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Supporting Sustainable Computing by Repurposing E-waste Smartphones as Tiny Data Centres

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Abstract—AI, data science, and other computing domains are fuelling an unprecedented increase in the demand for computing power. Satisfying this demand, however, brings significant environmental challenges as computing is energy-intensive and devices improve rapidly making older devices obsolete and resulting in a significant accumulation of e-waste. We contribute by examining the potential of repurposing smartphones classified as e-waste as small-scale data centres with the aim of extending the life-cycle of these devices, thus reducing e-waste accumulation and contributing toward more sustainable computing practices. We demonstrate how hardware features can be bypassed to enable reprogrammability at a cost of approximately 8€*. We use our prototype to implement a custom sensor data collection and analysis solution. We also showcase possible applications, highlighting the range of scenarios where re-purposing can be useful, as well as identifying challenges and potential future avenues for research. These include development of better tools to facilitate the re-purposing process and development of tools that are agnostic of the underlying hardware characteristics.*

Demand for computing power shows no signs of abating as artificial intelligence (AI), data science, and other computing domains continue to fuel the demand for computing power. In parallel, devices generate significant amounts of data, which requires ever-faster processing. Satisfying this growing demand for computing requires constant and significant investments to ensure that the sufficient power can indeed be available. This brings significant challenges for the sustainability of computing as devices are replaced frequently, with modern computing devices typically having a lifespan of $2-3$ years before becoming obsolete. This results in *significant*

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accumulation of e-waste as devices that are replaced are simply thrown away or broken down for minerals. Indeed, current estimates suggest the amount of e-waste will more than double by 2050 unless changes are made in the computing ecosystem [1]. If the device life cycle could be extended, this would result in significant savings in natural resources, help cut costs, and improve overall sustainability of the environment.

We contribute by demonstrating how e-waste devices, in our case obsolete smartphones, could be repurposed as *tiny data centres* that support localised data processing, e.g., by serving as edge or fog nodes for other devices [2]. This can bring significant benefits as, among others, it helps to extend the life cycle of devices, conserve natural resources, reduce the environmental impact of computing as a whole, save money, and promote a circular economy for computing hardware. Existing research has mostly focused on improving recycling practices [3], but this alone is not sufficient due to recycling being labourious and energy-intensive. Repurposing the devices can offer a complementary solution that can further improve resource usage.

We focus specifically on the idea of harnessing these devices as *tiny data centres*, which offer an opportunistic solution that can support the processing requirements of new and existing real-world applications. A tiny data centre is built by extracting the computing units from the original device designs, aggregating different computing units into one, and possibly bypassing their battery resources so that alternative power sources can be used instead. We first present application ideas for tiny data centres and discuss how different kinds of e-waste can be used to satisfy their demands. We then demonstrate the feasibility of tiny data centres by reporting on experiments where obsolete Nexus smartphone devices are repurposed. We also showcase encountered challenges as well as potential future avenues for research. These include the development of better tools to facilitate the repurposing process and the development of tools that are agnostic to the underlying hardware characteristics. Our work paves the way towards increasing the lifespan of outdated devices while promoting sustainable deployment practices for computing resources.

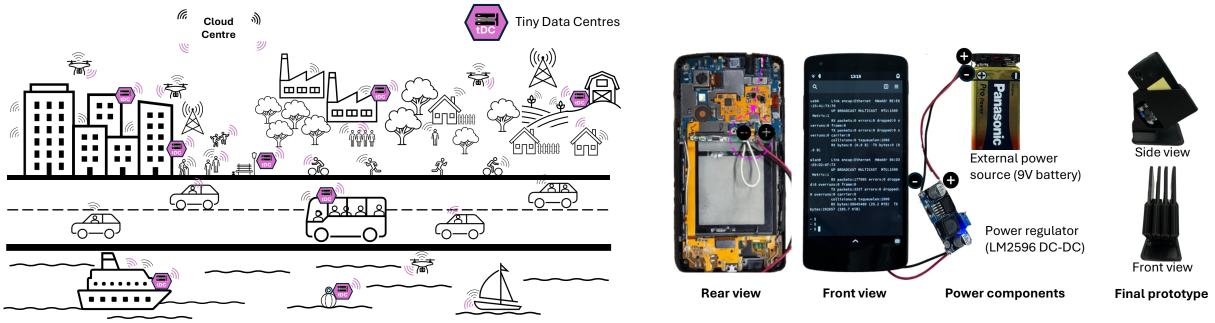
Emerging applications

Tiny data centres have the potential to enhance the processing capabilities of various applications, influence the design of existing applications, and enable new designs to utilise more sustainable energy sources. Below, we outline potential benefits of employing tiny data centres constructed from deprecated devices across different application areas. The computing demands of these scenarios vary, and we do not suggest that any obsolete devices can simply be transformed into tiny data centres that support these applications. In practice, the devices must possess the appropriate resources, particularly for the most computing-intensive applications, while other scenarios may utilise any devices that are no longer required for their original purpose. Figure 1 (a) illustrates our vision of repurposing e-waste smartphones as tiny data centres capable of supporting applications in any environment.

Autonomous vehicular applications: Tiny data centres can be seamlessly integrated as payload for a range of vehicular and drone-based applications. Ground vehicles can benefit the most from tiny data centres, as moderate payload does not introduce extra overhead in their operations [4]. Aerial and underwater vehicles leverage limited data bandwidth offloading and require a more careful assessment for additional payload augmentation [5]. Extra payload in these applications can influence the stability of the vehicle for navigation, which can lead to crashes and unexpected behaviours. Once integrated into the vehicles, tiny data centres can support new innovative applications, such as software delivery as a service (DaaS) and mobile infrastructure on demand, as well as data retrieval from deep ocean lander observatories [6].

Pervasive computing and IoT applications: The inherent characteristics and design of mobile devices facilitate the embedding of tiny data centres in a variety of everyday pervasive computing and IoT applications. This integration makes possible the development of more intelligent and interactive applications. For instance, toys and inanimate objects can be equipped with tiny data centres to promote better interactions and usability with users [7]. Likewise, the latest developments in cost-effective 3D printing technologies are rapidly enhancing rapid-prototyping deployments, making them more creative, artistic, and user-friendly. Tiny data centres can be easily encased into 3D design to support diverse computing demands and complexity of 3D printing applications, e.g., a 3D printing weather station [8].

Edge and fog computing applications: Tiny data centres can streamline the deployment of computing resources, optimising the availability of the cloud-edge continuum. Edge computing can leverage these tiny data centres to increase deployment density by strategically situating them in urban locations. Since these centres are composed of obsolete devices classified



(a) Deployment of repurposed e-waste as Tiny Data Centres (tDC)

(b) Use case prototype: Powering and assembling

FIGURE 1. Tiny data centres: (a) Vision of tiny data centres deployment. (b) Use case example of a tiny data centre prototype using 4 smartphones and a common power regulator.

as e-waste, they present minimal security concerns; if necessary, the devices can easily be replaced with other repurposed hardware. For instance, they can be deployed near bus stops or parks to conduct privacy-preserving crowd counting, providing valuable decision-making insights for city authorities [9]. Furthermore, tiny data centres can serve as intelligent proxies or gateways, facilitating autonomous interconnectivity for a range of multi-device applications. These applications include collaborative computing and sensing, coordinating autonomous vehicle navigation, and enabling federated learning for the training or inference of simple AI/ML models.

Renewable-by-design applications: Tiny data centres can be aggregated on demand to form robust processing infrastructures that support applications requiring dynamic deployments. This modular approach exemplifies renewable-by-design principles, as it allows for scalability and adaptability to meet changing needs while optimising resource use. A key consideration for these applications is the energy supply, which plays a crucial role in reducing carbon emissions. By integrating energy harvesting solutions—such as tidal or wave energy for underwater installations and wind power generated by vehicle acceleration for remote or urban deployments—these data centres can harness renewable energy sources effectively [10]. Additionally, sustainable energy solutions like solar harvesting and advanced battery systems can be employed to ensure continuous operation, aligning with the vision of renewable-by-design. The design of the data centres and their hosting structures must also prioritise sustainability to minimise the carbon footprint. For instance, the racks or casings for tiny data centres can be constructed from renewable materials, such as solar panels and magnolia wood, which is known for its durability in harsh conditions and is commonly used in space applications. The choice of materials can thus also promote a circular economy by utilising resources that can be replenished or are less harmful to the environment.

E-Waste to Tiny Data Centres

Transforming mobile phones into tiny data centres requires assessments of to what extent processing resources from mobile phones can be extracted to supply them with alternative energy sources other than the lithium battery. In the following, we describe our experience with processing resource extraction, showing a technique that can be used for bypassing the battery.

Old Phones: Four unused and operational Nexus 5 smartphones (LG-hammerhead) were used in the experiment. Their specifications included a 4.95-inch display with a resolution of 1080 × 1920 pixels and a pixel density of 445 ppi. They were equipped with a Qualcomm Snapdragon 800 processor (MSM8974) with four cores clocked at 2.3 GHz and an Adreno 330 GPU. The devices have 2 GB of RAM and 16 GB or 32 GB of internal storage available. The Nexus 5 has a 2300 mAh battery that supports fast and wireless charging. The Nexus 5 runs on Android 4.4 KitKat, the first Android version to support 64-bit architecture.

Apparatus: The LM2596 DC-DC module is employed to bypass the battery. Alternatively, for supplying energy to multiple mobile phones simultaneously, we utilise DFRobot DRF08x Fast Charge Buck modules. These modules support various input voltages from 6V to 32V and output different voltages from 3V to 12V (default 5V). Acting as a router to interconnect the mobile phones, we employ the GL-SF1200 AC1200

Wireless Gigabit Router.

Battery Bypassing: To remove the battery, we dismantled the outer plastic layer and inspected the small circuit board between the battery terminals and the phone. The phone connector featured four metal contacts: two larger ones for power (positive/negative) and ground, and two smaller ones for data and clock signals, like I2C, a serial communication protocol. To power the phone (3.8V), we connected the battery circuit's positive and negative wires to the output of an LM2596 DC-DC power supply, with a 9V battery.

Processing: To exploit the processing resources of interconnected mobile phones, first, all phones were rooted. After this, PostmarketOS was installed in each Nexus 5 using ADB (Android Debug Bridge) command line utilities. ADB grants access to the Unix shell, allowing the execution of a diversity of commands. A leader/worker architecture is adopted to test incremental gains in processing capabilities as different old phones are combined.

Benchmarks: We rely on the High-Performance Computing (HPC) challenge benchmarks to evaluate the performance of phones acting as an underlying computing infrastructure. Four benchmarks are used for comparison. The first, *HPL* (High-Performance LINPACK), measures the floating-point rate of execution of solving a dense system of linear equations using the High-Performance Linpack (HPL) library. Performance is typically measured in GFLOPS (Giga Floating-point Operations Per Second). The second, *Stream*, measures the sustainable memory bandwidth of a system by performing four simple vector kernels: Copy (simple data copy), Scale (multiplication of each element by a scalar), Add (addition of corresponding elements of two arrays), and Triad (a combination of scale and add). Performance is reported in GB/s (GigaBytes per second). The third, *Random Access*, measures the rate of integer random updates of memory, measured in Giga Updates per Second (GUPS), by performing a table update using a random address stream. Finally, *FFT (Fast Fourier Transform)* measures the floating-point rate of execution of a double-precision complex one-dimensional Discrete Fourier Transform (DFT) using the Cooley-Tukey algorithm. To obtain a baseline reference for comparison, we also run the same four HPC challenge benchmarks with a Raspberry Pi 4 Model B and an HP EliteBook 840 G5.

Results: Table 1 shows the results. From the table, we can observe that mobile phones have the lowest LINPACK score among the three devices, even when running a custom operating system (PostmarketOS) that outperforms the default Android OS. The Raspberry Pi has about five times the LINPACK score of the Nexus 5, and the HP EliteBook 840 G5 has about 15 times the LINPACK score of the Nexus 5. This shows that the Nexus 5 mobile phones have much lower processing power than the Raspberry Pi or laptops, which may limit their ability to handle compute-intensive tasks. This is also in line with the results obtained using the FFT score among the three devices. This suggests that old phones can be reused to perform computing tasks that are not bound by a time constraint, meaning that they do not require a real-time response.

Proof-of-Concept Demonstration

We next demonstrate the feasibility of utilising a re-purposed mobile phone to support the processing of IoT applications. We have developed an IoT application comprising a sensor node for data collection, an edge node (re-purposed mobile phone) for pre-processing, and a cloud dashboard (ThingSpeak) for visualisation. To thoroughly evaluate the efficiency of the edge node, we have implemented a separate server featuring InfluxDB and a Grafana dashboard. This setup allows us to analyse and optimise the performance of the edge node effectively. Both the sensor node and the edge node are connected to a WiFi network with internet access.

Sensor Node: The sensor node is composed of several components, including an ESP32 board, which serves as the central processing unit. Additionally, it incorporates a DHT22 digital temperature and humidity sensor for environmental monitoring and an APDS-9960 RGB sensor for capturing lighting condition data. The ESP32 board is responsible for the data collection process. It reads data from each sensor at 10-second intervals and then uploads it to the edge node for further processing and analysis. This setup enables real-time monitoring and analysis of environmental conditions, facilitating various applications such as smart home automation, industrial monitoring, or environmental sensing.

Edge Node: The edge node serves as a computing unit, utilising a re-purposed mobile phone to execute various computational tasks within the IoT framework. We have developed a Python web server application to facilitate data management and processing. This application functions as the intermediary between the sensor nodes and the cloud dashboard, orchestrating information flow between them. Upon receiving data from the sensor node, which includes streams for temperature, humidity, and RGB values, the edge node computes each data stream's average value

TABLE 1. HPC benchmark performance of different devices.

Devices	RAM (GB)	Chipset	OS	HPL (MFlops)	FFTE (MFlops)	STREAM (MB/s)	RandomAccess (GUPs)
Nexus 5 (1)	2	Qualcomm Snapdragon 800	Linux 3.4.0	162.7	10.6	2.99E-06	0.0070805
Nexus 5 (2)	2	Qualcomm Snapdragon 800	Linux 3.4.0	164.7	10.7	2.95E-06	0.0071716
Nexus 5 (3)	2	Qualcomm Snapdragon 800	Linux 3.4.0	163.6	10.7	2.98E-06	0.0070918
Nexus 5 (4)	2	Qualcomm Snapdragon 800	Linux 3.4.0	164.1	10.8	2.90E-06	0.0007049
Raspberry Pi 4 Model B	4	Cortex-A72 processor	Raspberry Pi OS	837.7	49.7	1.24E-05	0.0432023
HP EliteBook 840 G5	8	Intel Core i5-7200U	Ubuntu 22.04	2468.5	79.7	4.27E-05	0.1033035

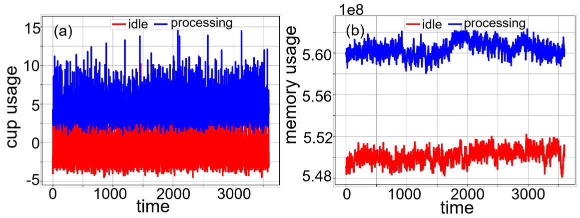


FIGURE 2. Mean CPU and memory usage.

at one-minute intervals. These calculated averages are then promptly uploaded to the designated cloud dashboard hosted on the ThingSpeak platform. To enhance the system's functionality and responsiveness, a specialised feature has been integrated specifically for the temperature data stream. In instances where the temperature exceeds a predefined threshold, such as 80℃, the system triggers an alarm mechanism. This alarm promptly initiates the transmission of notifications, alerting relevant stakeholders to the observed deviation from normal operating conditions.

To evaluate the performance of the edge device effectively, we rely on the Telegraf agent installed on the edge node and the InfluxDB server residing in the cloud. We use a Docker container housing the Telegraf agent on the edge node, demonstrating the adaptability and versatility of the re-purposed devices. Telegraf, operating within this containerised environment, gathers an extensive range of system-wide metrics, providing a comprehensive understanding of the edge device's behaviour and performance. Telegraf seamlessly transmits these metrics to the InfluxDB server at regular 1-second intervals, facilitating real-time monitoring and analysis of the edge device's performance characteristics. During our experiments with Telegraf, we primarily gathered data on CPU and memory usage both in idle states and while allocating computing resources for the IoT application.

Edge Node Energy Consumption: To guarantee proper voltage and current readings, we also investigated power consumption with an external battery instead of an inbuilt phone battery. Most of the time, discarded mobile phones have defective batteries and are also vulnerable to damage to the phone itself. Therefore, it is essential to remove the inbuilt battery and use alternative power sources when re-purposed devices are used. However, this is not trivial because most mobile devices have special circuits that control the phone's power supply. With the re-purposed Nexus 5 phone, we removed the inbuilt battery and connected the phone's battery terminals to the external DC power supply unit, see Figure 1 (b). Since the mobile phone needs only 3.5-3.7 V to power on, our external power supply unit consisted of an LM2596 DC-DC power regulator and a 9V Panasonic battery. Once the power supply unit was connected, the phone was turned on, and we ran the same experiment, albeit with only the weather station application without Telegraf, until the battery was fully discharged. We noticed that the mobile phone shut down after 3 hours and 40 minutes. At that point, the battery voltage dropped below 4.8V, which was most likely caused by either a calibration error of the LM2596, which does not provide sufficient power supply below that voltage level.

Results: Results for processing sensor data using our reused mobile phones are shown in Figure 2. We gathered CPU and memory usage data for one hour in both an idle state and while the IoT application was running. The application receives data from sensors every 6 seconds. The average CPU usage during application runtime was 4.13% (compared to 4.0% during idle), and memory usage was 534.4 MB (compared to 524.6 MB during idle). The mobile device has a total of 2 GB of RAM. When running on the external battery, the system was able to process data for 3 hours and 40 minutes. It processed approximately 2400 samples from sensors, totalling 12,000 data items (2400 samples multiplied by 5 data streams from sensors).

E-waste: Re-purposing and Recycling of components

Mobile Phone Contribution to E-waste: A mobile phone has a lifespan of 3.17 years, while the average household appliance has a lifespan of 3.65 years [11]. The main reasons for mobile phone disposal are physical damage, malfunction, lack of additional features, or outdated capacity [11]. Mobile phone disposal represents a significant portion of the e-waste problem [12]. It is mainly caused by single-use and out-of-life batteries. Mobile phones use lithium-ion batteries, which last about two to three years before their capacity drops below 80%, at which point they are recommended to be replaced or disposed of. However, this can be costly, risky, and harmful to the environment, as batteries contain toxic substances that can pollute the soil and water or cause fires and explosions [13]. Our work addresses the reuse of the computing units of mobile devices, and additional solutions, such as battery recycling, are also required to mitigate the harmful effects of e-waste.

E-waste Reuse and Recycling Practices: E-waste recycling involves extracting valuable materials, such as gold and precious metals, from discarded devices. Programs like MobileMuster in Australia, which collects old mobile phones through volunteers, help facilitate this process [11]. Despite awareness campaigns about the harmful effects of e-waste, they often do not translate into improved recycling behaviours [14]. While mobile phone recycling is being leveraged, reuse is a key aspect of sustainability, as it extends the lifespan of old phones through donation or resale. Repairing mobile phones is also part of reuse, as it aims to prolong their life. The mobile phone repair industry is growing, with a value of USD 1.3 billion. However, certain models, with complex features like soldered components or proprietary software, make repair or repurposing cumbersome. A 2020 study by iFixit—an online project that provides repair guides and tools for smartphones—revealed that the average repairability score for smartphones was just 4.6 out of 10, meaning most are challenging to repair, often contributing to e-waste. Modular phones, designed for easy disassembly and repair, offer a solution [15], [16]. These phones allow for component replacement and adaptation to different energy sources. For example, projects like SunCore and SunSite [17] have developed smartphones powered by solar energy. Our work demonstrates that repairing and reusing these devices may have highly beneficial uses beyond helping to reduce the burden on the environment.

Repurposed E-waste Maintainability and Performance: The processing capabilities of constrained devices are steadily increasing, with modern smartphones now offering performance levels comparable to last-generation personal computers. Compact GPU hardware is also gaining traction to enhance the performance of these devices. Smartphones are designed with cooling and optimised processing mechanisms to prevent overheating, making them ideal candidates for repurposing. Their built-in cooling features mean that additional cooling systems are often unnecessary, as smartphones are designed for mobile use. While the performance of old smartphones as tiny data centres may be limited, software optimisation and continuous advancements in algorithmic efficiency can still make older hardware viable. For example, DeepSeek's latest training and inference requirements demonstrate this potential [18]. Additionally, emerging methods like distillation offer tools and solutions to run sophisticated and small machine learning and deep learning models with a reduced carbon footprint and low processing requirements [18]. These developments further highlight the potential that tiny data centres can offer.

Long-Term Sustainability: Refurbished or recycled devices often do not match the efficiency of the latest models, which can impact their reliability. The cooling units of these devices are particularly susceptible to wear and tear, leading to decreased effectiveness. In the worst-case, this can result in more frequent component failures, while even in the best case, it may lead to thermal throttling that diminishes computing performance. To mitigate these challenges, tiny data centres should be designed with these limitations in mind, incorporating strategies such as redundancy, active monitoring, and predictive maintenance processes to ensure consistent operation. By implementing redundant systems, we can provide backup components that take over in case of failure, thereby minimising downtime. Cooling challenges can be addressed through innovative design approaches, such as partially or fully removing protective covers to enhance airflow and leveraging direct airflow strategies to maintain optimal operating temperatures. While we may anticipate a higher frequency of device failures due to the age and condition of refurbished components, the sheer volume of available devices can still make tiny data centres highly beneficial; by strategically managing these devices and implementing robust operational practices, we can harness their potential to create efficient and sustainable computing environments.

Discussion

On Modular Designs: While modular designs enable timely repairs and upgrades of deprecated devices, balancing high modularity with optimal ergonomics remains challenging. However, advancements in SLA (Stereolithography) printing may change this due to its low cost and highly detailed, precise, smooth, and durable object parts made from resin.

Beyond Disposal: Several projects and initiatives have explored alternative uses for old mobile phones. For example, smartphones have been repurposed as VR headsets using Google Cardboard. AlfredCamera is an initiative that turns old iPhones into security cameras, while LiveFrame transforms them into digital photo frames. Another approach is donating old devices for scientific computing. Apps like DreamLab and MyShake leverage their processing power for various analyses, such as COVID-19 monitoring and collaborative weather estimation [19].

Dubious Usage and User Trust: In addition to concerns about data privacy and security, users may be wary of trusting e-waste data centres due to the potential risk of spyware or other malware infecting their devices. To address these concerns, solutions could include endorsements from regulatory bodies, government institutions, NGOs, and trusted service providers.

Stakeholders: We recognise several interested parties in leveraging the repurposed e-waste. For instance, Passive Acoustic Monitoring (PAM) surveys by marine biologists, which rely on single-use batteries, can move to rechargeable Li-ion batteries with solar power, allowing for long-term acoustic and Eulerian observatories [20].

Other benchmarks: The benchmarks demonstrated that tiny data centres are effective in traditional computing tasks typically run on high-performance computing infrastructure. TDCs are not specifically designed for high-performance computing, and they have the potential to support other types of computing tasks. Future efforts should evaluate this potential further. For instance, spatial data has different processing requirements compared to traditional machine learning or artificial intelligence tasks, which predominantly involve matrix and tensor computations. By analyzing a wider range of benchmarks and data types, we can gain a better understanding of the potential and capabilities that tiny data centres can provide.

Fragmented Manufacturing Challenges: Device heterogeneity poses a significant challenge in e-waste repurposing, as varying hardware capabilities and configurations limit scalability. To overcome this, adaptable software frameworks are needed to accommodate diverse device specifications, computing power, and resource capabilities. These frameworks must efficiently coordinate task execution, optimally assigning workloads to align with each device's capabilities, ensuring that no device becomes a bottleneck. Additionally, robust security measures are crucial to protect sensitive data, particularly given the vulnerabilities associated with repurposed e-waste.

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