Localised FM Digital Audio Broadcasting using WiFi Mesh Networks

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SUBMISSION DATE / POSTED DATE

13-12-2020 / 12-01-2021

CITATION

Verma, Ashvin; Kar, Somesh; Ahuja, Priyanshi (2020): Localised FM Digital Audio Broadcasting using WiFi Mesh Networks. TechRxiv. Preprint. <https://doi.org/10.36227/techrxiv.13371068.v2>

DOI

[10.36227/techrxiv.13371068.v2](https://doi.org/10.36227/techrxiv.13371068.v2)

Glossary

ACK The acknowledgement of a TCP packet after verification of payload contents via a TCP checksum. 1–3

FFT The Fast Fourier Transform algorithm used to carry out Discrete Fourier Transform (DFT)s. 1, 5

LoS propagation Transmission of signals in a straight line between 2 points. 1, 2

Mesh Network A network topology consisting of dynamically connected nodes, intended to transmit information to a client most efficiently, a variant of an ad-hoc network. 1, 2

MIB The Ministry of Information and Broadcasting is a ministerial body of the Government of India, concerned with rules, regulations and laws concerning broadcasts and information. 1, 3

WiFi Mesh Networks Wireless Local Area Networks created in line with the 802.11s standard. 1, 2

WiFi Packet Data transmitted over 802.11s is split into TCP segments, the term used interchangeably with TCP packets, and verified via TCP checksums. 1, 2

WLAN Wireless Local Area Networks created in line with 802.11 standards. 1, 2

Acronyms

COTS Commercial Off the Shelf. 1, 4

CRS Community Radio Station. 1, 2

DAB Digital Audio Broadcasting. 1, 2, 4, 6, 10

DFT Discrete Fourier Transform. 1, 2, 5–7

FFT Fast Fourier Transform. 1, 5

MeshNet Mesh Network. 1, 2, 4, 6

PCM Pulse Code Modulation. 1

PSD Power Spectral Density. 1, 2, 5–7

PSNR Peak Signal to Noise Ratio. 1, 2, 5

RFI Radio-Frequency Interfere. 1, 2

SBC Single Board Computer. 1, 3, 4

TFR Time-Frequency Representation. 1, 5–7

WLAN Wireless Local Area Network. 1

Localised FM Digital Audio Broadcasting using WiFi Mesh Networks

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ARTICLE INFO

Keywords:

mesh network
WiFi mesh
accessible communication
local broadcasting
COTS
SBC

ABSTRACT

Digital Audio Broadcasting via FM radio transmission on the VHF-II Band remains widely in use despite advancements in other wireless technologies due to its accessibility, particularly in rural areas where Community Radio Station (CRS) help facilitate cultural expression and aid local information delivery. Current CRS are expensive and power-intensive while remaining challenging to scale, especially across hilly environments and uneven terrain.

This paper first examines the need for a low-cost, scalable CRS in 2 regions, namely India and African countries, using recent social science literature and reporting. Then, we evaluate the performance of the proposed community radio mesh system for range, scalability, and transmission quality. The system consists of low-cost and modular FM transmitter units connected to each other via a WiFi Mesh Network which is used to transmit digital audio signals from the hub node. Each transmitter unit then broadcasts this digital audio signal in the VHF-II band, supported by standard feature phones and other FM receivers. The transmitter units consist of COTS components running on open-source software.

The transmission quality has been analyzed using objective metrics such as Peak-Signal-to-Noise Ratio and interpreted from PSD spectrograms and the output of Discrete Fourier Transforms. While field trials and further research are necessary, the approach seems promising for rolling out mid-to-large scale community radio mesh systems.

1. Introduction

Radio transmission comes with hurdles, including Radio-Frequency Interference (RFI) due to electronic equipment and fading due to the signals reaching from multiple paths. In the case of LoS propagation, obstruction by obstacles and the horizon is also a considerable problem. In FM (VHF Band-II) transmission, RFI is usually also present from other sources also participating in DAB.

Current Community Radio Stations are expensive (with setup cost of 1.5 million INR according to some estimates [21]), scale poorly in uneven terrain and are power-intensive[8]. In response, we propose a novel approach using a system of interconnected FM transmitters, connected via a WiFi Mesh Networks to transmit an audio stream from the hub node to every other node for broadcast. WiFi ensures the reception of each WiFi Packet in a signal due to ACK, ensuring full fidelity transmission. This network can be scaled and configured as required due to COTS components and open-source software, to cover transmission deficiencies and accommodate uneven terrain. Only a line of access between transmitters is required, and since recordings can be cached, the network becomes free from the requirement of a consistent connection. The hub node has a microphone, and preliminary audio processing can be done on the node itself. It can also be connected to the internet and a screen (via the HDMI port).

Section 1 introduces the problem, examining social literature, and offers an overview of the solution. Section 2 discusses the methodology of the setup, system configurations. Section 3 introduces the setup of experiment, data is presented and analysed by interpretations via PSNR, DFT and PSD spectrogram output. Section 4 concludes the paper by summarising the key points and results from the study.

Figure 1: Traditional Rural Community Radio Broadcast Station

Source: <https://timesofindia.indiatimes.com/>

Appendix A calculates the free-path loss, whereas Appendix B covers costing of components.

1.1. Literature Review

FM transmission systems suffer from limitations due to operating primarily on LoS propagation, which elevate into difficulties in hilly regions. Current distributed systems which address this for FM transmission primarily use relays[14]; however, these simply rebroadcast the degraded signal they receive, leading to accumulation in transmission errors. Rural WLAN MeshNets on the other hand, are currently used solely for delivering broadband internet access, which remains inaccessible to many, despite increased availability.

Examining current methods of information broadcasting, we see the ubiquity varies drastically across the world. Below, we discuss primarily the rural areas of 2 regions of interest with significant socio-cultural, economic, and geographical differences: India and countries in the African continent.

India

First, we examine India. We consider are primarily 5 widespread means of mass communication and information dissemination: print, television, national radio, cellular networks, broadband internet. Traditional means of information broadcasting, including national and state television and radio, remain ubiquitous; however, they cannot fulfill local broadcasting needs as they cover large regions. Cellular and broadband networks, on the other hand, while widely available, are not simultaneously universally accessible, as they are homogeneously priced for all consumers and require a modern device, at a bare minimum a smartphone, making it economically inaccessible for the most impoverished[25]. Literacy in a language that the device supports is also an implicit requirement for availing these resources, in a country where there are 22 major languages recognized by the Indian Constitution [10], and 1369 rationalized mother tongues, according to the 2011 consensus[11].

Some forms of communication fulfilling the need for localized, decentralized communication are pre-existing community radio stations (CRS) and local print media. According to a report on community radio stations by the Ministry of Information and Broadcasting, Government of India [22], community radio has significant impacts on local cultural and personal expression, among others. Additionally, anywhere from 7,000 to 154,000, households were under the coverage of such a station per state. At the same time, it is observed that while the current range of community radio is 10-15 km, smaller villages may benefit from simpler and more affordable deployments, given existing community radio stations require expensive equipment (1.5 million INR according to estimates by the MIB) [21] which are power-intensive, and require greater regulation (due to signals being of high power) and hence training. They're also usually immobile, being installed in a fixed location. However, benefactors can easily receive radio communication using affordable receivers or the accessible feature phones(refer to B for cost analysis). This medium doesn't require any recurrent subscriptions, such as with print, and can be consumed with just a radio receiver. Furthermore, the print medium is limited to consumption by the literate, being slower in information dissemination, and unusable for urgent broadcasts.

African Countries

Now, we come to discuss the general situation of the countries on the African continent. Literacy rates in African countries lag staggeringly behind the world, even behind many underdeveloped countries in other continents, with an average literacy of 70% much below the world literacy rate average of 90% [29]. The region boasts between 1250 and 2100 natively spoken languages[7], with some countries also having multiple official languages. African countries have sought to increase the coverage of mediums, including television and mobile networks; however, the access to these mediums remains limited to only a small subsection of the population as it requires a consistent source of electricity to run. This is compounded by the fact that most of the

population lives in rural areas with very low population density. This makes it hard to justify the infrastructure cost for television, telephone lines, and cellular networks. Additionally, since these services are homogeneously priced, cellular, and internet service providers optimize average revenue over users. Hence, in developing countries the data rate can still be prohibitively expensive since availability does not equate to universal accessibility [25].

Community radio can allow them to keep up with the developments in their village and their neighbors as well as keeping track of the news. Other useful information such as agricultural advisories can also be dispensed via this medium. The radio's penetration factor is approximately 1 per 5 people in the entire population, whereas the penetration rate for telephone is 1 per 100 people. Reflecting this figure, there are often radio "talk clubs" where people come together to listen to the radio [18]. Radios are especially crucial for countries with higher illiteracy rates, where many speak indigenous languages, and using it means they do not need to read or write in other languages due to the oral nature of the medium. There have been significant achievements of community radio stations in the African continent in giving a voice to the poor, with room still for improvement [19] [8].

Community radio has been shown to be indispensable in Columbia and Bolivia as well[8]. There is a need expressed by various parties, including governments and international organizations (such as the United Nations) for expanding the reach of community radio. There is currently a lack of affordable and easily scalable community radio broadcast methods, especially those which would work well across hilly terrain. Additionally, even "low-power" transmitters typically require amplifiers[8], and can't connect directly to or access internet channels due to lack of device capability and/or linguistic difficulties for the user.

2. Methodology

2.1. Overview

The proposed approach consists of a system of SBC units spread across a critical coverage area, connected via a WLAN mesh network, by the 802.11s standard. Each unit is termed a "node" of the network, with a single recording and broadcasting hub node and other child nodes. The hub node has a microphone that can use the WiFi meshing to communicate between multiple children nodes to propagate the stream across recipients. Due to the packet nature of transmission on which WiFi operates to prevent errors, each packet must be verified and "acknowledged" by the recipient by the ACK signal, hence there is no data loss in transmission across units.

Each node, including the hub node then processes the audio stream to transmit as an FM signal in the VHF Band II, which consumer radio receivers are often configured to receive from, as it is commonly used for Digital Audio Broadcasting [16]. Due to the distributed architecture, each node utilizes low levels of power and can be placed strategically to required coverage areas.

2.2. Single Node Setup

For our setup, we use the Raspberry Pi Zero WH™ (with pre-soldered headers) for every node, a low-cost COTS SBC (see Appendix B) by the Raspberry Pi Foundation® aimed at encouraging computer science education, with support for 802.11n/s wireless LAN, a 1GHz single-core CPU, 512MB RAM, and a host of connectivity options such as Mini HDMI and USB On-The-Go ports. It is powered via micro-USB power[24]. The Pi's modular nature allows COTS components such as microphones to be added easily, although a mass-produced version may need custom manufactured enclosures and buttons. This makes it simple to prototype and eventually scale.

Figure 2: Conceptual Render made using Blender3D

The functioning of the radio transmission from any node is based on a Python library *PiFmAdv* calling a C program that maps the Peripheral Bus in physical memory into the virtual address space using `/dev/mem` and `mmap` with root access using `sudo`. Next, it sets the clock generator module to 'enabled' and sets it to output on GPIO pin 4 with an amperage of 16mA and on-board voltage of 3.3V. It also sets the frequency to a specific frequency; this provides a carrier. FM radios which detect this carrier stop the 'hissing sound' (white noise) and become silent. This is when we can transmit our desired audio in the form of a WAV file. Initially, modulation was attempted by adjusting the frequency using the fractional divider between 100.025 MHz and 99.975 MHz, which makes the audio signal using the CPU clock cycles on the GPIO pins of the Raspberry Pi Zero WH to generate FM frequencies; FM broadcasts were broadcast with a piece of ordinary wire connected to the GPIO pin 4; however, signal quality was poor and noisy. The Phase-Locked Loop Clock was used to combat this instead of the clock/fractional divider. In conjunction with a piece of wire acting as a low-cost antenna, this system functions as a capable FM transmitter. The PLLC present in the Raspberry Pi's GPU modulates an AC current to match a reference frequency. This can be used to generate a signal resonating at the desired FM frequency.

This is a method to use the GPIO pins already present on the Raspberry Pi to transmit a signal. For further research, however, the usage of external antennas could significantly enhance the signal's range and strength. All the WiFi transmissions are carried out via the soldered WiFi module, which uses a microstrip antenna. All the DAB antennas used in the

Figure 3: Raspberry Pi Zero WH Setup

experiment are omnidirectional to maximise local coverage by nodes and minimise areas with low-powered signals.

2.3. Network Configuration

The WLAN Mesh Network uses the 802.11s standard[13] using the *batman-adv* wrapper. It begins at the hub n_0 , then propagates to every node in the network. The first broadcast node has a depth of 1, and for each hop of the stream the child node gets a depth 1 higher than the parent. A mesh network allows flexible deployment since only LoS between directly connected nodes is required, allowing the network to be deployed selectively or over uneven terrain. It also helps overcome the effects of multipath fading. The same signal reaches at different times due to reflection and different paths taken, which is an issue with most terrestrial radio setups, remedied by verifying each packet of a stream. Additionally, the MeshNet allows the presence of redundant nodes in the network, whose failure does not cause the entire network or large segments to fail.

Figure 4: Representation of WiFi Mesh Network Topology with FM Transmission

Every node broadcasts the DAB signal using an omnidirectional antenna for propagation in all surrounding regions. Since phase shifts due to transmission delays may accumulate, directional antennae may be considered for future research for minimum overlap in node FM DAB radiation patterns to avoid destructive interference. At no point are the re-

Figure 5: Overhead Schematic for Setup of Experiments

ception properties of the GPIO pin antenna used, since the stream packets are received and transmitted via the WLAN mesh network. Each node equipped with a solar panel is a self-sufficient setup, requiring only minimal maintenance for clearing up the surface of the solar panels, and can be kept high for better LoS transmission, without much need for manual intervention.

For our experiment setup, we have used the Portronics POR-141 to receive FM signals, routing the output via an AUX cable to a Zoom H1 portable recorder.

3. Results & Discussion

The cloud-hosted Google[®] Collaboratory and local Jupyter notebooks were used for their Interactive Python environment. When file hosting was necessary, Amazon[®] Web Services S3[™] was used. Python libraries *NumPy* and *SciPy* were used for data manipulation, whereas *Matplotlib* was used for plotting audio waveforms and the frequency transforms. The Waveform Audio File Format (WAV/WAVE) was used for transmission and reception as it is uncompressed, and offers maximum fidelity for clearer analysis. The *wavio* module by GitHub user WarrenWeckesse was used to read WAV files. For transmission, a carrier frequency of 99.5 MHz is used.

A Discrete Fourier Transform has been applied to each audio waveform (using the Fast Fourier Transform (FFT) algorithm supplied by the *SciPy* or Scientific Python package) to transform the Time-Amplitude signal into a Time-Frequency Representation (TFR). The FFT can be used due to uniform sampling via PCM for WAV files. The absolute values of the Fourier-transformed signal indicate the magnitudes of the real-valued signal's frequencies. Frequencies up till $1/2$ of the sampling rate are examined, in accordance with the Nyquist–Shannon sampling theorem. PSD spectrograms have also been generated, for which the Blackman window [30] is used to minimize discontinuities and power leakage, with its lower side lobes despite greater bandwidth in the resulting Fourier Transform. They were generated through GNU Octave to provide a Time-Frequency Representation.

For Peak Signal to Noise Ratio (PSNR) calculations for a digital signal (in dB), the following equations were used, where A, B are the signals to be compared, each with k elements and MAX_I as maximum magnitude (of data type):

$$MSE(A,B) = \frac{\sum_{i=1}^k (A_i - B_i)^2}{k} \quad (1)$$

$$PSNR = 10 \cdot \log_{10} \frac{MAX_I^2}{MSE} \quad (2)$$

Figure 5 shows and labels the locations P1, P2, P3 and P4 used in Experiments 1-4. The walls were 0.3 meters in thickness and made of concrete.

3.1. Experiment 1

The audio file used here was of a monologue by a single speaker transmitted and received as a WAV file at a sampling rate $F_s = 44100$ Hz and duration $T = 64.85s$. The audio WAV remains consistent across the parts of Experiment 1, and is visualised in Figure 6. The codec used in the transmission is PCM S16 LE, where S16 specifies 16 bits/sample. LE signifies little-endian byte order. A window size of 1024 samples was used for PSD spectrograms, as frequency resolution was preferred over temporal resolution.

3.1.1. Hub Node FM Transmission

The first part (a) of the test was conducted to determine the range of the DAB signal from a node with obstructions in between. Only a single node, the "hub" node, using a Raspberry Pi Zero WH, was in operation at point P1. The receiver POR-141 in the next room at point P2 at a distance 6 metres receives the signal and then record the output using a Zoom H1 portable recorder. The signal was cropped out from the recording window to account for human error in pausing the record, visualised in Figure 7. The codec used in reception is PCM S24 LE, where S24 specifies 24 bits/sample. For PSNR, 24-bit samples were down-scaled to 16-bit samples.

The corrupted audio clip had distortions, and the signal strength seems to have weakened. Comparing the DFT distributions, it appears there are clusters of distortion around 10 kHz, above the maximum of 6 kHz in human voice to Guinness World Records Limited 2020 [12]. Musical instruments may however stretch till B_8 with a frequency of 7.9 kHz. Regardless, this may be used for further improvement through the design of filters. The PSD spectrogram broadly correlates with this as well, where noise seems to localised more to the higher-end frequency bins more than the lower frequency bins (5-10 kHz), although there is considerable distortion in other frequencies.

A PSNR of 68.45 dB was measured according to Eq. 2 taking into account transmission losses.

3.1.2. Child Node Transmission

The received transmission, part (b) of the experiment, was recorded in the same codec of PCM S16 LE and at the same

Figure 6: Representative Plots for Source Signal from Experiment 1

Figure 7: Representative Plots for Received Corrupted Signal from Experiment 1(a)

sample rate of 44100 samples/second, visualised in Figure 8. This test was conducted to test the effect of increasing distance and observing conservation of fidelity in transmitting via a MeshNet. The hub node was present at point P1, and the child node at P2 as per Figure 5, and both were transmitting concurrently. The receiver was at point P3, and the distance between the receiver and the child node was 30 metres.

There were some distortions across the frequency spectrum according to the PSD spectrogram and the TFR, which may be due to constructive and destructive interference, causing the amplitude spikes. In audibility, there were some shrill distortions. A PSNR of 63.92 was measured.

3.2. Experiment 2: Human Audio received from Depth-3 Nodes

This test was conducted to further test the performance of the mesh network by transmitting from a depth-3 node (since the transmission has likely hopped twice), across a greater distance and with a more detailed audio of greater duration, visualised in Figure 9. The "hub" node at point P1 transmitted the audio via MeshNet which eventually reached the child node at P4, after a depth-2 node and all 3 performed the DAB transmission concurrently. The receiver POR-141 was out of the building and across the street to receive the signal and then record the output using a Zoom H1 portable recorder, at a distance of 60 metres. A window size of 4096 samples was used (due to the long duration, setting a shorter

Figure 8: Representative Plots for Received Corrupted Signal from Experiment 1(b)

Figure 9: Representative Plots for Broadcast Signal for Experiment 2

Figure 10: Representative Plots for Received Corrupted Signal from Experiment 2

window did not give very perceptible temporal details). The signal was cropped out from the recording window to account for human error in starting and pausing the record.

The audio clip used for this experiment was a conversation of duration $T = 280s$. was an uncompressed raw WAV file format, at a sampling rate $F_s = 44100$ Hz. The codec used in the transmitting and transmitting were the PCM S16 LE, where S16 specifies 16 bits/sample.

The corrupted audio clip was audible, although with perceivable "crackle" noise, which seemed to appear as a salt-and-pepper noise on the PSD spectrogram (refer to Figure 10). The noise seemed to distort all frequency bins according to the Time-Frequency Representation. A PSNR of 60.38 dB was measured, lower than the preceding experiments, which can be attributed to the greater separation between closest transmitting node and receiver. The WiFi signal strength measured between the depth-2 child node (P3) to the depth-3 node (P4) was -50 dBm.

3.3. Experiment 3: Sine wave & Pulses

A pure-tone sine wave of 880 Hz, the A5 note, was generated to more closely test the distortion in frequency bins due to transmission (Figure 12a). A 50% duty-cycle square-wave of frequency 100 Hz was used to test distortion in the temporal qualities of the signal (Figure 12b). The placement setup was identical to Experiment 1(b), with the hub node at point P1 and a child node a point P2, both transmitting concurrently and a receiver at point P3. The audio format used for transmission as well as reception was the same with

a sampling rate $F_s = 44100$ Hz, and 16-bit mono audio.

The Time-Frequency Representation used the PSD spectrogram, and a smaller window of 256 samples were chosen since temporal resolution was of greater priority. In Figure 11 representing the square-wave pulses, the noise seems to be due to a spread of the signal, causing some overlap in the signal and hence interference. In Figure 12 representing the A5 note signal, there appears to be noise mostly limited to frequency bins beyond 3.5 kHz but especially around 15 kHz.

3.4. Network Considerations

The WiFi performance of the Raspberry Pi Zero WH has been bench-marked while performing our tests, including signal strength in dBm through using `iwinfo` and data transmission rate in mbits/s by transferring a file of 200 mbits via raw TCP between nodes, repeating the experiment and averaging the values. They are reported in Table 1.

Table 1
Signal Strength & Data Rate Tests between Nodes

Distance	Data Rate	Signal Strength
60 m ⁱ	73 mbits/s	-50 dBm
70 m ⁱⁱ	27 mbits/s	-76 dBm
100 m ⁱⁱⁱ	12 mbits/s	-76 dBm
100 m ^{iv}	15 mbits/s	-80 dBm

ⁱ 1 wall, 0.3m concrete ⁱⁱ Line of Sight ⁱⁱⁱ 2 walls, 0.3 concrete
^{iv} Line of Sight

Figure 11: Representative Plots for Pulse-wave Signals

Figure 12: Representative Plots for A5 (880 Hz) Signals

The bitrate of a 16-bit, stereo (uncompressed) WAV file with a sampling rate $F_s = 44100$ Hz is 1411.2 kbps, defined as CD-quality audio in accordance with the International Electrotechnical Commission [15]. By contrast, the lossy compression based MP3 format has a bitrate ceiling of 320 kbps, while providing bitrates as low as 92 kbps.

As the data transmission rate is much greater than the bitrate of recordings for distances as far as 100 metres, each node can cache audio when recordings are broadcast, hence not requiring a consistent connection throughout the duration of the broadcast.

The cost analysis for a system with 20 nodes was examined in Appendix B, with an estimated cumulative cost of 75,655 INR. In Figure 13, we analyse how such a system may be structured and function. A conservative maximum distance of 100 m between nodes (furthest WiFi reception of suitable bandwidth despite obstacles, check Table 1) is assumed, with the maximum DAB distance is a bit over half

of the 100 metre (testing has been done with 60 metre in Experiment 2, so that will be taken as a conservative estimate). There is overlap in some regions where power of the signal has diminished. According to the Free Space Path Loss calculations in Appendix A, the loss in power may be 85% 60 metres away, further from which a receiver will have usually fallen under the coverage of another node, or amplify the signal. The default power state of the nodes can be idle, and they can be set to transmission mode via instructions from the WiFi MeshNet. While the chosen placement of nodes is certainly not ideal, this setup does assume there are 2 0.3 metre concrete walls between each node and is structure to cover a rectangular area. The covered plot has a breadth of 1,243.6 metre, and a length of 1,026.5 metre, with an impressive coverage area of 1,276,555 m², although there were considerable gaps in coverage area. The network must be configured to ensure equitable access to all inhabitants of an area.

Figure 13: 20 Node WiFi MeshNet Setup for DAB (to scale)

4. Conclusion

The system performs favorably in our testing for scaling and quality. COTS components were easy to replace and upgrade. The proposed system provides a scalable option for deploying community radio systems, especially in hilly, uneven terrain and radio-sensitive areas due to selective coverage. Additionally, for the broadcast of recorded audio the system does not require a consistent connection due to caching. The broadcaster can modify features by editing the codebase and attaching modular hardware.

Section 3.4 analysed a real-world scenario with empirical

data for a closer look at a potential deployment. In lieu of its low-power requirements, it may be powered with renewable sources such as low-cost solar panels on the device itself (see Appendix B). Due to low output power levels, the signal will have a low Effective Radiated Power, hence regulatory approval for such a device may face reduced difficulties.

Traditional signal processing techniques like low-pass band filters may help performance and quality according to our analysis, and more sophisticated methods such as Deep Learning-based real-time noise suppression, recently achieved on more capable Pis[6] may also be considered. Directional antennae may be considered for extending WiFi and

Digital Audio Broadcasting range and avoid destructive interference between node DAB transmissions on the network if units acquire differing time lags during a live broadcast.

A need has been expressed by different parties, including governments such as the Government of India, for innovations in Community Radio transmission [5], and by international organisations such as the UN [18], due to their cultural and social impact. Our innovation seeks to meet some of these needs.

Acknowledgements

We'd like to thank the Head of Computer Science at our high school, Delhi Public School R.K Puram, Mr. Mukesh Kumar, who provided us the platform to come together and develop the idea.

We'd especially like to thank Mr. Pranshu Malik, for aiding us with all his expertise and answering every doubt we had. We'd also like to thank Mr. Sagnik Anupam for all his structural suggestions and guidance. We'd also like to extend our gratitude towards our colleague Mr. Alankar Dutta for his help in understanding audio data.

A. Radio

The ratio of power received to transmitted according to Friis [9] is defined as:

$$\frac{P_r}{P_t} = D_t D_r \left(\frac{\lambda}{4\pi d} \right)^2 \quad (3)$$

where:

- D_t is the directivity of the transmitting antenna
- D_r is the directivity of the receiving antenna
- λ is the signal wavelength,
- d is the distance between the antennas,

$\frac{P_r}{P_t} = 1.64 \cdot 5.01 \cdot \left(\frac{100}{4\pi \cdot 60} \right)^2 = 0.145$, assuming lack of multipath effects, same polarisation, lack of obstacles, a transmitting half-wave dipole antenna of directivity 1.64 [17], a receiving microstrip antenna of directivity 7 dB (typically from 6-8 dB according to Patil and Kharade [23]), which assumed to be relative to an isotropic antenna is a directivity of 5.01 and a distance of 60 meters between the antennae.

B. Cost Considerations

A low-end smartphone has an MRP of approximately [4] 6,500 INR, whereas a feature phone has an MRP of 1,000 INR [2], six-fold lower.

Table 2 gives a cost estimate for our setup in a network of 20 nodes powered by solar panels. The device can consist of a simple omnidirectional wire antenna and a Raspberry Pi Zero WH has a maximum power draw of 7.2W, 1.2A current and 6V for which we use a powerbank, as they commonly

Table 2

Cost Analysis for a MeshNet of Transmitters

Component	Quantity	Cost (INR)
Raspberry Pi Zero WH ^v	20	29600[28]
Female-Male Wire ^{vi}	40	55[26]
Solar Panel ^{vii}	20	40000[1]
PowerBank ^{viii}	20	18000[3]
Microphone	1	200[27]
Total	20 nodes	97855

^v Pre-Soldered GPIO Header Pins ^{vi} As antennas, available in bunches of 40, redundancy of 1/node ^{vii} IFITech Portable Solar Charger Panel ^{viii} PLM13ZM by Xiaomi, USB Type-A to USB OTG cable included

have powered USB ports, are easily rechargeable and usually intuitive to use.

The PLM13ZM model powerbank by Xiaomi is a good candidate, with a maximum power draw of 18W (supporting 5.1V/2.4A and 9V/2A) and capacity of 10 Ah, at a nominal voltage of 3.7V specified on device, equivalent to 133.2 kJ. On idle with WiFi active, the Pi Zero W seems to consume a current load of only 0.25A[20]. For the solar panel, we have considered the IFITech Portable Solar Charger Panel [1], which can deliver upto 5V, 6W regulated power, to charge the powerbank, and is lightweight, and water-resistant. It has $4.16 \cdot 10^{-2} m^2$ of solar panel area, with a specified 17%-20% transformation efficiency [1]. Since, with the exception of the broadcast node, the nodes are not meant to be displaced and their solar panels should not be obstructed often, we can consider daily solar radiant exposure on these solar panels.

As a case study, we consider Shillong, a hilly region in Meghalaya, India, and take the Mean Monthly Global Solar Radiant Exposure as provided by [31] taken over a period of 14 years, for an annual average of $16.27 \frac{MJ}{m^2 \cdot day}$, at a minimum monthly average of $14.11 \frac{MJ}{m^2 \cdot day}$ during January. With the specified solar panels, the daily energy output would be approximately 115.06 J, far below powerbank capacity. Taking an idle load of 0.25A for 10 hours, and active load of 1A across a 6V circuit for 1 hour, the total daily energy usage would approximately be 21 J, over fivefold less than the optimal energy collected, and hence potentially usable for other uses. However, the situation is a more complicated as batteries don't have unlimited capacity, solar panels give higher than average daily radiant power during sunlight hours, and transmission efficiencies can vary. Further experiments should help us to quantify results and measure uncertainty here, since we primarily use reported data as a source.

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