A Novel Signal Detection Method for Interference from Inverter Microwave Ovens in WLAN Systems

Kensuke Nakanishi*, Hiroki Mori*, Takeshi Kumagaya*, and Tsuguhide Aoki*

*Wireless System Laboratory, Corporate Research & Development Center, Toshiba Corp., Kanagawa, 212-8582, Japan
Email: {kensuke1.nakanishi, hiroki2.mori, takeshi.kumagaya, tsuguhide.aoki}@toshiba.co.jp

Abstract—Inverter microwave ovens (MWOs) are day-to-day appliances that can act as fatal interferers for 2.4 GHz wireless LAN (WLAN) systems. However, the interference is avoidable, if it is possible to detect the MWO signal. In this paper, we propose an inverter MWO signal detection method in the time and frequency domains for reliable wireless communication. The operating inverter MWOs inherently generate RF signal whose leakage power level drastically varies depending on the switching of the inverter. The proposed method recognizes the changing signal power level due to the switching. In addition, we confirm the effectiveness of the proposed method in the presence or absence of WLAN systems by using the experimental MWO data obtained in a shielded room. It is revealed that the proposed method is able to detect the inverter MWO signal correctly and is robust against different products, different receiving environment, and presence of other signals.

I. INTRODUCTION

IEEE 802.11 wireless LAN (WLAN) has become a prevailing technology owing to its high-data rate service and ease of deployment, and WLAN systems are widely used for their convenience in settings such as business lobbies and conference rooms. Some WLAN systems require higher reliability, such as logistics, medical monitoring in hospitals, and business transactions in retail and manufacturing, as well as voice and video applications. The IEEE 802.11 TGax actively continues to release new draft amendments for incorporating the latest technological advances to overcome new practical challenges with a focus on usage in dense deployment environments [1]. In addition, recent products such as access points are equipped with interference detection functions as a fundamental technology for addressing spectrum management [2], since a growing number of wireless devices operate in 2.4GHz industrial, scientific and medical (ISM) band in an uncoordinated manner competing not only with other wireless devices, but also with non-communicating devices such as microwave ovens (MWOs).

The inverter MWO (inv. MWO) is a new type of MWO that is now becoming widespread due to its better cooking performance and environmental friendliness. Although the inv. MWO is a non-communicating device, it occupies a wide frequency band with a high duty ratio. Typical transformer (trans.) and inv. MWOs contain single or multiple magnetrons that periodically turn on and off as the ac line voltage changes, and RF energy is generated only during on-periods while the driving voltage exceeds the threshold for the oscillation [3], [4]. The biggest difference between these two types is whether the high driving voltage is produced from the ac line voltage by supplying it to a step-up transformer directly or through an inverter. As a result, each type of MWO generates a high-power RF leakage signal at the frequency of the ac line (50 to 60 Hz) or at the switching frequency of the inverter (typically 30 to 50 kHz). The switching which occurs in inv. MWOs changes the oscillating frequency of signal based on the frequency of the ac line, which causes more severe interference with communicating devices from inv. MWOs than from trans. MWOs.

A lot of countermeasures has been considered to deal with the MWO interference. One simple solution is to communicate on the spectral resources free from MWO interference, and another is to apply higher transmission power on the occupied frequency. In [5], an interference-aware contention window adaptation algorithm has been proposed to mitigate the impact of MWO interference, while, in [6], link adaptation techniques such as rate adaptation and power control are discussed. Solutions assume the detection of the MWO signals, and the detections are generally executed based on their distinctive features. However, conventional methods are often too unreliable and time-consuming to be utilized for inv. MWO signals. In this paper, we start with the discussion on the issues of conventional methods in section II, and then, in section III, propose a new signal detection method for inv. MWO based on the continuous, large and fast change of the signal power caused by switching of the inverter (referred to simply as switching hereafter). In section IV, we demonstrate the performance of the proposed method in the presence or absence of WLAN systems by using actual MWO signals. The proposed method is able to detect the signals quickly and is robust against different products, different receiving environment, and presence of other signals, since switching is an inevitable time-domain feature of the inv. MWO signals. Finally, we conclude this paper in section V.

II. CONVENTIONAL MWO SIGNAL DETECTION METHOD

Conventional signal detection methods for MWOs generally utilize distinctive features such as duration, duty ratio, cyclostationarity, or frequency pattern [5], [7], [8], [9]. MWOs generate signals synchronizing to the frequency of the ac line as mentioned in the introduction, and the leakage signals exhibit particular features. However, these features are not always preserved at a receiver. More specifically, the duration and duty ratio vary depending on the received power, and the
duty ratio and cyclostationarity computed at the receiver may be disturbed by the presence of other signals. In addition, the features vary according to the product, the number of magnetrons, and the manufacturer. In particular, inv. MWOs have the following special features for delivering high cooking performance: the power and timing of signal emission is controlled automatically, and frequency patterns are varied in time so as to heat food uniformly. Thus, the duty ratio, cyclostationarity, and frequency pattern are unuseful for characterizing inv. MWOs. Furthermore, it is hard to estimate the occupied frequency from the above features of inv. MWOs. The speed of signal detection is also an important factor, which is generally in a trade-off relationship with reliability of detection. Calculation of duty ratio or cyclostationarity is time-consuming, since signals have to be received multiple times in order to determine the periodic nature. The challenge lies in robust, reliable and quick signal detection of any inv. MWO product even when the received signal changes for reasons such as the receiving environment or the presence of other signals.

III. PROPOSED SIGNAL DETECTION METHOD

A. Overview

In this section, we propose an inv. MWO signal detection method in both the time and frequency domains based on the switching. The proposed method detects signal first in the time domain and then in the frequency domain, with the frequency domain detection conducted on the signal detected in the time domain. The detections are executed on every oscillation of the inv. MWO, so the signal is detected quickly.

B. Detection in the time domain

The proposed method detects the inv. MWO signal interval ignoring the short off-period that occurs with the switching. The process in the time domain consists of the following four blocks: power calculation block, power comparison block, undesired signal elimination block, and signal detection block. Fig. 1 shows the block diagram.

1) Power calculation block: The proposed method operates on sampled I/Q data derived from the baseband signal output by the receiver, and the power calculation block computes the smoothed signal power (Fig. 2(b)). The sampled I/Q signal data is divided into blocks size of $N_b$, and the $n$-th block power is calculated as

$$P_n = \frac{1}{N_b} \sum_{k=1}^{N_b} p_{N_b(n-1)+k},$$

where $p_{N_b(n-1)+k}$ is the power of the $k$-th sampled I/Q data in the $n$-th block. Note that the value of $N_b$ depends on the switching frequency.

2) Power comparison block: In the power comparison block, the difference between consecutive block power $P_n$ and $P_{n-1}$ is calculated as

$$D_n = 10 \log_{10} \left( \frac{P_n}{P_{n-1}} \right).$$

As a result of smoothing in the previous block, the values of $D_n$ for noise and undesired signal (e.g. WLAN signal) are lower except around the beginning/end of the signal. In contrast, the values of $D_n$ are expected to be higher during inv. MWO oscillation (inv. MWO interval), since the values of $P_n$ varies drastically due to the switching.

3) Undesired signal elimination block: Next, undesired signals such as WLAN signals are eliminated to highlight the inv. MWO signals, where we use the fact that the undesired signals have high values of $D_n$ only around their beginning/end. Since the beginning/end of the signals is a part of each signal, it is possible to regard the undesired signals as impulse noise in
the values of \( D_n \). In this paper, a median filter is applied to eliminate the undesired signals

\[
D'_n = \text{MED} \left\{ D_{n-(q-1)},\, D_{n-(q-2)},\, \cdots,\, D_n \right\},
\]

(3)
where MED is an operation that finds the median value among \( q \)-tap samples. The median filter is a well-known filter as a non linear filter that is useful for reducing impulse noise, where the number of tap \( q \) depends on the incidence of undesired signals. As shown in Fig. 2(d), the undesired signal appears to be deleted by replacement with the median. Fig. 3 shows an example of the actual process starting from the power calculation block up to the undesired signal elimination block. We can see that the high values of \( D'_n \) are only obtained in inv. MWO interval.

4) Signal detection block: Let \( T_s \leq n \leq T_e \) denote the interval where the consecutive values of \( P_n \) are above a threshold \( P^\text{TH} \) which depends on the noise floor. Here, \( T_s \leq n \leq T_e \) ignores the off-periods shorter than the minimum off duration \( \gamma \), since the switching intermittently gives the short off-period where the values of \( P_n \) are below \( P^\text{TH} \). The switching frequency of the inverter is typically 30 to 50kHz, so \( \gamma \) should be a corresponding value of around \( \langle 30 \times 10^3 \rangle \) sec.

In the presence of undesired signals, it is possible that they overlap with the inv. MWO signals. In this case, \( T_s \leq n \leq T_e \) includes the undesired signals. Thus, we define a new interval \( t_s \leq n \leq t_e \) within \( T_s \leq n \leq T_e \) using the values of \( D'_n \), \( t_s \) and \( t_e \) are selected from among the following candidates

\[
t'_m \in \{ n \mid D^\text{TH}(n) < D'_n,\, T_s \leq n \leq T_e \},
\]

(4)
where \( t'_m \)'s are sorted in an ascending order: \( t'_{m-1} < t'_m \). From Eq. (4), the first \( t'_1 \) is set to \( t_s \): \( n = t'_1 \). On the other hand, defining \( \tau \) as the minimum \( t'_m \) which satisfies \( t'_m - t'_{m-1} \geq \Delta_1 \), \( t_e \) is selected:

\[
t_e = \max \{ t'_m \mid t'_m - t_s \leq \Delta_2,\, t'_m < \tau \},
\]

(5)
where \( t'_m - t'_{m-1} = 0 \) if \( m = 1 \), and \( \tau > T_e \) if there is no \( t'_m \) satisfying \( t'_m - t'_{m-1} > \Delta_1 \). \( \Delta_1 \) and \( \Delta_2 \) are parameters to prevent detecting signals that are too long duration. If some \( t'_m \)'s larger than \( t_e \) remain, the same operation is repeated over the remaining \( t'_m \)'s. Furthermore, defining \( \delta \) as the minimum duration, a detected signal of duration \( t_e - t_s < \delta \) is discarded to reduce false detection. Finally, the ratio \( r \) of values of \( D'_n \) in \( t_s \leq n \leq t_e \) beyond a threshold \( D^\text{TH}(n) \) is calculated, and an inv. MWO signal is detected, if \( r \) is larger than a threshold \( R \).

C. Detection in the frequency domain

The inv. MWO signal arbitrarily occupies the ISM band in order to heat food uniformly, and the power gradually changes in the frequency domain. Hence, it is impossible to clearly determine the occupied frequency. In this paper, considering the purpose of the signal detection, we define the occupied frequency of a detected signal as frequency bins where the active ratio defined below is more than a threshold \( \text{AR}_\text{TH} = 0.5 \). The active ratio is defined by the power \( P_{n,f} \) of the output of a windowing and discrete Fourier transform (DFT) operation for I/Q signal samples in a detected signal interval \( t_s \leq n \leq t_e \), where the DFT size is \( N_b \). Using a new threshold \( P^\text{TH}(f) \), the active ratio of each frequency bin \( f \) is calculated as

\[
\text{AR}(f) = \sum_{n=t_s}^{t_e} p_{n,f}/TD,
\]

(6)
where \( TD = t_e - t_s + 1 \) and

\[
p_{n,f} = \begin{cases} 1 & (P_{n,f} > P^\text{TH}(f)) \\ 0 & (P_{n,f} \leq P^\text{TH}(f)). \end{cases}
\]

(7)
Fig. 4(b) shows the \( \text{AR}(f) \) of the detected signal in the time domain.

When a detected signal is contaminated with undesired signals, the \( \text{AR}(f) \) calculated previously also includes the undesired signals as shown in Fig. 4. To distinguish between them by again using the characteristic of the switching, we define a weight for emphasizing the switching. Comparing the difference power

\[
D_{n,f} = \begin{cases} |P_{n,f} - P_{n-1,f}| & (n > t_s) \\ 0 & (n = t_s) \end{cases}
\]

(8)
with a new threshold \( D^\text{TH}(f) \), \( d_{n,f} \) is calculated as

\[
d_{n,f} = \begin{cases} 1 & (D_{n,f} > D^\text{TH}(f)) \\ 0 & (D_{n,f} \leq D^\text{TH}(f)). \end{cases}
\]

(9)
From Eqs. (7) and (9), the following weight is obtained

\[
W(f) = \sum_{n=t_s}^{t_e} (p_{n,f} \times d_{n,f}),
\]

(10)
and is normalized as

\[
W'(f) = W(f)/w_{\max},
\]

(11)
where \( w_{\max} \) is the maximum value of \( W(f) \). Applying \( W'(f) \) to \( \text{AR}(f) \) results in

\[
\text{AR}'(f) = W'(f) \times \text{AR}(f).
\]

(12)
Finally, comparing \( \text{AR}'(f) \) with a threshold \( \text{AR}_\text{TH} \), the occupied frequency is estimated ignoring undesired signals as shown in Fig. 4.
TABLE I
PARAMETERS

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<td>$q$</td>
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<tr>
<td>$P^{(5)}_{TH}$</td>
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<td>$\gamma$</td>
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TABLE II
REFERENCE SIGNALS

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<td>3</td>
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IV. PERFORMANCE EVALUATION

A. MWO signal acquisition experiment

In this section, we demonstrate the performance of the proposed method, using the MWO signals acquired in experiments described below. The setting parameters of the detector refer to Table I. Experiments were conducted in a shielded room with dimensions of 3.65m×4.63m×2.97m, and three kinds of inv. MWO were measured. The receiver used in the experiments was the NI USRP-2943R [10], with the center frequency set to 2.45GHz and the sampling rate set to 100MHz (16 bit ADC). The distance between the MWO and the receiver was 1.5m, and the receiver with a 2.4/5 dual band antenna (PSK3N3-24 55RS, MobileMark) at the RF port measured the leakage signal of the MWO for 10sec when the MWO was operated at a power of 500W. The MWO was operated by a 100V ac line with a frequency of 50Hz, and a 1000ml heat-resistant beaker with 800ml of water was placed at the center of the MWO (Exps. 1-3). Additional experiments were also conducted to obtain MWO signals with lower received power, by equipping the receiver with a 20dB (Exps. 4-6) or 40dB (Exps. 7-9) attenuator.

B. Performance evaluation in the time domain

Taking advantage of the fact that the experiments were conducted in a shielded room, we examined the ideal detection based on energy detection for use as a reference, that is, we determined the reference signals as the interval where the values of $R^{(5)}_{TH}(n-1)+k$ exceed the noise floor (ignoring the short off-period that occurs with switching) in order to evaluate the proposed signal detection. Table II shows the indexed reference signals obtained in this way, where signals with lower received power tend to be of shorter duration as discussed in section II. The reason is that the begging/end of signals is covered with noise. Defining the intervals of the detected signal and reference signal as [$t_e^{(det)}$, $t_e^{(ref)}$] and [$t_s^{(ref)}$, $t_e^{(ref)}$], respectively, if there exists $t_s^{(det)}$, $t_e^{(det)}$ overlapping with $t_s^{(ref)}$, $t_e^{(ref)}$, then it is considered that the signal corresponding to $t_s^{(det)}$, $t_e^{(det)}$ is detected, otherwise the signal is undetected. The detail of the detections is also evaluated as the mean of $LR = (t_e^{(det)} - t_s^{(det)} + 1)/(t_e^{(ref)} - t_s^{(ref)} + 1)$.

If $t_s^{(det)}$, $t_e^{(det)}$ does not overlap with any $t_s^{(ref)}$, $t_e^{(ref)}$, it is a false detection. Note that if $t_s^{(det)}$, $t_e^{(det)}$ overlaps with multiple reference signals, the detected signal is invalid, which indicates that one-to-one signal detection is only accepted. All the records of the signal data in the experiments start and end in noise interval, so there is no incomplete reference signal with $t_s^{(ref)}$ or $t_e^{(ref)}$ which correspond the middle of MWO signal.

Fig. 5 shows examples of the detected signals and detection process in the time domain, and Fig. 6 indicates the evaluation results of the signal detection for each inv. MWO in the absence of other signals. There were no false detections in any of the detected signals. From these results, we can see that the
performance gives 100% signal detection independent of the received power, since the detection is based on the switching. In detail, the detected signals slightly shorter than the reference signals. At the beginning of the signal, the median filter selects the lower $D_n$ of noise interval, and the inv. MWO signals have longer off-periods around the beginning and end of the signals as shown in Fig. 7, which mainly results in underestimation of the duration.

Next, we discuss the impact of the coexistence of undesired signals, utilizing IEEE 802.11n signals that are data packets (1500 bytes, 20MHz bandwidth and MCS 7) and ACK packets. Changing the D/U ratio (desired-to-undesired signal power ratio), in other words, changing the received power of the WLAN signals, we insert them into the signal data of Exps. 4-6 on either channel (CH 1 or CH 1, 6 and 11) by computer simulation, where 802.11n channel model D is applied. We assume that there is only one communication session per channel, and the traffic model is full buffer model. Here, we also assume no MWO interference on any communication sessions. This assumption is valid when there are no MWO signals on the channels, or when the MWO is in the range of the receiver (USRP) but out of range of the WLAN system as in the hidden terminal problem. When communication is performed only on CH 1, gaps between WLAN signals inevitably arise. Thus, the switching can be confirmed among undesired signals even when the power of the undesired signals is much higher than that of the MWO signals. Consequently, the detection is perfectly achieved. The evaluation results are shown in Fig. 8(a). In the case of communication performed on CH 1, 6, and 11, the gap between WLAN signals occasionally disappears. If the D/U ratio is high, namely if the MWO signals have higher power than the WLAN signal power, as shown in Fig. 9(a), the switching can be confirmed over the undesired signals, and the detection is performed as well. However, in the case of lower D/U ratio, the detection is disturbed as shown in Fig. 9(b). The evaluation results are shown in Fig. 8(b). From the results, it is concluded that detection is performed even in the presence of undesired signals, if the switching can be confirmed over or among the undesired signals.

We also examine the false detection for WLAN system and trans. MWO signals. WLAN signals are inserted to noise data recorded in a shielded room as the previous evaluation, and the trans. MWO signal is acquired in an experiment with the same setup as Exps. 1-3. Figs. 10(a)(b) show the each signal detection process. For WLAN signals either on CH 1 or CH 1, 6, and 11, the median filter works well to ignore the incidence of the WLAN signals. Few values of $D_n'$ are higher than $D_{TH}'$, although OFDM signal may have high energy variation among consecutive symbols. As a result, no false detection occurred. For trans. MWO signals, meanwhile, the transient part of them [4] may exhibit continuous and fast variation of the signal power. However, it does not lead to any false detections, since it is a part of the whole signal ($r < R$). From all of the results, we can conclude that the proposed method correctly performs signal detection.

C. Performance evaluation in the frequency domain

In this subsection, we firstly discuss the adequacy for detecting the occupied frequency $f$ using $AR'(f)$ instead of $AR(f)$. Here we use the detected signals on Exps. 4-6, and define the overestimation and underestimation ratios $O$ and $U$ as $O = |\hat{S} \setminus S|/|\hat{S}|$ and $U = |S \setminus \hat{S}|/|S|$ respectively, where frequency bin set $S$ and $\hat{S}$ are $S = \{ f | AR(f) > AR_{TH}' \}$ and $\hat{S} = \{ f | AR'(f) > AR_{TH}' \}$. $O$ and $U$ become higher, if $W'(f)$ is irrelevant to the presence of the MWO signal. We represent this situation as the random scheme where $W'(f)$ is not given by Eqs. (10) and (11) but [0, 1]-uniformly distributed random numbers. Fig. 11 shows the mean of $O$ or $U$ vs. $AR_{TH}'$, where $AR_{TH}'$ controls the trade-off between $O$ and $U$. Compared with the random scheme, the proposed method estimates the occupied frequency with lower $O$ and $U$. In particular, when a lower $AR_{TH}'$ is selected, the $U$ is less than...
0.1. It is indicated that the occupied frequency can be detected by lower \( \text{AR}_{\text{TH}}^{\prime} \), accompanied by overestimation.

Next, we reveal the effects of undesired signals. Assuming that undesired signals do not overlap with any inv. MWO signals in the frequency domain, Fig. 12 shows the mean \( \text{AR}(f) \) and \( \text{AR}^{\prime}(f) \) of the undesired signals under the same assumption as the previous subsection on CH 6, where \( \text{AR}(f) \) and \( \text{AR}^{\prime}(f) \) are calculated by using the actual \( T \) and \( u_{\text{max}} \) of the detected signals derived from all experiments, and the legends indicate the average received power. The results of \( \text{AR}^{\prime}(f) \) suggest that the undesired signal can be ignored on the inserted channel. However, one important fact is that when the received power is higher, the effect appears in other frequency bands. The reason is shown in Fig. 13. The DFT operation is carried out asynchronously to the (OFDM) symbols, that is, it can be executed over several symbols, which results in power leaking out of the channel. As a result, \( \text{AR}^{\prime}(f) \) increases, since this does not always happen.

Taking the results into consideration, in the case where the undesired signal overlaps with the inv. MWO signal, it is suggested that the undesired signals disturb the signal detection. The undesired signal always increases \( \text{AR}(f) \), which may result in overestimation of the occupied frequency of inv. MWO with low \( \text{AR}(f) \). When an undesired signal with a high duty ratio and power overlaps with an inv. MWO signal, the switching can be covered with the undesired signal on the channel, and the occupied frequency band can fail to be detected as well as the evaluation in the time domain, whereas on other channels, \( \text{AR}^{\prime}(f) \) increases as shown in Fig. 12, which can result in false detection.

Fig. 11. Over/underestimation ratios.

Fig. 12. \( \text{AR}(f) \) and \( \text{AR}^{\prime}(f) \) of undesired signals.

V. CONCLUSION

This paper was primarily motivated by the need to detect inv. MWO signals using means other than conventional methods, and proposed a new signal detection method. The proposed method is executed on every oscillation of inv. MWOs, so the signal is detected quickly. Performance evaluation indicates that the proposed method is able to detect the signals correctly and is robust against different products, different receiving environment, and presence of other signals. The downside of the proposed method is that the target interference type is limited. However, it is possible to apply it to interference that has the characteristic of switching such as fast switching jammers [11]. Evaluation in the real situations is left as our future work.

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