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Scalable & Reliable IoT Enabled By Dynamic Spectrum Management for M2M in LTE-A

Yue Gao, Zhijin Qin, Zhiyong Feng,

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Abstract

To underpin the predicted growth of the Internet of Things (IoT), a highly scalable, reliable and available connectivity technology will be required. Whilst numerous technologies are available today, the industry trend suggests that cellular systems will play a central role in ensuring IoT connectivity globally. With spectrum generally a bottleneck for 3GPP technologies, TV white space (TVWS) approaches are a very promising means to handle the billions of connected devices in a highly flexible, reliable and scalable way. To this end, we propose a cognitive radio enabled TD-LET test-bed to realize the dynamic spectrum management over TVWS. In order to reduce the data acquisition and improve the detection performance, we propose a hybrid framework for the dynamic spectrum management of machine-to-machine networks. In the proposed framework, compressed sensing is implemented with the aim to reduce the sampling rates for wideband spectrum sensing. A non-iterative reweighted compressive spectrum sensing algorithm is proposed with the weights being constructed by data from geolocation databases. Finally, the proposed hybrid framework is tested by means of simulated as well as real-world data.

Index Terms

Internet of things, machine-to-machine, compressive sensing, geolocation database, TD-LTE/LTE-A, TV white space, cognitive radio, machine-type communications.

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I. INTRODUCTION

The Internet of Things (IoT) is considered to be the next generation internet, being a significant add-on to the computer and mobile internet. It is expected to underpin large parts of the global economy by 2020. The underlying connectivity technology, the "Ethernet cable" of this emerging technology, is referred to as machine-to-machine (M2M) communications; or, in 3GPP standardization language, as machine-type communications (MTC).

Predictions related to the uptake and usage of M2M vary enormously. We have seen numbers suggested by the Wireless World Research Forum (WWRF) predicting trillions of connected devices; Ericsson, Cisco and the likes predict in the order of billions; whilst market research companies like ABI Research predict uptake in the order of hundreds of millions. The reason for this wide spread in prediction is due to differing assumptions on underlying technologies, which include Zigbee, Wifi, low power wide area (LPWA) and cellular technologies. The general industry feel, however, is that cellular technologies will bear a major share of the connectivity. Related to predictions of cellular modems, the most used air interface to date is 2G GSM. This is due to its technical capabilities of handling low-rate traffic in an energy efficient manner. Additionally, worldwide coverage is excellent, and modems fairly affordable. 3G UMTS technology, in contrast, is less energy efficient, enjoys less coverage and has more expensive modems. 4G LTE/LTE-A are technically very suitable to M2M but the modems, mainly due to patent costs, are very expensive to date [1].

In terms of challenges, there are a few directly coupled to spectrum issues, which are the focus of this paper. Notably, there is the problem of quickly growing project sizes, and strict requirements on service level agreements (SLAs). Indeed, once a specific IoT project goes ahead or the consumer uptake grows, it often entails deploying thousands of M2M-enabled nodes. Additionally, the requirements on network outage all stimulated by SLAs are very stringent [2]. These observations translate directly to spectrum issues. The SLA requirements may also not be met simply because the M2M technology uses unlicensed bands where Quality of Service (QoS) cannot be reliably provided. In this regard, TV White Space (TVWS) approaches offer not only a unique opportunity for opportunistic M2M access with support from regulators and technology advancement, but also a mid-range QoS between high quality of licensed cellular networks and uncontrollable unlicensed WIFI networks [3].

In the scope of TVWS, and more generally, there are very significant moves towards enabling

the opportunistic use of unused spectrum. Approaches to TVWS are already well-established in the US [4], and in other counties such as the UK there are major efforts, including field trials, towards the realisation of such geolocation database-driven methods, based on alternative rules [5–9]. Moreover, it is noted that, aside from the simple initial application to TVWS, there is potential for such approaches to apply to other bands of interest for opportunistic spectrum sharing. Such approaches can, in effect, "locally vary" the regulations based on the situation at that locality, which is what is already being done on a very simple level in TVWS under the UK model, e.g., through allowed equivalent isotropic radiated powers (EIRPs) being varied per TV channel, based on location and device characteristics, etc.

The Ofcom in UK has made regulations which enable licence exempt use of white space devices from 1st January 2016 as the first approach to implement dynamic spectrum sharing over TVWS in reality from regulatory point ivew [10]. The TVWS model in UK can potentially apply both in the scope of licensed access as well as license-exempt access. Further, it is noted that such a concept has all of the capabilities and information necessary to manage the interactions among the WSDs for MTC, as well as the protection of primary services. It is also observed that under LSA for example [11], similar approaches can apply to sharing that is authorized and managed within the scope of the license owner, not merely within the scope of direct management by the regulator. Indeed, the overlaps/similarities between what is required in the scope of TVWS and LSA have led to a major TVWS database provider within the Ofcom TVWS Pilot also providing the database service within LSA trials [12].

In order to avoid any harmful interference to primary services as well as to achieve mid-range QoS in TVWS, WSDs should have the knowledge of spectrum occupancy status. Geolocation database approach has been already discussed extensively within the context of key recent regulatory developments. The database approach poses challenges to protect licensed Digital Terrestrial Television (DTT) and the unregistered Programme Making and Special Events (PMSE) users in urban city scenarios, and to detect the co-existed unlicensed PMSE and WSDs in close proximity. Therefore, spectrum sensing would be the native approach to tackle these challenges. The value of spectrum sensing is widely recognized in the protection of unregistered PMSE services, especially in Europe where PMSE devices mostly operate on unlicensed basis without any record and the geolocation database approach can only protect registered systems. However, spectrum sensing may cause interference to some special channels, which are unaccessible but determined as free by sensing alone approach. Therefore, the cooperation of geolocation

database and spectrum sensing becomes an desirable for providing accurate spectrum occupancy information.

A. Related work

To date, some reserach works have been done on the cooperation of spectrum sensing and geolocation. In [13], a hybrid spectrum sensing and geolocation database framework is proposed, in which the utilization of spatial-temporal spectrum holes is maximized. A hybrid framework combing the advantages of both geolocation database and spectrum sensing is proposed in [14], in which different spectrum sensing modules are performed after the spectrum occupancies are initially determined by a geolocation database. Additionally, a similar hybrid framework has been implemented into an experimental platform that combines wireless microphone sensors with a web-based geolocation database access for PMSE to show its efficiency in [15]. Moreover, standards are currently being defined for the use of spectrum sensing information to assist geolocation databases, e.g., to verify or enhance their performance [16]. Hence, such hybrid systems might extend even beyond cognitive radio (CR) scenarios, more towards practical deployments assisting regulatory and other purposes in spectrum sharing.

Along with the development on the cooperation of spectrum sensing and geolocation database, wideband spectrum sensing has attracted much attention recently. However, the nature of MTC is that it only achieves low data rate. Therefore, high sampling rates are difficult to achieve at the devices used for MTC. Recently, compressive sensing (CS) [17] has been proposed to make sub-Nyquist sampling possible without loss any spectral information. The CS technique was first applied to the wideband spectrum sensing [18]. Subsequently, the centralized and distributed compressive spectrum sensing algorithms was proposed in [19, 20] respectively, with the requirement on the knowledge of sparsity level. Additionally, authors in [21] proposed to adjust the number of compressed measurements adaptively. However, the signal recovery is performed iteratively until the number of collected samples were enough for successful spectral recovery, which causes heavy computational complexities at SUs. A novel compressed sensing algorithm based on modulation classification and symbol rate recognition was proposed in [22] for the wideband signal spectrum sensing in the low SNR condition. Moreover, a compressive spectrum sensing algorithm with low complexity was proposed in [23] by utilizing the locally implemented geolocation database algorithm. Specifically, the data from geolocation database algorithm can provide a sparsity level estimation with a lower complexities than that required

in [21]. However, the DTT information is required to be maintained at SUs locally, which causes extra energy consumption. Furthermore, a sub-Nyquist wideband sensing algorithm working on the non-sparse spectral signals was proposed in [24] for M2M networks based on sparse Fast Fourier Transform. However, the corresponding energy consumption may still unaffordable for devices implemented for MTC in M2M network.

B. Motivation and contribution

Based on the existing work aforementioned, we firstly developed a CR enabled TD-LTE test-bed to realize dynamic spectrum management over TVWS. To the best of our knowledge, the proposed test-bed is the first CR enabled TD-LTE system operating in TVWS. Additionally, it is noted that the spectrum efficiency and energy efficiency are quite critical for MTC devices [25]. This motives us to extend our existing work on CR networks to the scope of 3GPP cellular MTC systems. The contributions of this paper are summarized as follows:

1) To realize the dynamic spectrum management over TVWS, an integrated solution framework has been conceived, which meets the demands for a large coverage in TVWS. Particularly, a CR enabled TD-LTE frame structure is proposed and the test-bed is built up with the sensing capability and protocol stack modifications.

2) In order to improve the energy efficiency at MTC devices, a new hybrid framework with compressive spectrum sensing and geolocation database is proposed. In the proposed framework, CS technique is invoked at the eBNs, HeBNs, and trusted non-3GPP access points (APs) to perform sub-Nyquist sampling, and the geolocation database is proposed to be implemented and maintained at the HeNB-GW and S-GW. In order to improve the detection performance and reduce the computational complexity, a non-iterative reweighted compressive spectrum sensing algorithm is proposed, in which the weights are constructed by data from geolocation database. In the proposed framework, geolocation database provides a rough estimation on sparsity level before spectrum sensing, which makes the proposed framework suitable for dynamic spectrum environment.

3) Additionally, performance analysis of the proposed design for the CR enabled TD-LTE test-bed is presented to show its efficiency on dynamic spectrum management. Furthermore, the proposed hybrid framework is tested by the simulated data as well as the real-time data provided by the RFeye node [26] and Nominet [27]. Numerical results show that the proposed hybrid framework is suitable for the MTC system.

C. Organization

The following of this is organized as follows. Section II introduces the proposed CR enabled TD-LTE test-bed over the TVWS. Section III presents the proposed hybrid framework combining compressive spectrum sensing and geolocation database for the M2M networks. Section IV provides the performance analysis for the proposed CR enabled TD-LTE test-bed. Section V presents the numerical analysis of the proposed hybrid framework. Section VI concludes this paper.

II. PROPOSED CR ENABLED TD-LTE TEST-BED OVER TVWS

In order to realize the dynamic spectrum management over TVWS, the CR enabled TD-LTE test-bed has been proposed in this paper, with spectrum sensing ability and protocol stack modifications. In the following of this section, the spectrum sensing algorithm used in the test-bed is firstly introduced. Additionally, the protocol stack modification proposed for the test-bed is presented.

A. Spectrum Sensing Algorithm for Analog TV Signal

As a key for the efficient spectrum utilization in TVWS, the Cognitive eNodeB (CeNB) has been proposed to operate the spectrum sensing in the CR enabled TD-LTE system, which has two advantages. First, the spectrum occupied and signalling overhead for the information exchange between CR users and CeNBs can be minimized. Second, the energy consumption for spectrum sensing by CR users can be saved.

Considering the analog TV signals as the dominant primary users in China, a feature detection based spectrum sensing method using the specific characteristic of analog TV signals (also called PAL-D in China) is proposed in this paper. Base on the standard in [28], the energy of the baseband TV signals is mostly concentrated on 1.25 MHz, chroma vice carrier on 5.68 MHz and audio FM carrier on 7.75 MHz as shown in Fig. 1. The procedure of the proposed feature detection method for analog TV signals is shown in Fig. 2. First, the TV RF signal is digitized and then down-converted to a baseband signal. If there are narrow band signals existing on 1.25 MHz, 5.68 MHz and 7.75 MHz, the analog TV signal is detected. Otherwise, the spectrum is unoccupied. Because the detection bandwidth is only 200 KHz compared to the 8 MHz for each TV channel, it can increase the spectrum sensing efficiency. The proposed feature detection
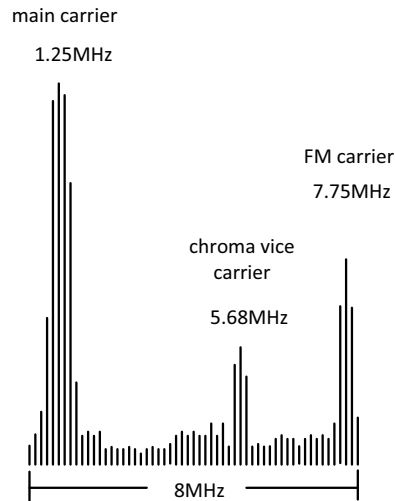
Fig. 1: Spectrum characteristics of analog TV signals.
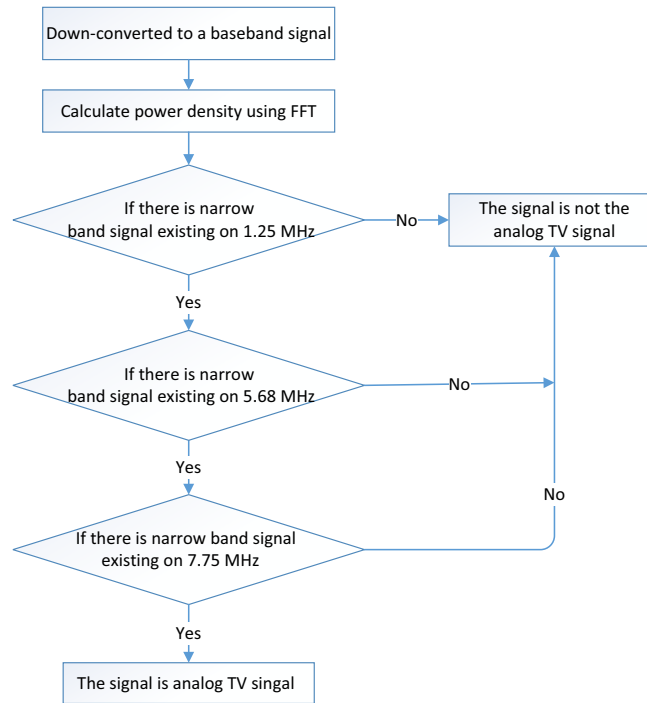

Fig. 2: Procedure of the feature detection method for analog TV signals.

method can also reduce the noise and the sampling time, which has a good performance under the low signal to noise ratio (SNR) condition.

The field experiments are implemented to test the performance of the proposed feature detection method, which is programmed into a baseband signal process board of the spectrum
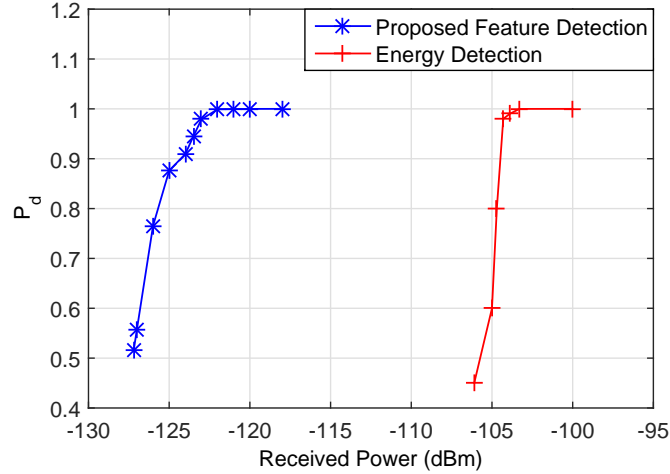
Fig. 3: Detection probability P_d against the received power level of TV signals

sensing modules. The Agilent N5182A MXG signal generator is used to generate analog TV signals. Spectrum sensing module receives analog TV signals through a cable and reports the detection results to the computer. The detection probability P_d and false alarm probability P_f can be determined by the experiment in Fig. 3, which denotes that the P_d can achieve 99.9% under $P_f = 1\%$. Also, the proposed feature detection method improves the weak signal detection ability significantly with the TV signal power level of -120 dBm, compared to the energy detection method.

B. Protocol Stack Modification for CR Enabled TD-LTE System

In this part, minimum modifications to the protocol stacks of TD-LTE system have been proposed to enable the TD-LTE system with CR abilities. Besides, the spectrum sensing results and network information exchange among CeNBs are supported. Therefore, modifications to the TD-LTE protocol stack for both CeNB and CR user are shown in the upper part of Fig. 4.

For the radio resource control (RRC) layer: The spectrum decision management module is designed in CeNB to make spectrum decision according to the spectrum sensing results from the spectrum sensing module. Two main spectrum management functions are proposed for RRC. The first one is the long-term spectrum management among different CeNBs to efficiently allocate and utilize the TVWS. The second one is the short-term spectrum management within CeNB. Thus, the CeNB can guarantee the QoS when channel condition changes during the spectrum
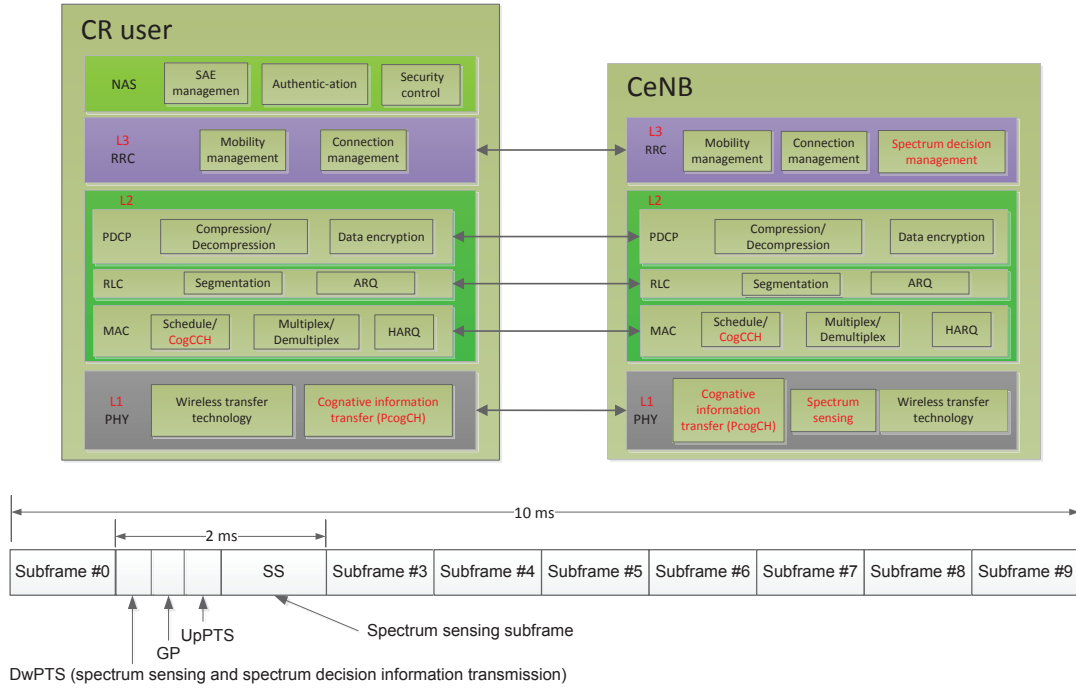
Fig. 4: Proposed CR enabled TD-LTE protocol stack and frame structure.

handover period. Additionally, the spectrum handover decision information will be delivered to lower layers through channels in both MAC and PHY layers.

For the medium access control (MAC) layer: It supports different types of data transmission on different types of logic channels which are determined by the type of data. Moreover, a new logic channel called cognitive channel (CogCH) is proposed both in CeNB and CR user to transmit CR-related RRC messages.

For the physical (PHY) layer: A physical channel called physical cognitive channel (PCogCH) is proposed in both CeNB and CR user to carry the spectrum decision information on the transport channel called Cognitive Channel (CogCH) and broadcast the spectrum decision to CR user through the special subframe. Then, CR user executes the spectrum decision after receiving the broadcast information. Furthermore, through the X2 interface between CeNBs, cooperative spectrum sensing is performed accordingly, which will be used between adjacent CeNBs for spectrum sensing information exchange and long term spectrum management.

Furthermore, the TD-LTE frame structure is modified to enable CR functions as shown in the lower part of Fig. 4. Within each 10 ms TD-LTE frame, the Guard Period (GP) in the special

subframe #1 is used for spectrum sensing which will not disrupt the communication between CeNBs and CR user. Moreover, the adjacent vacant uplink subframe #2 can also be used for the spectrum sensing of a wide range of TVWS. Therefore, the TD-LTE system performs spectrum sensing within 2 ms in each 10 ms frame period. Meanwhile, the spectrum sensing module will perform spectrum sensing and deliver the results to the RRC layer. The downlink piloting time slot (DwPTS) in the special subframe is chosen to transfer both spectrum sensing and spectrum decision information results of the previous frame.

III. PROPOSED HYBRID FRAMEWORK FOR M2M NETWORKS

Besides the realization of dynamic spectrum management over TVWS, we noted that a 3GPP cellular enabled MTC system is highly recommended for M2M networks due to high reliability and availability of cellular networks. An enhanced network architecture for ultra-dense MTC access to the 3GPP LTE-A core via HeNBs/HeNB-GWs and trusted non-3GPP APs had been introduced in [29]. One of the factors which prevent the 3GPP Cellular MTC system to be used as a universal solution is the energy consumption. In order to improve the energy efficiency and sense vacant channels accurately, a hybrid framework is proposed for M2M networks.

As shown in Fig. 5, in order to reduce the data acquisition cost for spectrum sensing, sub-Nyquist sampling is proposed to be performed at the eBNs, HeBNs and trusted non-3GPP access points (APs). In order to improve the performance of CS based spectrum sensing, a remote live geolocation database is implemented at the HeNB-GW and S-GW, which can provide prior information for the compressive spectrum sensing. Before the eBNs, HeBNs or the trusted non-3GPP APs perform spectrum sensing, they would send a request to the closest gateway to get the permitted transmission power for each TVWS channel. These data from geolocation database would benefit the compressive spectrum sensing as they can provide an estimation on the sparsity level of spectrum. Specifically, a non-iterative reweighted compressive spectrum sensing algorithm is proposed to recover the original signals by utilizing the data from geolocation database. Once the original signal is recovered , the sensing decisions on spectrum occupancy can be determined at eBNs, HeBNs and the the trusted non-3GPP APs. The sensing decisions would be sent back to the connected gateway, at which the database update would be conducted if there are some unregistered user found in the spectrum of interest. With the sensing decisions available, the devices connected to eBNs, HeBNs and the the trusted non-3GPP APs would be
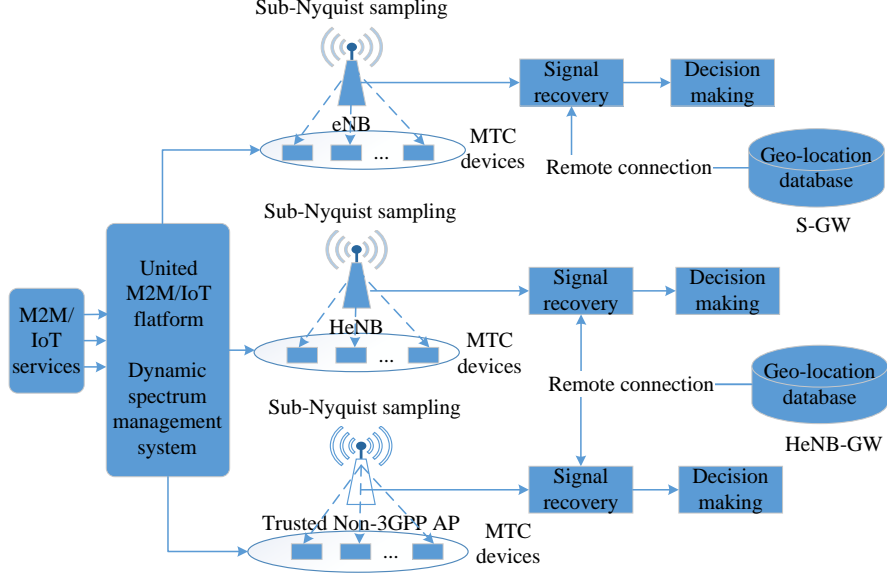
Fig. 5: The proposed hybrid framework combining compressive spectrum sensing and geolocation database in M2M networks.

aware of the information of vacant channels. For different types of devices, they can choose different channels for various services.

In the following of this section, the traditional compressive spectrum sensing model is introduced firstly. Based on this, a non-iterative reweighted compressive spectrum sensing algorithm is proposed for the designed hybrid framework, which can be utilized in M2M networks by invoking LTE-A.

A. Compressive spectrum sensing model

The compressive spectrum sensing model contains four main parts: sparse representation of received signals, compressed measurements collection, signal recovery and spectrum sensing decision making. In this model, it is assumed that the spectrum of interest can be divided into I channels, indexed by i ($i = 1, 2, \ldots, I$). The received signal at a WSD is $r(t) = h(t) * s(t) + n(t)$, where $s(t) \in C^{N \times 1}$ is the time domain representation of the transmitted signal, $h(t)$ is the channel gain between the transmitter and receiver, and $n(t) \sim \mathcal{CN}(0, \sigma^2 \mathbf{I}_N)$ refers to Additive White Gaussian Noise (AWGN).

Representation of the received signal $r(t)$ in frequency domain can be expressed as

$$r_f = h_f s_f + n_f, \tag{1}$$

where r_f, h_f, s_f and n_f are the discrete Fourier transform (DFT) of $r(t)$, $h(t)$, $s(t)$ and $n(t)$. As aforementioned, s_f is sparse as spectrum is normally underutilized in practice. This sparse property makes it possible to reduce the sampling rates at receivers without lossing any information.

When CS theory is invoked at a receiver, the collected compressed measurements can be expressed as

$$x = \Phi \mathcal{F}^{-1} r_f = \Theta r_f = \Theta \left(h_f s_f + n_f \right), \tag{2}$$

where $\Phi \in C^{P \times N}$ $(P < N)$ is a measurement matrix to collect the compressed measurements $x \in C^{P \times 1}$. Additionally, $\Theta = \Phi \mathcal{F}^{-1}$, where $\mathcal{F}^{-1}$ is inverse DFT matrix.

After the compressed measurements are collected at sub-Nyquist sampling rate at WSDs, the original signals should be reconstructed in order to make accurate decisions about spectrum occupancy. Signal recovery can be formulated as a convex optimization problem and solved by the reweighted l_1 minimization in an iterative approach:

1) Initialize $w_n^{(0)} = 1$, $n = 1, \ldots, N$, and iteration index $l = 0$.

2) Solve the reweighted l_1 minimization problem as follows:

$$\begin{aligned}
\hat{s}_f^{(l)} &= \arg \min \left\| W^{(l)} \hat{s}_f \right\|_1 \\
&\text{subject to } \left\| \Theta \cdot h_f \hat{s}_f - x \right\|_2^2 \leq \eta
\end{aligned}, \tag{3}$$

where $W = diag\left(w_1, w_2, \ldots, w_N \right)$ is the set of weights, and η is the noise tolerance.

3) Update the weight for each bin

$$w_n^{(l+1)} = \frac{1}{\left| \hat{s}_{fn}^{(l)} \right| + \varepsilon}, \tag{4}$$

where ε is a positive value to make sure that a zero-valued component in $\hat{s}_f$ does not strictly prohibit a nonzero estimate at the next step of weights update. It has been proved in [30] that the recovery performance of the reweighted l_1 minimization is robust to the choice of ε.

4) Terminate the iterative process on convergence or when l reaches to the specified maximum iteration l_{max}. Otherwise, $l = l + 1$ and go back to step (2).

B. Proposed non-iterative reweighted compressive spectrum sensing

In the traditional reweighted l_1 minimization based spectrum sensing (3), it is noticed that the key challenge is to find the optimal set of weights W in an iterative process for a better estimate

of the original signals. The iterations generate more computational complexities during signal recovery process. In order to reduce the computational complexity during the iterative signal recovery, a non-iterative reweighted compressive spectrum sensing is proposed.

In the proposed non-iterative reweighted compressive spectrum sensing algorithm, the feedback from geolocation database, which is implemented at the HeNB-GW and S-GW, is utilized for the weights construction to replace the iterative process in (4). During each sensing period, before performing spectrum sensing, eBNs, HeBNs or the trusted non-3GPP APs would send a request to related HeNB-GW and S-GW to get the current maximal allowable transmission power for each TVWS channel. In this case, the request is transmitted via the available cellular network. Subsequently, the weights are proposed to be given by

$$w_n = \frac{1}{P_{IB_i} + \varepsilon},$$
(5)

where w_n refer to the weight for each frequency bin of the original signal, and P_{IB_i} is the maximal allowable transmission power for the related ith TVWS channel, where the nth frequency bin locates. It can be obtained from the geolocation database at the HeNB-GW and S-GW. It should be pointed that the efficient algorithm for the DTT calculation in geolocation database proposed in [23] is adopted at the HeNB-GW and S-GW to improve the response speed.

After the weights are constructed, instead of performing the iterative process in (3), the original signal can be recovered by a non-iterative method as follows:

$$\min \left\| \hat{W} \hat{s}_f \right\|_1$$
$$\text{subject to } \left\| \Theta \cdot h_f \hat{s}_f - x \right\|_2^2 \leq \sigma_n^2,$$
(6)

where $\hat{W} = diag\left(w_1, w_2, \ldots, w_N\right)$ is the weight set calculated by (5). Subsequently, the spectrum estimation can be obtained by solving the following problem

$$\hat{s}_f = \arg \ \min \ \left\| \Theta \cdot h_f \hat{s}_f - x \right\|_2^2 + \lambda \hat{W} \cdot \hat{s}_f^2$$
(7)
$$= \hat{W} \Theta^{\mathrm{T}} \left(h_f \hat{s}_f \hat{W} \Theta^{\mathrm{T}} + \lambda \mathrm{I}_P \right)^{-1} x,$$

where λ is the Lagrangian factor.

After the reconstructed signal $\hat{s}_f$ is obtained by solving (7), energy detection is performed to determine the spectrum occupancy. Therefore, the energy of recovered signal is compared with a predefined threshold λ_d to make the decisions on spectrum occupancy [31]. The threshold λ_d can be given by

$$\lambda_d = \sigma^2 \left(1 + \frac{Q^{-1}\left(\bar{P}_f\right)}{\sqrt{N/2}} \right),$$
(8)

where $\bar{P}_f$ refers to the target probability of false alarm and N is the number of samples at Nyquist rate. If energy of the reconstructed signal is higher than threshold, the corresponding channel is determined as occupied. As a result, other devices are forbidden to access it. Otherwise, the corresponding channel is determined as vacant, and WSDs can access it to transmit unlicensed signals.

In the traditional reweighted compressive sensing algorithm, the computational complexity to solve the iterative l_1 problem is $\mathrm{O}\left(LP^3\right)$. With the proposed hybrid framework, the computational complexity for solving signal recovery problem is reduced to $\mathrm{O}\left(P^3\right)$. Additionally, for the l_1 minimization without weights information, the required computational complexity is at the level of $\mathrm{O}\left(\hat{P}^3\right)$, where $\hat{P}$ is much greater than P. Therefore, our proposed hybrid framework achieves the lowest complexity on signal recovery, which leads to a low energy consumption at MTC devices locally.

Additionally, as the geolocation database is invoked at the HeNB-GW and S-GW, no extra energy consumption is introduced at MTC devices. The geolocation database is maintained at the HeNB-GW and S-GW, which is less sensitive to the energy consumption. Meanwhile, as the cellular network is reliable and available widely, the connection between the MTC devices and the related gateway can be guaranteed with a high probability.

IV. PERFORMANCE ANALYSES OF PROPOSED CR ENABLED TD-LTE TEST-BED

The CR enabled TD-LTE test-bed has been designed and developed in Beijing University of Posts and Telecommunications (BUPT) with two CeNBs and eight CR users. Both CeNBs and CR users are implemented using the unified hardware platform in [32]. In this platform, the baseband signal processing functions are implemented on TI C6487 DSP. In this three-core DSP, one of the DSP core is used for downlink signal processing, the second one is used for uplink signal processing and the third one is for scheduling. The AD/DA operation is done on Xilinx FPGA, with the AURORA interface to DSP. Besides, the platform can also download different protocols from DSP dynamically, which is capable of reconfiguring its work mode and parameters intelligently to utilize the TVWS.

Considering each TV channel occupies a frequency of 8 MHz in China, the TD-LTE system can operate in 20 MHz bandwidth when three continuous TV channels (totally 24 MHz) are vacant. After CeNB detects the appearance of TV signal, the CeNB will execute spectrum handover and switch to another vacant spectrum band accordingly. Furthermore, the spectrum

Fig. 6: CR enabled TD-LTE Test-bed.

sensing results will also be sent to the geolocation database for vacant spectrum information update, which is used for vacant spectrum information coordination and synchronization among CeNBs. When continuous TV channels are less than three, the test-bed can apply the dynamic system bandwidth adjustment technology, which means that 15 MHz bandwidth is used when two continuous TV channels are vacant and 5 MHz bandwidth is used if only one TV channel is available. Therefore, the test-bed can dynamically change its system bandwidth in order to adapt to different vacant spectrum conditions in practical scenarios.

Proposed CR enabled TD-LTE test-bed has both the outdoor and indoor scenarios. In the outdoor scenario, CeNB is deployed on the roof of the building along the XINGTAN road with two mobile CR users. In the indoor scenario, the trial of the test-bed is shown in Fig. 6 with three analog TV signal transmitters deployed indoors as the primary TV broadcasting system. The CeNB and CR users are placed inside the room with a Light-of-Sight (LoS) propagation. The antennas for both CeNB and the CR users are 6 dBi rod-antenna. The transmit power of the CeNB is 20 dBm. Additionally, both CeNBs indoors and outdoors are connected to the geolocation database and advanced spectrum management (ASM) subsystem. Moreover, based on the global spectrum occupancy graph from the geolocation database, the ASM subsystem is responsible for an efficient spectrum management and coordination among different CeNBs by making decisions for the efficient vacant spectrum allocation.

In Fig. 7, the packet loss ratio of the CR enabled TD-LTE system is plotted during a period of 2 s by 200 samples with 10 ms for each sample. During the experiment, the TV transmitter is turned on at 1 s, and the packet loss ratio of the CR enabled TD-LTE system is fairly steady before
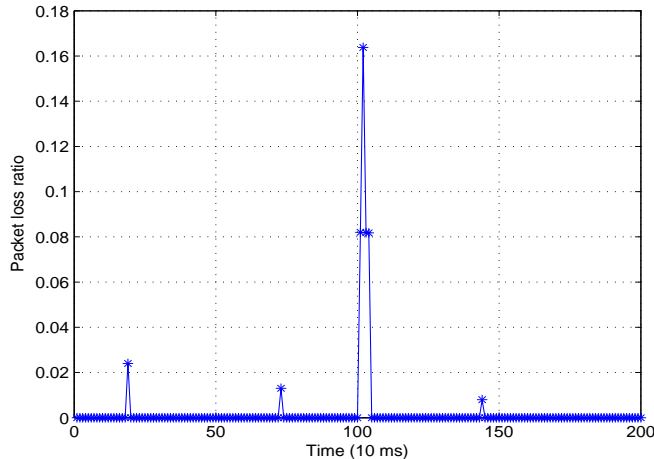
Fig. 7: Packet loss ratio during spectrum handover.

1 s and increases significantly after 1 s as depicted by the surge at the point of 100 samples. This indicates that the interference from TV signals is strong, which results in a tremendous packet loss. However, due to the accurate and timely TV signal detection and spectrum handover, the packet loss ratio of the CR based TD-LTE system can be quickly restored within 50 ms as shown in Fig. 7. The field experiments are carried out iteratively in both indoor and outdoor scenarios. In contrast to the silence period applied by IEEE 802.22 standard in [33], the proposed CR enabled TD-LTE test-bed can achieve the spectrum handover within 50 ms on average without severe performance deterioration or service dropout, which significantly outperforms the scheme of IEEE 802.22 using the avoiding time of 2 s in [34].

V. NUMERICAL ANALYSES OF PROPOSED HYBRID FRAMEWORK

In the simulation, PUs are assumed to be orthogonal frequency-division multiplexing (OFDM) signals, which is used by the DVB-T signals in TVWS from 470MHz to 790MHz in the UK [35]. There are a total of 40 channels in TVWS with a bandwidth of 8MHz for each channel. It is assumed that each PU is independent and only locates at one channel, and $\bar{P}_f$ is set to be 0.01. The transmission channel for signals is modeled as AWGN channel, and SNR is defined as the ratio of received signal power to the noise power in each TVWS channel ($SNR = \sigma_s^2/\sigma^2$), where σ_s^2 is defined as the transmitted signal power. In the following of this section, the proposed hybrid framework combining compressive spectrum sensing and geolocation database is tested on both the simulated and real-time data.
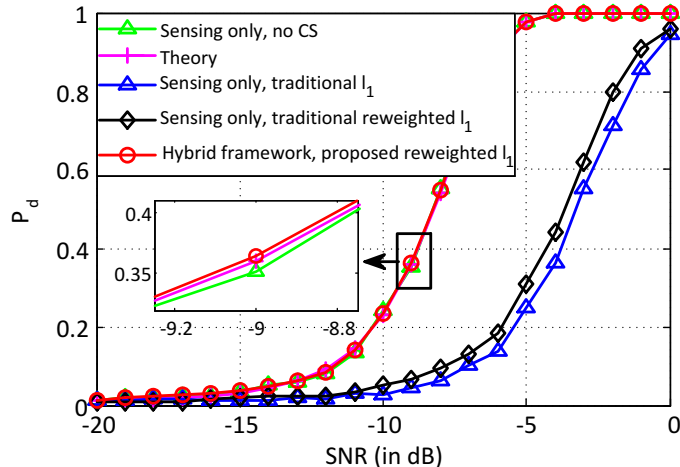
Fig. 8: Detection performance on the simulated signals and data under different SNR, compression ratio is 5%.

A. Numerical analyses on the simulated data

Fig. 8 shows detection performance of the sensing only scheme with the traditional l_1 and the traditional reweighted l_1, and the proposed hybrid framework with the proposed non-iterative reweighted compressive spectrum sensing algorithm. It is observed that the detection performance of sensing only scheme without CS implemented at an SU is matched with the theoretical curve, which is presented as a benchmark, which can be expressed as

$$P_d = Q \left(\frac{\frac{\lambda_d}{\sigma^2} - \left(1 + \frac{\sigma_s^2}{\sigma^2}\right)}{\left(1 + \frac{\sigma_s^2}{\sigma^2}\right) \Big/ \sqrt{N/2}} \right). \tag{9}$$

The maximal iteration number l_max is set to be 2 in the traditional reweighted l_1 minimization based spectrum sensing to obtain suitable values for the weights as it is shown that the signal recovery is perfect after the second reweighted iteration [30]. Fig. 8 shows that detection performance of the sensing only scheme with traditional l_1 minimization used for signal recovery is much lower than the theoretic curve due to the signal recovery errors caused by the low compression ratio (5%). When the traditional reweighted l_1 minimization is implemented for signal recovery in sensing only scheme, its performance is slightly improved in comparison with that of the traditional l_1 minimization. However, it is noticed that the detection performance is improved by about 7% to 8% while triple costs of computational complexities are introduced. When the proposed hybrid framework with non-iterative reweighted l_1 minimization is performed, P_d increases greatly which can almost match with the theoretic curve. The reason for the large
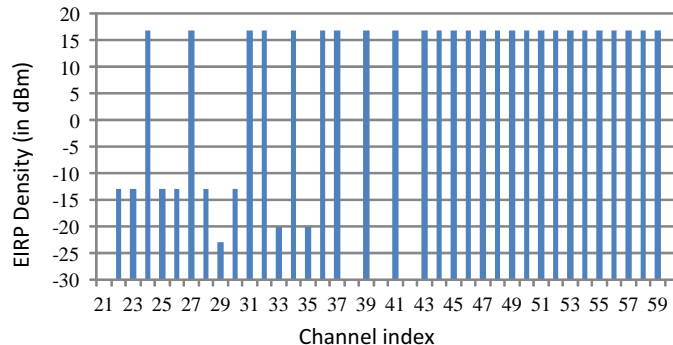
Fig. 9: Maximum permitted transmission power for each channel in TVWS at location (51.523021°N 0.041592°W) according to geolocation database provided by Nominet.

performance improvement is that the data at HeNB-GW or S-GW helps to obtain a set of weights which are more suitable for exact signal recovery. As a result, the proposed non-iterative reweighted l_1 minimization compressive spectrum sensing can achieve better detection performance, with 67% of computational complexity reduced in comparison with the traditional reweighted l_1 minimization algorithm. This is because the iterative signal recovery process is simplified and signal recovery would only have been performed once due to utilizing the data obtained from the geolocation database implemented at the HeNB-GW and S-GW.

B. Numerical analyses on the real-time data

After the proposed hybrid framework is validated by the simulations above, we test it by real-time signals sensed by the CRFS RFeye node and the live geolocation database from Nominet. The RFeye nodes used is located at (51.523021°N 0.041592°W), and the height is about 15 meters above ground. Nominet is one the geolocation database providers for Ofcom. When the geolocation database implemented at HeNB-GW and S-GW is replaced by the live database provided by Nominet, Fig. 9 shows the maximal allowable transmission power P_{IB} for each TVWS channel at (51.523021°N 0.041592°W), in which the RFeye node is implemented.

When the P_{IB} for each TVWS channel is obtained from Nominet's geolocation database, Fig. 10 shows the P_d and P_f of the sensing only scheme with traditional l_1 minimization and the proposed hybrid framework with the proposed non-iterative reweighted l_1 minimization under different thresholds. Here, the thresholds are experimental values, and the compression ratio is set to be 5%. We can see that both the P_d and P_f decrease with increasing threshold values. The proposed hybrid framework outperforms the sensing only scheme under different threshold
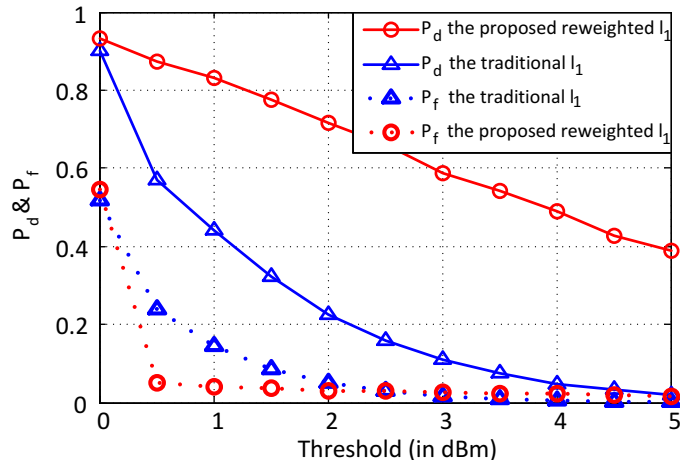
Fig. 10: Detection performance on the real-time signals and data under different thresholds.

values. It can be observed that P_d of the proposed hybrid framework decreases gradually with increasing threshold values. However, the P_f decreases significantly when threshold increases from 0 to 0.5. Once the threshold is higher than 0.5, the P_f of the proposed hybrid framework keeps to be flat. Therefore, we choose 0.5 as the suitable threshold to get a better tradeoff of P_d and P_f in the following simulations.

Fig. 11 shows the P_d and P_f of the sensing only scheme with traditional l_1 minimization and the proposed hybrid framework with non-iterative reweighted l_1 minimization on real-time signals and geolocation data under different compression ratios. In this scenario, the threshold value is set to be 0.5 according to analysis in Fig. 10. We can see that detection performance becomes better with increasing number of compressed measurements, and the proposed hybrid framework outperforms the sensing only scheme with the traditional l_1 minimization.

VI. CONCLUSIONS

This paper has argued a hybrid approach of spectrum sensing combined with geolocation databases to serve M2M/IoT scenarios. It has noted both important recent developments in geolocation database-assisted opportunistic spectrum sharing, and hybrid spectrum sensing with geolocation database approaches as interesting and practical ways forward to facilitate dynamic spectrum access. It has noted the need for simplicity and scalability in spectrum sensing approaches, leading to work on compressive sensing. Building on the scope of such approaches and observations, this paper has proposed both a cognitive radio enable TD-LET test-bed and a non-
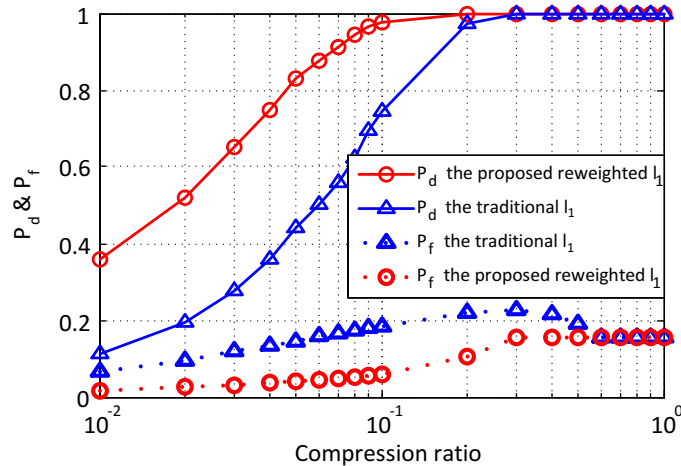
Fig. 11: Detection performance on the real-time signals and data under different compression ratios.

iterative reweighted compressive spectrum sensing algorithm assisted by geolocation databases. Furthermore, it has tested the concept by simulated as well as with real-world data over TV white space spectrum.

Such geolocation-database assisted sensing approaches, as well as the more conventional sensing-assisted geolocation database approaches, can be levied also to ensure reliability and quality of service among the secondary spectrum users, given the capabilities and information that such databases and the overarching frameworks typically have. Further exploration of the reliability that can be achieved for M2M/IoT opportunistic spectrum usage, through assistance and dynamic "tuning" by the database under such hybrid scenarios, is an area for interesting future work.

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