



Coalescent Computing

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ABSTRACT

As computational infrastructure extends to the edge, it will increasingly offer the same fine-grained resource provisioning mechanisms used in large-scale cloud datacenters, and advances in low-latency, wireless networking technology will allow service providers to blur the distinction between local and remote resources for commodity computing. From the users' perspectives, their devices will no longer have fixed computational power, but rather will appear to have flexible computational capabilities that vary subject to the shared, disaggregated edge resources available in their physical proximity. System software will transparently leverage these ephemeral resources to provide a better end-user experience. We discuss key systems challenges to enabling such tightly-coupled, disaggregated, and ephemeral infrastructure provisioning, advocate for more research in the area, and outline possible paths forward.

CCS CONCEPTS

- Computer systems organization → Cloud computing;
- Hardware → Wireless devices;
- Software and its engineering → Cloud computing.

KEYWORDS

edge computing, disaggregated hardware, operating systems, wireless networks

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1 INTRODUCTION

We envision edge deployments (i.e., “cloudlets” [52]) that expose virtualized resources which can *transparently* augment user devices, and which can automatically scale up or down based on available resources, user demand, user proximity (network latency), available network bandwidth, and spot pricing. From the users’ perspective, it appears as if their device (laptop, thin client, or smart phone) acquires increased computational power (increased memory or disk capacity, increased CPU count, or high-end GPU) when they wander near such a deployment, for example, into their local coffee shop¹. When the user leaves the area, the resources are revoked, and the user’s device appears as it did before.

Since Satyanarayanan first laid out the basis for this vision nearly two decades ago with Cyber Foraging [5], hardware, software, and networking technologies have advanced to the point where it will soon be possible for the transparent *coalescence* of disaggregated computational resources to client machines to occur at a fine granularity and over short time scales. We call this notion *Coalescent Computing*, a type of Cyber Foraging for disaggregated hardware at the edge.

Cyber Foraging generally relies on discoverable services in users’ local environments, and on the ability to *offload* application components to remote—and generally more capable—machines [51]. This offloading usually happens at the granularity of virtual machines [24]; while the end user may be unaware of the local/remote distinction in this scenario, it is still present for the application programmer and system software. Though applications can be automatically partitioned into loosely-coupled components to make them amenable to such cloud offload [11, 29], and while VM migration can be used to ship applications to the cloud transparently [23], we believe that there is an opportunity to leverage the increasingly hierarchical and disaggregated structure of cloud resources at the edge [60, 61] to support applications that are more tightly coupled, including enhanced gaming, augmented reality (AR) [70], virtual reality (VR) [65], interactive data analysis [53], and IoT [68].

One goal of classic distributed operating system work from the 70s and 80s was to hide loosely-coupled distributed machines behind the illusion of a single, logical system (a

¹The author acknowledges that since we are currently living in a pandemic some readers might find this particular example far-fetched!

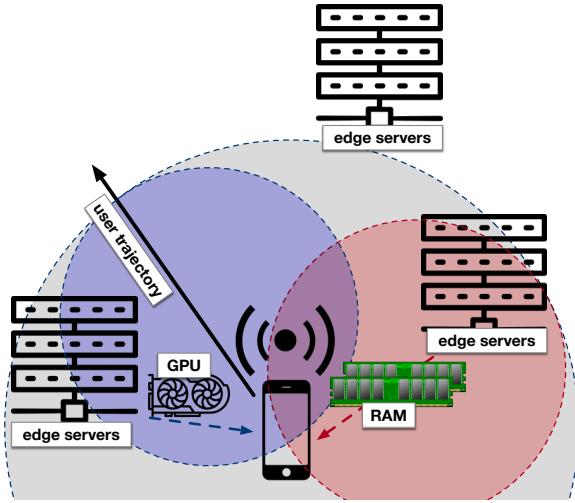


Figure 1: Coalescent Computing

single system image [9]). While commercially this did not come to pass (except for limited components, e.g. file systems), a natural question now arises: is it time to reconsider this aspiration for our modern computational ecosystem? In the datacenter, the answer seems to be yes. High-speed interconnects (e.g. InfiniBand) within the datacenter have increasingly made resource sharing between systems feasible [31, 62], for example shared remote memory [1, 15, 45, 71] or remote swap [2, 22, 49]. I/O device virtualization is becoming more sophisticated, with efficient offload enabled by API remoting [4, 16, 50], and device sharing among tenants [66]. These trends, along with hardware proposals for scale-out systems [21, 36, 43] and disaggregated hardware on the horizon [3, 12, 18, 28] point towards a datacenter that consists of loosely-coupled, disaggregated resources. LegoOS, a notable first step in disaggregated operating systems, embraces this view of the datacenter while retaining Linux ABI compatibility [55], and GiantVM demonstrates how to virtually and transparently compose datacenter resources [69].

While datacenters obviously benefit from low-latency, wired interconnects and relatively static hardware configurations, the momentum in disaggregation is encouraging for commodity computing at the edge as well, and we argue that there is a ripe opportunity for OS research to make Coalescent Computing a reality. Below we describe Coalescent Computing in more detail, discuss some of its key research challenges, and ideas for OS design to investigate the space.

2 COALESCENT COMPUTING

Coalescent Computing can be captured succinctly with the following principle:

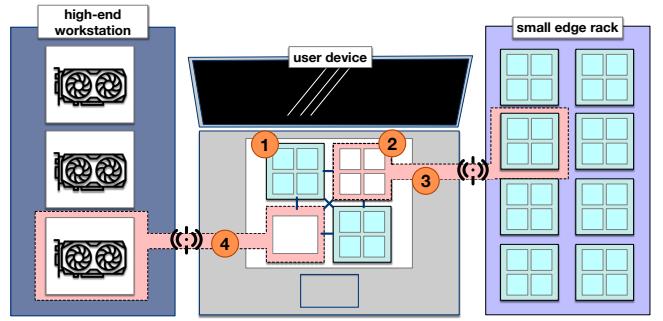


Figure 2: Coalescence of disaggregated remote cores and a GPU in the user's proximity.

Coalescence Principle: Users' devices experience a coalescence of resources proportional to proximity as users move through the physical environment.

Figure 1 depicts the Coalescence Principle at work. The number of resources coalesced into a user's device is inversely proportional to the user's network distance to the hosting machines². While in most cases those hosting machines will be stationary, in some cases, users with less constrained devices may offer their resources to nearby users, as in Femtocloud [25]. Other metrics, such as pricing, network congestion, and power budgets for the systems hosting disaggregated resources will also affect availability.

As a user navigates the physical environment, the OS on their device queries nearby resource availability, and puts in bids for resources based on current and historical system load. For instance, a user that just finished a recorded Zoom call might cause a CPU spike that triggers their OS to bid for nearby leasable CPUs to aid in video encoding. If no such resources are available, the system can either borrow resources from the traditional cloud (with a latency penalty), or fall back to local resources. Figure 2 depicts a scenario where a user is playing a CPU and GPU-intensive game that outstrips the abilities of his or her laptop. The user is in nearby proximity of a high-end workstation housing several GPUs and an edge rack that contains a collection of disaggregated CPUs. The user sees both physical resources on the local machine (1) and virtual resources from remote systems (2). To accommodate system load, the device's Coalescent OS transparently discovers, negotiates, and acquires a virtual GPU (4) and four virtual cores (3) from the rack over the wireless link. This reactionary resource provisioning is reminiscent of computational sprinting [38, 48] and JIT-provisioned Cyber Foraging [24], but it happens at the granularity of disaggregated cores and devices. Note that a corollary of the Coalescence Principle is that as users leave

²This may or may not correspond to physical distance, e.g. in wired settings.

the environment resources are relinquished and the system gracefully migrates any necessary computations or state back to the local machine, or to the cloud if WAN latencies can be tolerated.

We expect a system implementing Coalescent Computing to have the following properties:

Transparency. While users may set coalescence policies ahead of time, the system transparently acquires and relinquishes resources nearby in the environment; this is a key distinguisher from typical cloud offload. Acquisition here does not mean sole ownership of the physical remote resource, and does not necessarily imply that the user should be charged for it. For example, an idling user’s system may make resource reservations, but as long as the user is idle, the OS or monitor on the remote system is free to schedule other work. Quality-of-Service (QoS) policies and the degree of sharing can be determined by providers, and will likely change from user to user. Because users’ resource acquisition policies may be at odds with one another, and because applications have diverse requirements, policy enforcement will involve solving a challenging, multi-objective optimization problem [20] on hosts that expose resources. While there are effective techniques for solving such scheduling problems in the datacenter—for example with recommender systems [13] or reinforcement learning and Bayesian optimization [47]—in this setting user mobility will significantly affect resource availability and users’ devices may coalesce resources from different providers, rendering a centralized scheduling mechanism ineffective. One possible path forward is to combine application profiling (informing resource requests) with decentralized versions of ML-based schedulers (guiding resource grants). Thus, sets of leasable resources (servers, desktops, and possibly user devices) form ad hoc networks to run a distributed, coalescent scheduler.

The user can monitor currently “attached” resources using familiar means. For example, `/proc/cpuinfo` in a Coalescent OS exposing a Linux-like interface would include both physical CPUs on the device and virtual CPUs coalesced from a nearby edge server. Similarly, `/proc/meminfo` would show remotely coalesced pages (though sub-page granularity remote memory is a possibility [49]).

At a surface level, the OS sees the remote CPUs (and other resources) just like normal CPUs, and once they are properly initialized and booted, the OS can schedule work on them. However, the OS must take care in how it schedules work on remote resources when applications are tightly coupled, so must have some notion of resource localization (see Section 3.2). This bears some similarity to NUMA-awareness, but is more challenging given the inherent dynamism of resources whose coalescence depends on user proximity.

Performance. Users will expect their devices to be responsive. While there is more flexibility here than in the datacenter environment, the underlying technology presents more challenges too (Section 3). In particular, as resources attach and detach from user devices, it should not perceptibly affect response times.

While the single-system image abstraction is a compelling one (e.g., CPU cores come and go as the user moves around), not all applications will want to *use* those cores, since their use comes with a latency penalty. The system must be aware of the distinction between latency-sensitive and throughput-sensitive workloads [56], and must guide resource coalescence with that in mind. We believe that there is likely a sweet spot for applications that thrive in a coalescent setting. For applications with components that communicate quite often (e.g., a tightly-coupled, multi-threaded stencil code), decoupling the components will incur a significant penalty. On the other hand, loosely-coupled applications that perform bulk computations (e.g., rendering a single scene) can be sufficiently handled by offloading to a distant cloud. Thus, identifying applications that fit into this sweet spot is a primary concern.

Resilience. Though we can envision Coalescent Computing extending to wired environments³, systems will more often need to make do with unreliable wireless connections. A Coalescent OS must deal with dropped connections gracefully, for example using replication and fail-over, or by periodic checkpointing. In any case, techniques applied to achieve resilience should avoid centralized coordination given the ephemeral proximity of resources. However, some systems—for example edge servers housed in a back room cabinet—will be more static by nature, will have a constant power source, and will likely have a reliable wired connection to the internet, and thus should be weighted more heavily when choosing coordinating nodes.

Customizability. While users need not normally tend to resource coalescence policies, we anticipate that there will arise scenarios where customization will be advantageous. For example, users may set a lower threshold on battery levels at which the system discovers, negotiates, and leases resources, thus limiting power consumption by the wireless radio and by the system itself. Even if one user has a high-end laptop, he or she likely would not want another user pegging one of the CPUs when the battery is on its last leg. Other users might prefer more detailed performance tuning, for example setting thresholds on swap space using remote memory, capacity limits on leased resources, CPU load thresholds for offloading, and so on.

³For example, inductive charging surfaces seen in some coffee shops now might one day incorporate network interfaces.

Technology	Latency
SoL lower bound at 10m	33 ns
Cross-core cache-coherence	100-200 ns [30]
soNUMA (proposed)	300 ns [43]
Cross-socket (QPI)	355 ns [10]
Inter-processor Interrupts (IPI)	~500 ns [26]
PCIe Gen 3	900 ns [40]
InfiniBand RDMA (one-sided)	1 μ s [32]
WiFi 6E (reported)	~2 ms [14]
5G URLLC (reported)	1 ms [19, 37]
5G (first-hop)	14 ms [39]
Typical WiFi (90 th %ile)	20 ms [58]

Table 1: One-way latency for common and emerging networking technologies.

Privacy and Security. When users offload computation to cloud resources or instantiate VMs on public infrastructure, they place some degree of trust in the provider, since they direct the action. With Coalescent Computing, a user’s application may be run on untrusted hardware, potentially divulging sensitive information. Some malicious users may be incentivized to lease out their resources just to compromise other users’ data. Others may coalesce resources from nearby users (possibly coordinating with other bad actors nearby) to carry out a denial-of-service attack. Systems must have mechanisms in place to mitigate such scenarios. This is a problem that also plagues decentralized volunteer computing systems [17, 33]. Proper isolation using hardware support, virtualization, and collaborative monitoring and reporting of bad actors can alleviate the effects of malicious behavior.

3 CHALLENGES

We now discuss major challenges both in hardware and in OS design that impede progress in realizing Coalescent Computing.

3.1 Hardware

The overriding challenge for Coalescent Computing from the hardware perspective will be the performance characteristics of wireless links. Table 1 lists single-hop latencies for various interconnects up and down the stack reported by others. Cache line transfers on the coherence network between Nehalem cores land in the 100-200ns range, whereas high-performance InfiniBand cards are still more than 3X that latency at $\sim 1\mu$ s. As Shan et al. have already shown in the datacenter environment, this puts coherent resources off the table for now [55]. This especially rings true for wireless technologies (last four rows of Table 1). Typical WiFi

connections have reasonably low first-hop latency at 20ms, but there is a long tail that puts the damper on deterministic performance. However, emerging, ultra-low latency wireless standards like 5G URLCC (designed with applications like wireless factory automation and AR in mind) and WiFi 6E bring the latency down by an order of magnitude and are reported to reduce latency variance significantly. Coherence will still be out of reach, but with the right OS support we believe Coalescent Computing can be realized over these low-latency wireless links. For reference, the first row of the table shows the speed-of-light delay at 10m, which we can view as a lower bound on the latency of future wireless networking between edge systems. While there is much work on characterizing and improving the performance of wireless links, little has been done to guide automated decisions based on their properties. In particular, for a coalescent system to work properly, it must be able to infer signal strength (and user distance) accurately in order to project the impacts on application performance and thus guide coalescence dynamically. This is an open problem.

Unfortunately, current wireless interfaces are not suitable for operating with disaggregated resources. Prototype systems for disaggregated hardware today make heavy use of RDMA capabilities and fixed network latencies. WiFi interfaces could be optimized for Coalescent Computing, for example by customizing the wire protocol for resource acquisition, and by integrating low-power mechanisms for resource discovery, as in BlueTooth Low Energy (BLE). These NICs might also incorporate features we see in high-end cards today like RDMA, atomics, and memory protection. The NICs might also be integrated near the processors to act as a proxy socket to facilitate communication between remote resources, as in soNUMA [43].

While the OS may employ loosely-coupled monitors on remote resources (Section 3.2), users may want to customize the software they run on these resources. This will require enhanced lightweight virtualization in wireless NICs, namely self virtualization (e.g., SR-IOV) and boot protocols that incorporate disaggregated hardware (extended PXE). NICs on the users’ systems must coordinate with the BIOS (e.g. via a lightweight platform management controller or a BMC) in order to keep hardware information exposed to the OS (namely, ACPI tables that enumerate NUMA regions and processor information like the SRAT and SLIT tables) consistent with coalesced resources. ACPI likely needs to be extended to support Coalescent Computing, and platform hardware will need to route the boot sequence (e.g. the SIPI and IPI sequence on x86 chips) through something like an APICv [41] rather than applying the traditional *trap-and-emulate* model.

3.2 Software

A Coalescent OS will need to support the following: performance, disaggregation, resource discovery, adaptation, hardware heterogeneity, and fault tolerance. Several OSes from the research community support some of these features, but not all. For example, LegoOS is the first OS designed for disaggregated hardware [55], and provides a good foundation to build upon for Coalescent Computing. The idea of stateless, loosely-coupled monitors running on disaggregated hardware components will serve a Coalescent OS as well. However, the LegoOS design focuses on datacenter applications, and the ExCache-based memory management, the global resource managers, and the InfiniBand/RDMA-based RPC will not transfer easily to a wireless edge setting without significant hardware enhancements.

Performance. To reconcile privacy and performance, users will likely want their code and data to reside in isolated environments. This means that monitors will need to employ very lightweight, fast-start hardware virtualization, which we have previously shown is possible on the order of microseconds [64]. Light-weight, virtual execution environments will be launched on-demand to host second-level monitors from the mobile user’s system. Hardware monitors will isolate user monitors from one another. Virtualization hardware enhancements discussed in the previous section will make this more efficient, and a Coalescent OS will likely incorporate something like the *boot drivers* used in Barreelfish/DC to account for dynamically changing CPU information not supported in ACPI [67]. The CPU boot process will look much more like the plug-and-play PCI probing process present in commodity OSes today. For undersubscribed CPUs, the resource monitor may use CPU hot-remove functionality to space-partition the user monitor, reminiscent of co-kernels in Pisces [46]. As with Barreelfish/DC, decoupling the OS from the underlying hardware will allow for greater flexibility with dynamic OS updates as well, as was also demonstrated in K42 [8].

Performance will be mainly limited by network latency and bandwidth. A Coalescent OS will have to employ aggressive techniques to hide network latency and variability. The OS can avoid expensive coherence traffic by using message passing in lieu of shared memory, for example as is done in Barreelfish [7] and LegoOS. Serialization costs and software overheads must also be avoided, as we are learning with disks as SSDs become faster [35]. For remote memory performance, skewed access distributions may help [21], allowing caches to be used to take advantage of temporal locality, but it is unlikely to produce the same benefits we see in the datacenter. That said, similarities between users in geographical

proximity may offer hope, and the same principles that enable CDNs will present opportunities for deduplication and sharing in edge systems [61].

Coalescent systems will benefit from QoS policies. These policies can be set based on provider inputs (e.g. informed by user account balance), social credits (“how many CPU hours has the user leased out?”), current system load, physical proximity, and the user’s affinity for particular resources (“only coalesce memory, not CPU or accelerators”).

The system should also employ best effort coalescence of resources; namely, if network conditions are incapable of providing adequate performance, resource negotiations should fail, and applications can run on local resources or fall back to the traditional cloud. This best-effort behavior has already been demonstrated for servicing I/O requests in MittOS [27].

Generally speaking, as Schwarzkopf et al. aptly point out [54], deterministic performance was the albatross for early distributed OSes, and we must be mindful of the lessons learned there [59, 63]. Hardware improvements will certainly help, but exposing performance variability to the OS is paramount for it to make acceptable decisions.

Heterogeneity. Disaggregated CPUs, GPUs, FPGAs, memory, and storage will inevitably be more heterogeneous than in a typical datacenter. A Coalescent OS must handle this heterogeneity transparently. Monitors written for different devices can expose a unified interface, but applications must be able to run on diverse hardware, including different ISAs, especially as competitors to x86 gain prominence. This system might require applications be compiled into fat binaries, but a more flexible approach would employ an intermediate representation (IR) to dynamically adapt the application to the ISAs of nearby resources, as in Helios [42]. Such a system would make judicious use of just-in-time (JIT) compilers on edge nodes, or in cases where performance is less critical, language VMs. Using JIT compilation to address heterogeneity adds another layer of complexity for performance, as it can introduce even more variability. Managing this variability is critical for Coalescent Computing, but we have only scratched the surface of minimizing JIT compilation latency [34].

Resource Discovery. As users navigate the physical environment, their devices must query nearby systems for available resources. This resource discovery process must occur often enough to react to load spikes, but not so often as to drain device battery and congest the local network. The OS and hardware might employ UPnP here [44], as in Slingshot [57], but the protocol will likely need to be enhanced to include resource load information and performance characteristics. When negotiating coalescence, the OS will automatically

choose a subset of nearby resources subject to user preferences and system load.

Programming Model. The Coalescent OS can by default transparently migrate computation between local and remote machines. For example, for each new vCPU added to the system via Coalescence, the OS exposes a new run queue, e.g., over distributed shared memory. The OS can add a thread to the remote run queue as it would on the local system, but with a performance penalty. For example, the code in Listing 1 shows a trivial example of creating a worker thread that processes tasks in a shared queue. The Coalescent OS is free to schedule this thread on a remote vCPU if available. However, since the user is mobile, that remote vCPU may disappear. The remote worker thread might dequeue work from the shared queue then fail, losing that work. There are of course many techniques for handling failures and ensuring consistency in distributed systems, but in a language like C where mutations on shared state can happen anywhere, it is quite challenging to apply these techniques transparently.

```

1 static void worker() {
2     while (1) {
3         work_t * work = dequeue_work();
4         do_work(work);
5     }
6 }
7
8 void main() {
9     pthread_t thr;
10    pthread_create(&thr, NULL, worker, NULL);
11    pthread_join(thr, NULL);
12 }
```

Listing 1: Creating a worker thread.

One possibility is to expose remote resources and the potential for failure to the programmer. Listing 2 shows such an example using a CC-aware wrapper around the `pthreads` runtime. Here the programmer explicitly places constraints on the remote vCPUs that the thread can run on by specifying the maximum acceptable latency to the remote vCPU in μ s. The programmer also indicates that the system should favor remote vCPUs over local ones when available (EAGER_REMOTE). Finally, the programmer specifies that when a failure is detected by the runtime, the thread should be recreated on the local machine after a failure is handled by user-specified code (here the programmer provides code to recover the work queue, e.g., with a persistent write-ahead log).

```

1 #include <cthread.h>
2 static struct cthread_attrs {
3     .latency_bound = 100, // usec
```

```

4     .strategy      = EAGER_REMOTE,
5     .failure       = RETRY_LOCAL,
6 } cta;
7
8 static int handle_failure() {
9     return recover_work_queue();
10}
11
12 void main() {
13     cthread_t thr;
14     cthread_create(&thr, &cta, fun, NULL,
15     handle_failure);
16     cthread_join(thr, NULL);
17 }
```

Listing 2: Creating a worker thread with failure recovery using an explicit CC API.

In many cases, it will be preferable to manage *functions* running on remote resources, rather than execution contexts. In this case, the Coalescent OS can expose a function-as-a-service (FaaS) API as well. In addition to the typical FaaS event-triggered function invocation model, a CC FaaS API might also allow for RPC-like, *synchronous* invocations via language annotations. For example, a programmer might specify that a function can run on remote resources by using a *virtine* (virtual subroutine) [64], as shown in Listing 3.

```

1 virtine int fun() {
2     do_work();
3 }
```

Listing 3: Coalescence with a virtine.

In this case, if remote resources are available, the invocation of `fun` will cause a light-weight, isolated VM (or container) to be spawned on the remote vCPU and the function will run to completion.

Adaptation and Fault Tolerance. A Coalescent OS will need to adapt to changing network conditions and resource availability. Ideas from systems like Chroma apply here [6]; resources must be monitored, and application usage estimated so that applications can scale up and down depending on what is available. The system may leverage redundant computations across multiple resources to mitigate tail latency and for resilience.

To handle failures, a coalescent system will likely employ replicas and periodic checkpointing. Replication will be more challenging than in the datacenter environment given increased mobility, but replica selection can be informed by mobility characteristics of different systems. A server plugged into the wall would be a better choice for fail-over rather than a nearby laptop. Replicas might exist in hierarchies based on the environment. For example, a secondary

replica may be placed on the nearby edge server, and a tertiary replica may be instantiated in the cloud with relaxed consistency. Append-only storage can be used to persist state changes and aid in failure recovery.

When component or connection failures occur, or when the user moves out of range, the system must decide how to react. This will largely depend on application resource demands and latency sensitivity. For example, when a user training a neural network decides to move away from a resource-rich area, the training can be shipped off to the cloud to complete. However, a user running an immersive augmented reality application may prefer to have all computation and state migrated back to the local device, perhaps trading off degraded quality for responsiveness.

4 CONCLUSION

Several challenges remain for Coalescent Computing which we do not touch on here, but which we do plan to investigate. These include the storage interface, resource naming, and a more detailed treatment of privacy and security (e.g. authentication).

The building blocks for Coalescent Computing are gradually being put in place. We will soon stand at the confluence of disaggregated hardware, hierarchically distributed clouds, and ultra low-latency wireless networks. We argue that exploring systems that support this model will not only put more computational power at users' fingertips, but will also shed light on new avenues of systems research.

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