Radio coverage designs for LPWAN access network

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Internet of Things or IoT is an rapidly growing area of technology both commercially for applications in smart homes or in industrial application for level monitoring such as water tanks. This applications generally require a low amount of power to function. One emerging low power wide area network (LPWAN) technology which tries to fulfill this commercial need is Narrow band Internet of Things (NB-Iot). It has become a widely adopted standard for the enabling of wireless communications for Internet of Things (IoT) devices. With the current number of IoT devices, currently estimated at almost 22 billion and increasing exponentially. The knowledge and optimisation of IoT networks will become vitally important for future applications within this growing technologically dependent world.

This research report outlines the possibility of an NB-IoT network north of the central business district in Melbourne. The method to determine suitability is through simulation of the network coverage and gathering various performance metrics.

Introduction: The aim of this research into LP-WAN networks is to determine the coverage performance of existing cellular tower locations being utilised for Narrow band Internet of Things (NB-IoT) network. The simulation will take place using the various tools found in the Matlab software development environment. At the completion of this research undertaking the following areas will be investigated:

- Suitable SNR when transmitting transport blocks on shared downlink channel in the NB-IoT network.
- Coverage of NB-IoT in relation to RSS and SNR.
- Analyse the relationship between distance from transmitter sites to a receiver.
- Understand the current limitations of NB-IoT.

The motivation for studying this topic are in the hopes of understanding the current capabilities of NB-IoT. The contribution of this work from the various NB-IoT network performance data gathered could prove useful in future endeavours to generate algorithms which can optimise the network.

Overview of NB-IoT: The third generation partnership project (3GPP) as part of release 13 of long term evolution (LTE) standard, introduced a new form of low power wide area network (LPWAN) technology called Narrow Band Internet of Things (NB-IoT). The standard is focused on being as simple as possible to reduce overhead related to financial costs and power consumption. [1] Application of IoT can be classified into two categories that are based on data rate requirements. Firstly there is high data rate which consists of audio or video data transmission and then there is low data rate that includes activities such as meter readings where small amounts of data are sent over the network periodically. NB-IoT focuses on the low data rate category due to its overall market share within IoT. A survey by A-TECH engineering in 2017 found that 67 percent of total IoT services are classified with low data rate consumption [2]. The common activities that NB-IoT devices undertake do not require them to be mobile which is why they are not optimised for handover and are battery powered due to being installed in places without a power supply. Although handover is not a priority a large number of devices are in proximity of each other which results in the need for low signalling overhead. This was also the reasoning behind 3GPP pushing for a new release of LTE and the lack of backwards compatibility with previous LTE releases. Only in the idle state can cell reselection take place. NB-IoT is allocated a subset of LTE's frequency range depending on downlink and uplink. Majority of the frequency bands are located in the lower end of LTE's frequency range.

The simplified protocol stack of NB-IoT makes it favourable for low power usage data transmission. There are five components of the NB-IoT network. Firstly, is the NB-IoT terminal, these are the end devices which are connected to the network monitoring and transmitting data. Base stations, which are formally referred to as eNodeB (eNB) are the second layer of the network responsible for relaying information to and from the end devices. The third layer is the core network, this is the main network access architecture of NB-IoT. It does not differ from LTE. eNBs connect to a mobility management entity (MME) which is a control node for the access network [3] it allows for base stations to connect with the cloud network.Ultimately, NB-IoT standard seeks to provide large area coverage, low power consumption, affordability and be able to support a large network of devices.

Coverage and Performance: For NB-IoT to operate there is a minimum bandwidth requirement of 180 kHz. The radio coverage consists of link budget calculations to determine the maximum range of the IoT Access Network, factors that need to be considered when determining coverage include maximum transmission power levels, antenna gains, path loss models, receiver sensitivity, and minimum SNR threshold values to achieve an acceptable quality of service [4]. These desired qualities of the network can be benchmarked by using various parameters such as Maximum Coupling Loss (MCL), Target Signal to Noise Ratio (SNR) and block error rate (BLER). There are four physical downlink channels that work in succession of each other in the network where the above parameters are used to test performance of the overall NB-IoT network. They include the synchronization, broadcast, control and the downlink shared or data channel. [5]

Synchronization channel: This involves two signals called the Narrowband Primary Synchronisation Sequence (NPSS) and the Narrowband Secondary Synchronization Sequence (NSSS) both signals occupy the 180kHz bandwidth that NB-IoT operates at. NPSS signal is used for identification of the symbol timing and carrier frequency, while the NSSS is used to obtain the cell which the device is located within. This channel can be evaluated for its performance by measuring the time it takes to complete the synchronization sequence for the devices in the cell.

Broadcast channel: Formally referred to as the Narrowband Broadcast Channel (NPBCH) is the first subframe, within the LTE based frame of length 10ms [6], that is transmitted from the eNB. The data carried within this subframe is the Master Information Block (MIB) which is needed to acquire information from the cell. The subframe has a length of 34 bits with an additional 16 bits for cyclic redundancy check (CRC) for error detection,giving a total length of 50 bits. Performance of the channel is measured by the SNR where a block error rate (BLER) of 1 percent is highly desirable. The BLER is the quality of the connection that is calculated by dividing the number of incorrect blocks of data with the total number of blocks transmitted [7]. The CRC helps in its calculation by matching for the same CRC data in receiver and transmitter.

Control channel: The Narrowband Downlink Control Channel (NPDCCH) carries downlink control information. This data is integrated within a single subframe of length 23 bits. This channel's capabilities are assessed by looking at coverage; the chosen metric for this by 3GPP is maximum coupling loss (MCL). It is calculated by finding the difference between the power at the receiver and transmitter and not taking into account antenna gain [8]. Coding rate (CR), the amount of data transferred within a period of time, is also important in measuring performance in this channel. This is because it is related to the number of block repetitions that occur which directly affects MCL and BLER.

Data channel: The specific name of this channel is the Narrow band Down-link Shared Channel (NPDSCH), carrying the data which is unique for each user in the network. This has a variable length ranging from 256 to 680 bits with a 24 bit CRC subframe that is appended. The importance when measuring the performance of this channel is the transmission data rate which means it is closely related with the control channel. The maximum number of repetitions supported is 2048.

Battery Consumption: The battery lifetime for devices in NB-IoT have to be extremely long lasting due to the sheer number of devices that would need to have their battery replaced, that is why minimising battery consumption is of great importance. A method to reduce minimisation is called DRX [9]; it is the discontinuous reception and infrequent data packet transmission on the NPDCCH.

Limitations: The disadvantages with the current state of NB-IoT include the following:

- *Non-Uniform resource allocation*: Resources as part of 3GPP release 13 of NB-IoT allocates resources based on the total available power, demand from different channels and coverage range. This constantly changing demand of resources places a strain on energy consumption of the device which reduces battery life. There is a need for algorithms which handle resources in real time.[10]

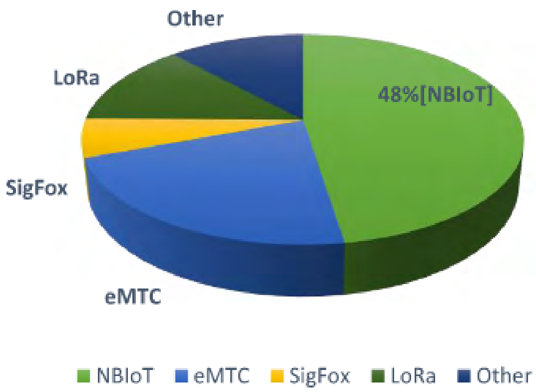

Fig. 1. Forecast for marketshare in IoT by 2025.

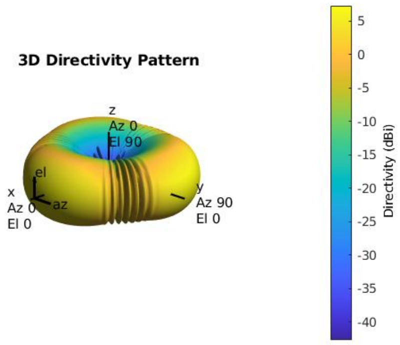

Fig. 2. Antenna Shape in 3D space

- *Poor Throughput*: The premise of NB-IoT and all LoRaWAN technology is to use as little power as possible. Therefore the power of the transmitted signal will be low.
- *Inter-channel interference*: The frequency allocation depending on the configured mode is asynchronous with all other cells in the network. Interference within each cell is also present due to small cells in a larger cell.
- *Spectral Efficiency*: In order to have extended coverage from eNB sites multiple repetitions are required. This results in reduction of spectral efficiency which is the amount of data that can be transmitted over a given spectrum. High channel capacity also needs to be maintained and this increases power consumption.
- *Latency*: This needs to be kept under 10 seconds in NB-IoT network and this becomes difficult due to different types of latency which can be experienced such as uplink/downlink and packet synchronization.
- *Security*: Due to simple design to fulfill the requirement for low power consumption it is difficult to allocate resources to defend against attacks on the network. Such attacks include data injection and transmitting deliberate interference signals.

Current State of NB-IoT: NB-IoT will continue to evolve with upcoming releases from 3GPP. It seeks to deliver enhanced user experience in selected areas through the addition of features such as increased positioning accuracy, increased data rates, the introduction of a lower device power class, improved non-anchor carrier operation, multicast, and authorization of coverage enhancements.[11] 5G and its usage of massive machine type communication there has been research into creating an open source NB-IoT networks [12]. This would enable faster and permission-less innovation [13]. It would also increase the speed in which the solutions can be generated for the current issues NB-IoT face such as security and non-uniform resource allocation. Power failure is an issue which has not been addressed with NB-IoT but there are design implementations of power failure reporting systems which work by storing energy in a super capacitor [14] that functions similar to an emergency electricity generator; it would send a distress signal to an eNB that the power has failed. From a financial standpoint NB-IoT is expected to have the leading market share within LPWAN technology with estimates of 48 percent by 2025 (Figure 1).

Design Implementation: To test NB-IoT downlink transmission performance, simulation was done using various tools in MATLAB. The assumptions that are made is that the effective noise power is -85 dBm, this will disregard the need to use temperature measurements to find thermal noise. The configuration of the antenna at the enB sites include being 3 directional with a 120 degree spacing and has a height of 30 metres. The transmitting frequency of each antenna will be 900 MHz. In figure 2 can be seen the overall shape of the antenna in 3-dimensional space with relative directivity.

The geographic coordinates of each antenna location of various sites in Melbourne central business district was given as per project specifications (Figure 3).

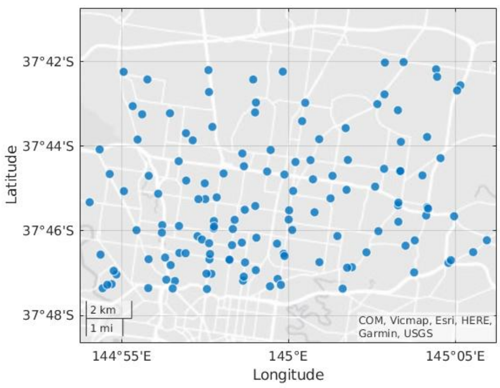

Fig. 3. Location of Transmitter sites

BLER vs SNR

The first simulation will be the transmission of blocks using the NPDSCH, to ultimately compute a BLER vs SNR graph. This will be done for two different coding/repetition rates: 1 and 32 to determine the receiver sensitivity value by getting the noise floor. This will be determined by analysing the graph where 5 percent BLER is first achieved and this will be used for the calculations of receiver sensitivity in 4 by substitution of the minimum SNR variable.

The three most important lines of code within MATLAB's BLER simulation code that will be used to configure for the 32 repetition rate as per project specifications.

```
numTrBlks = 100;
SNRdB = -35:1:0;
ireps = [5];
```

Line 1 is the total number of blocks that will be sent over the NPDSCH for the 32 repetition rate. 100 blocks were enough to get a satisfactory output for a repetition rate of 32, however using 1 repetition rate the number of blocks needed to be increased substantially to 500 due to the BLER. The next line samples a range of Signal to Noise values in decibel. The third line involves the repetition or coding rate where each integer increases the repetition rate by 8. Therefore a ireps value of 1 will give 1 repetition in the simulation and a ireps value of 5 will configure a coding rate of 32.

Relative Signal Strength (RSS)

The relative signal strength will be visualised in two ways: the first is through simulation to get a contour coverage map by using the longley-rice radio propagation model. This will determine the overall coverage from all eNBs while taking into account variances in terrain height. Each

$$Prx, min = P_N + NF + SNR_{min} = P_{N,eff} + SNR_{min}$$

Fig. 4. Receiver Sensitivity Equation

transmission site will be configured with the predefined conditions that are in the project specification and 3GPP recommendations. This will then be displayed with the coverage map functionality of the antenna toolbox The code configuration is shown below.

```
txs = txsite(   ...
     'Latitude', td(:,1), ...
     'Longitude', td(:,2), ...
     'AntennaHeight',30,...
     'TransmitterPower', 40, ...
     'TransmitterFrequency', fc);



array = phased.UCA('Element',antenna,'Radius',2,...
          'NumElements',3);


for i = 1:length(txs)
   txs(i).Antenna = array;
end

coverage(txs,rx, 'longley-rice',...
     'SignalStrengths',-110:10:0)
```

The second way RSS will be evaluated is by setting up a receiver antenna located at the geographic coordinates of RMIT building 80. Through usage of Matlab's communication and mapping toolbox the graph of RSS relative to distance of each eNB and the RSS from each eNB can be computed. The snippet of code below accomplishes this task.

```
rmit = [-37.808176661814905,
     144.96240622449]; %location of building 80

eff_nf = -85; %as specified

SNR_min = -10; %from BLER vs SNR graph

rx_sensitivity = eff_nf + SNR_min;

rx = rxsite('Name','RMIT Building 80', ...
        'Latitude', rmit(1), ...
        'Longitude', rmit(2), ...
        'ReceiverSensitivity', rx_sensitivity);

ss = sigstrength(rx,txs);

sites = 1:length(ss);

figure(2)

plot(sites,ss);
xlabel('Site Number')
ylabel('RSS(dBm)')

distgc = zeros(1,length(ss));
dist = zeros(1,length(ss));
max_rss = max(ss);
min_rss = min(ss);

for j = 1:length(ss)

     if ss(j) == max_rss
          max_rss = [td(j,1),td(j,2)];
     elseif ss(j) == min_rss
          min_rss = [td(j,1),td(j,2)];
     end

     distgc(j) = distance(td(j,1),td(j,2),...
     rmit(1),rmit(2));
     dist(j) = deg2km(distgc(j));

end
```

Using the data gathered of distance from the reference receiver point and the eNB locations a regression model can be computed to find the relationship between RSS and distance for the given simulation area within Melbourne.

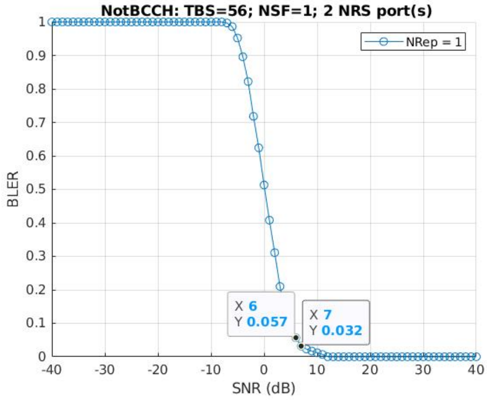

Fig. 5. BLER vs SNR for 1 Repetition

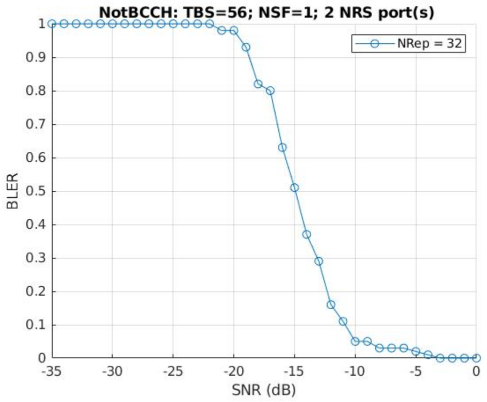

Fig. 6. BLER vs SNR for 32 Repetition

SNR Coverage

The signal to noise ratio contour coverage map was computed using the sinr() function in the antenna toolbox where the same data of the transmitter sites from the coverage map of the RSSI.

Below is a diagram of the entire design process to simulate various performance benchmarks in NB-IoT downlink coverage.

***Results**:*

BLER Simulation

The NB-IoT NPDSCH block simulation for a repetition rate of 1 that is transmitting a block size of 1000 is shown in Figure 5 graphed against SNR.

For the 32 repetition rate 100 blocks were transmitted down-link shared channel and similarly graphed as shown in Figure 6 the sampling SNR range was from -35dB to 0dB.

From these two simulations the 5 % BLER threshold can be determined for both repetition rates. Which will prove useful for other performance metrics such as the relative signal strength. For the simulation with 1 repetition rate the 5% threshold BLER SNR was approximately 6.28dB and for 32 repetition rate it was -10dB. These values were formed from interpolation between two data points that reside close to the 5% BLER threshold. The equation used is shown in Figure 7. For the 1 repetition rate the data points for SNR values of 6 and 7 were taken to determine the SNR for 5% BLER.

$$BLER = BLER_{p1} + (SNR - SNR_{p1})\frac{BLER_{p2} - BLER_{p1}}{SNR_{p2} - SNR_{p1}} \quad (1)$$

Fig. 7. Interpolation to get SNR values

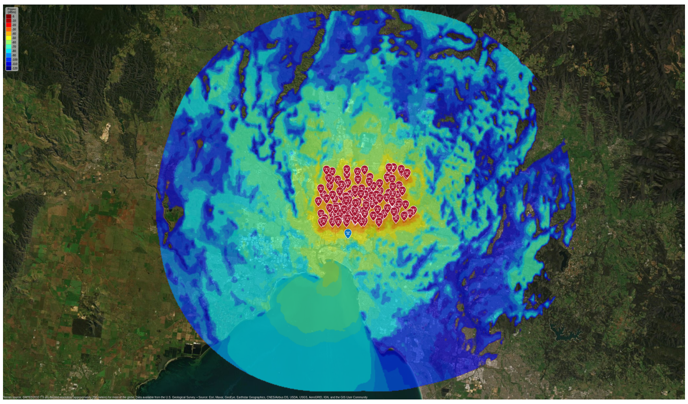

Fig. 8. RSS Contour Coverage Map

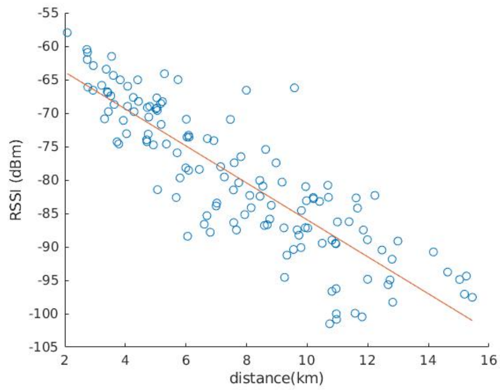

Fig. 9. Relationship between RSS and distance from a receiver

RSS Performance

The contour radio coverage map from the eNB sites are shown in Figure 8.

To cross reference check the radiation map a graph was plotted of distance of each eNB from a reference receiver site located at building 80 at RMIT as shown with blue marker in the coverage map (Figure 8). Linear regression was implemented and as expected the relationship between distance from each eNB to a receiver has a downwards trend as seen in Figure 9. The receiver location along with the lowest and highest signal strength were plotted on a graph for visualisation purposes, they shown in the map in Figure 10.

As can be seen from the coverage map due to the close proximity of the eNB sites there is a lot of interference with each of them; this would only be affected worse in real world due to sharing with LTE communication. As for coverage outside the cluster of eNB reception is low. The furthest distance from the receiver site to an eNB was approximately 16km; this can be the effective radius for an end device to operate on the network.

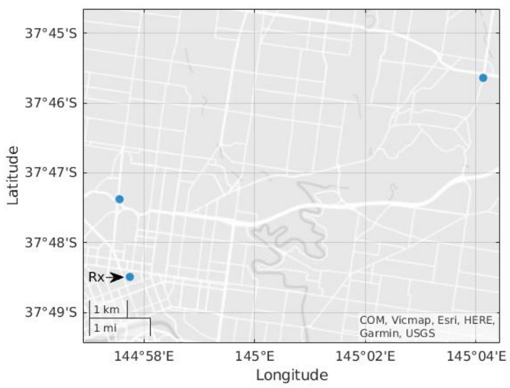

Fig. 10. Location of Highest and Lowest RSS relative to receiver

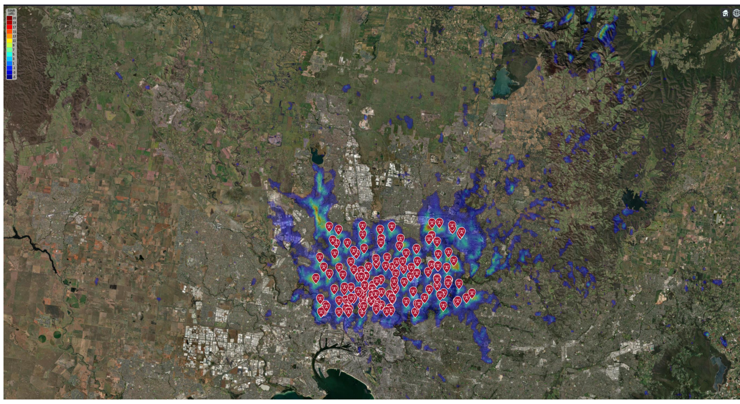

Fig. 11. SNR Contour Coverage Map

When comparing to other research findings there was a consensus that NB-IoT can provide up to 20 dB coverage enhancement this was not the case from the findings above from the coverage contour map the maximum power which could be received was around -10 dB.

SNR Performance

For each eNB, the signal source is the transmitter site in TXS with the greatest signal strength. The eNB with the same transmitter frequency acts as a source of interference. If the eNB is a scalar quantity there are no sources of interference the resultant map displays signal-to-noise ratio (SNR).There are small areas of high SINR due to having the same transmitter frequency of 900MHz. The SINR contour coverage map is shown in Figure 11 with a range from -10 to 10 dB because this was the 5% threshold BLER where SNR values for both repetion rates resided.

Further Investigation

To further investigate coverage based on SNR, the 5% BLER threshold for repetition rates of 1 repetition and 32 repetitions were distinguished through color selection in the coverage map in Matlab, this can be seen in Figure 12 and Figure 13 and the section of code that achieves this is shown below.

```
eff_nf = -85; %effective noise

SNR_min_c1 = 6.28;
%from BLER vs SNR graph
%where BLER is 5% for 1 rr

SNR_min_c2 = -10;
%from BLER vs SNR graph
%where BLER is 5% for 32 rr

rx_sensitivity_c1 = eff_nf + SNR_min_c1;

%Receiver sensitivity for 1 rr

rx_sensitivity_c2 = eff_nf + SNR_min_c2;

%Receiver sensitivity for 32 rr
coverage(txs, 'longley-rice',...
'Resolution', 350,...
'MaxRange', 6000,...
'SignalStrengths', rx_sensitivity_c1, ...
'Colors', 'blue',...
'ReceiverGain', 0, ...
'ReceiverAntennaHeight', 2) %1rr

coverage(txs, 'longley-rice',...
'Resolution', 350, ...
'MaxRange',6000, ...
'SignalStrengths', rx_sensitivity_c2,...
'ReceiverGain', 0,'ReceiverAntennaHeight', 2)
```

From these two coverage maps that 32 repetitions produces a larger coverage in areas where the coverage of the 1 repetition signal is limited

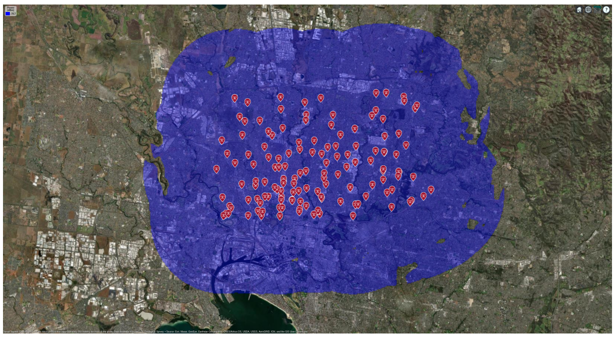

Fig. 12. Distinguished Coverage of 1 RR

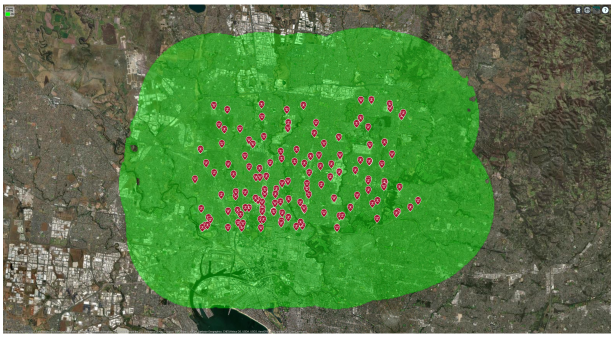

Fig. 13. Distinguished Coverage of 32 RR

due features in the terrain. The better propagation seen at a rate of 32 repetitions, would also carry through to a simulation and real-world environment, where the signal is more severely obscured by buildings. From the various performance analysis undertaken it can be determined that coverage is affected by the carrier frequency and the repetition rate.

Conclusion: The results from the various simulations of NB-IoT coverage demonstrate its feasibility within that specific area within Melbourne where cellular towers are located. From these simulations and research through review of current literature gave a greater appreciation and understanding for the processes which occur in the downlink transmission of transport blocks in an NB-IoT. Ultimately, the performance analysis of the network could prove useful in the future for tuning parameters and developing methods which optimise the network.

Source code used in research can be accessed here: **https://github.com/andrew-app/nbiot**

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