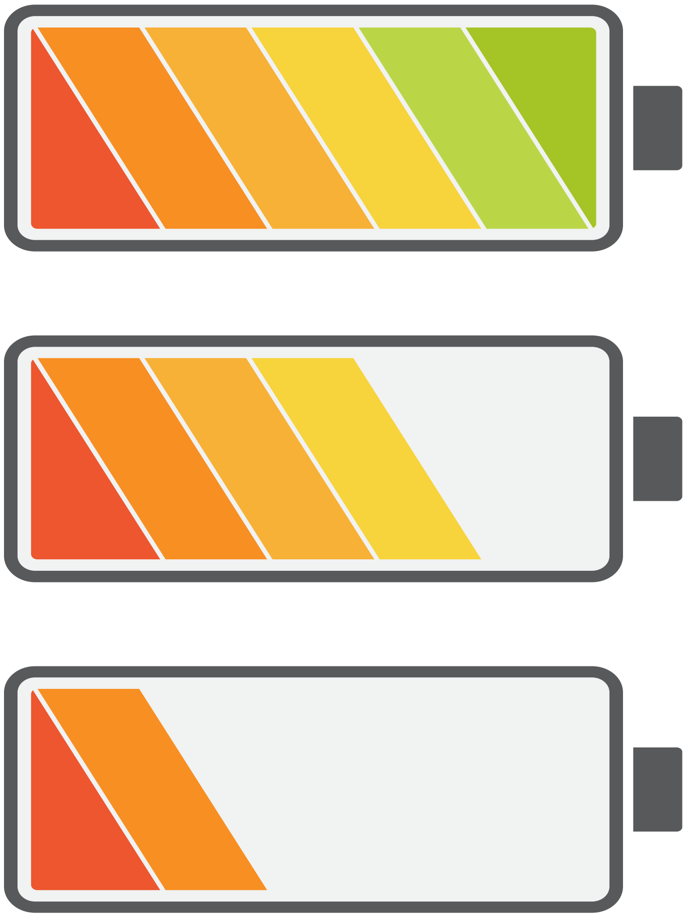


RF Wireless Power Transfer Using Beamforming & UWB

An SOP Report by Deven Jain

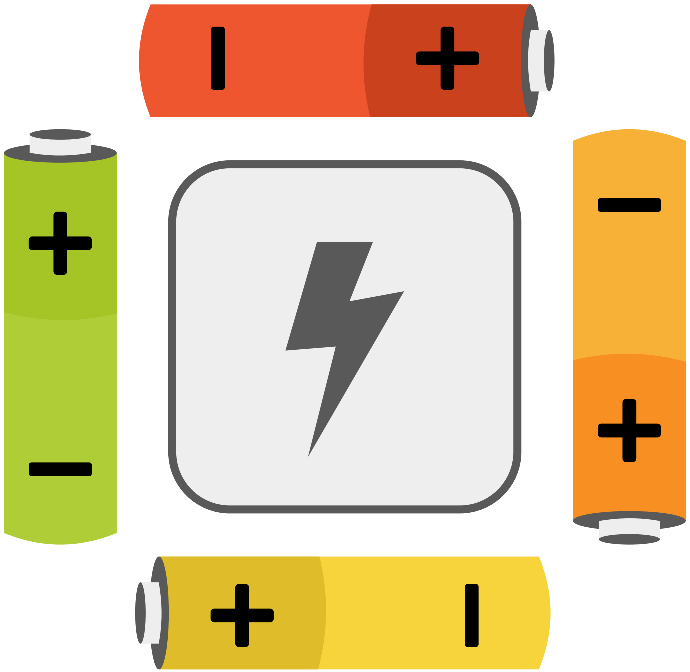
Batteries of Contents

01

The origin of the idea and what the need for this is going to be in the future.

02

Competitors/Existing Technology and Standardizations



03

Power Transfer Technology and details about the same

04

Final Verdict and the design proposal along with the tradeoffs.

The Conception of the Idea

What was the need for designing this?

X.X

XXXXXX

According to the Statisticians at Statista

3.6 devices

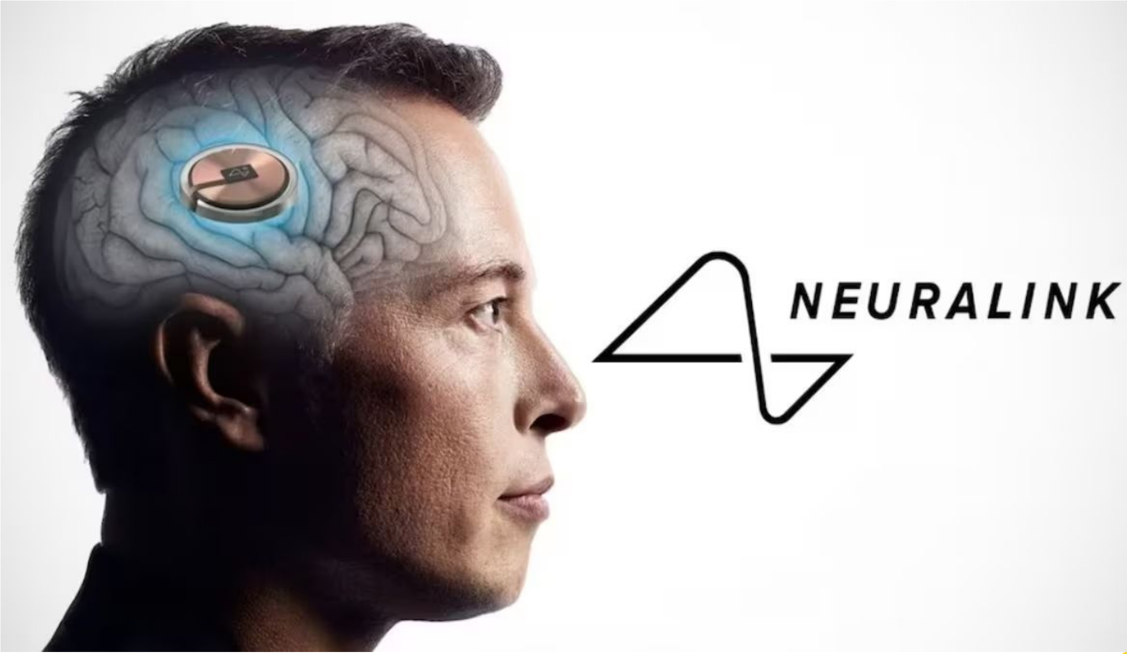
According to the Statisticians at Statista

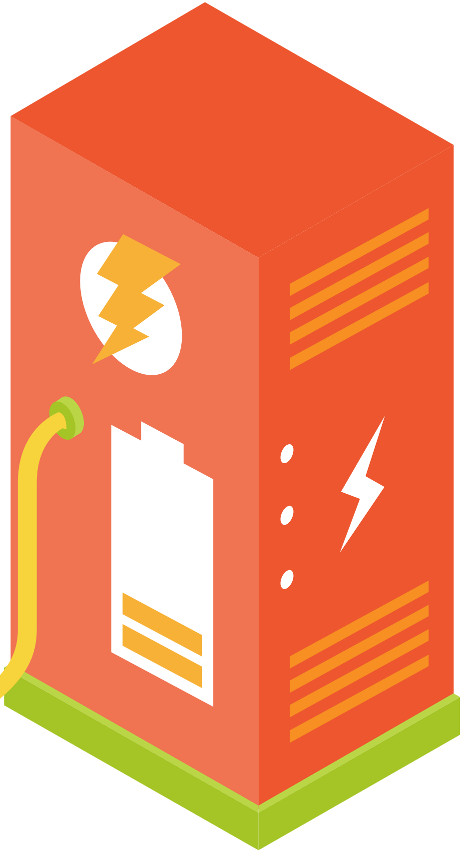
3.6

devices
per person!

Source

The Vision: The Neuralink

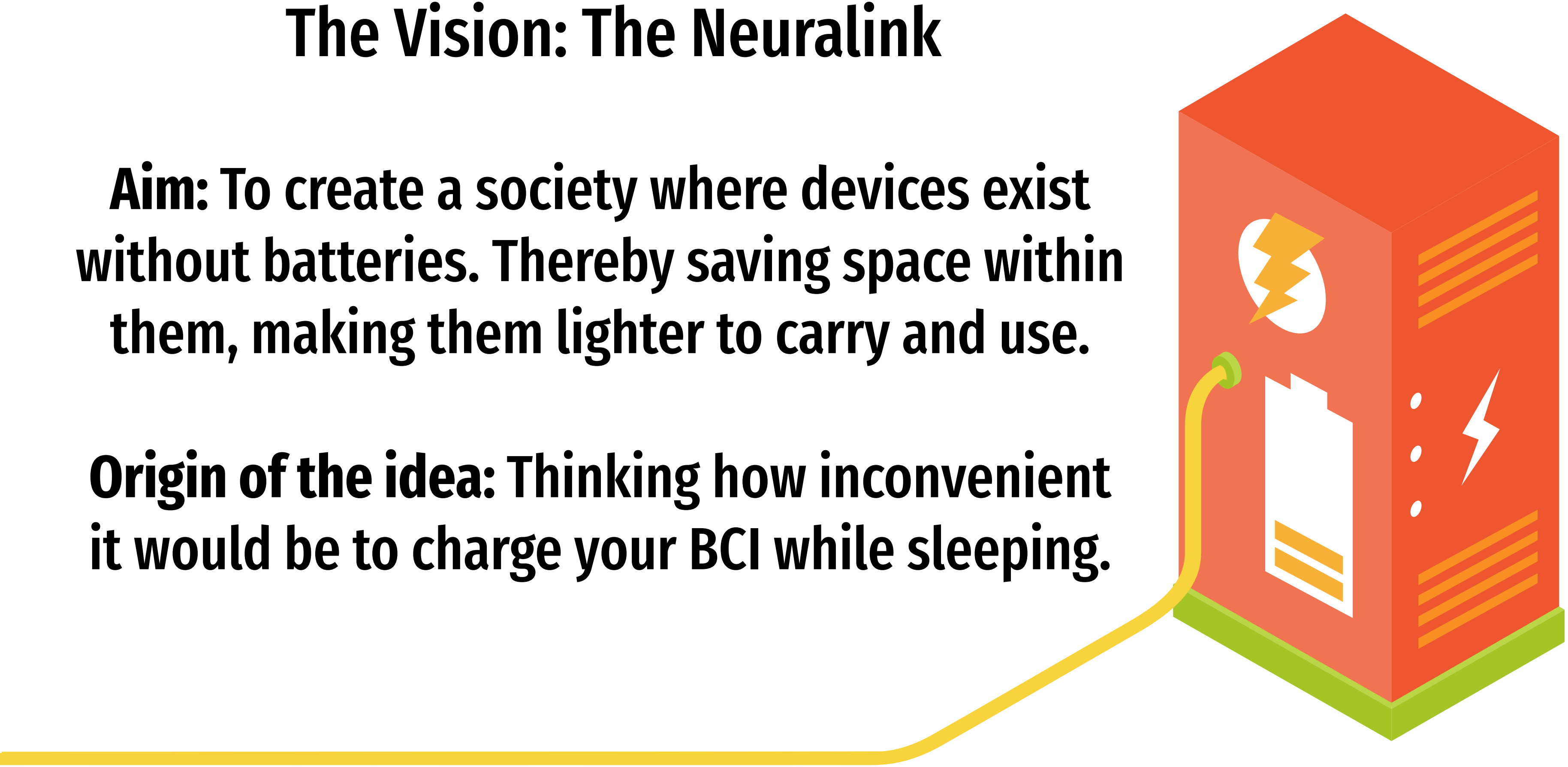




The Vision: The Neuralink

Aim: To create a society where devices exist without batteries. Thereby saving space within them, making them lighter to carry and use.

Origin of the idea: Thinking how inconvenient it would be to charge your BCI while sleeping.



The Vision: The Neuralink

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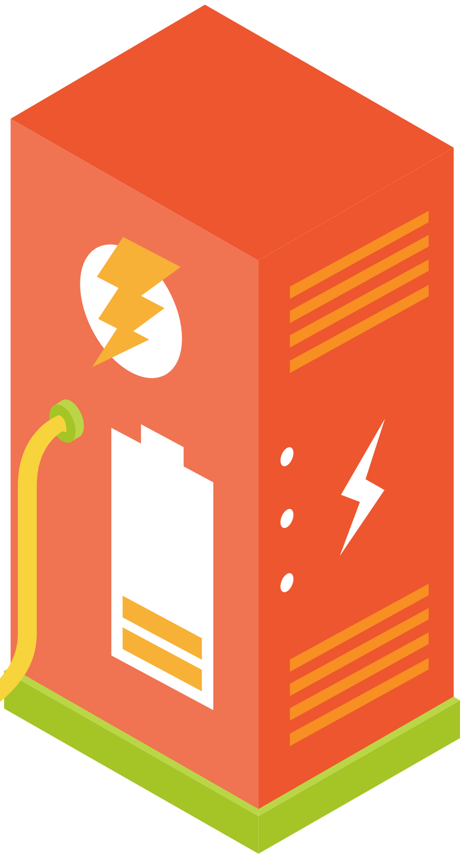


How much power is required?

1

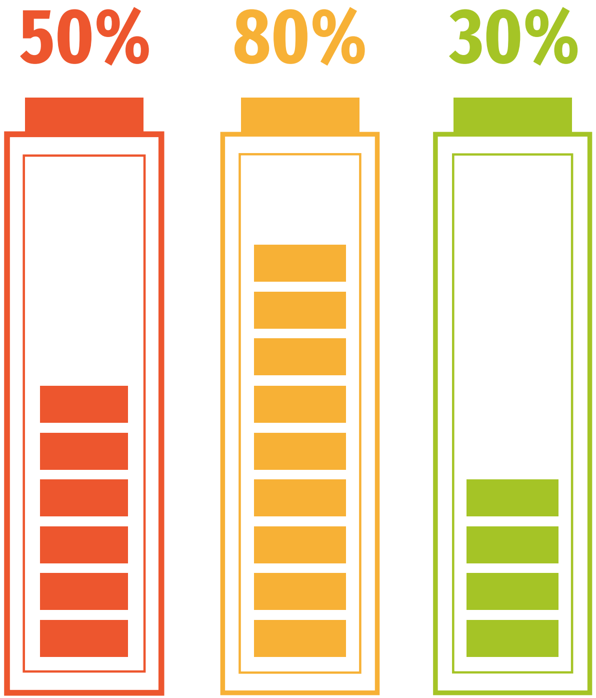
Smartphones:
On standby: 0.5-1 Watt
During active use: 1-5 Watts
Charging: 5-15 Watts

2

Smart Speakers:
Idle: 1-3 Watts
Active use: 3-5 Watts

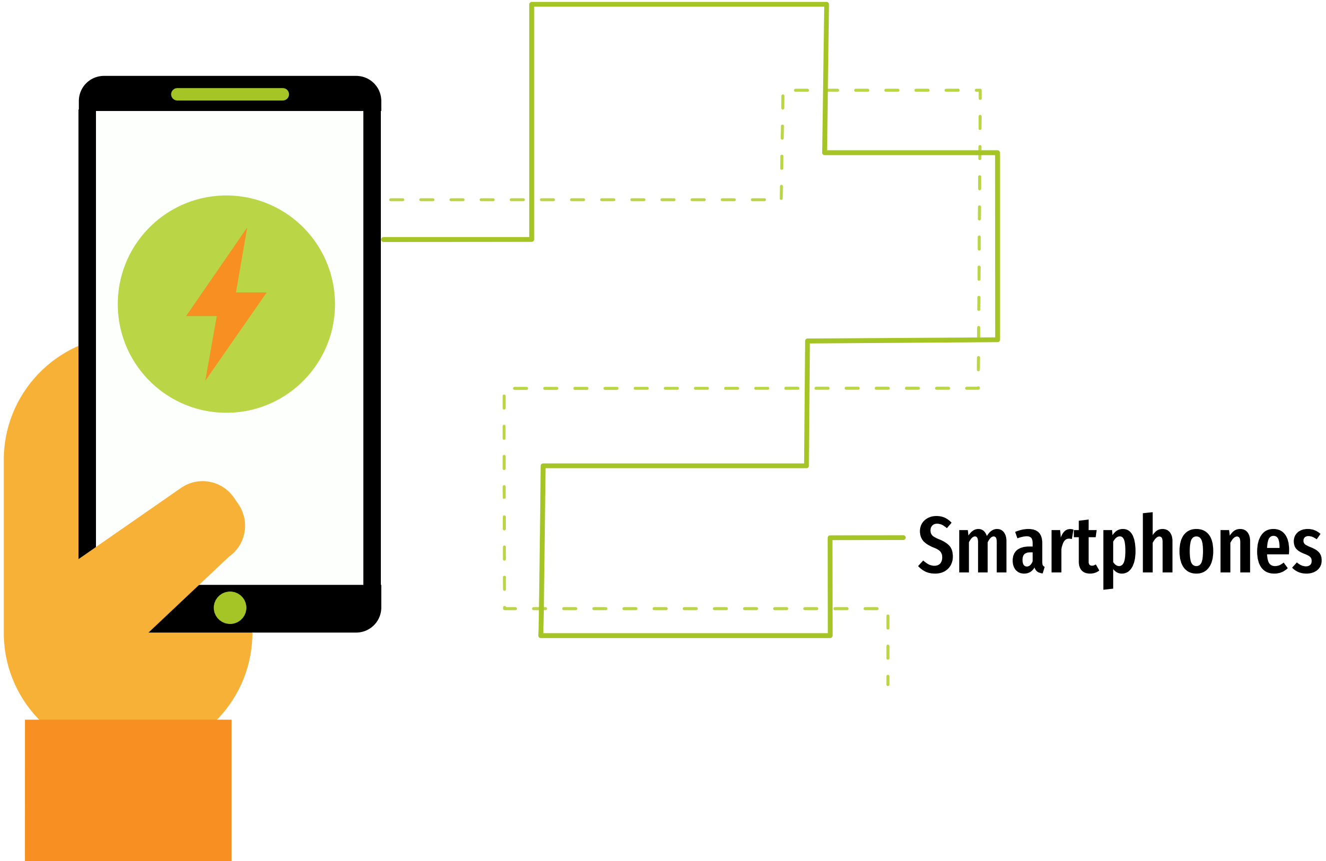
3

Laptops:
Light Use: 20-50 Watts
Moderate use: 50-100 Watts
Heavy use: 100-200 Watts or more

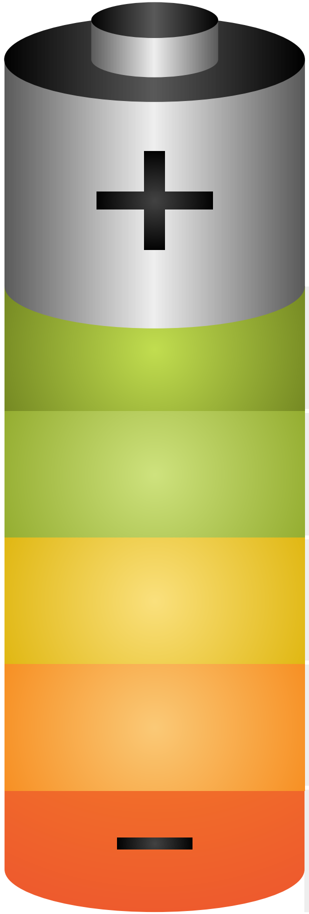


Source

Choice of Device for this Study

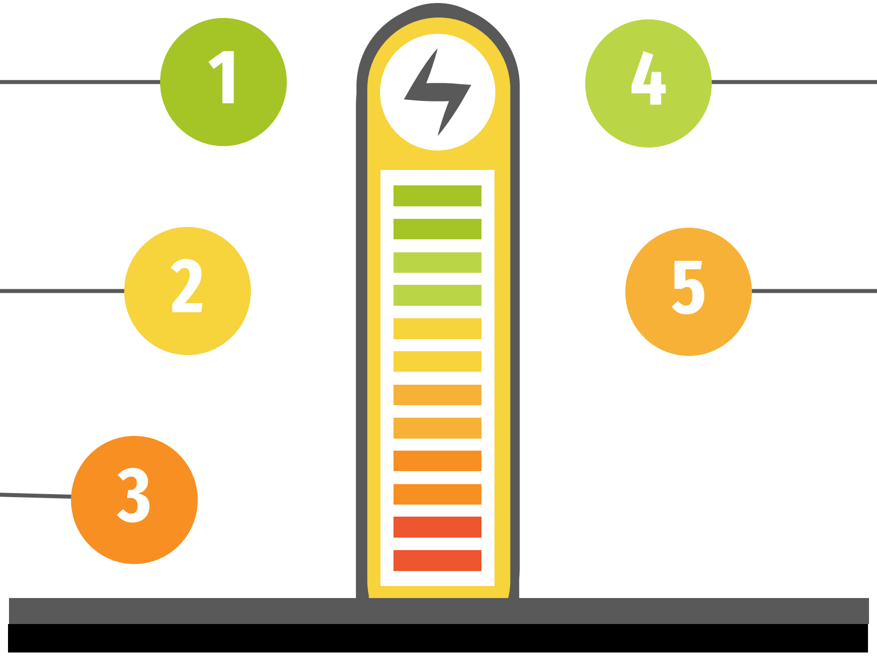


Section-Wise Conclusions



Device of focus for the study	Smartphones
Standardization & Existing chargers	XXXXXXXXXXX
Charging Technology Employed	XXXXXXXXXX
Device Localization Technology	XXXXXX
Blocks Required/Diagrams	XXXXXXXXXX

Project Journey and Progress



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Neuralink & Convenient WPT using RF

2 Current Tech.

Magnetic Coil Charging & AirFuel Standardization

3 Reducing Power Loss

To curb power losses - Beamforming

4 Device Location?

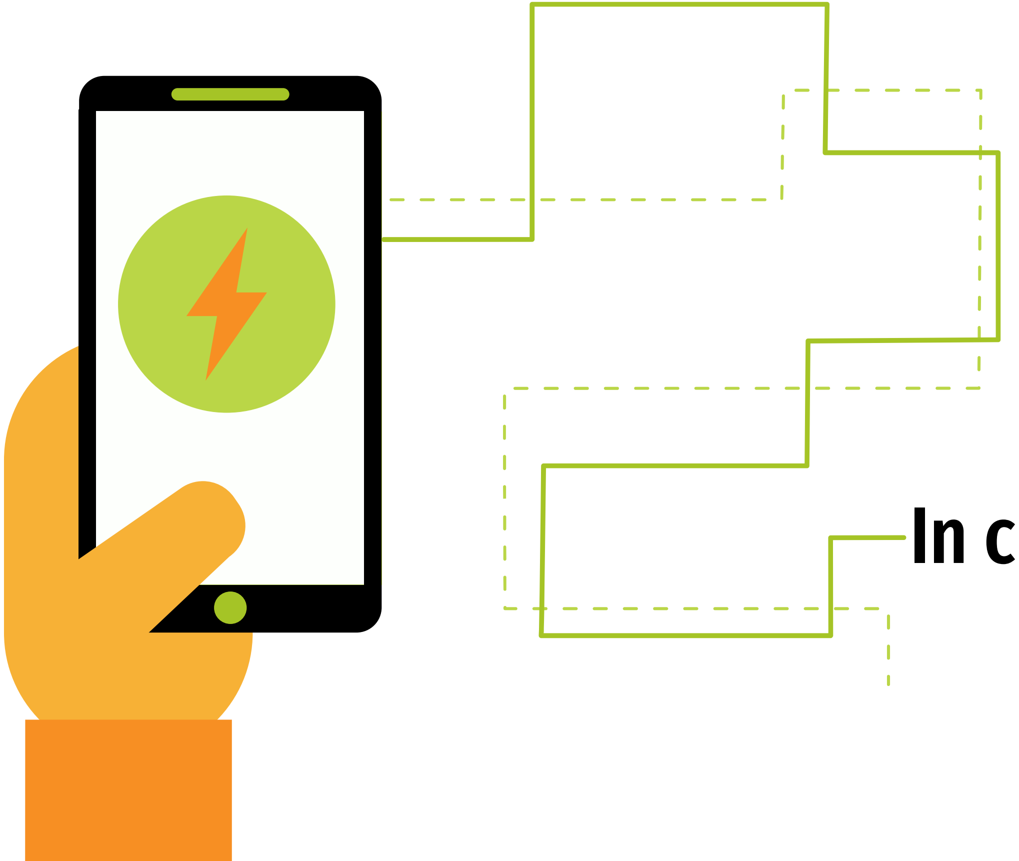
Found UWB technology to be better for locating device

5 Block Diagrams

Ideated Transmitting & Receiving end Block Diagrams

Existing Products/Studies

Current Technologies & Standardization



In charging Smartphones

Current Wireless Chargers

How to increase the range?

Resonant Repeaters: repeaters contain their own circuits and coils, allowing power to 'hop' over greater distances.

Dynamic Wireless Charging Theory: involves tweaking the currents in loop antennas to suppress radiation resistance and increase efficiency. This method has shown that it's possible to maintain high power transfer efficiency over longer distances, such as 18 cm, with over 80% efficiency.

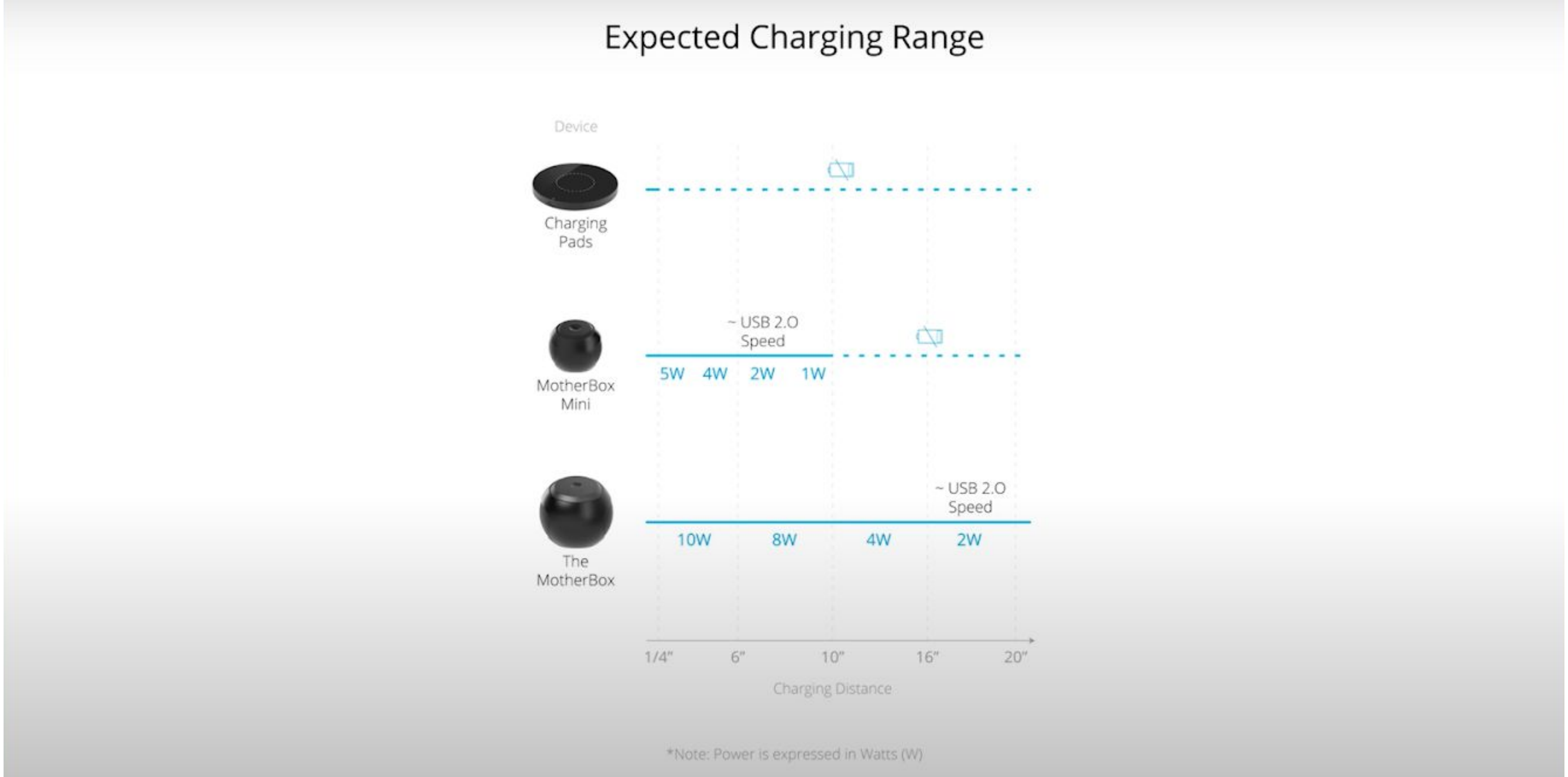
Current Wireless Chargers

Problem:

A lot of energy is wasted as heat.

Solution: RF Wireless Power Transfer!

The MotherBox



Bulky Receiver

Xiaomi Air Charging

Xiaomi Air Charging Working

Transmitter Side: A phase control array composed of 144 antennas transmits millimeter-wide waves directly to the phone through beamforming.

Xiaomi Air Charging Working

Receiver Side: The receiving antenna array composed of 14 antennas converts the millimeter wave signal emitted by the charging pile into electric energy through the rectifier circuit

Low Power Limit

Low Power Limit

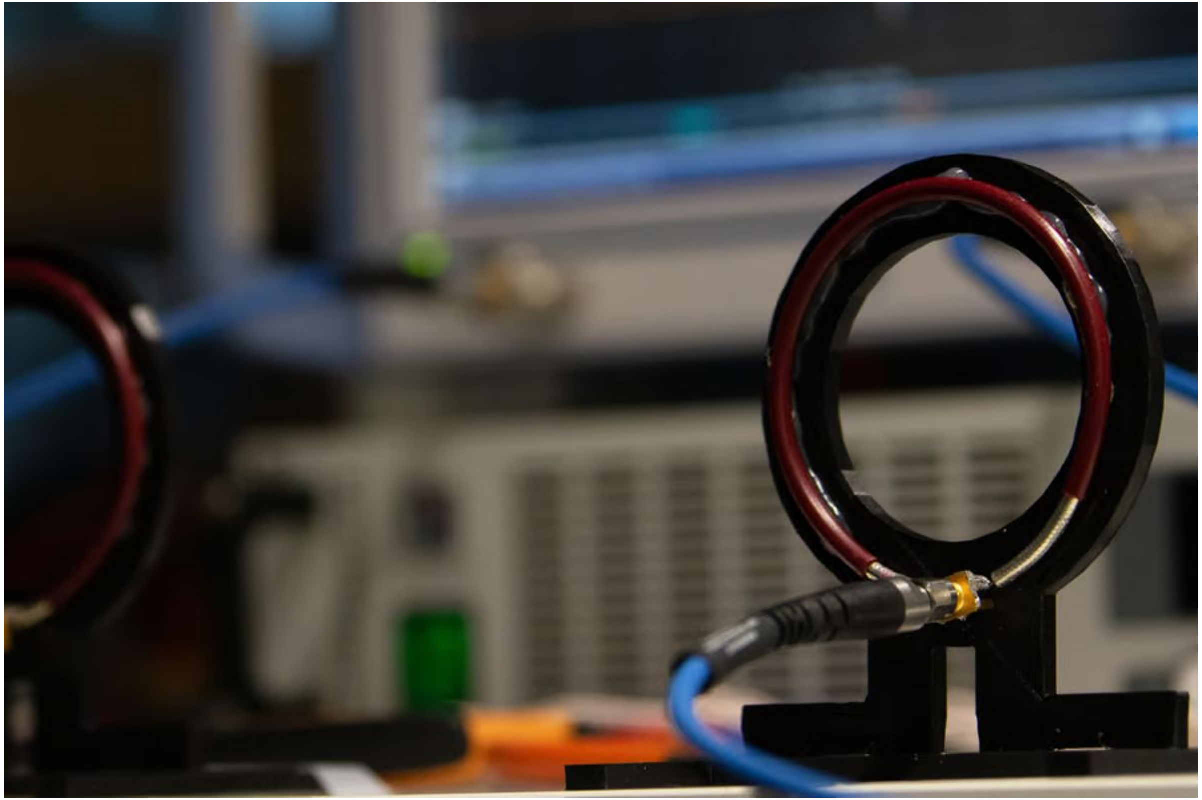
NOT A PROBLEM!

Xiaomi: Spatial Recognition

Xiaomi’s self-developed isolated charging pile has five phase interference antennas built in, which can accurately detect the location of the smartphone.

The Problem

1. RF Signals lose energy really quickly when travelling through air
2. On standby, smartphones use more power than these devices can supply
3. You are slowing the rate of your battery losing power
4. External Receiver to be designed before companies make them in-built
5. Energy spent not only in detecting the devices in the environment but also charging them



The team tested the idea using two loop antennas, each 7.2 cm (2.8 in) wide. By tweaking the currents in the antennas, they were able to suppress the radiation resistance in the loops and increase the efficiency. Even when placed 18 cm (7 in) apart, the power transfer efficiency remained high at over 80%.

Source

AirFuel™ RF Standardization

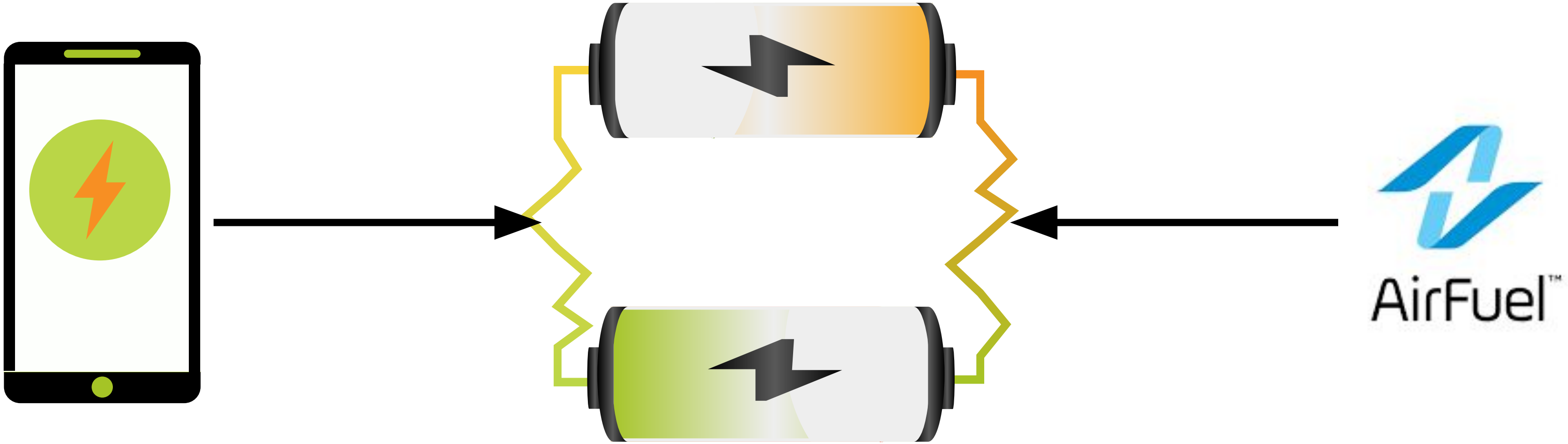
Source: https://airfuel.org/

Standardization: The AirFuel RF Std.

Notable Members: **Energous Corporation** and **Atmosic**

Atmosic: developing solutions that can power **IoT devices** irrespective of their location in homes and buildings.

SK Telesys: Contribution to development of these standards.



AirFuel RF Wireless Charging Standard

TABLE 11

Use case scenarios and conditions for beam WPT systems

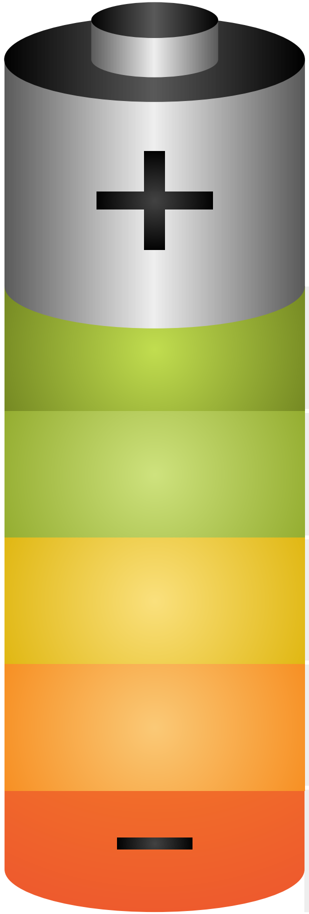
Beam WPT system	**System 4 920 MHz band**	**System 5 2.4 GHz band**	**System 6 5.7 GHz band**
Usage environment	Factory (Indoor), nursing home, etc.	Factory (indoor), plant (indoor), warehouse, etc.	Factory (indoor), plant (indoor), warehouse, etc.
Application	Charging and power supply to sensor network	Charging and power supply to sensors, display and information devices	Charging and power supply to sensors, display and information devices
Number of receiving devices per one WPT transmitter	5 to 10 devices (Simultaneous reception)	1 to several ten devices (Successive or sequential reception)	1 to several ten devices (Successive or sequential reception)
Power range	Several µW to several hundred µW	50 mW to 2 W	Several mW to several hundred mW
Power transfer distance	Less than 5 m	Less than 10 m	Less than 10 m

AirFuel RF Wireless Charging Standard

TABLE 11 (*end*)

Beam WPT system	System 4 920 MHz band	System 5 2.4 GHz band	System 6 5.7 GHz band
Coexistence with other wireless systems	Feasible. Take appropriate interference mitigation and radio protection measures	Feasible. Take appropriate interference mitigation and radio protection measures	Feasible. Take appropriate interference mitigation and radio protection measures
Power transfer while human bodies exist	Possible to transfer under the condition that limits of national radio exposure guidelines are cleared	Off	Off

Section-Wise Conclusions



Device of focus for the study	Smartphones
Standardization & Existing chargers	AirFuel, Magnetic
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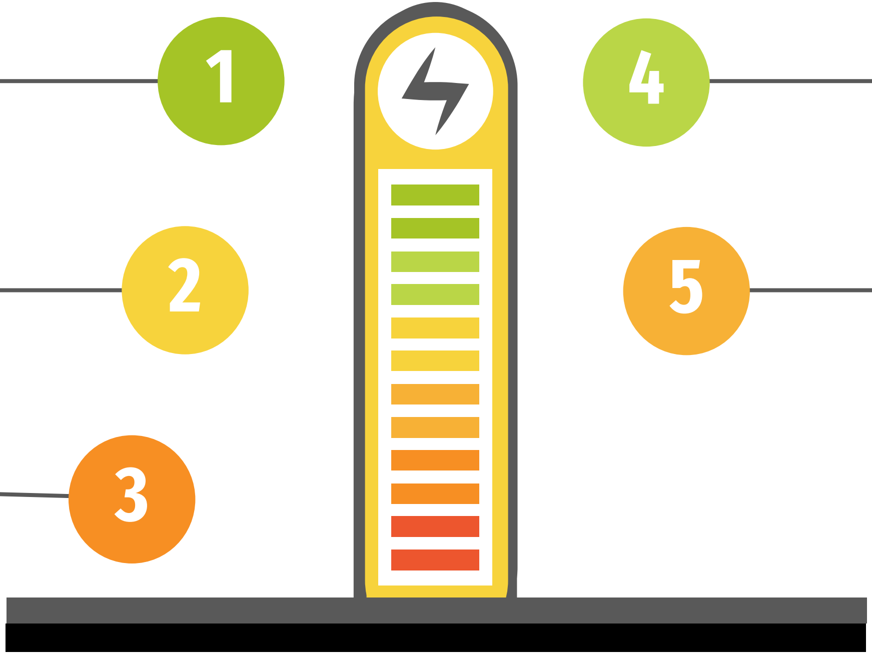
Device Localization Technology	XXXXXXX
Blocks Required/Diagrams	XXXXXXXXXXX

Project Journey and Progress



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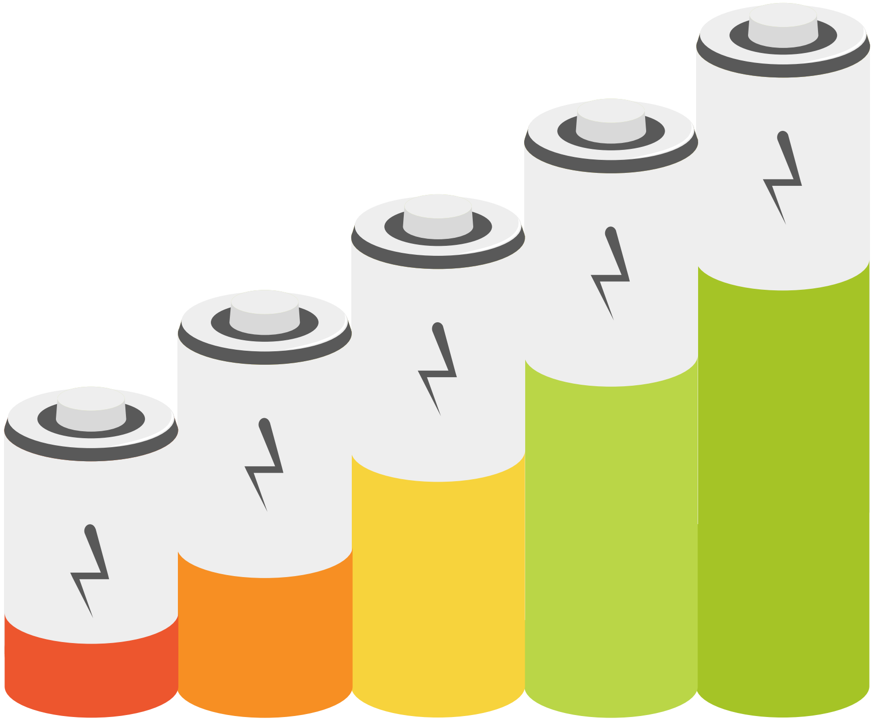
Dealing with Losses and Ideating Strategies

Reasons for Power Loss in RF WPT



Propagation Losses: as RF travels through space, signal fades due to free path loss. Energy dissipates in the air.

Antenna Efficiency: efficient ones make better transmitters & improve efficiency. Non-optimized ones create losses

Reflection and Scattering: obstacles, surfaces and materials cause reflection & scattering thus diverting energy away.

Dielectric & Conductive Losses: Dielectric (walls, furniture, & humans) & Conductive (metals) absorb RF energy.

Harvesting Circuit Efficiency: Rectifier circuits used to convert RF energy to DC power have inherent losses.

What is Propagation Loss in RF?

Definition: It's the decrease in power density of RF waves as they travel from the transmitter to the receiver.

Key Causes:

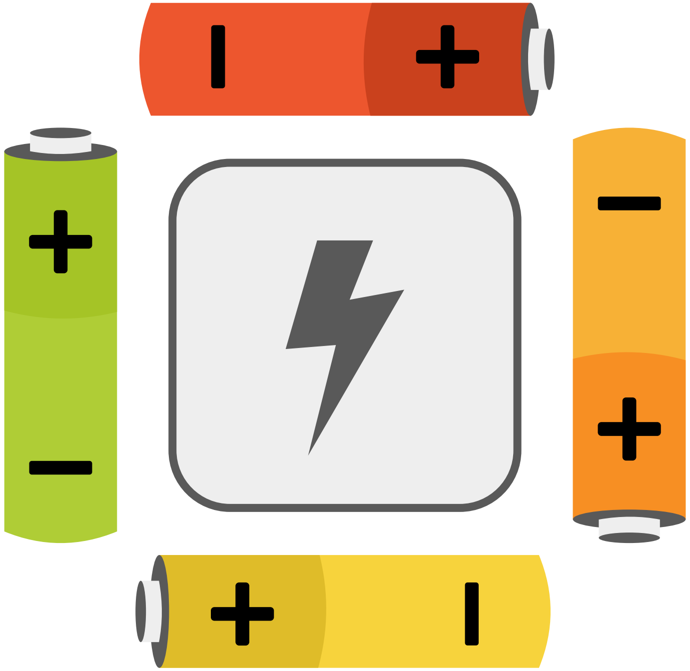
- **Distance Impact**: Power reduces with the square of the distance (Inverse Square Law).
- **Material Absorption**: Loss due to RF energy absorbed by materials.
- **Environmental Factors**: Scattering, diffraction, and atmospheric conditions affecting signal strength.

Free Space Path Loss (FSPL) Formula:

- Used to estimate signal strength loss in free space.
- **FSPL (dB) = 20 log10(d) + 20 log10(f) + 20 log10(4π/c)**
  Where: d = distance between antennas, f = frequency, c = speed of light.

Impact on Wireless Power Transfer:

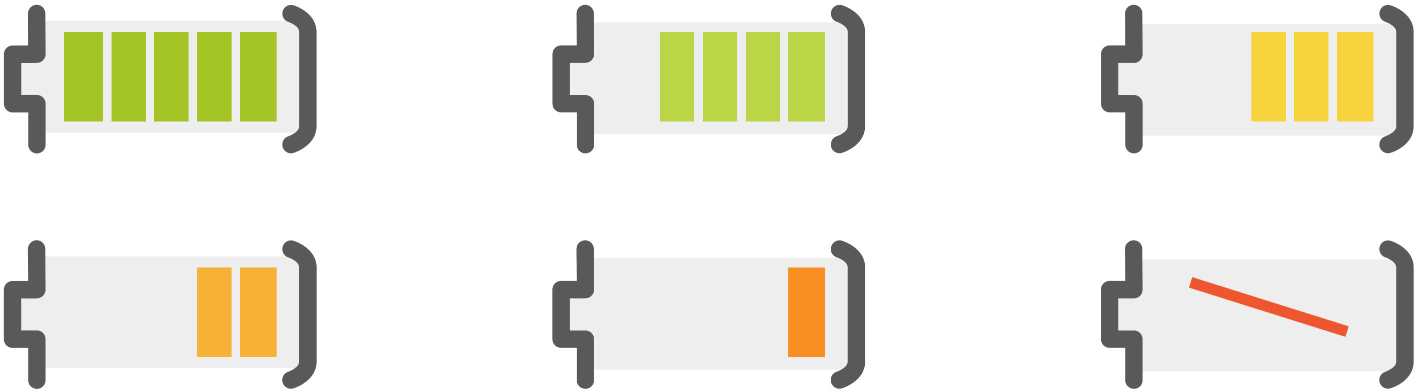
- Efficiency decreases with higher propagation loss.
- Critical in system design, especially for long distances.
- Mitigation through beamforming and MIMO technologies.



What is Propagation Loss in RF?

Mitigation Strategies:

- Directional antennas for focused energy transmission.
- Selecting frequencies with minimal atmospheric loss.
- Power adjustments to offset expected losses.



Reasons for Less/More power delivery - Interference

- RF waves, like all electromagnetic waves, exhibit properties of **interference**.
- When two or more waves meet, they can either lead to **constructive or destructive interference** depending on their phase relationship.
- In a room, waves emitted by the transmitter can **reflect off walls**, **ceilings,** and **other objects**, leading to **multiple paths** from the transmitter to the receiver.
- At certain points, these multipath signals might **align in phase**, causing **constructive interference** and a resultant **increase in power at the receiver**. At other points, the signals might be **out of phase**, causing **destructive interference** and a **reduction in power**.

Reasons for Less/More power delivery - Standing Waves

- RF waves can **reflect off surfaces** and combine with the original waves to form standing waves.
- **Standing waves** have **nodes and antinodes** that are stationary.
- The distance from the transmitter where maximum or minimum power transfer occurs can correspond to the **locations of these antinodes and nodes**

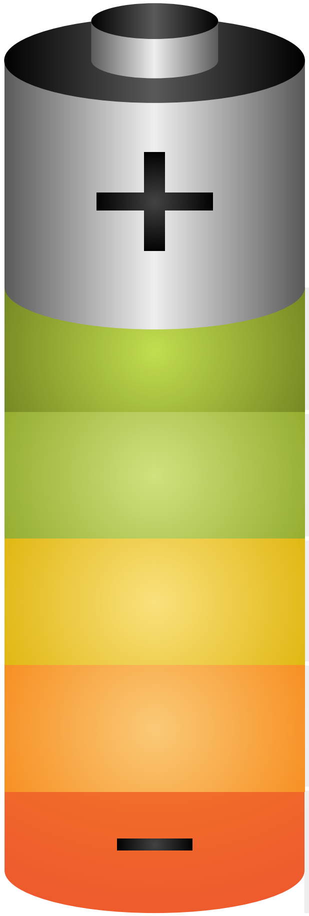
Reasons for Less/More power delivery - Beamforming and MIMO

- Aim to optimize the signal path and improve efficiency in wireless communication systems.

- **focuses the RF energy** into a directed **beam towards the receive**r, which can help **mitigate some of the effects** of destructive interference and **multipath fading**

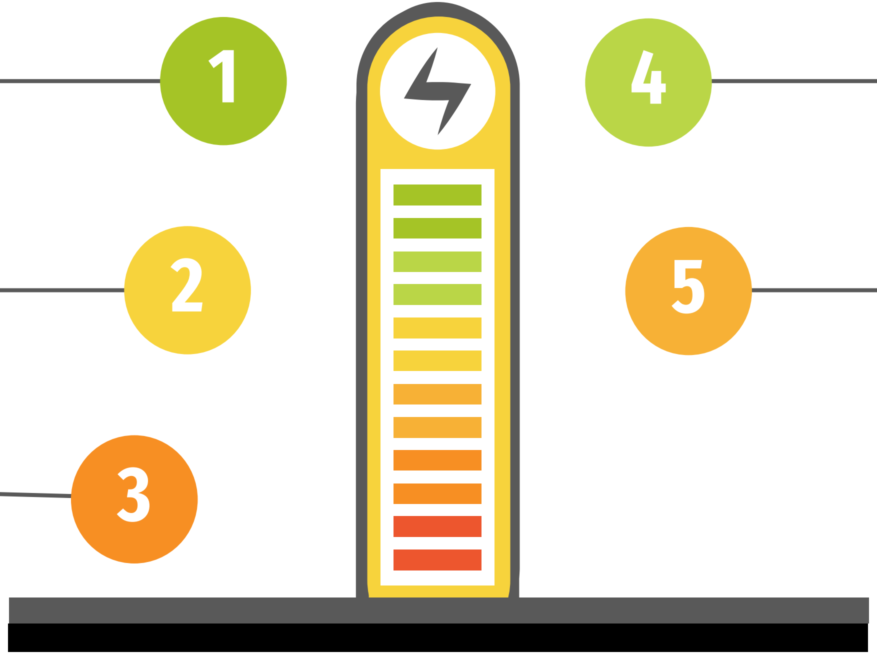
- **MIMO** uses **multiple antennas** at both the transmitter and receiver to create **several paths** for the data to travel, improving reliability and potentially power transfer efficiency.

Section-Wise Conclusions



Device of focus for the study	Smartphones
Standardization & Existing chargers	AirFuel, Magnetic
Charging Technology Employed	Beamforming
Device Localization Technology	XXXXXX
Blocks Required/Diagrams	XXXXXXXXXX

Project Journey and Progress



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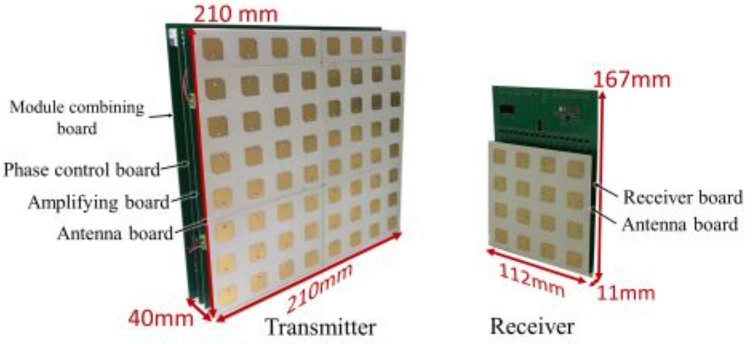
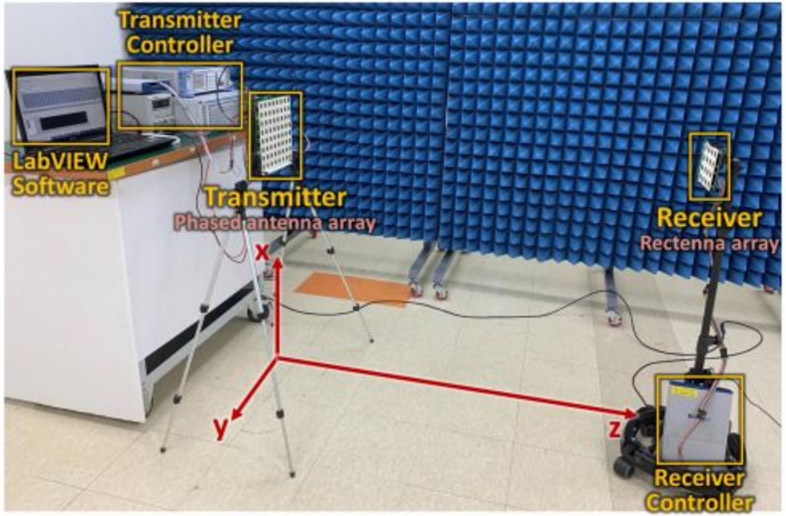
Beamforming: The Solution



(a) Transmitter and receiver

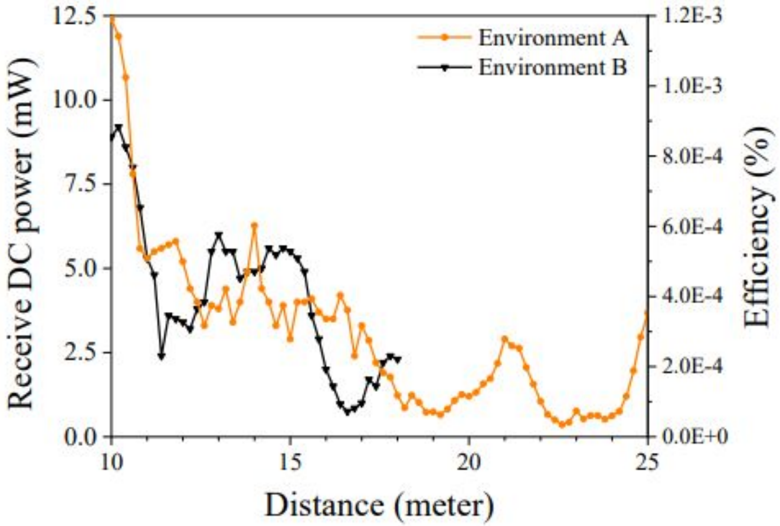


(b) Testbed setup

FIGURE 12. Experimental setup

(a) Test environment A

(b) Test environment B

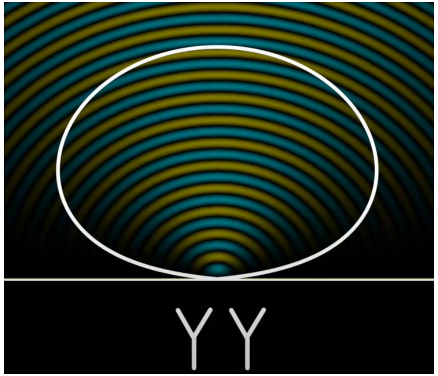


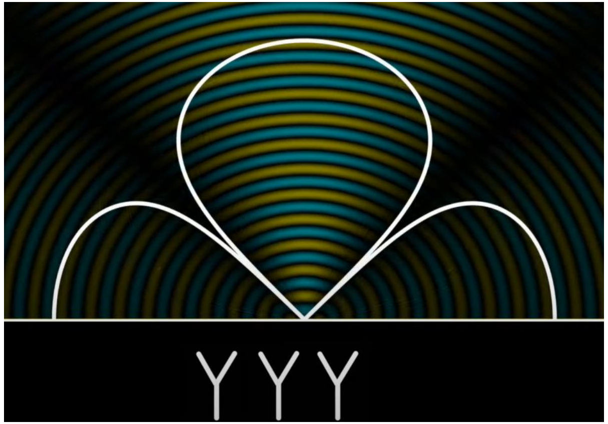
(c) Receive power and power transfer efficiency over distance

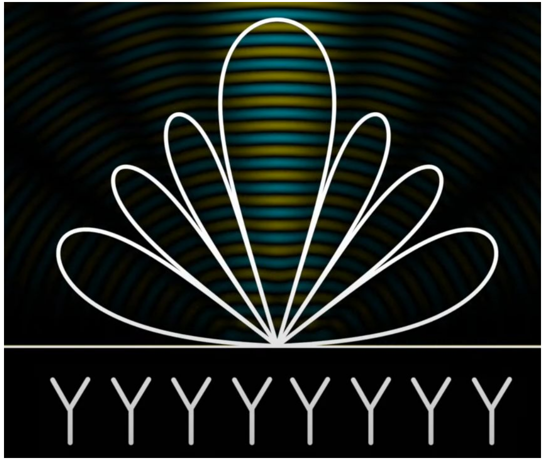
FIGURE 17. Power transfer test

Beamforming & Number of Antennas

More the number of antennas, thinner and stronger the beam



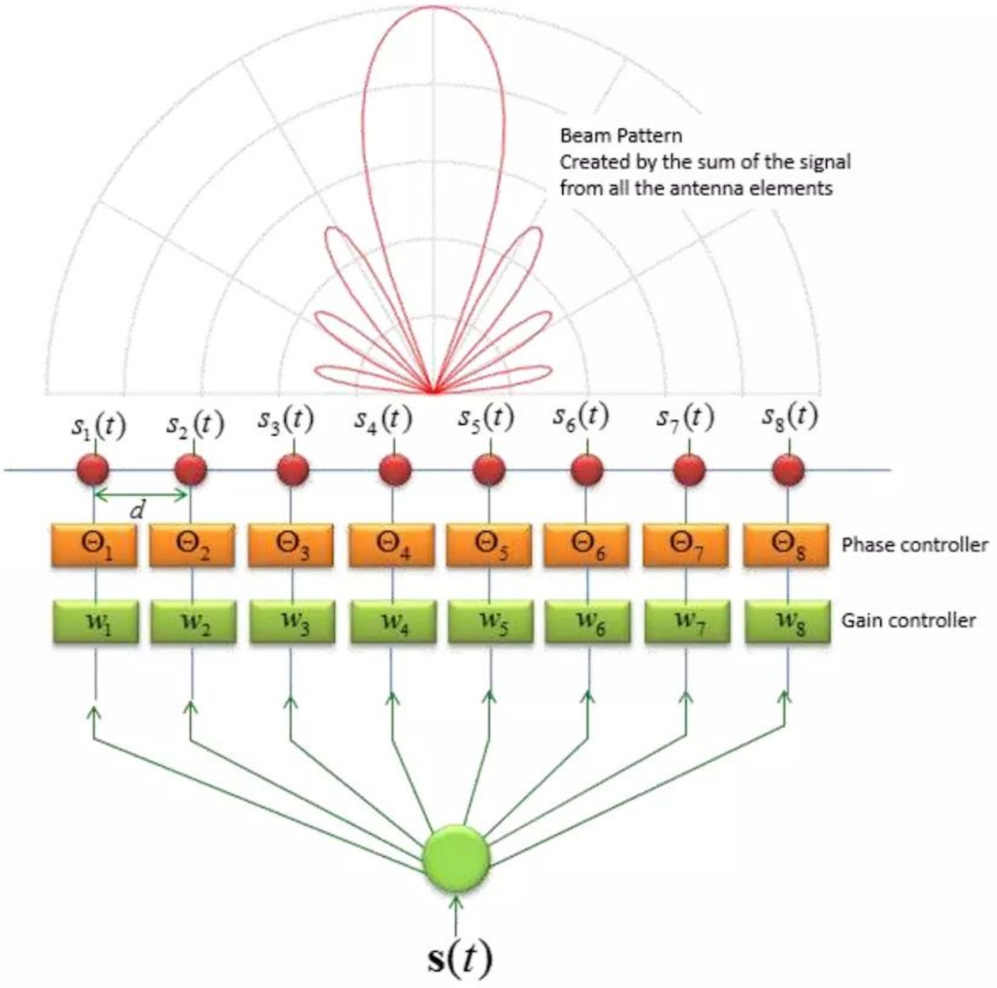




Basic Concept:
Phased Array Beam-Forming

- **Phased Array is a directive antenna** made with individual radiating sources (several units to thousands of elements).
- **Radiating Elements might be:** dipoles, open-ended waveguides, slotted waveguides, micro-strip antennas, helices, spirals etc.
- The **Shape and Direction** of pattern **is determined by:**

1. **Number** of Radiating Elements
2. Relative **Phases** and **Amplitudes** applied to each radiating element
3. **Spacing** between radiating elements
4. Operating **Frequency**

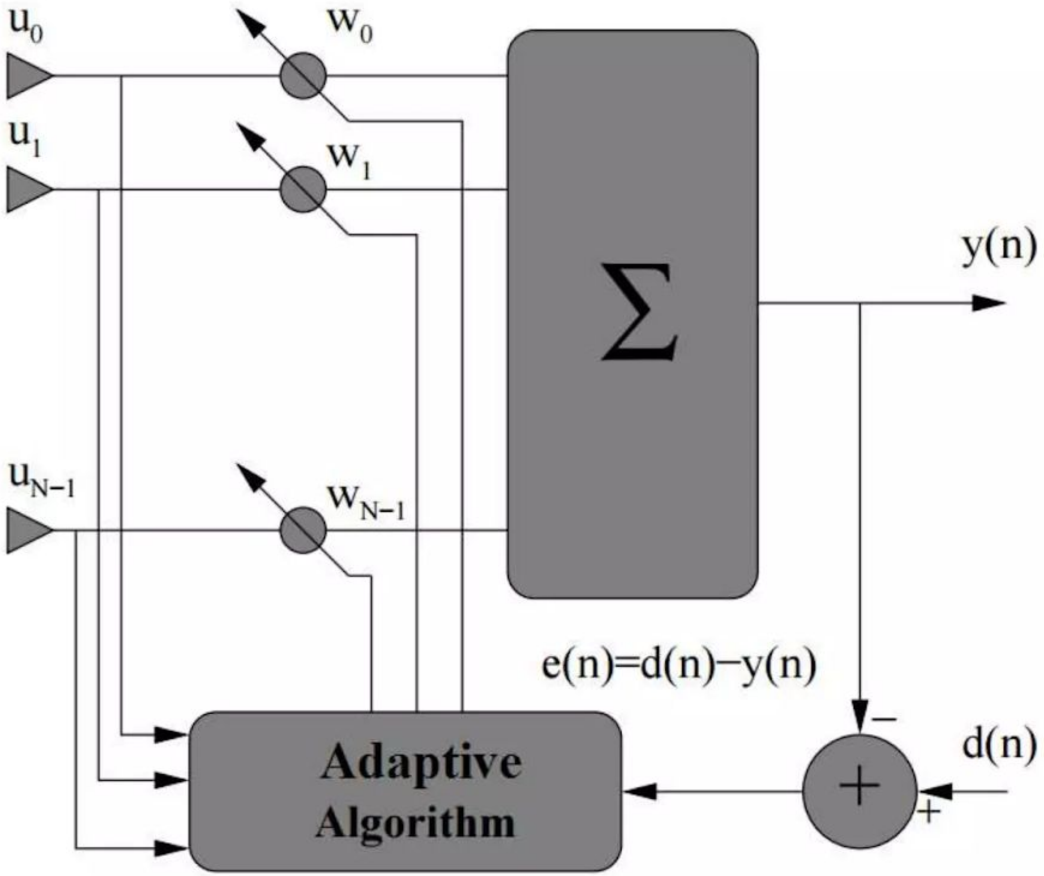


Generic Adaptive Antenna Array System

For **optimal transmission/reception** of the **desired signal d**, an adaptive update of the **Weight Vector W** is needed to steer spatial filtering beam to the **target's time-varying DOA** and thus get rid of **interferers**.

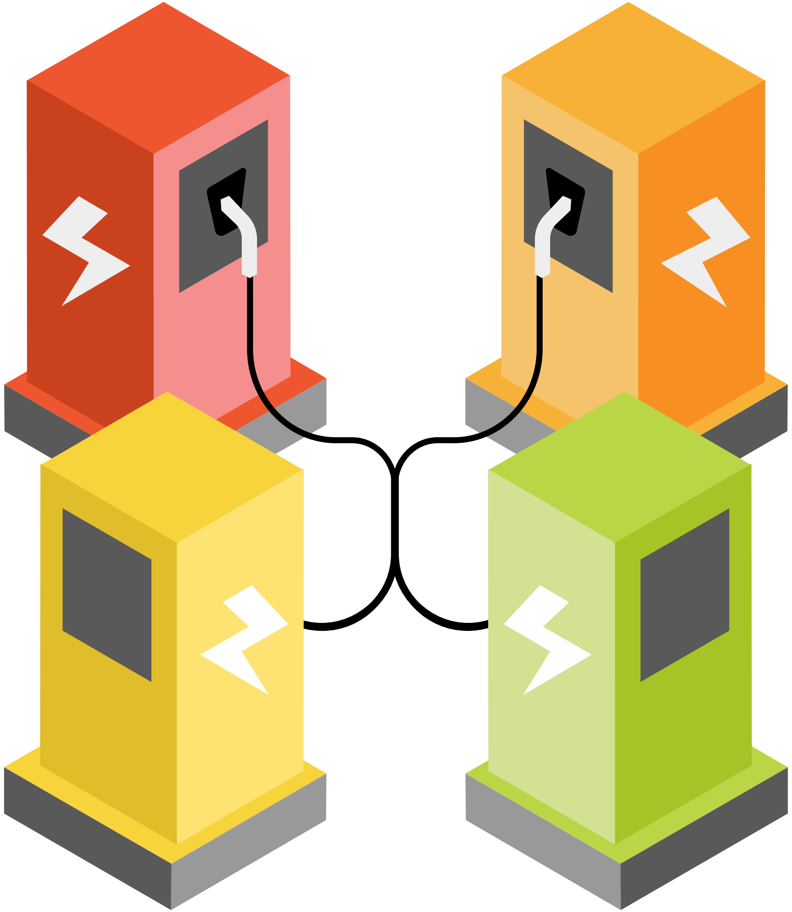
Adaptive Beamforming Schemes:

1. Least Mean Squares (LMS) Algorithm
2. Normalized LMS Algorithm
3. Recursive Least Square (RLS) Algorithm
4. Constant Modulus (CM) Algorithm



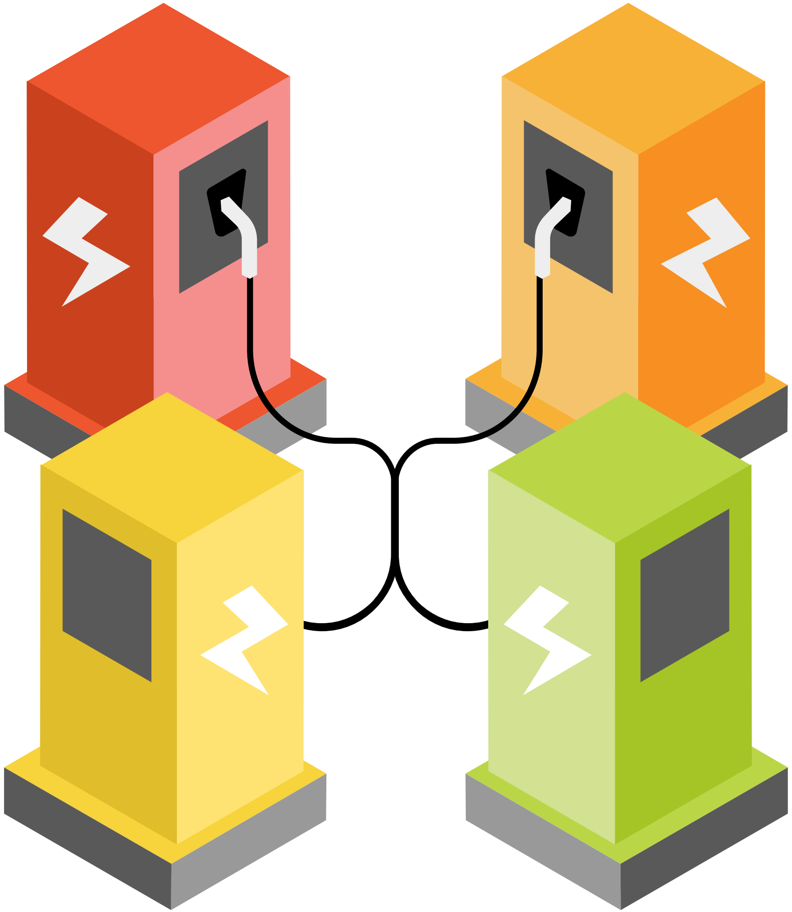
Different Beamforming Algorithms

1. Least Mean Squares (LMS)
2. Normalized LMS (NLMS)
3. Recursive Least Squares (RLS)
4. Constant Modulus (CM)



Different Beamforming Algorithms

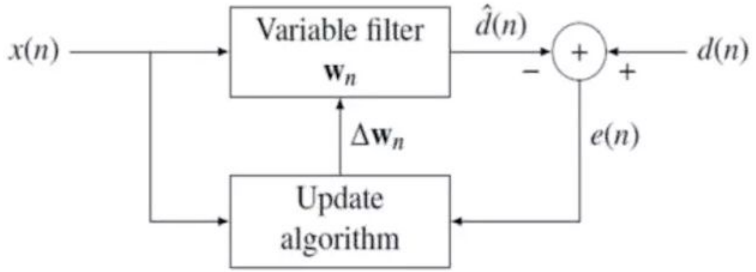
1. Least Mean Squares (LMS)
2. Normalized LMS (NLMS)
3. **Recursive Least Squares (RLS)**
4. Constant Modulus (CM)



Recursive Least Square (RLS) Algorithm

RLS Algorithm Summary

The RLS algorithm for a $\boldsymbol{p}^{th}$ order RLS filter can be summarized as:



Parameters: p = filter order

λ = forgetting factor

δ = value to initialize $\boldsymbol{P}(0)$

Initialization : $w(n) = 0$

$x(k) = 0, k = -p, \ldots, -1$

$d(k) = 0, k = -p, \ldots, -1$

$\boldsymbol{P}(0) = \delta^{-1} I_{p \times p}$

Computation: For $n = 0,1,2, \ldots$

$$x(n) = [x(n), x(n-1), \ldots, x(n-p)]^T$$

$$\alpha(n) = d(n) - x^T(n)\, w(n-1)$$

$$\boldsymbol{g}(n) = \frac{\boldsymbol{P}(n-1)\, x^*(n)}{\lambda + x^T(n)\, \boldsymbol{P}(n-1)\, x^*(n)}$$

$$\boldsymbol{P}(n) = \lambda^{-1} \boldsymbol{P}(n-1) - g(n)\, x^T(n) \lambda^{-1} \boldsymbol{P}(n-1)$$

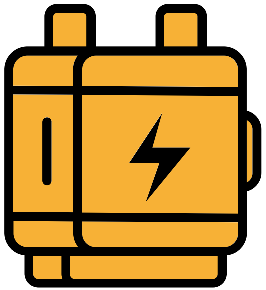
$$\mathrm{w}(n) = w(n-1) - \alpha(n)\, g(n)$$

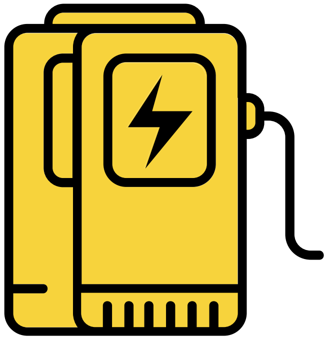
Advantages & DisAdvantages of RLS algorithm:

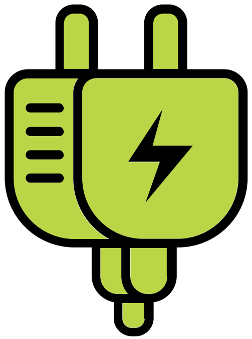
- No need to invert matrices, thereby saving computational power.
- It provides intuition behind its results.
- Faster than LMS and NLMS but more complex

Recursive Least Squares (RLS)

- RLS has a faster convergence rate than LMS and NLMS, meaning it can quickly adapt to changes.
- It might be the best choice in highly dynamic environments where the transmitter needs to rapidly adjust the power beam to track a moving receiver.
- However, RLS is computationally intensive. Which make it not very efficient.







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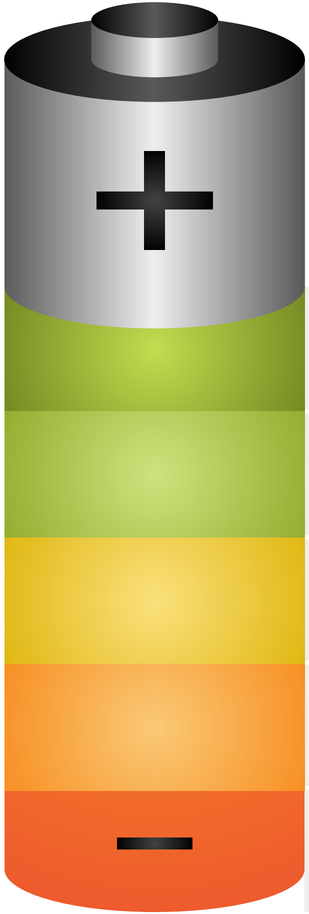

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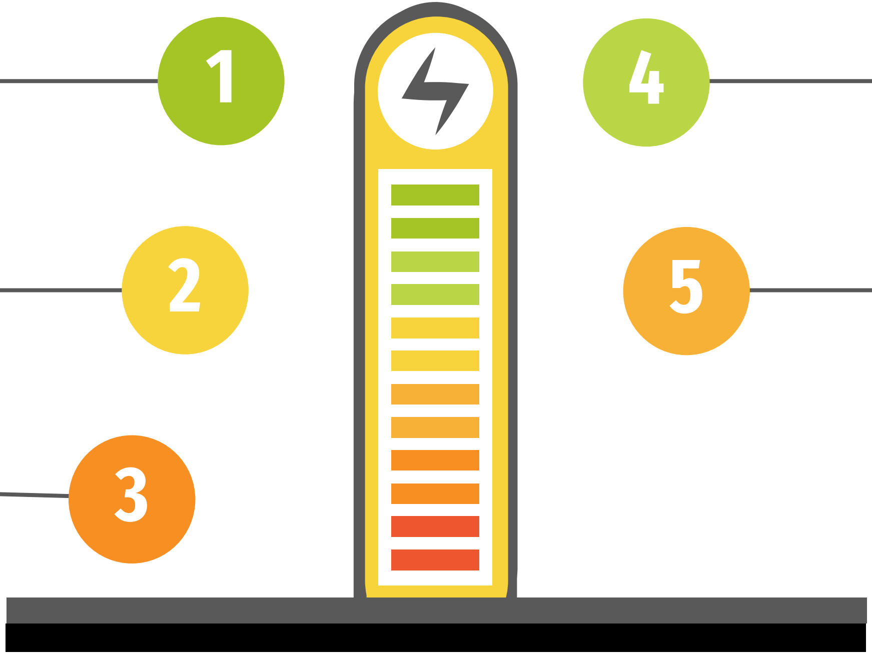

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Device Localisation: Is there something better??

Device Localisation: UWB

Ultra-Wideband (UWB)

- radio technology that transmits data over a wide spectrum of frequencies, typically greater than **500 MHz**
- Precise Localization: it’s ability to measure the time of flight (ToF) of pulses with high precision enables accurate determination of the distance between a transmitter and a receiver
- Low Power Consumption: despite high bandwidth, UWB transmits signals at very low energy levels, contributing to its low power consumption and making it ideal for battery-operated devices.
- Penetration Capabilities: signals can penetrate through obstacles such as walls and doors more effectively than signals with narrower bandwidths

Source

What is the frequency of operation of UWB?

- The frequency range of operation is typically from: **3.1 GHz to 10.6 GHz**
- This has been defined by the Federal Communications Commission (FCC).
- **Lower End of UWB Spectrum (3.1-4.8 GHz)**: Lower frequencies, longer wavelengths. Thus less likely to be absorbed by human tissues, hence **safe** for human exposure
- Since WiFi (2.4-5 GHz) and Bluetooth (2.4 GHz) operate in the (2.4 GHz - 5 GHz) range, ideally, we can use **UWB at the: 6-8 GHz range**
- **Reasons for not using 8-10.6 GHz**
- **Signal Attenuation:** Higher frequencies suffer from increased signal attenuation, especially when propagating through obstacles like walls, furniture, and human bodies
- **Interference**: High frequencies may interfere with other systems, such as satellite communications, radar, etc.

Role of Anchors in UWB

1. UWB anchors are fixed reference points with known positions that form the localization infrastructure.
2. Anchors are synchronized to maintain a common time reference for accurate ranging.
3. Anchors measure the time-of-arrival (ToA) or time-difference-of-arrival (TDoA) of UWB pulses from the target device (tag).
4. Trilateration or multilateration algorithms use range measurements to estimate the tag's position.
5. Anchor placement is crucial for optimal coverage and accuracy of the localization system.
6. Data fusion and filtering techniques can be employed to enhance the accuracy and robustness of location estimates.

Implementing DeepLearning Algo. for Device Localization

- The script *data-generator.py* is used to generate synthetic UWB data assuming 3 Anchor points in a room with dimensions **(10m, 10m, 5m)** with a smartphone placed at **(5m, 8m, 2m)** which it saves in the file *synthetic_uwb_data.csv*.
- The script *specific-example-bp.py* takes sample anchor distances values for 3 Anchors and uses the training set to train a model which uses Backpropagation to predict the coordinates of the phone. Here are the results obtained from the code:

```
Actual Location:
 X: 5
 Y: 8
 Z: 2
Predicted Location:
X: 5.029687
Y: 7.951255
Z: 2.04306
Percentage Accuracy: 98.88131459554037
PS D:\UWB-Backpropagation\DeepLearning-On-UWB-Data-for-Beamforming>
```

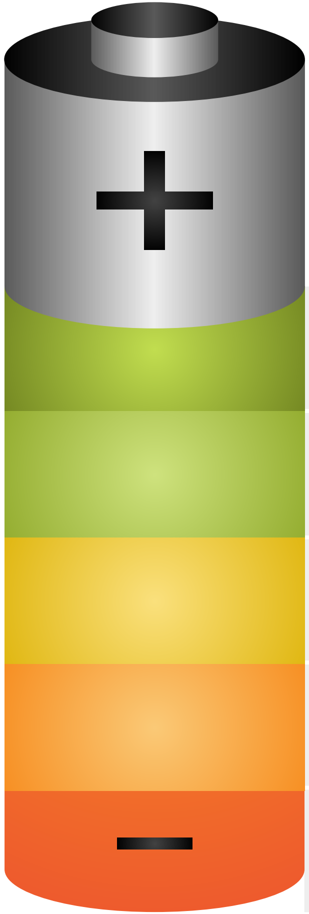
Implementing DeepLearning Algo. for Device Localization

- After the training is done, the script *backpropagation-algo.py* takes 10 random anchor values from the dataset and tries to predict the spatial coordinates for the same using the backpropagation algorithm. Here are a few results: (Full code in *github repo*)

```
Verification Results:
Sample 1:
Actual Coordinates: [5.02716609 7.99750635 2.04382855]
Predicted Coordinates: [5.020791  8.034988  1.9486222]
Accuracy: 89.75%

Sample 2:
Actual Coordinates: [4.91672968 7.95988147 1.96904265]
Predicted Coordinates: [4.918498 7.989941 2.019441]
Accuracy: 94.13%

Sample 3:
Actual Coordinates: [5.04195564 8.08314993 2.0290565 ]
Predicted Coordinates: [4.990877  8.102076  1.9825139]
Accuracy: 92.84%

Sample 4:
Actual Coordinates: [5.00653411 8.07381128 2.02704925]
Predicted Coordinates: [4.9593267 8.014121  2.0641682]
Accuracy: 91.53%
```

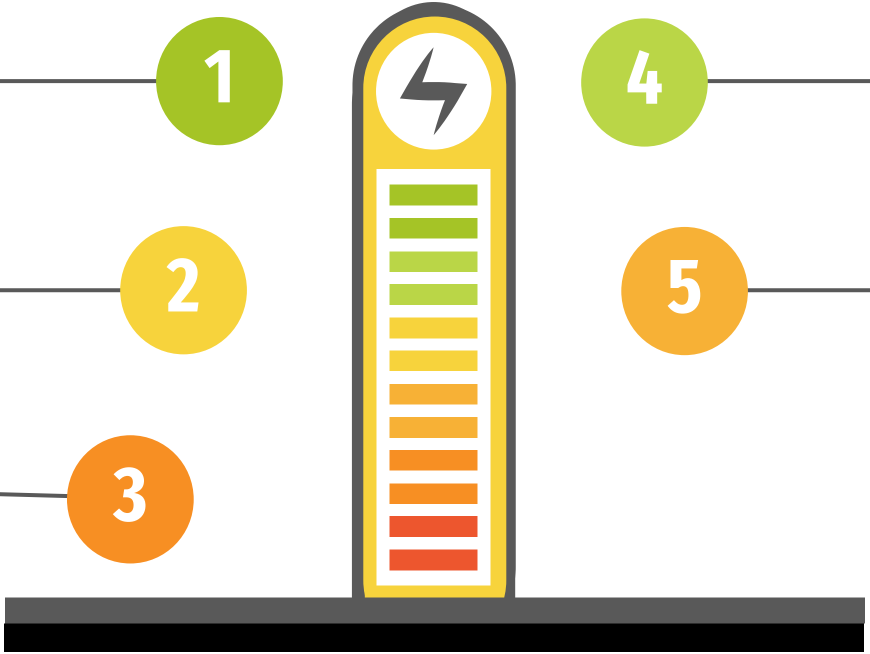
```
Sample 5:
Actual Coordinates: [5.05023512 8.04743965 1.92319476]
Predicted Coordinates: [4.995882  7.9776063 1.9290559]
Accuracy: 91.13%

Sample 6:
Actual Coordinates: [4.97133968 8.00649469 2.04170229]
Predicted Coordinates: [4.978837  7.998359  1.9618909]
Accuracy: 91.94%

Sample 7:
Actual Coordinates: [5.11958087 8.13327153 2.05375672]
Predicted Coordinates: [5.1380076 8.100814  1.9773233]
Accuracy: 91.49%

Sample 8:
Actual Coordinates: [4.98624727 8.14331077 1.99243416]
Predicted Coordinates: [5.0420218 8.169863  2.0263782]
Accuracy: 92.95%
```

Section-Wise Conclusions



Device of focus for the study	Smartphones
Standardization & Existing chargers	AirFuel, Magnetic
Charging Technology Employed	Beamforming
Device Localization Technology	UWB
Blocks Required/Diagrams	XXXXXXXXXXX

Project Journey and Progress



1 — Origin

Neuralink & Convenient WPT using RF

2 — Current Tech.

Magnetic Coil Charging & AirFuel Standardization

3 — Reducing Power Loss

To curb power losses - Beamforming

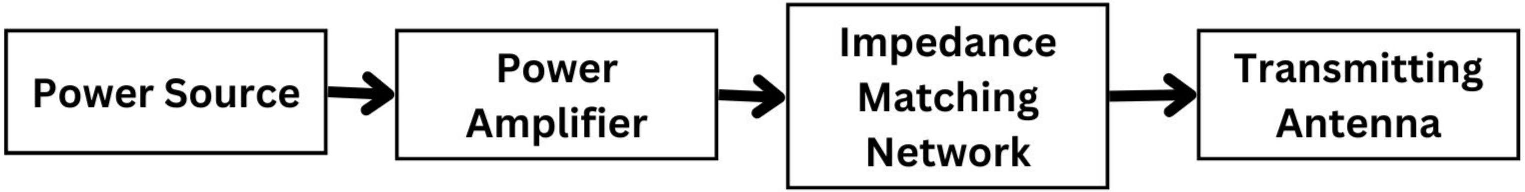
4 — Device Location?

Found UWB technology to be better for locating device

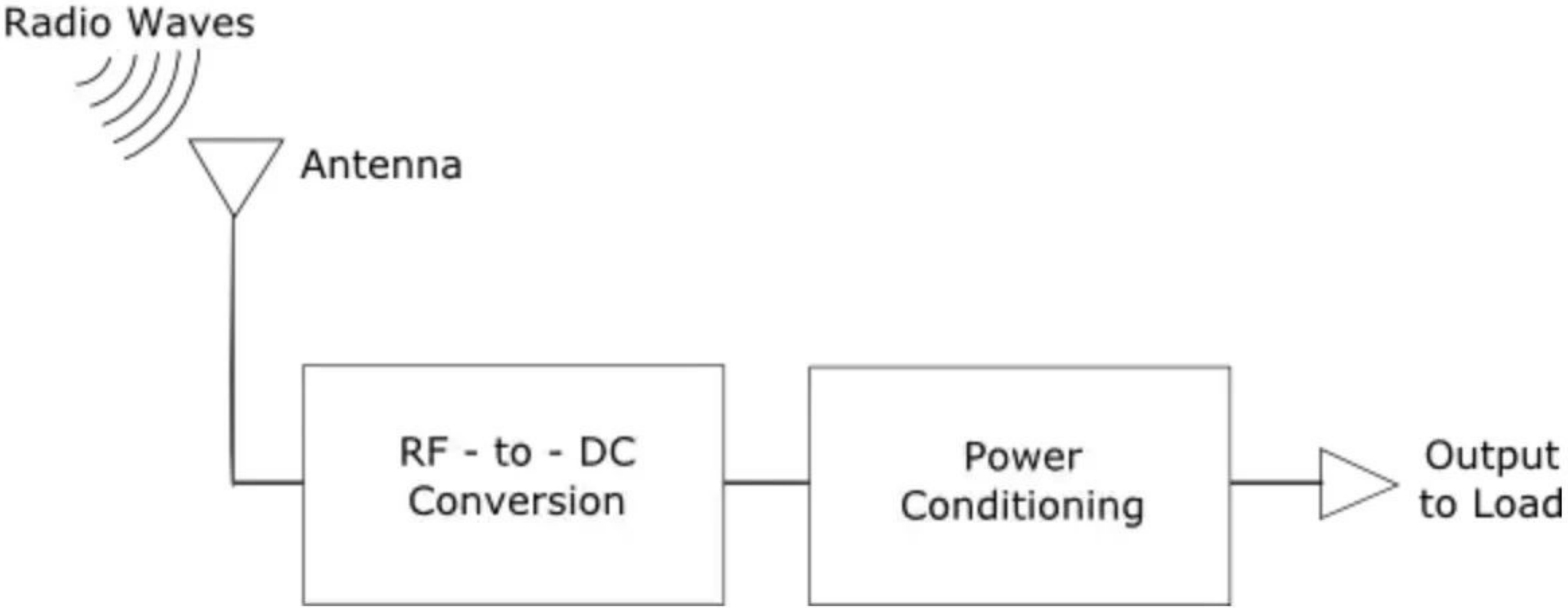
5 — Block Diagrams

Ideated Transmitting & Receiving end Block Diagrams

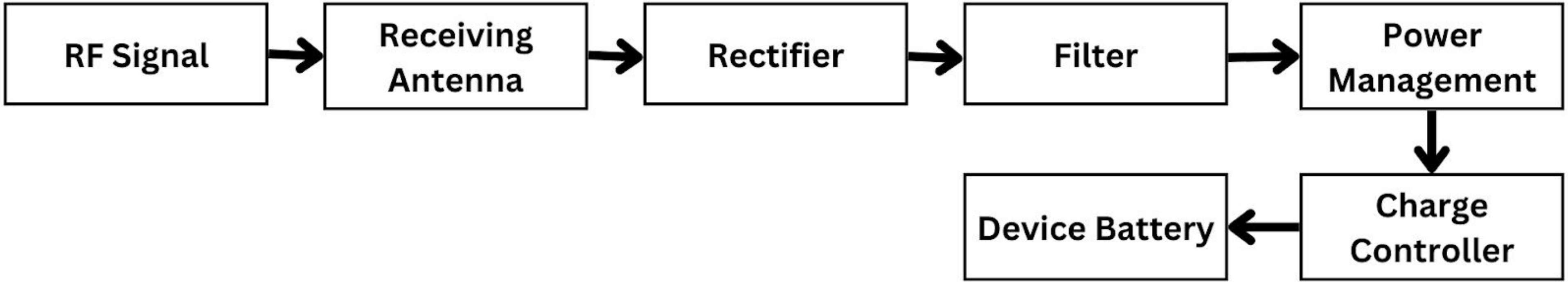
Block & Circuit Diagrams



Transmitting End Block Diagram


Radio Waves
Antenna
RF - to - DC Conversion
Power Conditioning
Output to Load

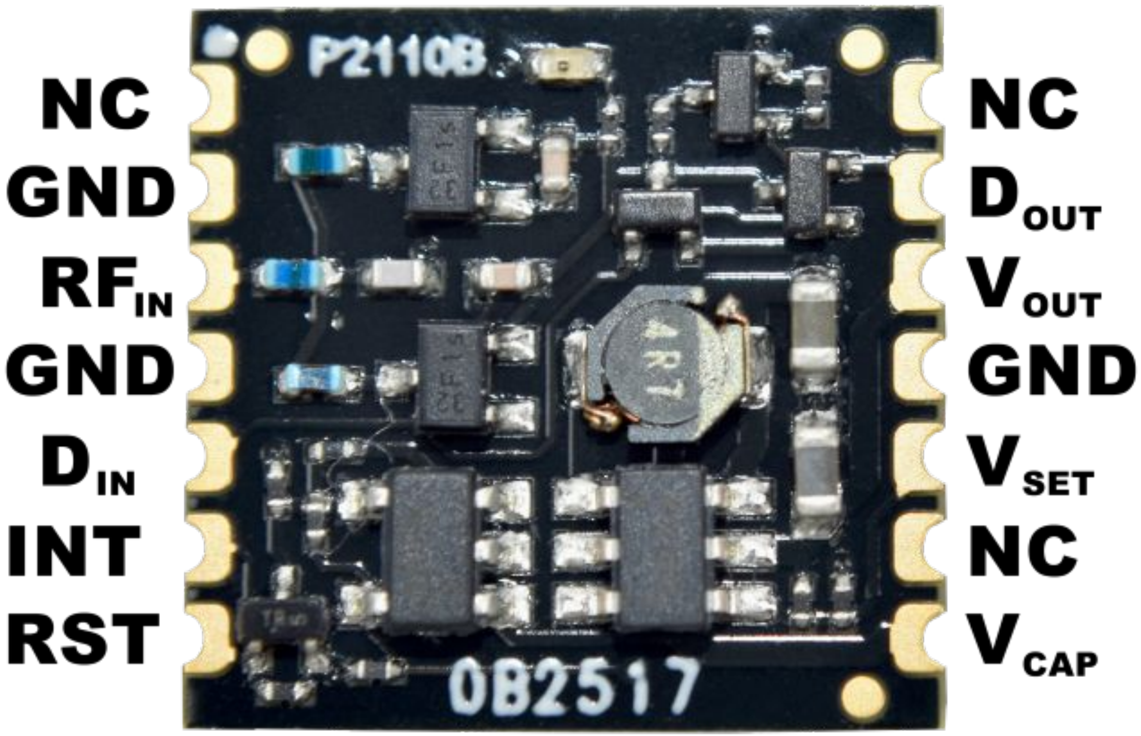
Source



Receiving End Block Diagram

Verdict

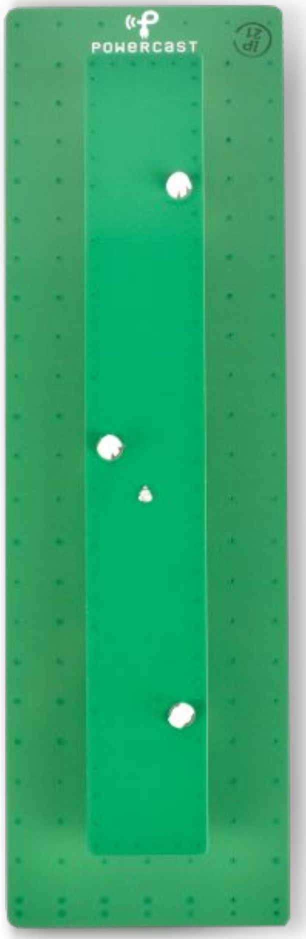
- antennas, wireless charging coils, PMICs (power management ICs), power receiver chips, etc. can yield systems capable of harvesting energy from RF.
- Specialized integrated circuits (ICs) designed specifically for RF-to-DC conversion are currently somewhat rare, with **Powercast** and **E-Peas** providing the only current commercial solutions
- The P2110 evaluation kit contains a 900 MHz transmitter, a 2.4GHz access point, two wireless sensor modules, and two P2110 evaluation boards based on the P2110 module.


NC
GND
RF$_{IN}$
GND
D$_{IN}$
INT
RST
NC
D$_{OUT}$
V$_{OUT}$
GND
V$_{SET}$
NC
V$_{CAP}$
P2110B
4R7
0B2517

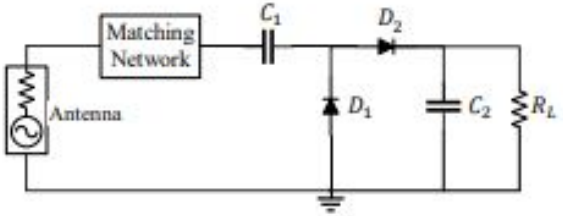
Source

RF Harvesting Antennas

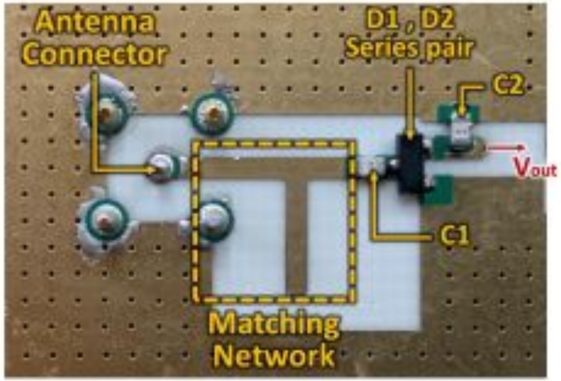
Antennas designed for the frequency of interest are connected to the RF-energy-harvesting chips, which in turn feed capacitors that store the charge



Source



(a) Schematic diagram

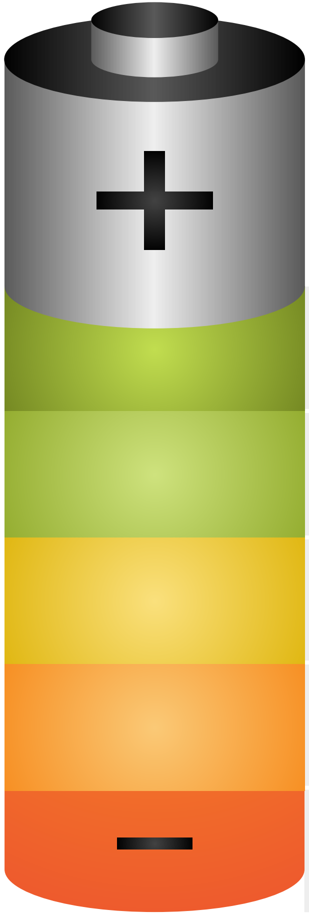


(b) Fabricated board

FIGURE 9. Rectifier design

In Fig. 9(a) C1 = 2 pF, C2 = 2 pF, RL = 1 kΩ

Section-Wise Conclusions



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Blocks Required/Diagrams	Shown at end

Thank You!