Overview of Swallow — A Scalable 480-core System for Investigating the Performance and Energy Efficiency of Many-core Applications and Operating Systems

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Abstract—We present Swallow, a scalable many-core architecture, with a current configuration of 480 × 32-bit processors. Swallow is an open-source architecture, designed from the ground up to deliver scalable increases in usable computational power to allow experimentation with many-core applications and the operating systems that support them.

Scalability is enabled by the creation of a tile-able system with a low-latency interconnect, featuring an attractive communication-to-computation ratio and the use of a distributed memory configuration.

We analyse the energy and computational and communication performances of Swallow. The system provides 240GIPS with each core consuming 71–193mW, dependent on workload. Power consumption per instruction is lower than almost all systems of comparable scale.

We also show how the use of a distributed operating system (nOS) allows the easy creation of scalable software to exploit Swallow’s potential. Finally, we show two use case studies: modelling neurons and the overlay of shared memory on a distributed memory system.

I. INTRODUCTION

This paper introduces the Swallow system, a highly scalable many-core system, which has been developed at the University of Bristol, UK.

Swallow has been developed as an experimental system for investigating techniques to progress energy efficient and scalable parallel systems. Key aims in the use of Swallow are:

1) To experiment with new techniques for parallel programming across hundreds of processing cores;
2) To factor energy consumption into both user programming paradigms and operating system decisions;
3) To develop a high-performance energy-aware operating system to support thousands of processing threads across hundreds of processing cores with minimal user interaction.

To support these aims, we needed to build a scalable and analysable many-core system, augmented with energy measurement and good processor-to-processor communication performance. Swallow is the realisation of this need.

Before we go on to explain the technical details of Swallow, we consider the need to make many-core systems and associated programs and operating systems. Computational needs are growing and many-core has been readily accepted as an energy- and cost-efficient method of continuing this growth, especially as we reach the limits of Moore Scaling. It is also well known that only some applications will parallelise to the extent needed to exploit a large-scale many-core system.

In the design of Swallow, we assumed two use cases: first, the conventional case where a user develops a highly parallelised implementation of a single application. Second, and since to exploit all 480 cores of Swallow, most such tasks would need to be in the “embarrassingly parallel” category [1], we also support multiple non-interacting applications running simultaneously. This allows more efficient system utilisation.

During the development of Swallow, we used a number of applications as motivating examples to evaluate the impact of our design decisions. Some are highly parallel, such as image processing, neural networks and streaming matching algorithms. Our other goal of many simultaneous tasks was supported by the development of a distributed multi-tasking operating system, nOS, which supports a number of smaller processes. nOS is detailed in another paper [2], so we focus on the category of parallelised algorithms in this paper.

II. REQUIREMENTS FOR SCALABLE MANY-CORE

To ensure that the features of the architecture used for evaluation of programming do not interfere with the fundamental properties that we are trying to explore, it is necessary to build a scalable architecture.
Building scalable many-core systems is an area well focused upon by the academic community, yet large-scale real and usable implementations are few and far between. The reason behind this is the fact that to build a scalable many-core system one needs:

- to source or create many components, such as processors, networks and memory systems that differ from those commonly available for single or multi-core systems;
- fresh programming practices; and
- a large investment of time and engineering effort.

We have solved the above problems in the following way:

- the use of a novel commercial processor architecture, which integrates on- and off-chip networks as a first-class primitive, in combination with a simplified memory hierarchy;
- the use and extension of a recently developed multi-core commercial programming language and the creation of design patterns for efficiently exploiting the underlying hardware’s capabilities; and
- a large investment of time and engineering effort.

A. Scale-free systems

Work extending from the PRAM model of computation (e.g. Valient, Gibbons, Culler [3], [4], [5]) shows a good agreement in the academic community that a scale-free computing system must have the following five properties:

1) Independent processors i.e. the behaviour and timing of any processor should not depend on the current activity of any of the other processors.
2) Storage where the total capacity per processor remains at least constant under scaling.
3) Storage where the access time is independent of the number of processors
4) A communication system whose capacity scales at least linearly with the number of processors and with a constant or predictable latency.
5) Predictable execution timing if processor-to-processor synchronisation is needed [3]

The establishment of the above properties yields a system where the performance of a single processor in the system is not constrained by the actions of other processors. Thus, each processor in the system can operate up to its maximum capacity and a system of \( N \) processors, each with processing capacity \( c_i \) can therefore have a maximum theoretical processing capacity of \( \sum_{i=1}^{N} c_i \). Note that this formulation is independent of whether or not the system is homogeneous or heterogeneous.

B. Scalable communication

Work by Valient, and extended by May [3], [6] shows that for each application in a parallel system there is a limiting bound on performance. Given a node’s data source and sink throughput \( e \) and that node’s communication throughput \( c \), and overall system data source and sink throughput \( E \) and total communication throughput \( C \), this can be expressed as:

\[
\text{Communication performance} = \max \left( \frac{e}{c}, \frac{E}{C} \right) \tag{1}
\]

Therefore, we can formally define the amount of communication bandwidth required to ensure that communication does not throttle performance as:

\[
\frac{e}{c} \leq 1 \land \frac{E}{C} \leq 1 \tag{2}
\]

However, it is not always necessary to build a system that guarantees both of these properties. Rent’s Rule [7] and the Berkeley Dwarves [8] give both a theoretical and empirical insight into the fact that the majority of data transfers in a parallel system are localised. Therefore, whilst we likely still desire a system with \( \frac{e}{c} \leq 1 \) in most circumstances, the system long range capacity may not need to be as large as suggested by Eqn. [3] nor need it have uniform capacity for most applications.

These observations also throw into question the usefulness of assertions, such as those made by the advocates of the PRAM model [3], [4]; that a scalable system must have at least a \( \log \_p \) scaling of communication latency with system size — whilst this is clearly necessary for systems with global communication or synchronisation, systems with only local traffic do not require such aggressive network performance and, for most real application scenarios with limited farmer-worker, or pipelined execution patterns, high performance local interconnect will provide a close match to the requirements.

For this reason, Swallow has been initially evaluated with a 2D mesh network structure. Swallow supports richer 2D and 3D networks, but at this stage we judge it unnecessary to implement these given our choice of application domains: our target of supporting multiple disjoint applications implies a degree of locality in communication and farmer-worker computations also demonstrate locality.

C. Scalable memory

The main bottleneck in modern computing systems is the memory sub-system. Compared to processing elements, most memories have very high latency and limited data bandwidth. This makes them the most important components to design for a scalable architecture.

For ease of programming, shared memory architectures are very common, in which multiple processors are interconnected to a shared storage structure. The demands on this interconnection are very high — commonly it must be a full cross-bar, limiting scalability. Further, contention on the memory system is increased and this reduces its average case performance for both latency and per-processor bandwidth.

There have been many optimisations to this problem, such as adding levels of independent caching between processors and the shared memory, but the shared memory model still demands that there be consistency in the view of each processor to the values stored in the shared structure. This has led to the development of cache coherency protocols, about which there is a wealth of literature. However, whilst advances have been made, the problem of coherent shared memory is fundamentally unscalable in the long term. This is evidenced by the very limited number of processors that shared memory systems tend to have (up to about 16).
Clearly, this will not meet our goal of scaling to thousands of processors, so we need a different approach, which we outline in Sect. III.

D. Summary of scalability requirements

The requirements outlined in § II-A give rise to the following design decisions in Swallow:

- Non-interacting instruction execution. Each processor performs computation independently, with any external interactions being explicitly defined in the programming language.
- Processors do not share memory, rather each processor has its own, independent memory. This approach ensures that a processor’s execution cannot depend on another processor’s memory access pattern.
- A simple memory hierarchy. Keeping the memory hierarchy simple ensures that memory accesses remain predictable.
- Explicit communication of data values between processors. Making communication explicit allows clear analysis of required data rates and the impact of communication latency on a program. It also allows analysis of data paths and aids allocation of communication resources.
- The communication network is well-provisioned in comparison to the volume of data that can be injected by the processors present in the system. Having a well-provisioned network reduces the chance that the network itself becomes a bottleneck and that data from one processor’s communication can interfere with that from other. Therefore processor independence is maintained.
- The communication network can be set to run in circuit-switched mode, which offers predictable and non-blocking communication.

The net effect of our design decisions is to create a system that is not only scalable in terms of processors, memory and network capacity, but also facilitates predictable execution, with the gains in system efficiency and static analysis that result.

In the following sections, we outline the details of the implementation that follows these decisions, and show how they result in the gains asserted above.

III. MEMORY SUBSYSTEM

In designing Swallow, we had a very specific goal in mind: to create a system that does not re-create any of the scalability problems suffered by most commercial and experimental many-core systems (see § I-C). It has been demonstrated time and time again that creating efficient shared memory is the most difficult problem that these systems present. Shared memory causes bottlenecks when consistency must be preserved across even small numbers of processing nodes, and with Swallow we wished to build a system that scales to many thousands.

This necessitates aggressive design decisions and, at an early stage, the design decision was made to build Swallow as a distributed memory system. Each core possesses its own private memory. Amongst other things, this gives us a guarantee of non-interference. In order to ensure scalability of software, as well as hardware, we wished to extend this to provide predictability of access times too, and for this reason, Swallow is also a cache-free design that has a single level of memory hierarchy above the registers.

Taken together, this ensures that every processing node in Swallow has predictable memory and computational timings, easing the job of a programmer in creating balanced and scalable distributed computations. An effect of this decision is that processing nodes have direct access to only 64kB of store, which is shared between instructions and data.

Swallow also incorporates a single 256Mbit DRAM on each slice, which is attached to one of the cores on the board as an I/O device. The DRAM can then be accessed by running a thread on this core with a memory controller functionality. We have developed code that is able to emulate the hardware functionality of a larger memory in software. A memory coordinator process listens for memory address requests, coming as messages from Swallow cores and either commits or returns data values in response to this. Note that, from the point of view of an accessing core, this makes the DRAM appear in just the same way as any other processor; the task that it is running is to load and store data. Therefore, the assumptions about predictability of individual cores’ timings and local memory accesses still hold.

Whilst the size of local stores would appear a limiting factor for both programs and data, this is not often the case in practice. The program size is not a fundamental limiting factor, since any computation can be structured as a series of computations, spread across multiple cores, producing ‘pipelined’ computation (see Fig. 25). Data storage capacity is also not a fundamental limit on the applications that may be supported. Large data sets can be addressed in a number of ways:

1) A farmer-worker (or scatter-gather) approach can be used to split the data into sub-sets and each sub-set assigned to a separate processor, each executing the same program. This also requires a coordinating node and appropriate I/O (See Fig. 25).

2) The computation can be arranged as a set of streaming computations, where only a small part of a larger data set is ever stored at a processing node at one time. A much larger proportion of the set is stored across all nodes involved in the computation (blue line, Fig. 3), and the entirety of the data set is then stored either externally (via Swallow’s network interface) or on Swallow’s on-board, but off-processor DRAM.

We assert that streaming is much preferred from an efficiency point of view, since it introduces no centralised point of contention. However, many contemporary algorithms and high-level programming languages are constructed using the scatter-gather approach, so we must support this too.

A. Nodes as remote data storage

We also make a key observation in the construction of a large-scale distributed memory system: a node where no processing takes place can be used instead as a remote data store. Thus, any data size can be stored at the expense
of a proportional number of processors. In a small-scale system, sacrificing processing ability is unlikely to satisfy throughput. However, in a system like with hundreds of nodes, it is likely that some processors will be unusable for a given application, and their resources dedicated to storage with minimal impact on the computation. i.e. we can support many, small computing units a few large ones without changing the underlying fabric. Our approach of deploying idle cores as a physical rearrangement of both the boards and the links. Using the mounting holes and flexible FFC-type cables. This allows the mounting holes and flexible FFC-type cables to be overlaid into the system with 4k word overlays. The card measures 105mm wide x 140mm high, and consumes a maximum of 5W at 12V. Multiple slices can be stacked in 3-D or spread out in 2-D, using off-board network links. A slice comprises sixteen processors, each with their own memory, 10 bi-directional on-board network links and 10 slice-to-slice links (green) and debug interfaces (magenta), slice-to-slice links (green) and debug interfaces (yellow and blue). The card measures 105mm wide x 140mm high, and consumes a maximum of 5W at 12V. Multiple slices can be stacked in 3-D or spread out in 2-D, using the mounting holes and flexible FFC-type cables. This allows physical rearrangement of both the boards and the links. Using

**Figure 2:** *Swallow* target computational paradigms

**Figure 3:** Memory available per task with number of tasks.

| Linked address | Region | Overlay ID | Run-time address |
|----------------|--------|------------|------------------|
| 0x0000—0x0fff  | T0 Code| <not overlaid> | 0x0000—0x0fff    |
| 0x1000—0x1fff  | T0 Code| 0          | 0x1000—0x1fff    |
| 0x2000—0x2fff  | T0 Code| 1          | 0x1000—0x1fff    |
| 0x3000—0x3fff  | T0 Code| <not overlaid> | 0x2000—0x2fff    |

**Figure 4:** Code overlays and how they relate to memory addresses still based on physical addresses. This means timing critical sections of code can be guaranteed not to be changed by simply disallowing them to be overlaid.

However, we do not recommend the use of overlays: the use of interrupts and the need to wait during execution for additional instructions to be loaded across the network both result in a reduction of predictability in the target application. It is better to re-engineer the application to make use of either fewer instructions, less static data or more processors. If this cannot be done, then overlays provide an alternative solution.

**IV. SWALLOW OVERVIEW**

In this section, we explain the design choices made when realising *Swallow*.

**A. Scalable construction**

For economic and reliability reasons, we decided to construct *Swallow* from *slices*. A slice is shown in Fig. 1. Each *Swallow* slice comprises sixteen processors, each with their own memory, 10 bi-directional on-board network links and 10 off-board network links.

We highlight the PEs (red), SDRAM and SPI interfaces (magenta), slice-to-slice links (green) and debug interfaces (yellow and blue). The card measures 105mm wide x 140mm high, and consumes a maximum of 5W at 12V. Multiple slices can be stacked in 3-D or spread out in 2-D, using the mounting holes and flexible FFC-type cables. This allows physical rearrangement of both the boards and the links. Using
this arrangement, both 2-D and 3-D network topologies can be created and grid and non-grid topologies may be used.

We built 40 slices of Swallow, enabling the construction of a 640 processor system, however yield issues (mostly with connectors) mean that the largest machine we have been able to build and fully test is 480 cores.

B. Processor choice

A design decision was made to use commercially available parts wherever possible in the construction of Swallow. For processor selection, this meant evaluating the commercially-available cores. We searched for systems with the scalable computational properties outlined in SII-A. According to our definition, this requires a data path with timing predictability, simple flat memory and a rich interconnect. A summary of our findings is in Tab. I.

As can be seen, few commercial processors present the necessary characteristics of a scalable architecture. The XMOS XS-1 architecture is the only candidate to provide all of these. We further investigated the architecture and determined that its feature set was an excellent match for our system requirements.

Here are the key technical characteristics of the XMOS XS-1 architecture:

- In-order single-scalar processor
- Every instruction completes in one cycle (except port- or network-based I/O, which may block)
- Overhead-free context switching of up to eight hardware threads
- Network input and output as ISA-level primitives
- Memory accesses are single cycle
- Predictable execution at all levels means that thread timing is statically analysable
- A built in network, which extends on- and off-chip. The network supports up to $2^{16}$ nodes, and its operating speed can be controlled in software.

There are five widely available devices based on the XS-1 implementation. Three single-core, one dual-core and one quad-core device. To maximise the density of the final configuration, whilst leaving power budgets modest, the dual-core device was selected (XS1-L2A). The rated operating frequency of this device is 500MHz, so each core offers 500 million integer operations a second, which is shared across at least four threads. The maximum per-thread rate is 125MIPS.

C. Thread throughput

Fig. 5 shows that the per-thread throughput and processor aggregate throughput scales predictably, according to the number of threads active (i.e. in the running state) in the system. The data is taken from [9] and shows the effect of the 4-slot pipeline in the XS-1 architecture: per-thread throughput if constant for up-to four threads, then declines linearly. We also see that processor aggregate throughput is maximised when at least four threads are active.

D. Network-on-Chip Implementation

Swallow builds on the network that is included in the XS-1 architecture. In this architecture, each processor is supplied with four external communication links. Links are flexibly allocated, with partitioning and routing being set in software. Links can be aggregated to form a single logical channel with increased bandwidth; or connected separately to different parts of the network, to include the dimensionality of the resulting network topology. They may also be left unused. Links connect to 12-ported switches, one per core. Routing selection at switches is implemented as a series of longest-prefix address comparisons and is very efficient, leading to low-latency routing.

V. SWALLOW INTERCONNECT

Swallow contains a rich, high performance interconnect, suitable for supporting arbitrary traffic types and a mix of parallel or non-parallel applications. In the following sections we give an overview of the interconnect and implementation details.

Given our three target use cases of farmer-worker, pipelined and multiple independent applications, it is not necessary to produce a fully-connected interconnect topology. Communication patterns of the use-cases exhibit high spatial locality and clustering of associated processing elements. In this case, topologies such as a 2D mesh that are not universally scalable remain useful in providing acceptable latency and bandwidth in a many-core system.

This has the beneficial side-effect that expensive high-degree topologies (e.g. Clos, hypercube) become unnecessary to show the fundamental properties under investigation. With Swallow, this allows us to simplify the topology with fixed degree, independent of the number of nodes.

A. Network topology

The device chosen for the Swallow system contains two processing cores and exposes four network links, in the way shown in Fig. 6. The two internal links contain four times the bandwidth of the external links and data words can be transferred from the core to the network hardware with just three cycles of latency (6ns). This compares with 80ns for the
BlueGene/Q system [10]. In Swallow, the external links are then arranged to connect North, South, East and West to other devices, which are notionally arranged in a grid pattern.

An interesting artefact of Swallow’s device selection is that, as seen in Fig. 6, it is not possible to make a conventional mesh topology. The internal links already utilised by the core-to-core connection mean that an attempt to create such a grid in-fact results in the creation of a ‘lattice’ structure, resembling that shown in Fig. 7. This presents interesting routing challenges, since a default X-Y approach will not lead to a fully connected network. To solve this, we implemented a new network routing table generation tool, which uses dimension-ordered routing to solve the connectivity problem.

The network is effectively composed of two layers, with each layer containing half of the available cores. One layer routes in the vertical dimension and the other layer routes in the horizontal dimension. Each node in the network also has a connection to a node in the opposite layer, which takes place within a chip package. This topology requires that 2D routes be translated into a form of 2.5D routing, where routing between layers is required to change horizontal/vertical direction. The dimension order routing strategy that we use prioritises the vertical dimension first. If a node is attached to the horizontal layer and a vertical communication is required, the data must therefore be sent to the other layer first. In this scheme, there will be at most two layer transitions; the case being two nodes attached to the horizontal layer that do not share the same vertical index.

Swallow links use flexible cables, allowing the physical topology of the network to be adjusted across a wide variety of configurations, further extending the range of experiments that can be carried out. New routing algorithms are simply programmed in software to cope with these.

B. Network implementation

Swallow nodes contain one processor, one switch and 12 network links. Each network link in Swallow is physically formatted over five wires in each direction and uses wormhole routing with credit-based flow control. This is abstracted at the instruction set level into channel communication which can take the form of either channel switched or packetized operation.

In packet operation, routes are opened with a three byte header prefixed to the front of the first token emitted from a communication channel end. Any network links utilised along the route in that direction are held open by the channel until a closing control token is emitted. If the close token is never emitted, the links are permanently held open, effectively creating a dedicated channel between two endpoints. This is the mechanism for realising channel switching. Packetized transfers incur an overhead from the header and switch setup time, resulting in a typical effective data rate of approximately

| Processor                  | Cores × data width | In-order pipeline type | Cache       | Memory configuration | Multi-core interconnect | Time deterministic | Overall suitability |
|----------------------------|--------------------|------------------------|-------------|----------------------|------------------------|--------------------|---------------------|
| ARM Cortex M               | 1 × 32-bit         | Single-scalar          | Optional    | <varies>             | No ☑                  | If no caches ☑    | ☑                   |
| ARM Cortex A, single core  | 1 × 32-bit         | Super-scalar           | Yes         | <varies>             | No ☑                  | No ☑               | ☑                   |
| ARM Cortex A, multi-core   | 4 × 32-bit         | Super-scalar           | Yes         | <varies>             | Memory coherent ☑      | No ☑               | ☑                   |
| Parallela Epiphany         | 64 × 32-bit        | Super-scalar           | No          | Local + global SRAM  | Network-on-Chip ☑      | No ☑               | ☑                   |
| XOMS XS-1                  | 1 × 32-bit         | Single-scalar          | No          | Unified, single cycle SRAM | Network-on-Chip ☑      | Yes ☑              | ☑                   |
| MSPi30                     | 1 × 16-bit         | Single-scalar          | No          | I-Flash + D-SRAM     | No ☑                  | Yes ☑              | ☑                   |
| AVR                        | 1 × 8-bit          | Single-scalar          | No          | I-Flash + D-SRAM     | No ☑                  | No ☑               | ☑                   |
| Quark                      | 1 × 32-bit         | Single-scalar          | Yes         | Unified DRAM         | Ethernet ☑             | No ☑               | ☑                   |

Table I: Comparison of candidate Swallow processors (suitable: ☑; unsuitable: ☑). Only the XS-1 meets all requirements.
435Mbit/s, depending on packet size.

**Channel switching** increases the effective data rate to 500Mbit/s by removing header and control token overheads, but physical links become unavailable to other channels. Multiple links can be assigned to the same routing direction where a new communication will use the next unused link. This increases bandwidth, provided the number of concurrent communications in that direction is equal to or greater than the number of links.

C. Network details

Each link uses the same signalling protocol, but may run at different speeds. The link connections and speed settings used in **Swallow** are shown in Fig. 6. We can see that internal bandwidths (red and blue) exceed external bandwidths (green) by a factor of four and allows a node to be configured with an inactive processor and used only for routing, with no impact on the overall bandwidth of the resulting network. Data has a maximum throughput of 500Mbit/s per internal link and 125Mbit/s per external link, giving a device package internal bandwidths of 2Gbit/s and external bandwidth of 500Mbit/s.

Links send data in eight-bit tokens comprised of two-bit symbols. A token’s transmit time is $3T_s + T_t$, where $T_s$ is the inter-symbol delay and $T_t$ the inter-token delay, measured in switch clock cycles. The fastest possible mode is $T_s = 2, T_t = 1$, yielding the aforementioned 500Mbit/s at 500 MHz. The external links must be run with larger delays to preserve signal integrity, giving 125Mbit/s throughput per external link.

The total core to core latency for an eight-bit token is 270 nS. The total core to core latency for a 32 bit word between packages is 360 ns, equivalent to the time taken to for the sending thread to execute 45 instructions. Between two cores in a package, this reduces to 40 instructions. Core-local channel communication can take place in 50 nS, or approximately 6 instructions. These timings are taken following a synchronisation between communicating channel ends, which incurs a small overhead.

D. Ratio of communication to computation

We can calculate the theoretical maximum ratio of communication to computation for **Swallow**. It is possible for a single thread of execution on a **Swallow** processor to issue 125MIPS. Byte or 32-bit long communication instructions complete in a single cycle, implying a maximum per-thread communications throughput 4Gbit/s. There are up to four threads, so the maximum process demand is 16Gbit/s.

However, in reality the serialisation of the data onto and from the network requires one cycle per byte at a frequency of 500MHz (External links 125MHz) to traverse the network interface. Any communication instructions of the same type issued from any thread within this time will block until the network interface is again free. Thus, the maximum available rate of issuing communication from the processor is one byte sent and one byte received every cycle (every 2ns [External 8ns cycle]) across all threads.

This information is known at compile time, and thus well-structured programs for **Swallow** will take this into account, giving a new calculation. Therefore, we can calculate that the maximum e value of a well-formed set of threads in **Swallow** is 4Gbit/s. e is 2Gbit/s, implying an e/c ratio of 2.

The available data rate on device external network links is one quarter that of the internal links (a byte requires 64ns to transmit, giving a peak data rate of 125Mbit/s). In the case of high levels of network traffic, this means that the network will either congest at these interfaces, if the same route is required by all four threads, causing $E/C = 32$, or in the case that all four streams take different paths, the congestion does not occur and $E/C = 8$. So, globally, **Swallow** provides a range of execution to communication throughputs of $8 \leq E/C \leq 32$.

E. External network interface

Communication into and out of **Swallow** is performed by the use of an ethernet bridge module. This module attaches to the **Swallow** network and is addressable as a node in the network. However, all data to and from an external interface. Using this bridge, we are able to bootstrap, load programs and data into **Swallow** as well as to stream data in and out of it at run time.

**Swallow** supports any number of ethernet interfaces, up to two per slice being supported (on the South external links). Each bridge can support up to 80Mbit/s of data transfer in each direction, so this places a limit on what proportion of the overall network traffic can be external traffic (≈ $\frac{80}{480} \approx 0.167$). This limit is only due to the construction of the bridge module software – future versions could potentially match the total network capacity.

VI. Energy Measurement

**Swallow** was designed to be an energy-transparent system. To this end, a number of power measurement points have been designed into the system. **Swallow** cores are powered by five separate switch-mode power supplies, each fed from a main 5V switched supply. Four of these supply 1V to the cores, with each supply powering two devices (four cores). The fifth supplies I/O pins across all devices, as well as the ancillary reset and configuration circuitry.

Each power supply has a shunt resistor on its output and associated probe points. We created a daughter-board that incorporates sensitive differential voltage amplifiers and a high-speed multi-channel analogue-to-digital converter. The resulting system is able to measure individual power supply energy consumption at up to 2MSps, or 1MSps if all supplies wish to be sampled simultaneously. The schematic for the system is available online as part of the **Swallow** project open source contribution (see Sect. XI).

A novel feature of this energy measurement is that the measurement data can be offloaded to the **Swallow** slice itself. In this way, it is possible to create a program that can measure its own power consumption and adapt to the results. Alternatively, the results can be streamed out of the system using the ethernet interface.

Due to the separate measurement points, **Swallow** can also monitor the balance of energy consumed by the processing cores and the external communication channels. In a system
Table II: Per-bit energies for three types of Swallow link

| Link type           | Data Rate | Max Link Power | Energy per bit |
|---------------------|-----------|----------------|----------------|
| On-die              | 500Mbit/s | 1.4mW          | 1.63pJ/bit     |
| On-board, vertical  | 125Mbit/s | 13.3mW         | 106pJ/bit      |
| On-board, horizontal| 125Mbit/s | 12.6mW         | 101pJ/bit      |
| Off-board, 30cm FFC | 125Mbit/s | 680mW          | 5440pJ/bit     |

such as ours, there are non-negligible capacitances on the communication links, both on board and on the flexible cables. Swallow presents a high data rate on these links and so one would expect a measurable amount of power to be dissipated on the links. We present the energy per bit for each link in Tab. II.

The links are quite energy efficient, using approximately 100pJ/bit for package-to-package transmission at a data rate of 125Mbit/s. The low value can be attributed to the sparse encoding on the link, which requires only four wire transitions to signal a byte of data. Therefore, the worst case energy usage in communication is one half that for a naive serial or parallel link. Once transmissions go off-board via long flexible cables, the capacitance of those cables becomes the dominating factor for energy, and the energy cost per bit rises by approximately $50 \times$. Shortening the cables would reduce the cost proportionately, so a more optimised design would do this.

### VII. ENERGY PROPORIONALITY

In order for a many-core system to be scalable, its energy consumption must be both scalable and proportional to the computation it is undertaking. Modern high-performance computing centres consume vast quantities of energy, and energy density issues is the most important throttle of continued integration of more and more compute power into a fixed space. Scalable computing systems must therefore be both energy efficient and consume energy proportionally to the compute being undertaken. Swallow is both energy efficient and energy proportional, so is scalable.

#### A. Swallow is energy efficient

Swallow is energy efficient since the processor and memory architecture is targeted for the embedded application space, where energy is a primary design goal. A single processor in Swallow consumes a maximum of 193mW, when active, leading to 3.1W/slice. Losses in the on-board power supplies and other support logic increase the overall power consumption to ~ 4.5W/slice (equivalent to 260mW/core, so a complete 480 core, 30 slice system consumes only 134W.

Overall, we see that approximately 26% of power is used in power supply conversion, support logic and I/O, 30% is consumed in performing computation, 40% is wasted in non-computational static and dynamic power, and the remaining 4% is used for network interfacing (Fig. 8).

![Figure 8: Power consumption breakdown per Swallow node](image)

#### B. Swallow is energy proportional

Swallow is energy proportional since it supports dynamic frequency scaling, based on run-time load factors. Fig. 9 shows how power consumption of a stripe of four processors scales with the clock frequency that is set on the devices.

The power consumed per core goes from 193mW at 500MHz to 65mW at 71MHz when cores are fully loaded with work (blue squares), and 113mW at 500MHz to 50mW at 71MHz when all cores and threads are idle (red diamonds). The characteristics are linear, giving a directly energy proportional response to clock speed $f$,

$$\text{Power consumption per core} = (46 + 0.3f) \text{mW}$$

Thus, we see that the static power dissipation is 46mW/core and the dynamic dissipation is 0.30mW/Hz.

Although the current version of Swallow does not support voltage scaling, newer devices using the XS-1 ISA do support full DVFS. The additional power savings from voltage scaling on top of frequency scaling can be reliably calculated from knowing the power formula $P = CV^2f$, where $C$ is the capacitance of the switching transistors and $V$ is $V_{dd}$. We have determined the minimum allowable voltage experimentally to be 0.6V at 71MHz and 0.95V at 500MHz, and calculate the equivalent DVFS savings for Swallow in Tab. 10.

### VIII. AN OPERATING SYSTEM FOR SWALLOW

A key enabler for a large-scale computing system, such as Swallow is to abstract away implementation details such as...
thread creation, mapping, network configuration and energy optimisation and just provide a programmer with the primitives needed to construct programs in the styles that Swallow targets. Therefore, an operating system has been created for Swallow, which provides the above functionality and optimises run-time scenarios with limited programmer intervention. The operating system is called nOS (a nano-Operating System), and is outlined in a separate publication \[2\].

In other work, we are building extensions to nOS in energy measurement and actively adapts workloads to run-time energy consumption.

IX. RELATED WORK

There are few embedded systems made at the same scale as Swallow, with even fewer being designed for general purpose computation.

The Tilera Tile \[11\] comes the closest to matching Swallow’s goals and form. The Tile 64 system comprises a 64-core system with a series of overlaid networks to provide low latency and high throughput between cores in a software configurable way. The effect is to provide a very agreeable $E/C$ of 2.4 with 64 cores, and general purpose computation is supported as well as sophisticated network traffic manipulation. The system is highly optimised for streaming traffic, but relies on adding additional networks to improve network performance in larger systems. This is clearly scalable in the long-run, so provides a limit for the architecture’s growth.

The Centip3De system \[12\] aims to use 3-D stacked dies to implement a 64-core system based on the ARM Cortex-M3 processor. Whilst its scale is within an order of magnitude of Swallow, it is clear that the system, which relies on a series of crossbars and coherent DRAM storage, is not as fundamentally scalable as needed to build truly large systems. Further, the design choices leave it with an undesirable $E/C$ ratio of 55.

In Tab. \[III\] we see that the SpiNNaker system \[13\] bears strong resemblance to the XMOS XS-1 architecture used by Swallow, and was also designed to be interconnected and scale to thousands of processing nodes via interconnection of 100Mbit/s IEEE1355 standard links. The T400 family devices were scaled to a 42-core machine to produce B0042 boards capable of highly parallel computation.

### A. Comparison of E/C ratio of contemporary many-core systems

We now compare Swallow’s communication-to-computation ratio compares to that of other contemporary many-core systems. The key data is displayed in Tab. \[III\].

We see that there is a wide range of $e/c$ and $E/C$ values, ranging from 0.075–55. Notably, all systems display a minimum 14-fold drop in communication capacity when measured globally, as opposed to locally. The SpiNNaker system fares best, but is not general purpose; in this category, Swallow and Tile have the lowest reductions in communication capacity: 16 and 32 times, respectively.

These data illustrate the difficulties in building scalable networks of a large size, and emphasise the importance of designing carefully for global throughput, if the application domain requires this.

### B. Energy comparison to contemporary many-core systems

In Tab. \[IV\] we compare the power consumption of Swallow with a variety of contemporary many-core systems. Its power per core is in the middle of the range, which can be explained by the fact its operating frequency and process node is also in the middle of the group.

The SpiNNaker device has similar characteristics per node \[13\]. It is designed with lower performance ARM9 cores in 130nm, each with 64kB of data and 32kB of instruction memory and a single DRAM per slice. It consumes 87mW of power, averaged across its 1,036,800 processors. It is much more densely integrated than Swallow, with 17 cores per device and is application specific. If Swallow had these economies of scale and improved clocking, an equivalent level of power efficiency is very possible to obtain.

The Centip3De system exploits near-threshold computing in 130nm, small ARM Cortex-M3 cores and consumes 203—1851mW/core, depending on its configuration \[12\]. Centip3De’s high power cost is mainly due its cache-centric design, which Swallow has abandoned.

Tilera’s 64 core device \[16\] consumes 300mW/core (19.2W/device). Adapteva’s specialised floating point
Epiphany architecture is claimed to require < 2W for a 28nm 64-core device (31mW/core), but this data is not currently verified.

X. APPLICATIONS FOR SWALLOW

Swallow is built as a general purpose compute system. However, its scale means that only a selection of applications will be able to exploit all of the parallelism that it exposes. We have implemented algorithms such as image recognition, path searching and network simulation, all of which map well to either the farmer-worker or pipelined paradigms.

We do not have space to describe them all, but in this section we introduce two case studies run on Swallow. We describe their behaviour and and show that they scale well.

A. Case study I: neural network simulation

We created a simulation of a neural network using the Izhikevich spiking neuron model, as adopted by Furber et al. [13] and Moore et al. [17]. We took the approach that a single neuron is represented by its own copy of the state variables from the Izhikevich model, and that many neurons can be combined onto a single core. Neurons are connected by message passing, which simulates their spiking behaviour. Using the event-driven nature of the processors, neurons sleep until a stimulus arrives. This increases the scalability of the computation by ensuring that simulation computations need only occur for those neurons that receive new stimuli in a simulation time-step.

A neuron’s state variables are few and take little data memory: 8 bytes of state plus 10 bytes of even buffer space. The simulation code is also compact: 1.1kBytes of shared code, with each copy requiring 336Bytes of stack. Thus, it would appear that the simulation is very efficiently scalable both in amalgamating many neurons onto a single core and in distributing neurons across cores. The memory-based limit on a single core is thus 191 neurons.

In terms of memory usage, the scaling of the number of neurons with cores can be made linear. In terms of computational performance, it is also linear. However, the real limit on scaling for this simulation is provided by the need to communicate ‘spikes’ between neurons. In the Izhikevich model, a neuron may spike in response to a stimulus. Both the stimulus and spike are represented in Swallow by the arrival and departure of messages on the network.

To provide a realistic simulation of a human brain, each neuron should be connected to at least 10% of the neuron population (of size \( N \))\(^{[13]} \). Every spike that it manufactures must be delivered as an input to each of these connected neurons. This entails large-scale multi-cast of messages. It is tempting to reduce this percentage, to ensure that the computation remains tractable. However, this also renders the simulation worthless as a simulation of the human brain. For this reason, we treat 10% as a minimum connectivity constraint on our simulation.

Under this constraint, scaling becomes surprisingly difficult.Whilst Swallow’s network is flexible, it only implements point-to-point routing and the hardware routing tables do not have the capacity to store the required number of entries to link every neuron to every other neuron. So, we must use software routing, overlaid on the point-to-point network to manufacture the multi-cast needed by spike outputs. The interesting thing here is that the routing table then used by the software router becomes the dominant factor in scaling the simulation, since it must indicate which 10% of the population of neurons are connected to each neuron. Since each neuron has different connectivity (initialised randomly in our simulations), each neuron must store a unique copy of this table. Under the strategy that a connection is stored by a single bit, each neuron must keep a table at least \( N \) bits long.

Whilst this size is relatively small compared to the core memory for a single neuron, the addition of neurons to the simulation not only results on more neurons needed per core, but also a larger table for each neuron. This results in a double whammy and soon one must remove neurons from cores in order to allocate sufficient memory to each. Then, the only way to maintain scaling is to add more processors, each simulating fewer and fewer neurons. This results in an asymptotic limit of \( P \) neurons in the simulation for large \( P \).

The curves in Fig. 11 show the effect of this scaling, under the assumption that 100,000 cores are available. The x-axis shows the number of neurons allocated per core. The red line then shows how the total number of neurons simulated the number of processors needed to do so increases by \( P = N^2 \). For the Swallow architecture, there is a hard memory limit of 100,000 neurons, which would require 100,000 processors! Therefore, the actual number of neurons that we have been able to simulate with our 480 processors is much more modest – in the mid thousands of neurons.

This poor scaling is well understood in the community. There have been attempts to solve it by increasing the network connectivity (e.g. the partially connected toroidal network of SpiNNaker), by substituting random accesses to memory for...
connectivity (e.g. the large DRAM banks of BlueHive), but all approaches are eventually constrained by the fact that connectivity cannot continually increase at a rate of $N^2$.

Thus, Swallow has a natural limit for these kinds of problems and a large Swallow system would be better placed running multiple simultaneous copies of more modest neural simulations — say 10,000 neurons, than attempting to scale up the number of neurons in a given simulation. Therefore, the fundamental scaling property of the simulation has given us an insight into the most efficient realisation.

### B. Case study II: emulating shared memory

We now show a case study that explores how Swallow is powerful enough to allow the assumptions underlying the computational model to be broken. Assume that our goal is to offer a global shared memory to our user programs. It can be done in a number of ways, but one efficient way is to add a single large memory store and allocate a thread of execution as a memory controller that responds to read and write requests to memory locations.

The thread and channel IDs of such a controller can be passed to all instances of nOS, which then support user calls such as `shared_read(address)` and `shared_write(address)` by translating them into communication to and from the controller.

Of course, this strategy has a single point of contention and, in the presence of frequent transfers can also cause congestion in the network.

A more elegant strategy emulates shared memory using a collection of $n$ distributed memories of size $m_0 \ldots m_{n-1}$ bits to produce a total capacity of size $\sum_{i=0}^{n-1} m_i$ bits. The realisation of such involves each nOS instance acting as a memory controller for a sub-section of address space. In the optimal case, $m_0 \ldots m_{n-1}$ are equal and the controller can be identified simply by calculating the nOS instance ID as `address%n`.

### XI. OPEN SOURCE RELEASE

Swallow is an open source project and will be released under the CC-BY-SA 4.0 International licenses (for design elements and documentation). The Swallow nOS operating system is released under GPLv3 at [https://github.com/simonhollis/swallow-nos](https://github.com/simonhollis/swallow-nos) Support code and libraries for the hardware platform will be released under a compatible license in the near future.

The latest status of all releases can be found at [http://www.cs.bris.ac.uk/Research/Micro/swallow.jsp](http://www.cs.bris.ac.uk/Research/Micro/swallow.jsp)

### XII. CONCLUSIONS

We have presented a new processing system architecture named Swallow. Swallow is designed to be inherently scalable to thousands of cores. This led to design decisions, such as distributed memory, a scalable network on- and off-chip implementation, with a best case computation to communication ratio of 8.

Swallow is modular and our example system comprises 480 cores and network nodes. It is highly energy efficient, using only 193mW/core with four active threads. Swallow supports dynamic frequency scaling and this allows an energy reduction to as little as 50mW/core when idle.

Key application paradigms targeted by Swallow include farmer-worker and computational pipelines and case studies have been shown to motivate this application space. We have also shown how large data sets and large application code bases can be supported even when individual processing nodes have limited storage. A distributed operating system has also been designed to ease programmer interaction and make runtime optimisations.

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