Before the

FEDERAL COMMUNICATIONS COMMISSION
Washington, D.C. 20554

In the Matter of

Unlicensed Operation in the TV Broadcast Bands	ET Docket No. 04-186
Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band	ET Docket No. 02-380

Comments from Communications Research Centre Canada

Introduction

The Communications Research Centre (CRC) Canada would like to suggest a new geo-location technique for unlicensed devises in the TV broadcast bands through DTV transmitter identification watermark. The transmitter identification technique has been adopted by the Advanced Television System Committee (ATSC) as ATSC Standard A/110: Synchronization Standard for Distributed Transmission[1]. In ATSC A/110, a unique watermark signal is superimposed to each ATSC DTV station's signal as its transmitter identification. With the embedded watermark, the transmitting source of any ATSC DTV signal can be easily traced. Since the location of television broadcasting stations is known, any unlicensed device can calculate its position when it can receive the watermark from a few DTV stations at separate locations. The proposed geo-location technique has a very robust performance due to the extremely strong DTV signals. DTV Broadcast signals are easier to be received indoors than conventional Global Positioning System (GPS) signals.

Unlicensed devices in the TV broadcast bands must be able to identify the channels occupied by television stations and those occupied by other unlicensed devices The traditional way of identifying unused DTV channels based on the DTV signal strength or energy is not always reliable, particularly when the unlicensed device is operating indoors. With strong multipath effect, the field strength of the DTV signal can vary significantly within very short distance. However, location information is more reliable in determining the available spectrum for unlicensed devices. In addition to presenting a position location system, this document presents a possible method of identifying channels that are occupied by a television signal.

Geo-location Techniques

[1] ATSC, ATSC Standard A/110: Synchronization Standard for Distributed Transmission, July 2004.

There are several geo-location techniques to determine the location of wireless receiving devices, ranging from direction-of-arrival detection to calculation of signal strength loss. The proposed position location is based on multiple distance measurements between known reference points as shown in Figure 1, i.e., signals from different DTV transmitters have to be identified for the determination of the geographic coordinates. Distance-based geo-location techniques involve measurement and calculation of the distance between a receiver and one or more DTV transmitters whose locations are known. If one measures the precise time a signal leaves a transmitter and the precise time the signal arrives at a receiver, one can determine the time of arrival (TOA); the time it takes for the signal to reach the receiver. This method has been described in details in the EURASIP Journal on Applied Signal Processing[2]. This new geo-location technique, based on DTV TxID or watermark signal, can be realized through the following steps:

1) Identify the sources for all DTV signals received at one location. This is based on the calculation of cross-correlation between the DTV signals and local TxID sequences. The ATSC field SYNC signal can be used for a quick synchronization of the TxID sequence.
2) Calculate the pseudo-range between receiver and each DTV transmitter.
3) Determine the coordinates of the receiver by solving a non-linear equation system.

Normally at least two DTV stations at different location are needed to estimate the location of the unlicensed devices successfully. The proximity of additional transmitters can allow the use of optimization techniques to increase the positioning accuracy or to reduce the impact of multipath distortion.

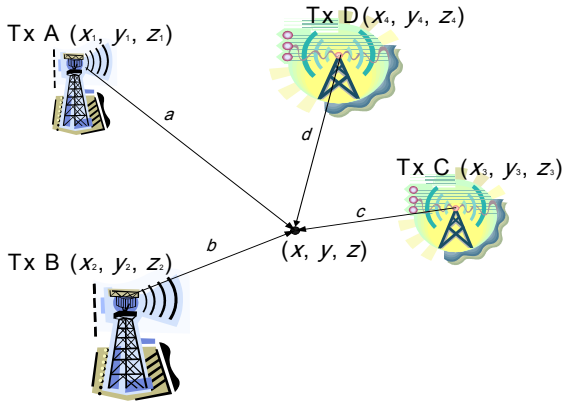


Figure 1 Position location system using DTV transmitters.

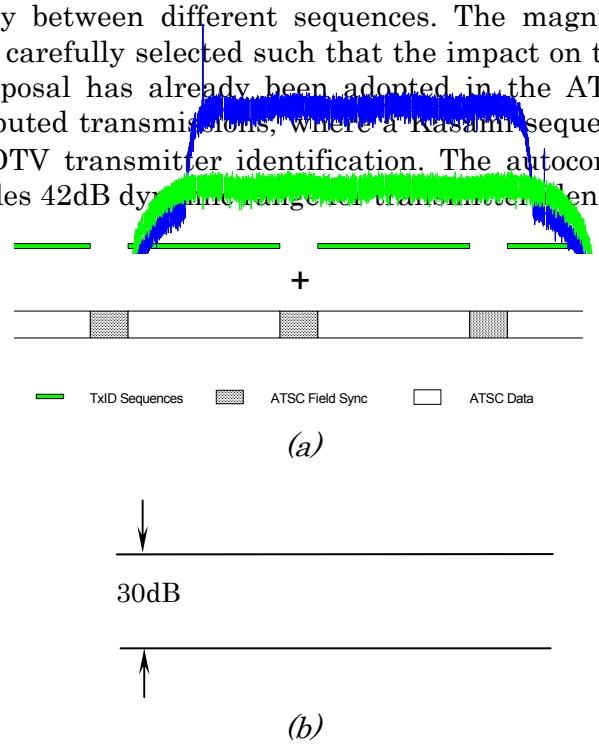
Watermark in DTV signal

With the ATSC A/110, it is possible to assign a unique pseudo random sequence to each DTV transmitter as a RF watermark for transmitter identification (TxID)

[2] X. Wang, Y. Wu, and J.Y. Chouinard "A New Position System Using DTV Transmitter Identification Watermark Signals", EURASIP Journal on Applied Signal Processing, Volume 2006, Pages 1-11, 2006.

purpose. With the large number of DTV transmitters, the need for transmitter identification has become essential since it enables the broadcast authorities and operators to identify the source of in-band interference. In addition, this sequence can be used by unlicensed devices operating in the TV band to identify which channels are used by DTV stations. The phase modulation of each TxID sequence can also lead to a robust data transmission approach, which can be used to broadcast the timing and geo-location information for each transmitter. Using relatively simple signal processing, DTV signals from different transmitters can be identified. By varying the phase of the TxID sequence, the timing and location information for each DTV transmitter can also be sent out. Since the locations of the DTV transmitters are known, it is possible to locate the position of the receiver when the DTV signals from multiple DTV transmitters can be successfully received and identified.

In 2004, X. Wang[3], Y. Wu, and B. Caron described the transmitter identification system using embedded pseudo random sequences. A unique PN sequence is assigned to each individual transmitter; different transmitters are identified based on the orthogonality between different sequences. The magnitude of the pseudo random sequence is carefully selected such that the impact on the DTV reception is negligible. This proposal has already been adopted in the ATSC synchronization standard[4] for distributed transmissions, where a Kasami sequence with a period of $2^{16}-1$ is used for DTV transmitter identification. The autocorrelation function of this sequence provides 42dB dynamic range for transmitter identification[5] [6].



[3] X. Wang, Y. Wu, and B. Caron, "Transmitter Identification Using Embedded Pseudo Random Sequences", *IEEE Trans. Broadcasting,* pp. 244-252, Sept. 2004

[4] ATSC, ATSC Standard A/110: Synchronization Standard for Distributed Transmission, July 2004

[5] R. E. Ziemer and R. L. Peterson, "Digital Communications and Spread Spectrum Systems", Macmillan, 1985.

[6] D. V. Sarwate and M. B. Pursley, "Cross Correlation Properties of Pseudorandom and Related Sequences", *Proceedings of the IEEE*, vol.68, no.5, pp.593-619, May 1980.

Figure 2 Illustration of the ATSC DTV signal with embedded spread spectrum sequences.
(a) Time domain, (b) Frequency domain.

The principle of the transmitter identification is illustrated in Figure 2, both in time and frequency domain. Denote the DTV signals for the i-th transmitter before and after the injection of the pseudo random sequence $x_i(n)$ as $d_i(n)$ and $d_i'(n)$, respectively. The superimposition of the watermark to DTV signal can be described by

$$d_i'(n) = d_i(n) + \rho x_i(n) \tag{1}$$

where ρ is a gain coefficient to control the injection level of the identification sequence, which can be different from transmitter to transmitter. However, it would be convenient for the identification process if the gain is the same for all the transmitters. After passing through the channel h_i, the received signal from the i-th transmitter, r_i, can be formulated as

$$r_i(n) = d_i'(n) \otimes h_i + w(n) \tag{2}$$

where $w(n)$ is the additive white Gaussian noise (AWGN) of the receiver. To identify the existence of the i-th transmitter, the cross-correlation between $r_i(n)$ and the locally generated $x_i(n)$ has to be calculated

$$\begin{aligned} R_{rx_i}(m) &= \sum_{n=0}^{N-1} r(n) x_i(n-m) \\ &= \sum_{n=0}^{N-1} \left\{ \left[d_i(n) + \rho x_i(n) \right] \otimes h_i + w_i(n) \right\} \cdot x_i(n-m) \\ &= \rho R_{x_i x_i} \otimes h_i + \left\{ \sum_{n=0}^{N-1} d_i(n) x_i(n-m) \right\} \otimes h_i + \sum_{n=0}^{N-1} w_i(n) x_i(n-m) \end{aligned} \tag{3}$$

where N is the length of the transmitter identification watermark $x_i(n)$. The first term on the last line of eq.(3), i.e. the autocorrelation function $R_{x_i x_i}$, exists only when watermark signal $\rho x_i(n)$ is found in the received signal. The existence of the i-th transmitter can then be determined by the correlation peak in (3) since the watermark signal $\rho x_i(n)$ is uniquely associated with the i-th transmitter. Eq.(3) also indicates that the correlation peak in the first term on the last line undergoes the same attenuation and channel distortion as the DTV signal described by the second term. To evaluate the robustness of transmitter identification process, a simplified AWGN channel model is applied to eq.(3)

$$R_{rx_i}(m) = A\rho R_{x_i x_i} + A \sum_{n=0}^{N-1} d_i(n) x_i(n-m) + \sum_{n=0}^{N-1} w_i(n) x_i(n-m) \tag{4}$$

where A is an constant associated with the path loss. Due to the large N for transmitter identification sequence, central limit theorem can be applied to the second and third items in (4), whose variances can be determined as $NA^2\sigma_d^2$ and $N\sigma_w^2$, where σ_d^2 and σ_w^2 are the variances of the DTV signal and AWGN noise. The

signal to interference and noise ratio (*SINR*) of the autocorrelation peak for transmitter identification in (4) can be determined as

$$\begin{aligned} SINR &= 10\log_{10}\left\{\frac{A^2\rho^2N^2}{NA^2\sigma_d^2+N\sigma_w^2}\right\} \\ &= 10\log_{10}N - 10\log_{10}\left(\frac{A^2\sigma_d^2+\sigma_w^2}{A^2\rho^2}\right) \\ &= 10\log_{10}N - 10\log_{10}\left\{\frac{A^2\sigma_d^2\left(1+\frac{\sigma_w^2}{A^2\sigma_d^2}\right)}{A^2\rho^2}\right\} \end{aligned} \tag{5}$$

Eq. (5) can be further arranged as

$$SINR = 10\log_{10}N - 10\log_{10}\left(\frac{\sigma_d^2}{\rho^2}\right) - 10\log_{10}\left(1+\frac{\sigma_w^2}{A^2\sigma_d^2}\right) \tag{6}$$

Note that the second term in (6) is the injection ratio of the transmitter identification watermark and $\frac{\sigma_w^2}{A^2\sigma_d^2}$ is the inverse of the signal-to-noise ratio (*SNR*) of the received signal, which makes the third item in eq.(6) negligible for any reasonable *SNR*, i.e. $\frac{\sigma_w^2}{A^2\sigma_d^2} << 1$. Because the TxID watermark is inserted at a certain power level proportional to DTV signal, the fixed relationship is maintained after both signals pass through the same multipath channel. Additive Gaussian noise from the receiver has virtually no impact on the TxID process, unless the received signal is significantly weaker than the noise introduced by the receiver, i.e., the DTV signal is under the receiver's noise floor. Due to the high transmission power of DTV stations and short distance between the receiver and transmitter, eq. (6) holds even for the reception sites inside buildings since the excess path losses due to the building penetration is usually around 10~20dB [7] [8]. As a result, the robustness of the transmitter identification process is dominated by the first two terms in eq.(6). For the TxID system[9], *SINR* in (6) is 18dB when one Kasami sequence is used or 24dB when four Kasami sequences in one field are combined for transmitter identification. Considering the high transmission power of the DTV stations, the coverage limitation for the transmitter identification and the proposed position location is the shape of the earth, rather than the signal strength of the DTV signal.

The impact of the co-channel interference from the DTV stations on the same channel with different programs usually is very limited since the coverage of these DTV stations are well separated through the DTV spectrum allocation process. That's why co-channel interference is not considered in eq. (1) to (6). The other

---

[7] H. Hashemi, "The Indoor Radio Propagation Channel", Proceedings of the IEEE, vol.81, no.7, pp.943-968, July 1993

[8] D. Molkdar, "Review on Radio Propagation into and within Buildings", IEE Proceedings-H, vol.138, no. 1, pp.61-73, Feb. 1991.

[9] ATSC, ATSC Standard A/110: Synchronization Standard for Distributed Transmission, July 2004.

scenario for co-channel interference is from DTV transmitters broadcasting the same program on the same channel due to the deployment of single frequency networks (SFN), in which same content is broadcasted from different transmitters on the same frequency[10]. TV band devices do not need to know about all DTV transmitters operating in SFN, they should, however, know that different transmitter identification numbers[11] are assigned to the different transmitters that make up a SFN. However, the strength of the TV signals at one given location from different SFN transmitters can vary significantly due to the different distances from the receiver as well as the different propagation environment. It is therefore very important to analyze the robustness of the transmitter identification under this circumstance since the combined DTV signals from different SFN transmitters will interfere with the transmitter identification process.

With co-channel interference from SFN, the overall received signal $r(n)$ can be re-formulated as:

$$r(n) = \sum_{i=1}^{M} \left[d_i'(n) \otimes h_i + u(n) \right] \tag{7}$$

where M is the total number of TV signals from the SFN. The existence of the j-th transmitter is unknown without any further identification process. Details of existence and strength of each specific transmitter at the reception site can be achieved by calculating a correlation function. For instance, cross-correlation between $r(n)$ and $x_j(n)$ can indicate the existence and provide strength information about the j-th transmitter:

$$\begin{aligned} R_{rx_j}(m) = \rho R_{x_j x_j} \otimes h_j + \sum_{i=1, i \neq j}^{M} \rho R_{x_i x_j} \otimes h_i + \sum_{n=0}^{N-1} \sum_{i=1}^{M} \left[d_i(n) \otimes h_i \right] x_j(n-m) \\ + \sum_{n=0}^{N-1} u(n) x_j(n-m) \end{aligned} \tag{8}$$

With the orthogonal property of the selected pseudo random sequence, $R_{x_j x_j}$ can be approximated as a Delta Kronecker function. The second term can be neglected since different transmitter identification sequences are orthogonal. The third item in eq.(8) is the combined interference from the SFN DTV signals of the j-th transmitter and the other transmitters. Therefore, the received channel response h_j from the j-th transmitter can be approximated by R_{rx_j}. An interference analysis for eq.(8) with AWGN channel model lead to

$$SINR = 10\log_{10} N - 10\log_{10}\left[\frac{\sigma_d^2}{\rho^2} \left(1 + \sum_{i=1, i \neq j}^{M} \frac{A_i^2}{A_j^2} \right) \right] - 10\log_{10}\left(1 + \frac{\sigma_w^2}{\sum_{i=1}^{M} A_i^2 \sigma_d^2} \right) \tag{9}$$

Comparing eq. (6) and (9), the impact of the co-channel stations in SFN

[10] A. Mattsson, "Single Frequency Networks in DTV", *IEEE Trans. Broadcasting*, vol.51, no.4, Dec. 2005.

[11] ATSC, ATSC Standard A/110: Synchronization Standard for Distributed Transmission, July 2004.

environment can be evaluated by the second term in (9). When the co-channel DTV signal is stronger than the signal from the particular station under identification process, the robustness of transmitter identification is reduced. However, co-channel DTV signals, about 10dB stronger, can be tolerated due to the large margin in the transmitter identification system[12]. Simple averaging of the transmitter identification results in the time domain would reduce the impact of the DTV interference by $10\log_{10} P$, where P is the number of averaging. The complexity associated with averaging is minimal since different DTV signal segments for TxID can be averaged first before the cross-correlation. Further performance improvement can be achieved by the DTV signal cancellation approach. However, the complexity of position location receiver will be increased since the DTV signal has to be re-constructed based on the demodulation result.

Time and Frequency Synchronization

It is noted that transmitter identification sequence is synchronized with the DTV frame structure, since the time synchronization between the DTV signal *d(k)* and the embedded transmitter identification code *x(k)* can substantially reduce the amount of the correlation computation during the identification process. Some time and frequency domain features of the DTV signal, for instance the ATSC PN511 sequence can be used for the timing and frequency synchronization purpose. Here the synchronization algorithm for ATSC is presented. The field Sync in ATSC signal, i.e., the PN-511 sequence in the *d(k)*, can provide an accurate starting point of TxID sequence using some auto-correlation techniques. In this case, cross-correlation in (8) is only to be computed during the delay spread of the transmitter impulse response. Denote the PN511 sequence as $p(n),\ n = 0,\ldots,\ldots,511$, the timing synchronization process between the local TxID sequence in the received DTV signal and local TXID code is based on the cross-correlation between the received signal and the PN511

$$R_{pr}(k) = \frac{1}{511}\sum_{n=0}^{510} p(n)r(n+k) \tag{10}$$

where k is the timing search range. For a satisfactory performance of the receiver, the first search range for the PN511 sequence has to be longer than one DTV field. The largest correlation peak provides the synchronization time information. After the first acquisition of timing, the correlation range can then reduced to a range of several data symbols for the following correlation, in case there is only one transmitter.

Very often the receiver's clock is not locked to the frequency at the transmitter side, due to the substantial attenuation of the signal. The residual frequency offset due to the drifting of the local oscillator will definitely impact the correlation function in (8). It's very common that an oscillator for the position location system may have a frequency offset up to several hundreds Hertz. The destructive effect of the frequency offset is mainly because of the phase rotation of the data samples, which in fact reduces the effective TxID sequence length. The correlation peak will be reduced due the existence of the frequency offset.

---

[12] X. Wang, Y. Wu, and B. Caron, "Transmitter Identification Using Embedded Pseudo Random Sequences", *IEEE Trans. Broadcasting,* pp. 244-252, Sept. 2004.

Let Δf be the frequency drifting for the local oscillator. Here we assume this offset remains unchanged during one ATSC field. We also assume an AWGN channel for the convenience of the analysis. The received signal becomes

$$r(n) = [d(n) + \rho x(n)]\exp(j2\pi\Delta f n T_s) + n(n) \tag{11}$$

The output from the channel estimation correlator is

$$\begin{aligned} R_{rx}(m) &= \frac{1}{N}\sum_{n=0}^{N-1} r(n)x^*(n-m) \\ &= \frac{1}{N}\sum_{n=0}^{N-1}\left(e^{j2\pi\Delta f n T_s}\cdot x(n)x(n-m)^*\right) + n'(n) \\ &= \begin{cases} \dfrac{\sin(N\pi\Delta f T_s)}{N\sin(\pi\Delta f T_s)} R_{pp} + n'(n) & m = 0 \\ n''(n) & \text{elsewhere} \end{cases} \end{aligned} \tag{12}$$

where

$$n'(n) = \frac{1}{N}\sum_{n=0}^{N-1}\left(e^{j2\pi\Delta f n T_s}\cdot d(n)x(n-m)^*\right) + n(n)$$

and

$$n''(n) = \frac{1}{N}\sum_{n=0}^{N-1}\left(e^{j2\pi\Delta f n T_s}\cdot d(n)x(n-m)^*\right) + n(n)$$

It can be seen clearly from (12) that the main peak of the cross-correlation function in (8) now will be modulated by a *sinc* shaped function with its amplitude less than one. The maximum of the correlation function will be determined by the normalized frequency offset. The approach we proposed here for the estimation of the frequency drifting is based on the frequency domain correlation between the received signal and the local TxID sequence after the timing synchronization is achieved. The implementation procedure for the proposed frequency offset estimation and compensation are as follows:

Step.1 Set the maximum of the frequency domain correlation function $R^F_{\max} = 0$.

Step.2 Create a complex TxID code signal as a local reference. This will generate the VSB modulated TxID signal x_{VSB} based on the local Kasami sequence.

Step.3 Compute $X^*(\omega) = F(x_{VSB})^*$ where F is the Fourier transform operator, and * is the conjugate operator.

Step.4 For $\omega = \omega_{nom} - \omega_{offset}$ to $\omega = \omega_{nom} + \omega_{offset}$ with a step of $2\omega_{offset}/L$ (L is the number of the searches).

- Compute the $R'(\omega)$, which is the Fourier transform of one field of DTV signal modulated with a carrier frequency ω, based on the timing synchronization information derived during the timing synchronization stage.
- Obtain the frequency domain correlation between the local TxID signal and the received signal,

$$R_{pr}(\omega) = \frac{1}{N}\sum_{n=0}^{N} R'(\omega)X^*(\omega) \tag{13}$$

Step.5 Upon exiting from the process, the frequency ω with maximum frequency domain correlation is the estimated frequency offset.
Step 6. Remove the estimated frequency offset obtained in step 5 from the received signal.

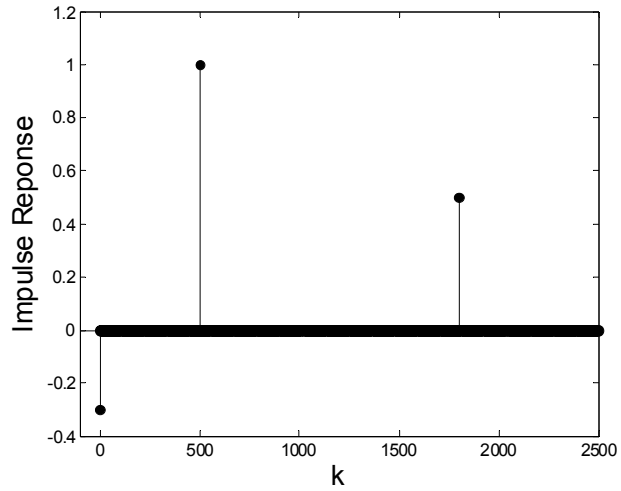
Numerical Results

Numerical simulations of the proposed transmitter identification system have been carried out. Code generator for Kasami sequence was developed in Matlab. Simulations of the transmitter identification and channel estimation using embedded Kasami sequence with period of $2^{16}-1$ have been carried out. Raised-cosine pulse shaping and limited bandwidth effects were also included in this simulation. To guarantee that the DTV signal was not impaired by the TxID signal, the Kasami sequence was injected 30 dB below the DTV signal to prevent degradation as discussed earlier. A channel with a 6 dB and a 10 dB echoes were used for the desired transmitter. Simulation results are shown in Figure 3. It is observed that the dynamic range used for transmitter identification with $2^{16}-1$ Kasami sequences is only around 12 dB without any post-processing. This dynamic range is good enough for transmitter identification, but may be low for channel estimation and low-level interference signal identification. Superimposition of the correlation functions can be used to improve the dynamic range, as this will smooth out the in-band DTV interference. A time domain averaging technique was employed in Figure 3(b). The improvement in TxID dynamic range is calculated as $10\log_{10} P$ dB, where P is the number of averaging times.

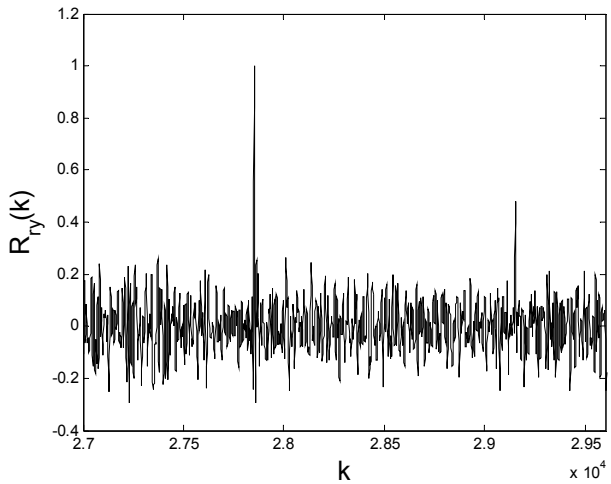
It is also noted that band pass filtering effects from the transmitter and receiver front ends are neglected in eq. (4) for simplicity. In this case, the TxID results are in fact the convolution of the channel response in Figure 3(a) with the combined impulse response of transmitter and receiver front ends. For TxID purpose, Figure 3(b) is accurate enough, since only the strength of the main signal and strong multipath are to be identified. More precise channel estimation and interference identification may be obtained by reducing the band limiting effects via deconvolution techniques, as indicated in Figure 3(c). The dynamic range in Figure 3(c) is about 30 dB.

Conclusion

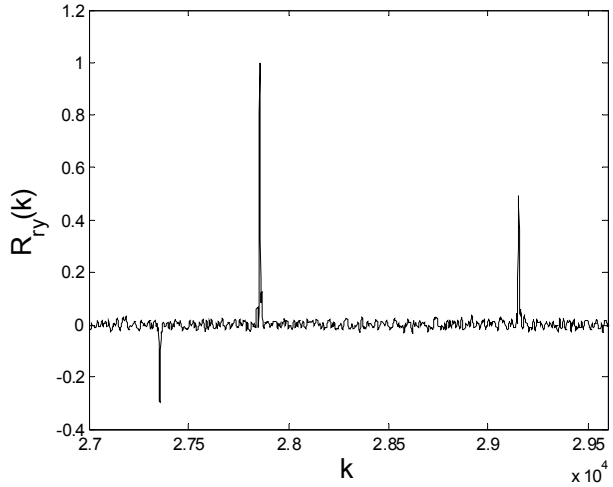
The unique propagation characteristics of wireless signals in the TV band are one of the main reasons why this band is being desired by proponents of unlicensed devices. However, by their nature, unlicensed devices, once widely deployed, can be difficult to manage and become a source of interference if governing rules prove ineffective. Since a number of unlicensed devices are expected to operate indoors, GPS signals by their propagation nature will be unavailable to such a receiver to determine its position. The technique described in this paper will work as well indoor or outdoor. An effective geo-location technique implementation is critical to the development of the simple rules to prevent unlicensed devices from interfering with the general public enjoyment of television broadcast stations.



(a)



(b)



(c)

Figure 3 Example of ATSC Transmitter Identification Using Kasami Sequence. (a) Multipath used in the simulation, (b) Identification results, (c) Identification results after 60 times averaging.