

1 Introduction

Despite the ubiquity, capacity and apparent efficacy, modern communication systems are wasteful, inefficient and in need of reform. Most of the bits of data collected by our sensing systems are unessential, and only serve to necessitate data compression wasting computation time before transmission. For example, people regularly use a camera with a resolution of several megapixels only to upload a file of a few kilobytes to Facebook. Devices are unable to make dynamic decisions about how to transmit this data, leading to both spectral exhaustion on some frequencies whilst much of the available radio spectrum lies fallow.

There is an almost ubiquitous growing demand for mobile and wireless data, with consumers demanding faster speeds and better quality connections in more places. Consequently 4G is now being rolled out in the UK and US and with 5G being planned for 2020 and beyond [?].

However, there is constrained amount of frequencies over which to transmit this information; and demand for frequencies that provide sufficient bandwidth, good range and in-building penetration is high.

Not all spectrum is used in all places and at all times, and judicious spectrum management, by developing approaches to use white spaces where they occur, would likely be beneficial.

This project addresses these issues, by reviewing a novel acquisition and decompression framework for data: a way in which we need only sense the most informative bits of data. This framework is then applied to the problem of sensing spectral opportunities dynamically, to make better use of available spectrum.

The key uniting both these applications is that data and spectra are *sparse*: that is they have a representations which are 'smaller' than their respective dimension. For example, images and audio can be compressed into file formats much smaller than when initially recorded (compare the relative sizes of bitmap and JPEG images).

The sole focus of this research is to use the sparsity of the spectrum to uncover transmission opportunities, allowing better use of spectrum more generally.

We are motivated by the need to send more data over wireless networks, whilst at the same time having a constrained frequency set over which to transmit this information. This issue could be alleviated by users dynamically allocating spectrum on a per-transmission basis: without the ability to gain knowledge of spectral conditions this can never become a reality however.

The requirement for increasing bandwidth isn't just a pressing issue for today: in the next decade it is forecast that network operators will need to provide for three-orders of magnitude (1000 times) more capacity. Demand is continually outstripping supply - motivated by the ubiquity of smart-phones, and the consumers appetites for media.

At the same time as this demand for ever more data, there is an increasing scarcity of radio spectrum over which to transmit. New frequencies are rarely cleared for commercial purposes, and when they are they go for high prices. A

decade ago the UK auction for 3g spectrum licenses raised an estimated 22.4 billion [?] for the UK treasury, indicating the seriousness of the market players requirements for new spectrum. The recent 4g spectrum auction raised 2.3 billion [?]- with initial networks being rolled out by the end of 2013.

However, a closer inspection of the frequency allocation suggests this scarcity is artificial, it's more a product of regulatory oversight over time. As the constraints on spectrum requirement became more complex, so did the solutions to that problem - at the cost of leaving much of the spectrum idle for most of the time.

For example: much of the spectrum is allocated to TV broadcast, radio broadcast and mobile. However, if we look closer, the allocations aren't even for specific companies - they're simply categories. Within these, OFCOM may have many licensees within each category.

Also interesting to note is how much frequency the Government allocates to itself (the red bar underneath the blocks indicates Government use). Compare this to the actual utilisation of spectrum: much of it is not used at all. Figure ?? shows a snapshot of frequency utilisation in three diverse locations in the UK over the radio spectrum, note that many frequencies are not utilised (coloured blue) whilst others have significant activity (coloured yellow). Note that the plot for Southwark (central London) is barely different from Braddock - a rural area.

Broadly, access to spectrum is managed in two, complementary ways, namely through licensed and licence exempt access. Licensing authorises a particular user (or users) to access a specific frequency band. Licence exemption allows any user to access a band provided they meet certain technical requirements intended to limit the impact of interference on other spectrum users.

A licence exempt approach might be particularly suitable for managing access to white spaces. Devices seeking to access white spaces need a robust mechanism for learning of the frequencies that can be used at a particular time and location. One approach is to refer to a database, which maps the location of white spaces based on knowledge of existing spectrum users. An alternative approach is for devices to detect white spaces by monitoring spectrum use.

The advantages of spectrum monitoring [?] over maintaining a database of space-frequency data are the ability of networks to make use of low-cost low-power devices, only capable of making local (as opposed to national) communications, keeping the cost of the network low and opportunistic channel usage for bursty traffic, reducing channel collisions in dense networks.

The realisation of any Cognitive Radio standard (such as IEEE 802.22 [?]), requires the co-existence of primary (e.g. TV users) and secondary (everybody else who wants to use TVWS spectrum) users of the frequency spectrum to ensure proper interference mitigation and appropriate network behaviour. We note, that whereas TVWS bands are an initial step towards dynamic spectrum access, the principles and approaches we describe are applicable to other frequency bands - in particular it makes ultra-wideband spectrum sensing possible.

The challenges of this technology are that Cognitive Radios (CRs) must sense whether spectrum is available, and must be able to detect very weak primary

user signals. Furthermore they must sense over a wide bandwidth (due to the amount of TVWS spectrum proposed), which challenges traditional Nyquist sampling techniques, because the sampling rates required are not technically feasible with current RF or Analogue-to-Digital conversion technology.

How do we then go about solving this issue - how can we obtain the most significant bits of information from our sensing mechanism, whilst obviating the need to compress the data once we are done? How do we dynamically assign spectrum? The work of Candes, Tao [?] and Donoho [?], has shown that instead of measuring the information we require directly (and then compressing it), we can measure 'holographic' and non-linear random projections between our measurement space and the space where our data is sparse. This requires only the knowledge that the signal is compressible via some transform - both the acquisition protocol and the reconstruction algorithm are agnostic to the type of signal. What is surprising is that the sampling kernels are fixed independently of the signal, are non-adaptive and these projections are sufficient to reconstruct the signal - as if we had an Oracle to tell us where the non-zero components of our signal are.

This work has had a large impact in medical imaging since it's inception: for example, it's now possible to take an image of a patient's heart within a single breath, as well as dynamic imaging of the heart ([?] figures 7 and 9).

Modern digital signal processing techniques (such as modulation techniques) are far more spectrally efficient than their historic analogue counterparts, which has in part contributed to the spectrum crisis. All this is changing though: from the beginning of 2013 all TV in the UK will be transmitted digitally. Historically, television in the UK was broadcast using analogue signals requiring 32 multiplexes. Digital TV requires 6 multiplexes, on the other hand.

This freeing up of TV frequencies represents an opportunity: these frequencies have good propagation characteristics (they suffer less with free space path loss relative to higher frequencies), whilst still providing good bandwidth for data transmission. These TV frequencies are being opened up to civilian and commercial users: spectral holes will be able to be exploited opportunistically by devices, so long as they don't interfere with the reception of TV. Historically, this is the single largest gift of new spectrum, and because there is no requirement for licensing this spectrum is free.

As with all technological innovations, this will not only improve existing infrastructure but also new classes of devices to transmit, for instance; applications such as passive sensor networks) which only need spectrum intermittently to transmit monitoring results), inter-vehicle communication for real time traffic monitoring and wireless internet at broadband data rates have all been proposed.

Despite all of this hype, dynamic spectrum access won't become a reality unless spectral holes can be robustly detected. The requirement that secondary users exploit the new spectrum politely, without interference to primary user makes spectrum sensing essential to TV white-space (TVWS) technologies. The realisation of any Cognitive Radio standard (such as IEEE 802.22), requires the co-existence of primary (TV users) and secondary (everybody else who wants to use TVWS spectrum) users of the frequency spectrum to ensure proper in-

interference mitigation and appropriate network behaviour.

Users of TVWS (Cognitive Radios) must sense whether spectrum is available, and must be able to detect very weak primary user signals. Furthermore they must sense over a wide bandwidth (due to the amount of TVWS spectrum proposed), which challenges traditional Nyquist sampling techniques, because the sampling rates required are not technically feasible with current RF or Analogue-to-Digital conversion technology.

Sensing should enable devices to detect the presence of TV signals in a band and provide smart and adaptive (and possibly distributed) solutions to band identification.

Spectrum sensing should involve:

1. Sensing to detect white spaces.
2. Co-existence with similar devices.
3. Frequency monitoring of other devices.
4. Interference management.
5. Spectrum mobility and transmission power control when needed.

As described earlier, the available spectrum is highly underutilised, and can be thought of as a collection of narrowband transmissions over a wideband channel. As such, the spectrum we're sensing is sparse. This makes it an ideal candidate for sparse recovery techniques such as Compressive Sensing.

The structure of the report is as follows: first a few methods for sensing narrowband signals (i.e. channels where the frequency response is approximately flat, and where the bandwidth is smaller than the coherence bandwidth of the channel) are discussed and the limitations of these are highlighted for the problem of sensing spectrum for Cognitive Radios. Then (more appropriate) wideband sensing techniques are discussed.

Compressive Sensing, and Group Testing are then introduced and it is argued that they offer appropriate solutions to the sensing problems for cognitive radios. Sampling schemes married to these reconstruction algorithms are discussed.

Finally the results and simulations performed over the time-frame of the project are discussed, with reference to further work.

2 Introduction

Due to the inherent sparsity of spectral utilisation, Compressive Sensing (CS) [?] is an appropriate formalism within which to tackle this problem. CS has recently emerged as a new sampling paradigm allowing images to be taken from a single pixel camera for example. Applying this to wireless communication, we are able to reconstruct sparse signals at sampling rates below what would be required by Nyquist theory, for example the works [?], and [?] detail how this sampling can be achieved.

However, even with CS, spectrum sensing from a single machine will be costly as the proposed TVWS band will be over a large frequency range (for instance in the UK the proposed TVWS band is from 470 MHz to 790 MHz, requiring traditional sampling rates of ~ 600 MHz). CS at a single sensor would still require high sampling rates. In this report we propose a distributed model, which allows a sensing budget at each node far below what is required by centralised CS.