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

- 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

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.
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

```java
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.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](http://openjdk.java.net/jeps/337)
  - Java Bug System: [https://bugs.openjdk.java.net/browse/JDK-8195160](https://bugs.openjdk.java.net/browse/JDK-8195160)
  - Patch under review: [http://cr.openjdk.java.net/~ylu/8195160.09/](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
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

```java
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

```java
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

```java
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 avoided which contributes to kernel utilization reductions
- Up to 75% reduction on 95th percentile latency

95th percentile latency across various transfer size

<table>
<thead>
<tr>
<th>Transfer Size</th>
<th>Non-RDMA</th>
<th>RDMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>512B</td>
<td>0.52</td>
<td>0.86</td>
</tr>
<tr>
<td>1KB</td>
<td>0.43</td>
<td>0.76</td>
</tr>
<tr>
<td>2KB</td>
<td>0.21</td>
<td>0.86</td>
</tr>
<tr>
<td>4KB</td>
<td>0.23</td>
<td>0.57</td>
</tr>
<tr>
<td>8KB</td>
<td>0.21</td>
<td>0.35</td>
</tr>
<tr>
<td>16KB</td>
<td>0.25</td>
<td>0.35</td>
</tr>
<tr>
<td>32KB</td>
<td>0.35</td>
<td>0.25</td>
</tr>
<tr>
<td>64KB</td>
<td>0.35</td>
<td>0.21</td>
</tr>
<tr>
<td>128KB</td>
<td>0.57</td>
<td>0.23</td>
</tr>
<tr>
<td>256KB</td>
<td>0.76</td>
<td>0.21</td>
</tr>
<tr>
<td>512KB</td>
<td>0.86</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Lower is better
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
Thank you