Accelerating I/O in Cloud – A Data Driven Approach and Case Studies

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Why are we here?

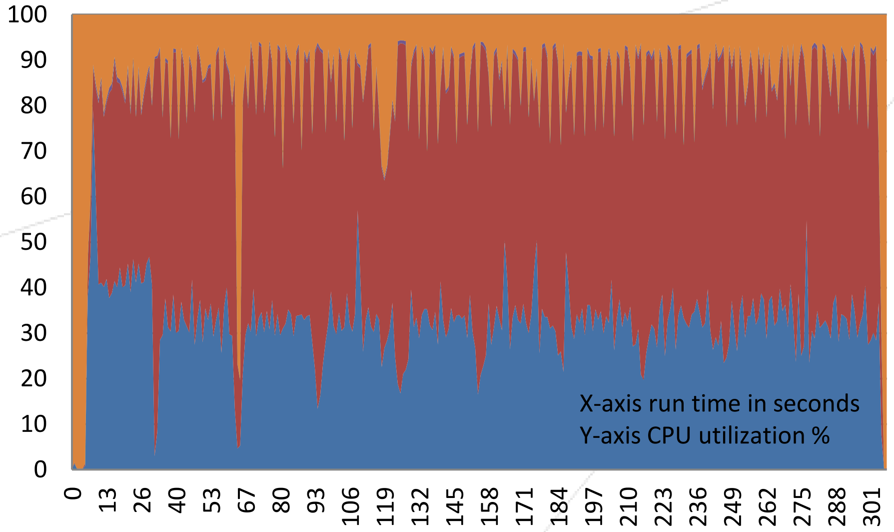
- Modern hardware being continuously developed and adopted into cloud
  - Core count growth
  - Spinning disks to NVMe drives
  - Networking standards evolving faster 10G → 25G → 100G w/ RDMA
- Requires software tuning/optimizations to take full advantage of the hardware is challenging

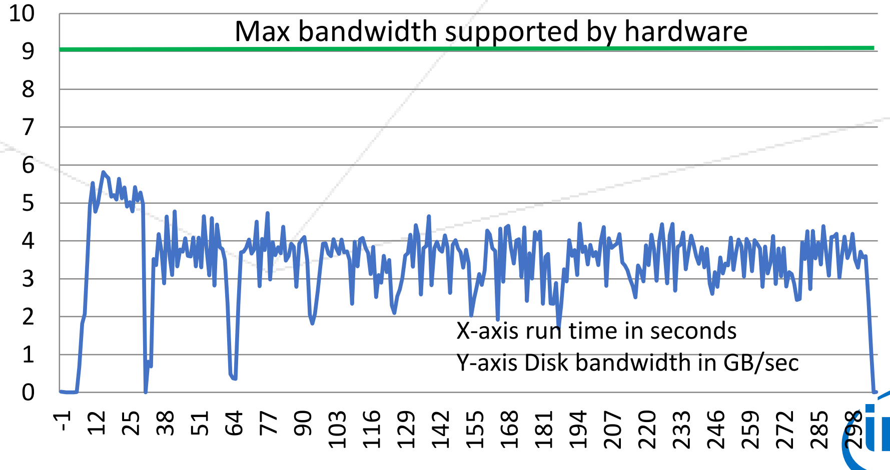
Why are we here?

- Many cloud frameworks are built in Java
- Java I/O is lacking native features as available in C/C++
  - Catching up with new feature enablement in line with modern hardware development
  - New 6 month Java release cadence might help
- Developers
  - Exploring new technologies for performance vs. stay compatible

Apache Cassandra-Stress read performance

- CPU and storage utilization on a tuned performance node (56C, 192GB DRAM, 4 NVMe drives)
- 55% CPU cycles spent in kernel
  - 47% in memory management and IRQ locks
  - Highest function on the call chain: try_to_unmap_one (9.5%) hints to kernel memory page swapping
- Disk 50% utilized: bandwidth and iops





What is being swapped?

- Java uses buffered I/O by default
- All I/O buffered by kernel in DRAM (filesystem cache)
- Kernel constantly refill/cleanup the filesystem cache, especially at high throughput level provided by multi-cores and NVMe drives

Bypass the filesystem cache

- "Direct I/O is a system-wide feature that supports direct reads/writes from/to storage device to/from user memory space bypassing system page cache." – Facebook RocksDB Wiki[1]
- Enabled on many database applications built in C/C++
- Direct I/O support added to Java* SE Development Kit 10
  - GA release on March 2018
  - APIs are designed for easy use and minimal changes to applications

1. https://github.com/facebook/rocksdb/wiki/Direct-IO

Direct I/O's Pros

- No CPU cycles or memory bandwidth spent in copies between filesystem cache and user space
- Avoid filesystem cache thrashing
- Provide consistent I/O throughput and latency
- Avoid redundant caching when application already has its own caching

Direct I/O's Cons

- Direct I/O is not intentioned for traditional spinning devices
- Might not be suitable for sequential I/O which greatly benefits from filesystem cache
- Need extra programming effort to handle the alignment between I/O size, user buffer and storage device block size.

DIRECT I/O Java API

Enum: ExtendedOpenOption

Enum Constant: DIRECT

Description: Flag for Direct I/O defined as one of the ExtendedOpenOption. The flag could be used in FileChannel.open()

Class: FileStore and inherited classes

Method: public int getBlockSize() throws IOException

Description: Return the block size for the disk in bytes. The value could be used for Direct I/O alignment.

Java Code Example – Buffered IO

```
import java.nio.file.Paths;
import java.nio.file.Path;
import java.nio.channels.FileChannel;
import java.nio.ByteBuffer;
import java.nio.file.FileStore;
import java.nio.file.Files;

public class testDirectIO {
  public static void main (String[] args) throws IOException {
    int fileSize = 8192;
    File datafile = File.createTempFile(“myfile", null);
    datafile.deleteOnExit();

    FileOutputStream fos = new FileOutputStream(datafile);
    fos.write(new byte[fileSize]);
    fos.close();
    String path = datafile.getAbsolutePath();
    Path p = Paths.get(path);

    FileChannel newChannel = FileChannel.open(p);

    ByteBuffer buf = ByteBuffer.allocateDirect(fileSize);
    int result = newChannel.read(buf);

    newChannel.close();
  }
}
```

Java Code Example – DIRECT I/O

```
import java.nio.file.Paths;
import java.nio.file.Path;
import java.nio.channels.FileChannel;
import java.nio.ByteBuffer;
import com.sun.nio.file.ExtendedOpenOption;
import java.nio.file.FileStore;
import java.nio.file.Files;

public class testDirectIO {
  public static void main (String[] args) throws IOException {
    int fileSize = 8192;
    File datafile = File.createTempFile(“myfile", null);
    datafile.deleteOnExit();

    FileOutputStream fos = new FileOutputStream(datafile);
    fos.write(new byte[fileSize]);
    fos.close();
    String path = datafile.getAbsolutePath();
    Path p = Paths.get(path);

    FileChannel newChannel = FileChannel.open(p,
ExtendedOpenOption.DIRECT);

    FileStore store = Files.getFileStore(p);
    int alignment = store.getBlockSize();
    ByteBuffer buf = ByteBuffer.allocateDirect(fileSize +
alignment).alignedSlice(alignment);
    int result = newChannel.read(buf);

    newChannel.close();
  }
}
```

Improvements with Direct I/O

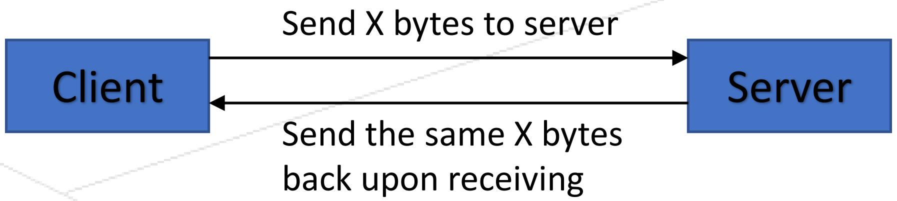
- Kernel time reduce from 55% to 5% → less overhead
- User time increase from 35% to 65% → more meaningful work are done
- Disk bandwidth improved by 2.1x and all 4 NVMe SSDs are fully utilized
- 2.2x throughput improvements on throughput with 90% reduction on 99th percentile latency
- Details on Apache* Cassandra* code changes are available at https://issues.apache.org/jira/browse/CASSANDRA-14466

Who else may benefit from Direct I/O?

- Applications that read randomly
  - A “proof of concept” implemented to Apache HBase* bucket cache
  - Random reads shows up to 2.2x improvement on throughput and 56% reduction on average latency across different load levels
- Applications with build-in cache(s)
  - Ex: Apache Cassandra*, Apache HBase*
- Applications that generate single-use temporarily files
  - Ex: Apache Spark* shuffle service
- Multi-tenanted applications running on the same platform

Network transfer performance

- Micro workload for measuring network latency across different transfer sizes



  - Single threaded
  - Latency is measured at the client side as round trip time
- 35% CPU utilization observed with 32KBytes transfer size on 10Gb NIC
  - 30% are spent in kernel. Mostly handling memory copies and tcp transmissions
- Network device is far from being utilized

TCP/IP networking

- Java supports socket-based networking
  - Based on traditional TCP/IP stack
  - Leverage kernel socket APIs, EX: bind, listen, connect, accept, send and receive
- High kernel utilization is due to multiple back-forth memory copies between kernel and user spaces
- Network bandwidth not scaling with increased device capabilities
- Modern devices need an optimized networking stack for high bandwidth and low latency

Remote Direct Memory Access (RDMA)

- Enable RDMA capable network adapters to transfer data directly to/from application memory
- Data transfers bypass OS kernel
- Avoid multiple data copies between user and kernel spaces
- Permit high-throughput, low-latency networking
- Useful in massively parallel computer clusters

Information Source: https://en.wikipedia.org/wiki/Remote_direct_memory_access

Enable RDMA in Java

- Work-in-progress
  - Java Enhancement Proposal (JEP): http://openjdk.java.net/jeps/337
  - Java Bug System: https://bugs.openjdk.java.net/browse/JDK-8195160
  - Patch under review: http://cr.openjdk.java.net/~ylu/8195160.09/
- Applications aiming at high network throughput and/or low latency may benefit from the feature:
  - Apache* Spark*: shuffle service
  - Apache* HBase* and Apache* Cassandra*: data replication, node repair, peer-peer communication
  - Others

Proposed Java API for RDMA

Class: jdk.net.Sockets

Methods:

- openRdmaSocket: return a RDMA Socket
- openRdmaServerSocket: return a RDMA Server Socket
- openRdmaSocketChannel: return a RDMA SocketChannel
- openRdmaServerSocketChannel: return a RDMA ServerSocketChannel
- openRdmaSelector: return a RDMA channel selector

Java Server Side Code Example with TCP/IP

```
import java.nio.channels.ServerSocketChannel;
import java.nio.channels.SocketChannel;
import java.nio.ByteBuffer;
import java.io.IOException;
import java.net.InetSocketAddress;
import java.net.InetAddress;

public class WebServer {
    public static void main (String [] args)
            throws IOException {

        ServerSocketChannel ssc = ServerSocketChannel.open();
        InetAddress addr = InetAddress.getLocalHost();

        InetSocketAddress hostAddress = new InetSocketAddress(addr, 9000);
        ssc.bind(hostAddress);
        SocketChannel client = ssc.accept();
        int xfSize = Integer.parseInt(args[0]);
        ByteBuffer buffer = ByteBuffer.allocate(xfSize);
        int readCount = 0;
        int writeCount = 0;
        int readB = 0;
        int writeB = 0;

        while (readCount < xfSize) {
            readB = client.read(buffer);
            readCount = readCount + readB;
        }
        buffer.flip();
        while (writeCount < xfSize) {
            writeB = client.write(buffer);
            writeCount = writeCount + writeB;
        }
        client.close();
        ssc.close();
    }
}
```

Java Server Side Code Example with RDMA

```
import java.nio.channels.ServerSocketChannel;
import java.nio.channels.SocketChannel;
import java.nio.ByteBuffer;
import java.io.IOException;
import java.net.InetSocketAddress;
import java.net.InetAddress;
import jdk.net.Sockets;

public class WebServer {
    public static void main (String [] args)
          throws IOException {

        ServerSocketChannel ssc = Sockets.openRdmaServerSocketChannel();
        InetAddress addr = InetAddress.getLocalHost();

        InetSocketAddress hostAddress = new InetSocketAddress(addr, 9000);
        ssc.bind(hostAddress);
        SocketChannel client = ssc.accept();
        int xfSize = Integer.parseInt(args[0]);
        ByteBuffer buffer = ByteBuffer.allocate(xfSize);
        int readCount = 0;
        int writeCount = 0;
        int readB = 0;
        int writeB = 0;

        while (readCount < xfSize) {
            readB = client.read(buffer);
            readCount = readCount + readB;
        }
        buffer.flip();
        while (writeCount < xfSize) {
            writeB = client.write(buffer);
            writeCount = writeCount + writeB;
        }
        client.close();
        ssc.close();
    }
}
```

Java Client Side Code Example with TCP/IP

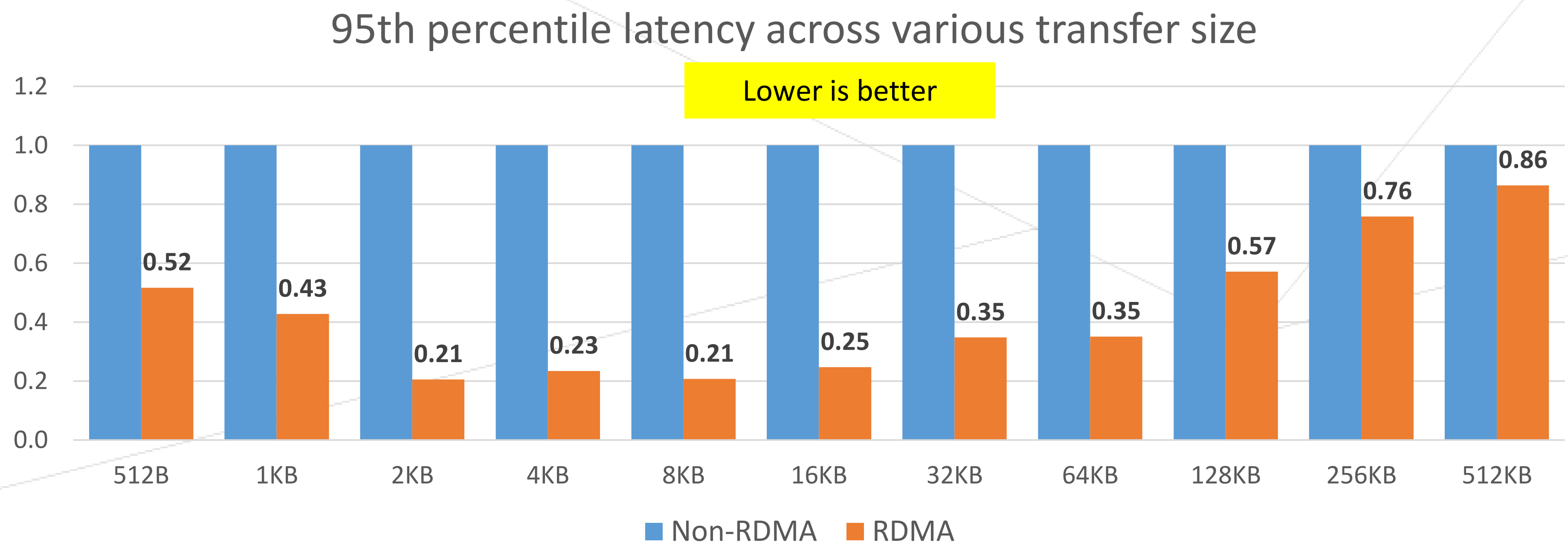
```
import java.io.IOException;
import java.net.InetSocketAddress;
import java.nio.ByteBuffer;
import java.nio.channels.SocketChannel;

public class WebClient {
  public static void main(String args[]) throws IOException {
    int xfSize = Integer.parseInt(args[0]);
    InetSocketAddress hostAddress = new
InetSocketAddress("30.30.30.1", 9000);

    SocketChannel client = SocketChannel.open();
    client.connect(hostAddress);

    ByteBuffer buf = ByteBuffer.allocate(xfSize);
    for (int i = 0; i < xfSize; i++) {
      buf.put((byte)'a');
    }
    buf.flip();
    int writeB = 0;
    int writeCount = 0;
    int readB = 0;
    int readCount = 0;

    while (writeCount < xfSize) {
      writeB = client.write(buf);
      writeCount = writeCount + writeB;
    }
    buf.flip();
    while (readCount < xfSize) {
      readB = client.read(buf);
      readCount = readCount + readB;
    }
    client.close();
  }
}
```

Java Client Side Code Example with RDMA

```
import java.io.IOException;
import java.net.InetSocketAddress;
import java.nio.ByteBuffer;
import java.nio.channels.SocketChannel;
import jdk.net.Sockets;

public class WebClient {
   public static void main(String args[]) throws IOException {
      int xfSize = Integer.parseInt(args[0]);
      InetSocketAddress hostAddress = new
InetSocketAddress("30.30.30.1", 9000);

      SocketChannel client = Sockets.openRdmaSocketChannel();
      client.connect(hostAddress);

      ByteBuffer buf = ByteBuffer.allocate(xfSize);
      for (int i = 0; i < xfSize; i++) {
         buf.put((byte)'a');
      }
      buf.flip();
      int writeB = 0;
      int writeCount = 0;
      int readB = 0;
      int readCount = 0;

      while (writeCount < xfSize) {
         writeB = client.write(buf);
         writeCount = writeCount + writeB;
      }
      buf.flip();
      while (readCount < xfSize) {
         readB = client.read(buf);
         readCount = readCount + readB;
      }
      client.close();
   }
}
```

Improvement with RDMA

- With 32KB transfer size
  - Overall CPU utilization improved from 35% to 60%
  - User space utilization improves from 6% to 47%
  - Memory copies between user and kernel spaces are avoid which contributes to kernel utilization reductions
- Up to 75% reduction on 95th percentile latency



Summary

- I/O infrastructure is key to cloud ecosystem
- New Java libraries and APIs are being developed to scale modern storage and networking hardware devices
- Exploring new features and optimize applications to take full advantage of the hardware

Q/A

Thank you