Partisan: Enabling Cloud-Scale Erlang Applications

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Abstract
In this work, we present an alternative distribution layer for Erlang, named Partisan. Partisan is a topology-agnostic distributed programming model and distribution layer that supports several network topologies for different application scenarios: full mesh, peer-to-peer, client-server, and publish-subscribe. Partisan allows application developers to specify the network topology at runtime, rather than encoding topology-specific concerns into application code. Partisan additionally adds support for more channels, enabling users to distribute messages over multiple channels, sometimes in parallel.

We implement and evaluate Partisan in the Erlang programming language and use it in the evaluation of three scenarios. The first scenario compares the raw performance between Distributed Erlang and Partisan, and shows that Partisan performs on par with or better than Distributed Erlang. The second scenario demonstrates that distributing traffic over multiple connections enables Partisan to perform up to 18x better under normal conditions, and up to 30x better in situations with network congestion and high concurrency. The third scenario demonstrates, using existing applications, that configuring the topology at runtime allows applications to perform up to 13.5x better or scale to clusters of thousands of nodes over the general-purpose runtime distribution layer.

1 Introduction
Building cloud-scale distributed applications is becoming increasingly commonplace. Once a restricted domain for either scientific computing or data warehousing applications, distributed applications are now pervasive. Examples of modern distributed applications are:

- distributed databases or infrastructure components that communicate using the full mesh model;
- rich-web or mobile applications that communicate using the client-server model;
- peer-to-peer applications that communicate with other nodes using the peer-to-peer model;
- Internet of Things applications that send data to and receive data from a data center location using the publish-subscribe model.

Despite the pervasiveness of distributed applications, runtime support for building cloud-scale distributed applications remains rare, requiring application developers to build and maintain a communications framework in addition to their application code.

While not yet the norm in industry, there are some notable counterexamples, all of which are implementations of a distributed actor model; for example: Akka Cluster [20], Microsoft Orleans [5], and Distributed Erlang [31]. Each of these frameworks enables transparent distributed programming for the platforms they are designed for, but all three optimize for a single type of application: low-latency, small-object messaging between nodes in a single cluster, operating inside the data center, using the full mesh model.

However, the modern examples of distributed applications enumerated above show that a single topology is insufficient for the various types of cloud-scale applications that are being written today.

In this paper, we present the design of Partisan, a distributed programming model and distribution layer for Erlang that is meant to be used as an alternative to Distributed Erlang. Partisan introduces two important improvements over Distributed Erlang: (1) the addition of multiple runtime-selectable cluster topologies, and (2) the ability to gain additional parallelism by distributing messages over multiple communication channels.

Applications that are developed using the Partisan programming model can specify the cluster topology at runtime. This runtime selection allows applications to choose the most efficient topology for the application at hand without having to modify application code.

Partisan’s default topology resembles the default (full mesh) topology of Distributed Erlang. However, unlike
Distributed Erlang, Partisan can distribute traffic over multiple connections to avoid congestion problems observed in Distributed Erlang.

As Distributed Erlang is general purpose, it can’t perform efficiently for all application scenarios. We consider two application scenarios; (1) a distributed database that deals with large objects on smaller clusters (10s of nodes), and (2) a lightweight replicated key-value store for mobile applications that runs on large clusters (100-1000s of nodes).

By leveraging communication channels, we demonstrate up to a 30x improvement on point-to-point messaging, as well as an 13.5x improvement on the distributed database application. By enabling application developers to specify the topology at runtime, we demonstrate the ability to scale the lightweight key-value store application from a cluster of 256 nodes to a cluster of 1024 nodes.

The contributions of this paper are the following:

- the design of the Partisan programming model that supports the runtime specification of multiple cluster topologies;
- the design of the channel-based full mesh backend that enables greater parallelism than possible in Distributed Erlang;
- an open-source implementation of Partisan that supports five cluster topologies; and
- a detailed evaluation of Partisan demonstrating increased parallelism through the use of multiple communication channels and increased scalability by specializing the topology to the application at runtime.

2 Preliminaries: Distributed Erlang

Erlang [2] is a general purpose, concurrent, functional programming language developed by Ericsson in 1986 for the construction of highly-available, fault-tolerant concurrent telephony applications. Erlang has seen much success in industry: Ericsson’s AXD301 ATM switch, WhatsApp’s mobile chat application, and the distributed database Riak (used by the UK’s NHS.) [13]

Erlang applications are constructed using lightweight processes that communicate with one another. These processes do not share memory: they are strongly isolated and communicate with one another only through asynchronous message passing. When one node sends another a message using a primitive operation `!` (or `send`), it is delivered into the receiving processes mailbox (i.e. queue) and a primitive operation `receive` is used to remove a message from the mailbox and handle it in application code. Processes in Erlang are identified by process identifiers, which can be sent as messages themselves. Erlang additionally provides functionality that allows processes to monitor other processes and be notified either when a process crashes or exits normally by delivering a message to the monitoring process. Programs in Erlang are written in functional-style, using single-assignment variables with pattern matching.

Distributed Erlang is an extension that supports transparent Erlang programming within a cluster of nodes. Several industry products rely on Distributed Erlang, with the largest known Distributed Erlang cluster being operated by Ericsson at 200 nodes[1]. Distributed Erlang, by default, establishes a full mesh for connectivity: when a new node joins the cluster by establishing a connection to a node already in the cluster, it will also establish connections to all of the nodes known by its peer, ensuring full connectivity between all of the nodes.

3 Partisan

Partisan is a distributed programming model and distribution layer that is realized as an Erlang library. aimed at providing cloud-scale Erlang applications. Partisan is meant to be used in lieu of Distributed Erlang to enable the development of cloud-scale distributed Erlang applications. Partisan exposes functions that support asynchronous programming regardless of the topology being used, therefore allowing the developer to alter the topology during development or at deployment time.

3.1 Programming Model

Partisan’s programming model provides two sets of operations: membership operations, that are used for joining and removing Erlang nodes from the cluster; and messaging operations, that are used for asynchronously delivering messages between Erlang nodes in the cluster.

Partisan’s programming model is designed to be topology-agnostic and asynchronous. Therefore, all operations in Partisan return immediately and have backend-specific behavior. For example, when joining a node in full mesh mode, the node must be connected to every other node in the cluster; when joining a node in the client-server mode, if the node is a client, the node will be redirected to a server node for the connection.

Messaging in Partisan is asynchronous and best-effort: in full mesh mode, messages will be directly sent to the Erlang node; in peer-to-peer mode, a message may have to be forwarded through several nodes to reach its destination based on what connections exist in the cluster.

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1 Personal communication with author.
### 3.2 API

We now describe the shared API provided by Partisan that is shared across all of Partisan’s membership backend modules.

- **Join.** Join a node to the cluster. This call simulates the \texttt{net\_kernel:connect} functionality.

- **Self Leave.** Explicitly leave the cluster. This call simulates the \texttt{net\_kernel:stop} functionality.

- **Leave.** Explicitly have a node leave the cluster. This call, when executed at a node in the cluster, will cause \texttt{Node} to invoke self leave.

- **Members.** Return cluster members known locally at this node. In the event that the peer-to-peer membership library is used, this will only be members that are directly connected; with the full membership backend, this will be all members of the cluster. This call simulates the \texttt{nodes} functionality.

- **Forward Message.** Forward a message to a remote node using best effort delivery. Returns to the caller immediately and attempts to deliver the message asynchronously. This call simulates the \texttt{erlang:send(!)} functionality.

- **Cast Message.** Delivery an asynchronous message to a remote \texttt{gen\_server} using best effort delivery. Returns to the caller immediately. This call simulates the \texttt{gen\_server:cast} functionality.

| Functionality | Partisan API | Equivalent Distributed Erlang API |
|---------------|--------------|-----------------------------------|
| Join node to cluster | \texttt{join(Node)} | \texttt{net\_kernel:connect(Node)} |
| Remove node from the cluster | \texttt{leave(Node)} | \texttt{net\_kernel:stop()} |
| Return locally known members of the cluster | \texttt{members()} | \texttt{nodes()} |
| Forward message asynchronously | forward_message(Node, Channel, RemotePid, Message, Options) | \texttt{erlang:send(RemotePid, Message)} |
| Forward message asynchronously to gen\_server | cast_message(Node, Channel, RemotePid, Message, Options) | \texttt{gen\_server:cast(ServerRef, Message)} |

Table 1: Partisan API

### 3.3 Topologies

Partisan provides several backend modules for different network topologies. The topology used by Partisan is specified in the application environment at runtime.

- **Static.** In static mode, Partisan will only connect to other nodes that have been explicitly configured at the time of node deployment time.

- **Full Mesh.** In full mesh mode, Partisan will ensure all nodes in the cluster are fully connected; in that, each node will connect to every other node in the cluster directly, ensuring each node has full knowledge of the entire cluster. This topology is an implementation of the default configuration of Distributed Erlang.

- **Client-Server.** In client-server mode, Partisan will ensure that all nodes tagged as clients only connect to nodes tagged as server; and all nodes tagged as server nodes will connect to one another. Client-server is an implementation of the traditional topology used by rich-web and mobile applications.

- **Peer-to-Peer.** In peer-to-peer mode, Partisan will have all clients connect to one other client in the system and the resulting network will approximate an Erdős-Rényi [12][11] model.

- **Publish-Subscribe.** In publish-subscribe mode, Partisan will connect to preconfigured AMQP [30] message broker for node-to-node messaging and dissemination of cluster membership information.
3.3.1 Static Membership

Partisan’s static membership backend assumes that nodes participating in the system will specify the nodes that they wish to connect to at deployment time: these nodes are specified in a configuration file, or in source code, and assumes a static network where nodes will not join or leave. This backend module is primarily used for testing because it reduces nondeterminism in the network.

The static membership backend uses a single TCP connection for communication between each node in the cluster, and the failure detector reports failures when this connection drops. Static membership operates similarly to the default Distributed Erlang configuration, with the only restriction that nodes cannot be added or removed from the cluster during cluster operation.

3.3.2 Full Mesh Membership

Partisan’s full mesh backend provides similar functionality to what is provided by the default configuration of Distributed Erlang: connections are established between all nodes in the cluster using a single TCP connection. Membership is dynamic: nodes can explicitly join or leave the cluster whenever they desire.

Partisan extends this traditional behavior with a number of new features to alleviate head-of-line blocking problems and other performance issues in the design of both Distributed Erlang and Scalable Distributed Erlang.

Channels. Partisan’s full mesh backend supports multiple connections between nodes in the cluster using channels. This allows traffic within a cluster to be classified accordingly, and load balanced across the multiple connections established between each node.

For each channel, and each peer in the cluster, Partisan maintains a single TCP connection. When a node wishes to send a message to another node in the cluster, a channel is optionally specified. If a connection exists for that channel and that peer, that connection process will be sent a message to be delivered over the TCP connection. If a connection for the channel does not exist, or a channel is not specified, a default channel and its associated TCP connection is used to deliver the message.

Monotonic Channels. Partisan’s full mesh backend allows these named channels to be classified as monotonic or not. Monotonic channels have a property where each message sent on the channel will subsume a previous message on the channel. Monotonic channels are useful for performing load shedding when a particular channel is overloaded with redundant messages.

Channel Parallelism. Partisan has the ability to open multiple TCP connections per channel. This enables additional parallelism by dispatching and load balancing traffic across multiple TCP connections for the same named channel and type of traffic.

Membership. Membership is tracked at each node using a set and gossiped [10] to other nodes in the cluster. Connections are automatically established as new nodes join the cluster. Periodically, each node in the cluster will send a copy of this set to its peers. Upon receipt of the message, the set will be merged with the node’s local copy of the set. This process will continue until a fixed point is reached.

3.3.3 Client-Server Membership

Partisan’s client-server backend assumes that each node in the system is tagged as either a client or a server. Membership is dynamic, but clients are only allowed to connect to other nodes tagged as servers; server nodes are only allowed to connect to other nodes tagged as servers. The client-server topology resembles the traditional hub-and-spoke topology, and can be implemented by reusing the full mesh topology, and restricting node connections between nodes based on their tags.

3.3.4 Peer-to-Peer Membership

Partisan’s peer-to-peer backend builds upon the HyParView [19] membership protocol and the Plumtree [18] epidemic broadcast protocol, both of which are Hybrid Gossip protocols, where a two-phase approach is used to pair an efficient dissemination protocol with a resilient repair protocol used to ensure the efficient protocol can recover from network partitions.

HyParView. HyParView is a hybrid gossip algorithm that provides a resilient membership protocol by using partial views to provide global system connectivity in a scalable way. Using partial views ensures scalability; however since each node only sees part of the system, it is possible that failures of other nodes break connectivity or greatly increase routing length. To overcome these problems, HyParView uses two different partial views that are maintained with different strategies. The challenge is to ensure that the combination of all partial views at all nodes form a single connected component.

Plumtree. Plumtree is a hybrid gossip algorithm that provides reliable broadcast by combining a deterministic tree-based broadcast protocol with a gossip protocol. The tree-based protocol constructs and uses a spanning tree to achieve efficient broadcast. However, it is not resilient to node failures. The gossip protocol is able to repair the tree when node failures occur. Thus the Plumtree protocol combines the efficiency of spanning trees with the resilience of gossip.
**Transitive Delivery.** In a HyParView cluster, nodes may want to message other nodes that are not directly connected. To maintain the existing semantics of Distributed Erlang, Partisan needs a mechanism to support messaging between any two nodes in a cluster.

To achieve this, Partisan’s peer-to-peer membership backend uses an instance of the Plumtree protocol to compute a spanning tree rooted at each node. Periodically, using a configurable interval, Partisan will broadcast a heartbeat message with a timestamp using Plumtree to ensure the tree is maintained; in the event the tree is disconnected, the normal Plumtree repair process is used. When attempting to send to a node that is not directly connected, the spanning tree is used to forward the message down the leaves of the tree in a best-effort method for delivering the message to the desired node. This is similar to the approach taken by Cimbiosys [25] to prevent livelocks in their anti-entropy system.

### 3.3.5 Publish-Subscribe Membership

Partisan’s publish-subscribe backend builds upon the Advanced Message Queueing Protocol (AMQP) standard. AMQP is a wire-level protocol, and therefore only specifies the format messages should take. This allows Partisan to operate on top of arbitrary backends that support the AMQP standard, such as cloud-based offerings like Amazon’s Simple Queue Service, Google’s Cloud Pub/Sub and Microsoft’s Azure Service Bus, and local, on-premise solutions like RabbitMQ.

Partisan’s publish-subscribe backend also only establishes outbound connections from nodes for bidirectional messaging, which makes it ideal for use in environments where outbound communication is prohibited, such as Amazon’s Lambda and Google’s Cloud Functions.

When using the publish-subscribe backend, a single queue is used for dissemination of membership information, that is subscribed to by all nodes participating in the system. For each Erlang node in the membership, a queue is registered for messages destined for that node; each Erlang node subscribes to its own channel.

### 3.4 Design Considerations

In order to provide a topology agnostic programming model, we do not support features of Distributed Erlang that are unable to be supported across all topologies.

**Remote Monitoring** Monitors in Erlang allow processes to be notified when other processes terminate. Remote monitoring is straightforward: as long as a connection remains open to the remote host where the process being monitored is executing, the monitor will operate correctly. However, if the connection to the remote host is lost, regardless of process state, the monitor will report the process as terminated.

Remote monitoring introduces a number of complications, as it is only possible if the node where the remote process is executing is directly connected. This is further complicated because of the topologies Partisan supports:

- **Client-server backend.** Client nodes only know about one or more servers, and therefore cannot remotely monitor processes on other client nodes.
- **Peer-to-peer backend.** Nodes are only partially connected, the remote processes may not be executing on one of the connected nodes. The only alternative would be to directly connect that node, causing the cluster to reorganize.
- **Publish-subscribe backend.** Remote monitoring is not possible given no connections are maintained directly between nodes.

If remote monitoring is required, Partisan can additionally connect nodes over Distributed Erlang to provide this functionality.

**Synchronous Invocations** The generic server abstraction gen_server contains two methods for making calls: cast, for asynchronous invocation, and call, for synchronous invocation. call, for synchronous invocation relies on the use of a monitor, whereas cast, for asynchronous invocation, does not. When a call is made, a monitor is is placed on the gen_server process that the call is being made to, and if that process dies, the call returns with an error code instead of blocking and waiting for a response indefinitely. A similar issue exists for the generic finite state machine, gen_fsm. Since these calls rely on the use of a remote monitor, these calls are unsupported by default.

**Process Identifiers** Process identifiers in Distributed Erlang combine a unique node identifier with process identifier to identify the process globally. The node identifier is encoded as an integer, and is relative to the node the process identifier is being viewed from. As local processes always have the node identifier of 0, when process identifiers are transmitted between nodes, the process identifiers are translated based on the receiving node’s membership view.

Supporting process identifiers in Partisan, without changing the internal implementation of Erlang’s process identifiers, is not possible without allowing nodes to directly connect to every other node. Instead of relying on Erlang’s process identifiers, Partisan recommends that processes that wish to receive messages from remote processes locally register a name that can be used instead of a process identifier when sending the message. We envision that a future version of Partisan could handle this automatically as part of message serialization.
Message Ordering  Distributed Erlang provides unreliable FIFO delivery between any two sending processes [27]. This means that, given two processes, the receiver will always receive messages from the sender in sending order; however, groups of messages may be omitted, as long as ordering is preserved.

Partisan provides best-effort ordering, depending on the topology and configuration of that topology. Given two peers, we make the following guarantees:

- **Full mesh backend.** With a single connection between peers, ordering is preserved between reconnections. With multiple channels, ordering is preserved per channel between reconnections. With multiple connections per channel, ordering is only preserved, between reconnections, if a routing partition key for the sender is provided; no guarantees are provided under random partitioning.
- **Client-server backend.** Same as the full mesh model, only ordering is only preserved between client and server nodes.
- **Peer-to-peer backend.** Messages may take any path to reach a recipient, FIFO is not guaranteed.
- **Publish-subscribe backend.** FIFO is guaranteed for the lifetime of the broker and exchange.

3.5 Implementation

Partisan is implemented as a library for Erlang 19.3 and requires no modifications to either the compiler or VM. It is implemented in 6.7 KLOC and is available as open source on GitHub [8]. The open source implementation of Partisan has several industry adopters.

Cluster topologies are Erlang modules that implement the partisan_peer_service_manager behavior. Users can implement their own topologies by providing a module that implements this behavior. Client applications interact with the Partisan system through the partisan_peer_service module, which exposes the API presented in Table 3.1.

Monotonic channels are implemented as Erlang processes that receive messages to be sent on the network to another node in the system. Whenever a monotonic channel process receives a message to be delivered over the channel, if the process’s mailbox contains more than 1 message in the queue, the message is dropped. These messages are only dropped within a particular window: the system will ensure that at least 1 message is sent within a particular window, to ensure progress.

Our implementation uses the following optimizations:

- **Binary Serialization.** Serialization to Erlang’s external term format occurs inside the Erlang VM, and in Distributed Erlang, can maximize sharing of the underlying data structures before transmitting the data structure on the wire. However, since serialization is invoked outside the VM in Partisan, a one-time binary object is generated off-heap and immediately dereferenced once the object is transmitted. Therefore, we cannot take advantage of reusing existing, shared structures. Using a technique from Thompson [29], recursive terms are encoded as lists and base types encoded as binaries before transmission to maximize binary reuse. This serializer to users implementing their own backend.

- **Overflow of LISTEN Queue.** When building large clusters using the full mesh backend, the TCP LISTEN queue can overflow when other members of the cluster establish new connections. For example, a cluster of N nodes, when growing to a cluster of N + 1 nodes will cause the cluster to establish N new connections to the joining node. This is exacerbated when using both the channel and parallelism features of the full mesh backend; causing a joining node to receive N * C * P inbound connections at the same moment, overflowing the node’s LISTEN queue, causing timeouts. To mitigate this, when existing nodes learn about a joining node they should connect to, only establish a single connection to a joining node every refresh interval.

- **Connection Cache.** To avoid any unnecessary contention when sending messages, a cache (implemented as an ETS table) is used to store the list of open connections. ETS (Erlang Term Storage) tables are processes that manage shared memory storage tables in the VM that can be concurrently accessed by multiple processes for reading. This cache is available to users implementing their own backend.

4 Evaluation

To evaluate the design decisions behind Partisan, and to validate its implementation, we focus on providing answers to the following overarching questions:

- Can a distribution layer removed from the Erlang VM perform on-par or better than one provided within the Erlang VM?
- Is it advantageous to separate different kinds of messages into dedicated channels? If so, what level of parallelism is best?
- Can the runtime selection of a network topology offer better performance than a general-purpose topology that provided by the system implementation?
- How do realistic applications, including one on a large cluster, perform atop of the Partisan distribution layer?

We answer these questions in the following subsections.
Figure 1: Performance of 1 channel Partisan vs. Distributed Erlang.

In Section 4.1, we demonstrate that a library-based implementation of a distribution layer can outperform a general-purpose distribution layer provided the runtime. We evaluate the performance of both Distributed Erlang and Partisan under different network latencies and varying workloads.

In Section 4.2, we examine the benefits of channels. We demonstrate that using multiple channels can prevent interference between different types of messages. We further demonstrate that parallelizing transmission on such channels can be beneficial when there is either high concurrency or when there is increasing network latency. Both of these design decisions allow us to mitigate the effects of head-of-line blocking.

To demonstrate that no single topology is sufficient for optimal performance of all applications, in Section 4.3 we examine two existing Erlang applications. The first, Riak Core [17], is the underlying infrastructure for the distributed database Riak [3], the research database Antidote [28], and several industry products [15, 24, 23]. The second, is the research language, Lasp [21], designed for large-scale, coordination-free programming.

4.1 Distribution as a Library

Distributed Erlang is implemented as an extension within the Erlang virtual machine. Message serialization, connection maintenance, and data transmission are all handled by mechanisms inside of the virtual machine that minimize redundant data serialization, and avoid penalties from messages copies between different processes heaps. As Partisan is implemented as a library, we set out to evaluate the viability of running a distribution layer that does not cohabit the virtual machine.

To evaluate this, we ran a two node Erlang cluster, simulating 1ms and 20ms RTT latencies and recorded the execution time taken for \( N \) processes running on the second node to receive 1,000 messages sent \( N \) worker processes running on the first node. Figure 1 demonstrates that Partisan’s distribution layer, implemented in Erlang, can achieve the same performance as the VM-supported Distributed Erlang, and in some cases, outperform Distributed Erlang.

4.2 Distributing Messages into Channels

Riak Core is a distributed programming framework in Erlang based on the Amazon Dynamo [9] model. In Dynamo, a distributed hash table is used to route requests among nodes in a cluster. The hash space is broken into a set of partitions, and distributed to a fixed set of virtual nodes, each of which is claimed by a node using a claim algorithm, then stored in a data structure, known as the ring. Requests are routed using consistent hashing, which minimizes the impact of reshuffling when nodes join or leave the cluster.

Background processes, such as Riak Core’s metadata anti-entropy and Riak Core’s ring gossip, can interfere with messages in the request path, as they transmit large

\[ \text{1ms and 20ms are representative of intra-}, \text{and inter- availability zone latencies using Amazon AWS, respectively.} \]
objects on the same channel as requests, and can create interference, such as head-of-line blocking problems. To examine the effect of this, we ran the same unicast benchmark on a 3 node Riak Core cluster comparing Distributed Erlang and Partisan. Partisan was configured to distribute traffic across 3 channels: request traffic, metadata anti-entropy traffic, and ring gossip.

Figure 2 demonstrates that performance of Partisan, when moving background activities to separate channels, is at best, 12.5 times faster, averaging an order of magnitude of improvement.

Under increasing network latency or increasing concurrency, Partisan can leverage additional connections per channel to scale near linearly. Figure 3 demonstrates the same unicast benchmark under different levels of concurrency, by increasing the number of workers while maintaining a fixed set of 8 connections for a single channel with a 1MB payload. However, under low concurrency, when the cost of sending the message is minimal, the additional connections are less beneficial and mostly add overhead to the Erlang scheduler.

Each sender has affinity to a particular connection, using the workers’s process identifier to determine which connection to use to route it’s traffic to the destination. Figure 4 demonstrates the benefits from leveraging additional connections in different latency configurations for a 1MB payload.

4.3 No “One Size Fits All” Topology

To motivate the use of multiple topologies, we implement two applications in Riak Core, and one large-scale application in Lasp.

4.3.1 Riak Core

Our first application is a simple echo service, implemented on a 3 node Riak Core cluster. For each request, we generate a binary object, uniformly select a partition to send the request to, and wait for a reply containing the original message before issuing the next request. We use the aforementioned benchmarking strategy: we record the execution time for $N$ worker processes to issue 1,000 requests from 1 node uniformly to partitions distributed across the cluster. When there is more than one connection available per channel, Partisan is configured to partition traffic based on the partition identifier.

Figure 5 demonstrates that Partisan exhibits an order of magnitude improvement over Distributed Erlang at low latencies, and approaches two orders of magnitude as the latency increases. This is due to the fact that as concurrency and network latency increases, Partisan can more efficiently leverage the use of additional connections to exploit parallelism.

Our second application is a memory-based key-value store, similar to the Riak database, implemented on a 3 node Riak Core cluster. Each request uses a quorum intersection request pattern, where get and put requests are issued to 3 partitions, based on where the key is hashed.
to Riak Core’s distributed hash table (along with its two clockwise neighbors), and the response is returned to the user once 2 out of the 3 partitions have replied. This pattern involves multiple nodes in the request path, and each partition simulates a 1ms storage delay in the request path. We reuse the aforementioned benchmarking strategy: we record the execution time for \( N \) worker processes issue 1,000 requests from 1 node uniformly to partitions distributed across the cluster using Riak Core’s claim algorithm. We vary the workload 1:1 between get and put operations, with selecting keys from a normal distribution of 10,000 keys, with an object payload of 1MB. Similar to Figure 5, Figure 6 also demonstrates that on a KV workload, Partisan can achieve an order of magnitude improvement over Distributed Erlang.

4.3.2 Lasp

Lasp is a programming model designed for large-scale coordination-free programming. Applications in Lasp are written using shared state: this shared state is stored in an underlying key-value store, and is fully replicated between all nodes in the system. Applications always modify their own copy of the shared state, and propagate the effects of their changes to other nodes in the network. Lasp ensures that applications always converge to the same result on every node through the use of convergent data structures known as Conflict-Free Replicated Data Types \(^{26}\), combined with monotone programming \(^{1}\).

For our Lasp application, we simulate an advertisement counter, modeled after the Rovio advertisement counter scenario for Angry Birds, where each client keeps a replica of distributed counters, incrementing each counter when an advertisement is displayed. Once a certain number of impressions are reached, the counter is disabled. The advertisement interval was fixed at 10 seconds, and the propagation interval for state was fixed at 5 seconds. The total number of impressions was configured to ensure that the experiment would run for 30 minutes. We evaluated both client-server and peer-to-peer topologies for varying cluster sizes, ranging from 32 all the way up to 1,024 node clusters. For both topologies, we propagate the full state of the objects in the local store to the nodes’s peers at each propagation interval.

For this evaluation, we used a total of 70 m3.2xlarge instances in the Amazon EC2 cloud computing environment, within the same region and availability zone. We used the Apache Mesos \(^{16}\) cluster computing framework to subdivide each of these machines into smaller,

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\(^{3}\)1ms is representative of a sequential seek of 1MB of data.
fully-isolated machines using cgroups. Each virtual machine, representing a single Lasp node, communicated with other nodes in the cluster using Partisan.

Figure 7 demonstrates that, in this experiment, the client-server topology fails to scale above a 256 node cluster whereas the peer-to-peer topology scales to 1,024 (at which point we encountered issues with Apache Mesos.) Transmission growth is reported as the total across all nodes and is impacted by two factors:

1) **Choice of topology.** The client-server topology has no redundancy and uses the server as a coordination point; whereas, the peer-to-peer topology has redundancy introduced as part of the resiliency of the topology.

2) **Choice of data structure.** The distributed data

Figure 5: Partisan vs. Distributed Erlang: single vnode Echo service implemented in Riak Core.

Figure 6: Partisan vs. Distributed Erlang: memory-based KVS implemented in Riak Core.
structure used, the G-Counter, grows on the order of the number of clients in the system.

We refer the readers to [22] for a full treatment of the large-scale Lasp evaluation.

5 Related Work

Ghaffari [12] has identified several factors that limit the scalability of Distributed Erlang:

1) Global Commands. When 0.01 percent of commands are global commands, commands that require coordination of all nodes in the cluster using a mechanism similar to 2PL/2PC, operations can take up to 20 seconds, and cluster scalability is limited to ≈ 60 nodes.

2) Data Size. Increasing payload sizes of messages between nodes limits the throughput of the cluster. Ghaffari does not provide explanation for this, but presumably this problem arises from head-of-line blocking and the cost of serialization and deserialization.

3) Remote Procedure Calls. Remote Procedure Calls limit scalability, as each call is serialized through a single server process that handles all Remote Procedure Calls. Head-of-line blocking, and the maximum throughput of a single process, obviously contribute to the scalability problems of scaling RPC in Erlang.

Ghaffari et al. [14] also identified that Remote Procedure Call invocations were a limiting factor in Riak 1.1.1’s ≈ 60 node limitation on linear scalability, but that as no global operations were used by the database, was not limited by global operations.

Chechina et al. [7] propose that there are two fundamental challenges that must be overcome in Distributed Erlang to scale to hundreds of nodes. Specifically, (i) transitive connection sharing, and (ii) explicit process placement. In the case of (i), transitive connection sharing between all nodes in the cluster requires that each instance of the Erlang VM maintains data structures quadratic in the number of nodes in the cluster. In the case of (ii), once clusters grow large enough, determining where to place computational processes in the network becomes a challenge to ensure proper supervision, fault-tolerance, and balanced cluster performance.

The authors propose two solutions, two components of Scalable Distributed Erlang, to solve these problems:

1) Reducing transitive connection sharing. By subdividing nodes into smaller groups and only supporting full connectivity within each group and not across groups, nodes limit the number of nodes that they have to connect to, perform failure detection on, and replicate the global process registry of. In this model, each node can become a member of multiple groups and can explicitly request a connection with another node in the system, without transitive connection sharing.

2) Semi-explicit process placement. When spawning a new process, per-node attributes can be used to filter the list of available nodes to choose from for hosting that process. This allows developers to target nodes by available memory, or other user-defined attributes.

While these changes enable Scalable Distributed Erlang to break through the scalability bottleneck with global operations previously identified by Ghaffari et al. [14], scaling up to 256 nodes [6], these solutions still assume that explicit process naming through the global registry is desirable, from an application developer point of view. Additionally, a node that participates in too many groups also will fall into the same trap of replicating too much information.

Existing distributed actor systems, such as Akka Cluster [20] and Microsoft’s Orleans [5, 4] share similar designs to Riak Core. While these systems differ slight in their programming models, they both use a distributed hash table for distributing the placement of actors within the cluster. We believe the techniques in presented in this paper are applicable to both of these systems, as they have been demonstrated as applicable to Riak Core.

6 Conclusion

We presented Partisan, a distributed programming model and distribution layer for Erlang that provides the ability for users to specify cluster topologies at runtime, without requiring modifications to application code. Partisan’s default topology outperforms Distributed Erlang through the use of channels that can exploit parallelism under high concurrency or increasing latency, thereby reducing the impact of network interference such as head-of-line blocking. These design decisions resulted in a 13.5x - 30x performance improvement for real Erlang applications. As our modifications have demonstrated performance gains for Riak Core, we believe these design decisions can lead to improved performance for systems with similar designs, such as Microsoft Orleans and Akka Cluster.
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