using the same update rule as the proposed method 1. After sufficient convergence of the adaptive filters, the canceller output will be composed by the collision signal and the additive thermal noise[2]. Therefore, in the second step, we control the combining weight to maximize the power ratio between the collision signal and the noise to improve the SNR. Defining channel matrix from CN to SN as

$$\boldsymbol{H} = \begin{pmatrix} h_1^0 & \cdots & h_1^{L-1} \\ \vdots & \ddots & \vdots \\ h_M^0 & \cdots & h_M^{L-1} \end{pmatrix}, \tag{18}$$

the power of the combiner output is given by

$$\begin{aligned} E[|z(n)|^2] &= E[|\hat{\boldsymbol{w}}^{\mathrm{H}} \boldsymbol{y}(n)|^2] \\ &= E[|\hat{\boldsymbol{w}}^{\mathrm{H}} (\boldsymbol{H}\boldsymbol{i}(n) + \boldsymbol{v}(n))|^2] \\ &= \sigma_i^2 \hat{\boldsymbol{w}}^{\mathrm{H}} \boldsymbol{H}\boldsymbol{H}^{\mathrm{H}} \hat{\boldsymbol{w}} + \sigma_v^2 \hat{\boldsymbol{w}}^{\mathrm{H}} \hat{\boldsymbol{w}}. \end{aligned} \tag{19}$$

Thus, the optimum combiner weight is obtained by the maximization of the objective function

$$G = \frac{\sigma_i^2}{\sigma_v^2} \cdot \frac{\hat{\boldsymbol{w}}^{\mathrm{H}} \boldsymbol{H}\boldsymbol{H}^{\mathrm{H}} \hat{\boldsymbol{w}}}{\hat{\boldsymbol{w}}^{\mathrm{H}} \hat{\boldsymbol{w}}}, \tag{20}$$

where the solution is the eigenvector of $\boldsymbol{H}\boldsymbol{H}^{\mathrm{H}}$ corresponding to the maximum eigenvalue.

If channel matrix $\boldsymbol{H}$ is unknown, instead of $\boldsymbol{H}\boldsymbol{H}^{\mathrm{H}}$, we utilize a sample autocorrelation matrix of $\boldsymbol{y}(n)$ obtained by the update rule of

$$\boldsymbol{R}_y(n) = \lambda \boldsymbol{R}_y(n-1) + (1-\lambda) \boldsymbol{y}(n) \boldsymbol{y}(n)^{\mathrm{H}}, \tag{21}$$

where λ $(0 < \lambda < 1)$ is a forgetting factor, since the optimum weight also corresponds to the eigenvector of $\boldsymbol{R}_y = E[\boldsymbol{y}(n)\boldsymbol{y}(n)^{\mathrm{H}}]$ corresponding to the maximum eigenvalue. The proposed method 2 detects the collisions by evaluating the instantaneous combiner output power.

C. Proposed method 3: packet collision detection using correlation with preamble signals

In wireless LAN systems of IEEE802.11a/g/n, a common preamble signal is used in all the transmitted packets. Thus, the preamble signal transmitted from other wireless terminal is available to any nodes. Using this feature, here we propose the third collision detection method using the correlation between the canceller output and the preamble signal. Note that this approach can be applied to both the proposed method 1 and 2. In the proposed method 3, SN detects the collision by observing squared absolute values of the correlations between the canceller output signal $y(n)$ or combining signal $z(n)$ and preamble signals $p(n)$ as

$$\begin{aligned} \mathrm{Cor}_y(n) &= \left| \sum_m y(m+n) p^*(m) \right|^2, \\ \mathrm{Cor}_z(n) &= \left| \sum_m z(m+n) p^*(m) \right|^2, \end{aligned} \tag{22}$$

respectively.

[2]Quantization noise is included as well in practical scenarios.

TABLE I
SYSTEM PARAMETERS

Transmission scheme	OFDM
FFTsize	64
Guard interval	16
OFDM symbol length	80
Modulation scheme	QPSK
Quantization bit	8
Quantization scheme	Uniform quantization
Channel	Rayleigh fading
Number of antennas in proposed method 2	4
Channel estimation	Least square using preamble

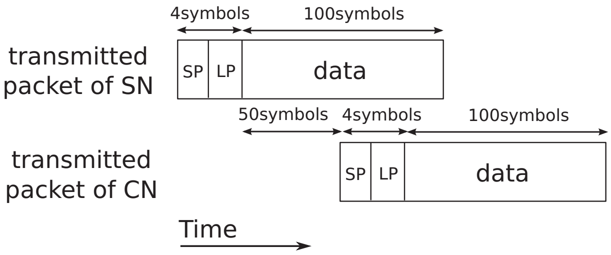

Fig. 5. Length and timing of transmitted packets

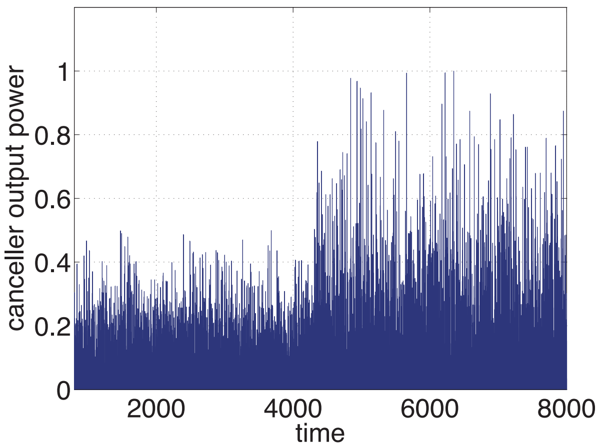

Fig. 6. Performance of proposed method 1 (SNR=60 dB, SIR=40 dB)

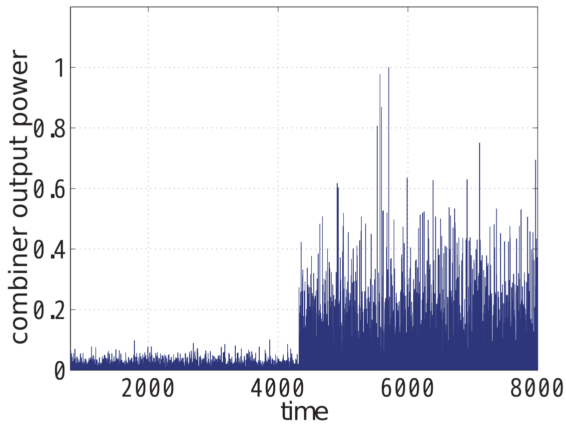

Fig. 7. Performance of proposed method 2 (SNR=60 dB, SIR=40 dB)

IV. NUMERICAL RESULTS

Table I summarizes the conditions of the numerical experiments. The frame configuration of the transmitted signals including preamble is based on IEEE802.11n, and the number of transmitted OFDM symbols and the transmission timing are shown in Fig. 5. In the figure, SP and LP respectively denote short and long preambles, and their total length is 160 samples. The collision takes place at the 4321-th sample of the transmitted signal from SN. Henceforth, we define SNR and SIR as

$$\mathrm{SNR} = \frac{\text{received power of self-interference}}{\text{noise power}},$$

$$\mathrm{SIR} = \frac{\text{received power of self-interference}}{\text{received power of collision signal}},$$

respectively.

Figure 6 and Figure 7 show the canceller output instantaneous power and the combiner output instantaneous power of the proposed method 1 and 2, respectively, for the case with SNR=60 dB and SIR=40 dB. Here, the instantaneous power is normalized so that the maximum value becomes one in both figures. From the figures, we can confirm the collision can be detected by the increase of the power in both methods. Comparing Fig. 7 and6, we can also see that the power ratio of the evaluated signals before and after the collision is larger for the case with the proposed method 2, which confirms the validity of the proposed approach.

Figure 8 shows the detection error rate of the proposed method 2 for the case with SNR=60 dB and SIR=40 dB, where the detection error is defined as the average rate of the false-positive and false-negative. Note that the threshold for the collision detection is determined so that the rates of false-positive and false-negative to be the same. From the figure, we can see that the detection error rate decreases by increasing the number of Rx. antennas.

Figures 9 and 10 show the combiner output power and the correlation output of the proposed method 2 and the proposed method 3 combined with the proposed method 1 for the case with SNR=70 dB and SIR=50 dB. The proposed method 2 in Fig. 9 cannot detect the collision in this case, while the proposed method 3 can detect the collision.

If we further increase the power of self-interference and set SNR=75 dB and SIR=55 dB, the proposed method 3 using a single antenna cannot detect the collision as shown in Fig. 11, however, the combined use of the proposed method 2 and 3 can detect the collision even for such a strong self-interference as depicted in Fig. 12. Thus, we have confirmed that the proposed method can cope with the self-interference of 55 dB with 4-element antenna array and 8 bit AD converter. If we assumed 40 dB isolation in the RF part as discussed in Sect. II, the hybrid system could cope with up to 95 dB greater self-interference.

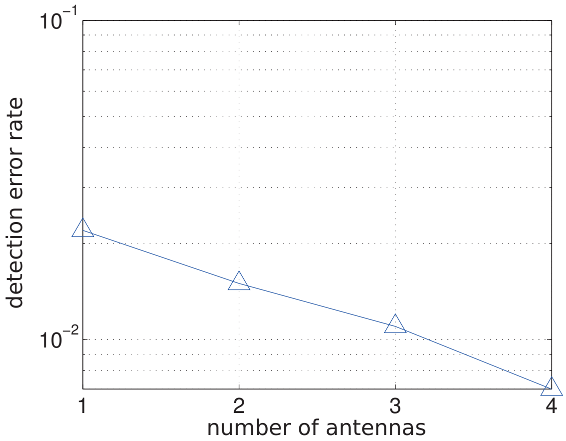

Fig. 8. Detection error rate of proposed method 2 (SNR=60 dB, SIR=40 dB)

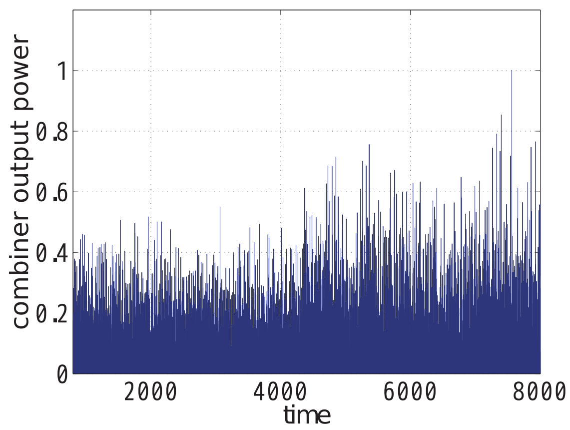

Fig. 9. Performance of proposed method 2 (SNR=70 dB, SIR=50 dB)

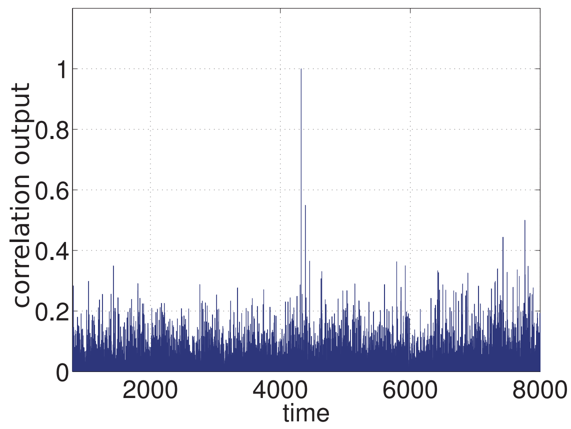

Fig. 10. Performance of proposed method 3 with single antenna (SNR=70 dB, SIR=50 dB)

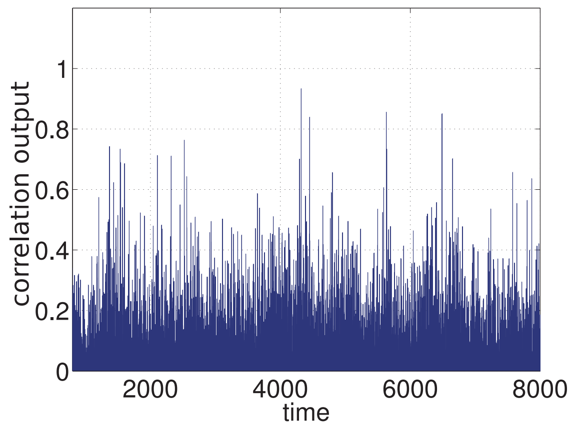

Fig. 11. Proposed method 3 with single antenna (SNR=75 dB, SIR=55 dB)

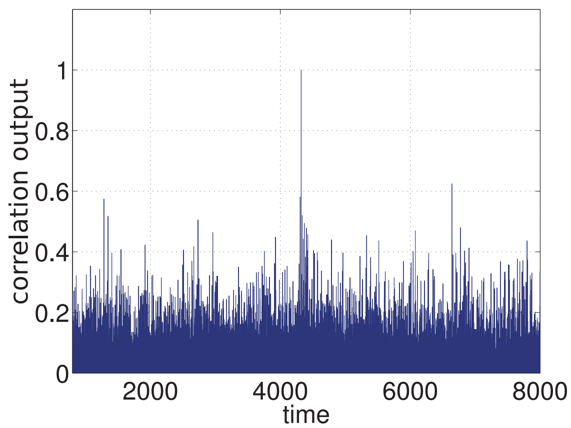

Fig. 12. Proposed method 3 with 4-element antenna array (SNR=75 dB, SIR=55 dB)

V. Conclusions

In this paper, we have proposed wireless packet collision detection methods using self-interference canceller. In the proposed method, a sending node transmits and receives signals simultaneously, and cancels the components of self-interference from the received signal by using the adaptive filter. The collision is detected by evaluating the change of the instantaneous power of the canceller output. Moreover, We have extended the method using an antenna array and/or preamble of wireless LANs. We evaluated the proposed methods by numerical simulation and demonstrated the validity of the proposed approach.

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