Introduction

Every year, millions of home routers are thrown away [1], when people change providers or upgrade their system. This leads to waste of perfectly functional products, which could instead be upcycled. Our project idea is to upcycle an old home router to a wireless access point (WAP) for use in small offices or by individuals working from home with weak WiFi coverage around the house. This low-cost modification turns an old router into a high-performance WiFi signal extender for your existing local network whilst reducing landfill / recycling requirements.
First, we looked at what features commercial WAP devices offer and made a list of 'necessary' and 'nice to have' features

Table 1 – Necessities & Commodities for a WAP.

Necessary:	Nice to Have:
Wall/Ceiling mount	**Single cable for Power and communication protocols (POE)**
WLAN input port	Ethernet ports to extend the wireless system in a Daisy Chain manner
Status LEDs	WPS (WiFi off/on) button and Device Reset button
Power supply input	**Easy mounting mechanism (less than 4 holes in the ceiling/wall required)**
Power button	USB port to convert the router into a Wirelessly Accessible File Server

The use of a single cable for power and communication protocols is desirable for several reasons. As the WAP will be capable of mounting in unusual locations, power sockets will not always be available nearby so reducing the number of wires will ease the installation process and cost. Moreover, POE-Compatible switches and injectors are relatively commonplace and accessible.
With the rough concept outline defined, it was found that some network routers can be flashed with an open-source operating system called OpenWRT to unlock further functionality. While there are other toolkits for software modification that support a wider range of routers, OpenWRT is open source, receives regular updates and is very reliable. It was determined that the **PlusNet Hub One router** would be a suitable candidate for this project because of its high-speed processer, dual band WiFi functionality and excellent availability in the used market.

RE Approach

Before the disassembly began, a list of features was compiled that could be useful or require modification for our product:

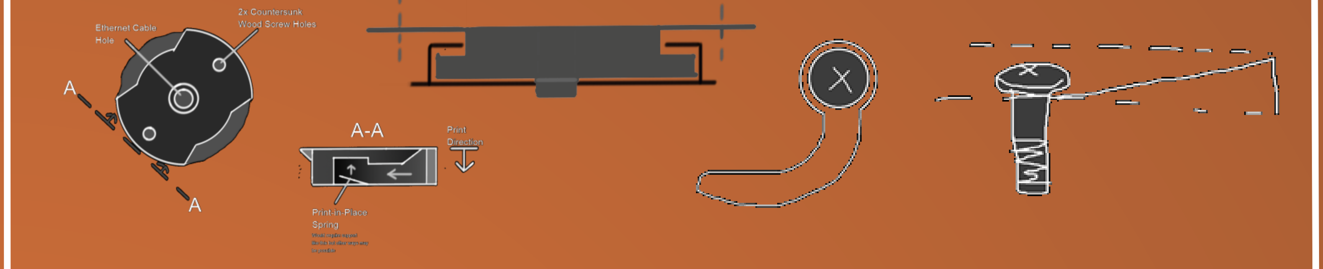
- All ports are on the back of the router which prevents it from being mounted to a surface without extruding far from the surface
- Large retractable legs which may prevent the router sitting flat on a surface
- No wall-mounting capabilities whatsoever
- A power socket and USB socket in the back
- When powered, several indicator LEDs light up on the front panel
- WPS, Reset and Power buttons are present on the top of the router
- 1 WLAN and several Ethernet ports are on the back of the router

❑ Inspection of device for useful features
  - Several ports but all facing in the wrong direction
  - LEDs available on the front panel

❑ Step-by-Step disassembly
  - Draft a disassembly procedure (including possible mounting methods i.e bolts, clips, adhesive)
    Some devices might be assembled through press-fit or other single-use clip mechanisms that can be damaged. Sometimes these can be easily replaced but occasionally, for devices that are not meant to be taken apart, donor devices might need to be sourced which can be damaged in the reverse engineering process
    Use appropriate tools (we used guitar picks and fingernails to open the router)
  - Add discovered features to a list. Details on detected PCB mounting methods, device assembly and component design explained in 'Re-applicable Features & Parts'
    - ❖ LED translucent panel to disperse the point-light from LEDs
    - ❖ Stiffening structures on large surface areas.
    - ❖ Position locking stand-offs
    - ❖ PCB mounting screws

❑ Design Procedure selection
  - Looking at the gathered feature list, the following design list was gathered:
    - ❖ Single cable communication and power isn't available
    - ❖ No suitable ceiling/wall mount
    - ❖ Available power button
    - ❖ Available Ethernet and power interfaces which needs to be modified
    - ❖ Re-use front panel but rear case needs to be redesigned the wall mount
  - Develop an understanding based on hypothesis for the different solutions found in Device-under-Test (DUT).
    - ❖ Significance of 'ribs' on front and back panels
    - ❖ External button mechanism
    - ❖ Extendable legs mechanism
    - ❖ Ventilation solution
    - ❖ Methods behind keeping the DUT sealed/closed
  - With these elements identified, they corresponding parts can be removed as the new design will not have all the features of DUT hence there is no need to re-model them into the new design
  - Model re-applicable elements in CAD. Measurements carried out with Vernier calipers and a ruler. These will be used as reference for any newly designed parts.

The Design Process:
The engineering process described above highlighted the need for a new design for the back case to include a mounting mechanism. Below are the different concepts that the team came up with:
Twist and lock mechanism (left - implemented) *Rails and clip (centre - not ideal for printing)* *Gravity held twist and lock (right - less practical)*



Subsequently, advantages and disadvantages of each set of designs were weighed up, and features selected from each. A mechanical lock was labelled as a valuable health and safety feature as it can prevent the WAP from falling off the surface. The first two design offered a lockable solution however the second one could struggle with smooth surface area inside the guide rails. This enabled a more detailed design to be produced using CAD software, before testing and evaluation (through physical prototyping and observation), and finally a redesign to incorporate changes.

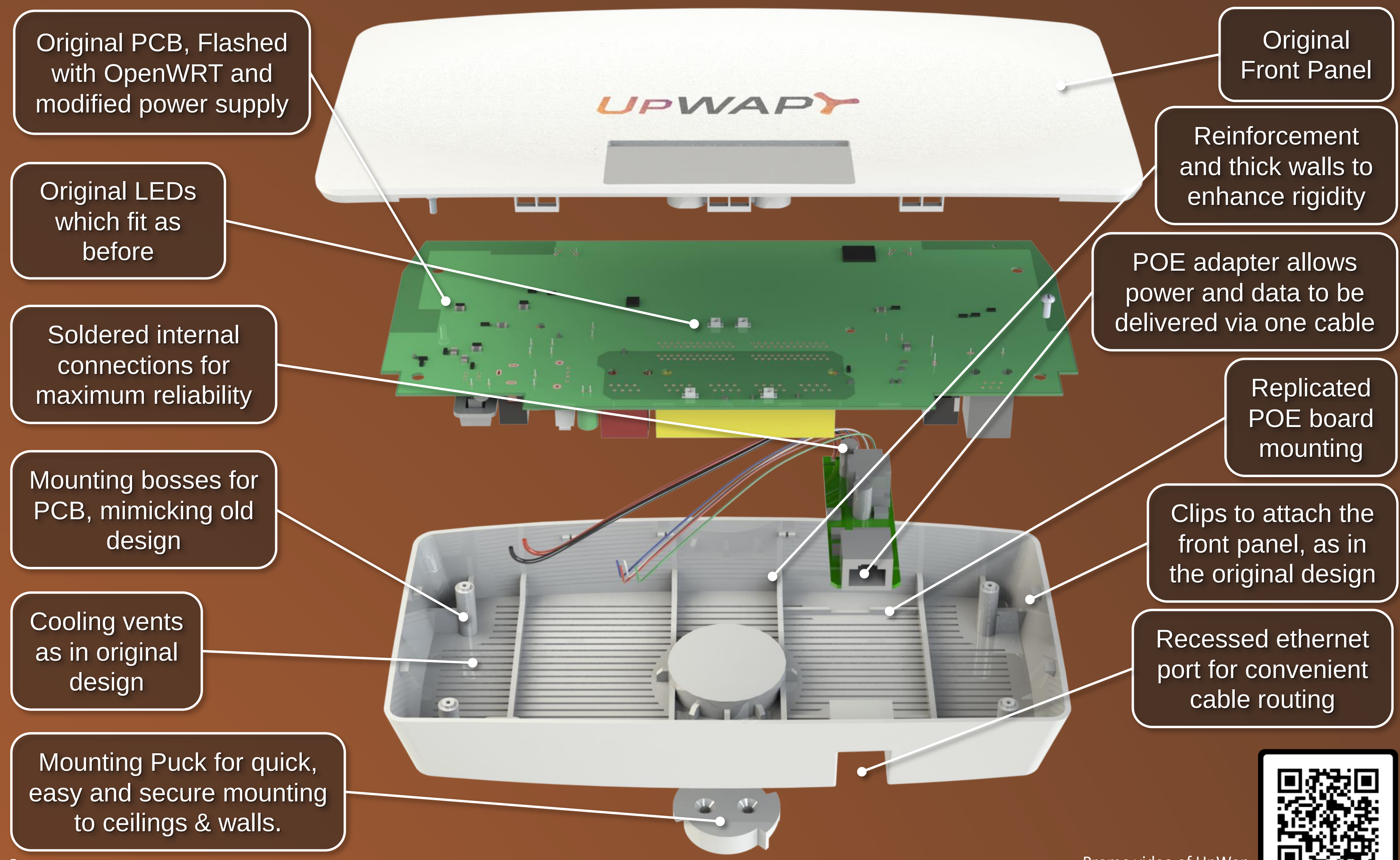
Upcycled Product Design

After gathering information on the existing product, mounting mechanism design and project plan, all of these components are assembled together. The front panel was modelled with CAD to ensure the new components fit with the re-applicable parts. Information on mounting methodology, the dimensions of screw holes, the spacing etc. was used to generate a new back case which now fits both the main PCB and the PoE board. The re-applicable front panel allows for clear LED visibility as seen in Figure 2.

The main PCB in the original design is held by 2 screws as shown in Figure 3. This mounting method provides a solid fit and hence a similar method is used to hold the PCB in the new case (Figure 1). The PoE board mounting points were inspired by its original packaging as shown in figure 4. The board rests on 4 ribs holding each corner and is sandwiched between 2 cover pieces however in the new design, it's a press fit using the existing corner slots.
Cables from the PoE board are routed to pin holes left after de-soldering the power socket and WAN (Wide Area Network) port. The pinout has been tested against Fast-Ethernet RJ45 socket datasheets to ensure correct connections.
Inside ribs of back case have been strongly inspired by the ones in the original device and so were the vents. These haven't been changed much on purpose as without extensive FEA simulations on exact CAD models with the same material properties it is hard to obtain an accurate stress simulation. As a result, the design that has proved successful with the original design, will be used. The case also has a socket for the Power Ethernet plug which is all that is required for proper device operation as visible in Figure 6.
On the back of the case, the mounting mechanism is visible alongside the corresponding wall mount. Principle of design can be seen in Figure 1 where the back case contains the receptacle and the element mounted to the ceiling acts like a plug. The router is slid onto the mount, twisted and locked with the visible hooks. To dismount the WAP, the device needs to be pressed against the mount to disconnect the hooks and twist in the opposite way. Both elements have undergone FEA simulations to ensure sufficient tensile strength (illustrative results are presented in Figure 7)

Purposeful Omissions

Several features that are undesirable to add or carry forward to the new design including 4 additional ethernet ports, which whilst accessible on the original product would simply complicate the upcycled one (significant soldering required to reorientate and reposition them), vastly increasing manufacturing costs without significant usability improvements; whilst they would allow for daisy chaining of WAPs, a similar setup can be achieved using an ethernet switch.
Lack of external button interface; whilst they could be used for additional functionality, they were deemed as unnecessary and the complex assembly required to allow for their use would increase the price and complexity of the manufacturing process.
The removal of the ADSL connection was easily justified, as WAPs do not need access to a WANs, and access to the USB port was removed since it was deemed unnecessary for the straightforward function of a WAP. Finally, the feet were removed as they hinder mounting ability and stick out, potentially snagging on passing objects/people.



Promo video of UpWap and its mounting mechanism

SCAN ME

Figure 1 – An exploded view of the final assembly.

Evaluation

The router used for this project, the Plusnet Hub One, is widely available second hand as it is now end of life. The PCB in the BT Hub 5A is identical to that in this router, therefore it would also make a good candidate for this project. Table 2 contains a list of some comparable commercial options, while Table 3 contains a full cost-breakdown of this product.
It is clear to see that the cost of UpWAP is significantly less than any commercial solution, and if manufactured on a large scale, it could be reduced further. This makes UpWAP a compelling alternative.The design itself is realistic; being easily printable with limited post processing required to produce a fully featured and user-friendly new product. The new casing is carefully designed, fitting new circuitry and mounts in a small space, whilst allowing for quick and easy assembly, as would be required to save manufacturing and material costs if commercialised.
Finite-Element simulations show that the casing and mounting is more than adequate to cope with the WAP's static weight and therefore it is unlikely that the WAP is at risk of falling on someone and injuring them. Some further testing may be required before commercialisation, since in reverse engineering uncertainty presents itself, where functionality of all original features isn't always clear, load bearing limits of structural elements are unknown, and introduced functionality is unproven and not guaranteed to work reliability on the original hardware.
A further uncertainty and significant challenge in reverse engineering this product was obtaining accurate dimensions to design the new casing around. Since the original front and rear plates are made up of compound curves, modelling them would be easier, much quicker, and more accurate using a 3D scanner. On a similar note, additive manufacturing tolerances resulted on a need for notable post processing and re-dimensioning of parts that would otherwise fit as desired.
A final noteworthy challenge that was faced in the manufacturing involved the de-soldering and replacement of PCB components, which without professional equipment and experience was a tricky and time consuming task; this would be greatest limitation in commercialising this upcycled product.
The product is designed such that all added components are recyclable/biodegradable; electronics can be removed by undoing just 2 screws then recycled, and the new back of the casing is printed using PLA allowing it to be composted. The front of the case, which uses an ABS/PC blend, can also be recycled. The old, unused rear casing section is also the same material so can be recycled at the manufacturing stage. Some difficulties may arise in recycling certain electronics components, which is one of the reasons for this project to begin, therefore further suggestions may be made as to how to extend the electronics life further, e.g. reuse as a file server.

Table 2 – List of some popular commercial dual-band access points with active POE for comparison.

Access Point [3]	Cost [3]
TP-Link EAP225	£66.48
ZyXEL Cloud AX1800	£69.99
NETGEAR WAX214	£93.50
Cisco WAP121-E-K9-G5	£99.00
Ubiquiti UBI-UAP-AC-PRO	£137.97

Table 3 – Bill of Materials & Cost breakdown. Assuming £20/kg of PLA, that a total of 109g was used, a fixed cost per print of 30p and a cost of 2p per 5 min.

Part	Purchase Cost	Material Cost	Manufacturing Cost	Total
Router PCB Original Front Panel 2x Original Screw	£3.00	-	-	£3.00
POE PCB	£6.73	-	-	£6.73
Rear Casing Mounting Puck	-	£2.18	£1.98	£4.16
Overall Total				**£13.89**

Figure 6 – The completed product, acting as an access point while powered over ethernet.

Re-applicable Features & Parts

Existing Components

The PlusNet router's housing consists of a front and rear section, both of which are likely made from plastic injection moulded ABS. In both cases, a number of smaller parts are attached to serve different functions, for example the light disperser is attached to the front panel using plastic heat-formed rivets. Given the wall/ceiling mounted nature of the access point, it was determined that the feet on the rear of the case were no longer needed, but that it would be desirable to keep the activity and power lights on the front. In addition, there was found to be more room in the rear of the case for mounting the POE board, and the clips in the rear of the case would be simpler to manufacture using additive methods as they don't have far-reaching protrusions. For these reasons, it was decided to keep the front panel and re-design the rear panel to assemble them in the same way as the existing router. This has the added benefit of providing a nicely finished look to the device which could have been difficult to achieve using additive methods.

Housing Clips

The two bodies that make up the existing housing have a number of integrated snap-lock clips, made from the same material as the bodies themselves. The principle for all these clips is the same – the elasticity of the material is utilised to prevent separation after the parts have been forced together. Chamfers are used on either side of the clip to allow them to easily slide over each other in one direction, while faces normal to the fitting direction prevent un-clipping without a large amount of force.
While this fastening technique saves weight, cost, and assembly time, it does make the item considerably more difficult to open without damage, and consequently more difficult to reverse-engineer and modify. In this case, while four of the clips were damaged beyond use, the remaining 9 were deemed sufficient to mount the two components together. Clip type A and B, shown in the diagram below, appear to be the main clips used to hold the components together, while clips C and D are seem to be less crucial and may only be needed to prevent rattling. This conclusion was drawn as clip types C and D both have a much weaker construction and are therefore are likely designed to take less load.
The new rear case is designed to make use of all clips by mimicking the geometry of the existing design.

PCB Mounting

In the router, the PCB was fastened using two screws, while the it sat on a further four locating bosses. Bosses on the front of the case then clamped the PCB to the rear of the case as the two parts were snapped together. Figure 3 demonstrates the location of the two fastening mechanisms. While the four locating bosses are retained in the new design, the two centre bosses through which screws held down the PCB were removed to make way for the POE board. This was deemed reasonable because access to all the ports on the main PCB has been entirely restricted and this would have been the only way to apply excessive force to it under normal use.
In a similar way, the PCB in the POE splitter is sandwiched between the two halves of the housing which are held together using snap-lock clips. It is retained in the planar direction using four ribs which slot into cut-outs in the PCB. In the new housing, a similar approach was used to locate the PCB and this is demonstrated in Figure 4.

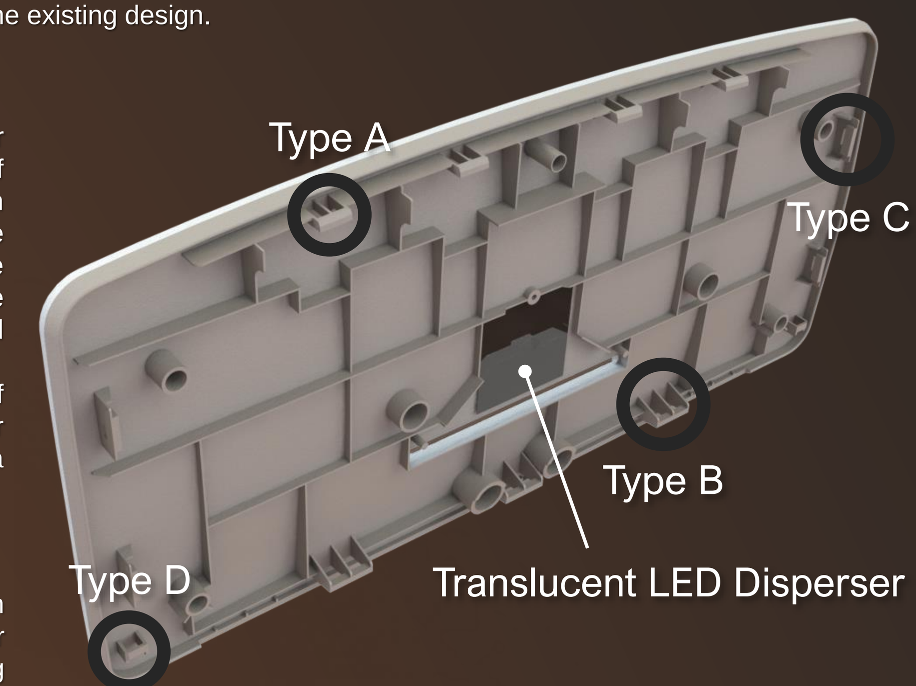


Figure 2 – A CAD model of the front panel

Reinforcement

Both the front and rear of the Router's casing has substantial reinforcement in the form of ribs and fillets, and the compound curves that form the shells of the parts add to their rigidity. Therefore it was important to consider the strength of the redesigned casing and add suitable reinforcement, notably to the bosses which are vulnerable to snapping.

Cooling

The router's back casing was almost entirely covered in louvred vents to aid cooling of the processor by convection, therefore it was assumed that a similar quantity of cooling holes would be required in the new design. However, it was chosen to have the vents pass straight through rather than have them louvred because the FFF manufacturing method would require a substantial amount of supports, adding to the time, cost and post-processing work for the part.
Although the WAP is designed to mount to ceilings and walls, the retention mechanism used means that there always will be an air gap between the surface and the back casing, ensuring that air can flow into and out of the case.

Figure 3 – The original back casing with PCB mounting points circled in red and blue, highlighting areas where the front panel and screws clamp the PCB respectively.

Power-Over-Ethernet

Power over Ethernet enables the powering of a device through an ethernet cable. Commonly used in commercial and enterprise equipment, it is desirable because it removes the need for outlets at each node.
The Plusnet Hub One requires around 7.5W [6] of power at 12V DC, and given that most 'Passive' POE implementations are incompatible and can damage hardware when plugged into the wrong devices, it was decided that an 'Active' POE solution was needed, especially given the home setting of the target audience. Here, it was chosen to use the IEEE 802.3af standard as this can supply about twice the required power and is the most widely used [7] and therefore is compatible with many other devices.
Given the 'Active' nature of the power delivery, a secondary 'POE Splitter' board was purchased to separate the power and ethernet lines, which were later soldered directly to the main PCB. When used in conjunction with a POE injector and a test network, the implementation was found to work flawlessly. Figure 4 shows the POE board in its original casing and in-situ in the new case.

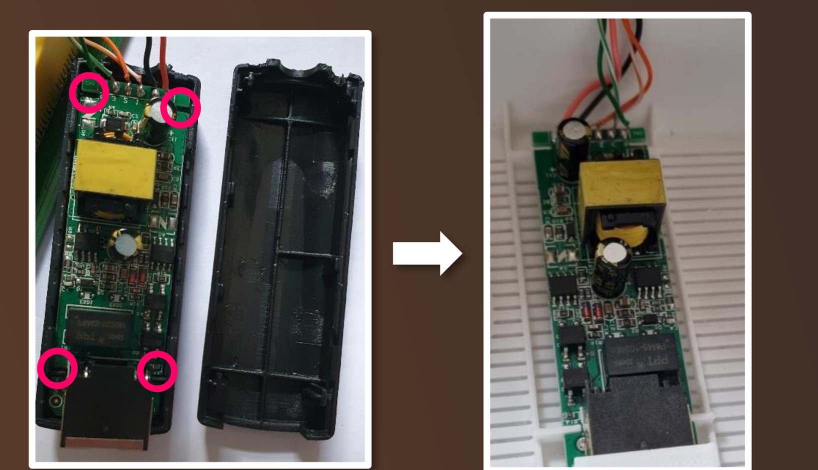


Figure 4 – The original POE casing with PCB (left), and the POE PCB mounting in the new case (right).

OpenWRT Installation

The stock Plusnet Hub One comes with restrictive proprietary firmware which is designed to be easy for the average user to configure. For more configuration options, namely the implementation of IEEE 802.11r which is a fast-roaming/transition protocol designed for use in networks with multiple access points[4], OpenWRT was installed by soldering a connection onto the TTL UART interface and connecting to the device from a computer using PUTTY. To configure the device as an access point, the DHCP server was disabled, a static IP was set, and the relevant wireless and security settings were enabled. For the installation and setup processes, an existing guide was followed [5], and pre-made software tools were used [5].

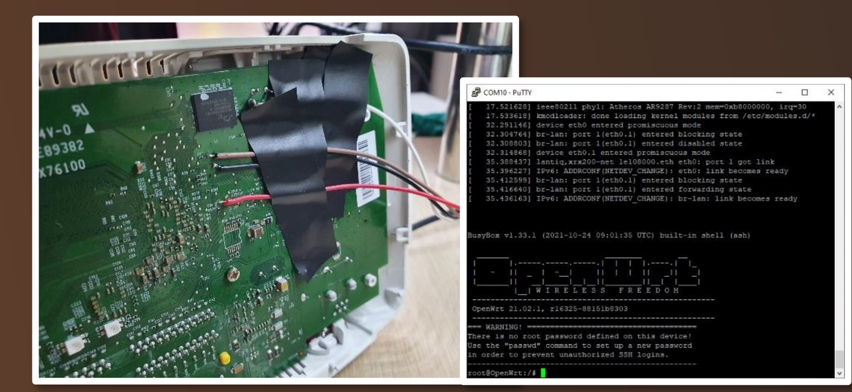


Figure 5 – Connected to the serial TTL UART interface on the router. Using this, OpenWRT was installed (serial prompt shown to right).

Health, Safety & FEA

Several health and safety considerations were made throughout the design of the upcycled product to ensure a reliable, user friendly, and safe experience. For instance, significant time was spent developing a mechanical locking mechanism for mounting to prevent accidental detachments for ceiling or wall mounting. In addition, great care was taken to prevent risks of shocks, or damage to the electronics by shrinking gaps in the casing, shortening wires so they're held in place within the casing, and carefully mounting circuitry such that no conductive elements touch the casing. No sharp edges are used either to limit risk of injury in the case of a knock. Finally, FEA was carried out on the redesigned case and mount to ensure a safe, secure hold and identify any weak points. Figure 7 shows the results from these analyses.

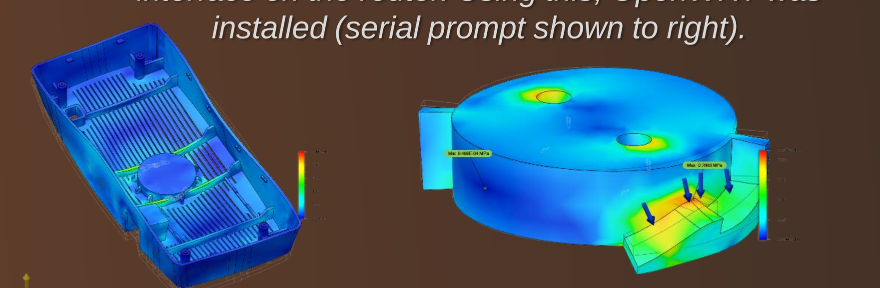


Figure 7 – FEA results on the housing and mounting puck.

UPWAP

MECH3775
Coursework 2:
Reverse Engineering

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OpenWrt WIRELESS FREEDOM [1]

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