Accelerating Mobile Applications through Flip-Flop Replication

Gordon et al. 2015

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University of Pittsburgh -- ECE 2195 Special Topics: Edge Computing

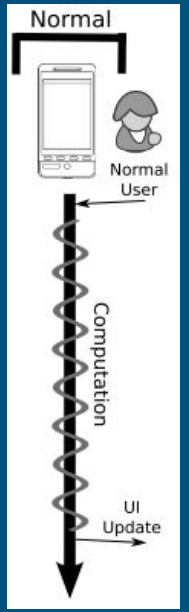
Overview

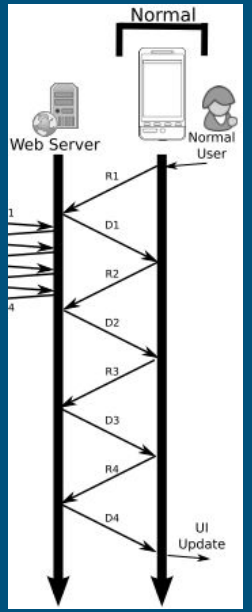
- Challenges with offloading mobile computation & dynamic cost evaluation
- *Tango* introduces scaled-redundancy to flip-flop between mobile & remote processing
- Comparing Tango with Android Application Benchmarks
- Follow-up advances
- Conclusions

Mobile Computing Workload (1)

- Mobile devices limitations
  - Has poorer computational performance due to low-power circuitry
  - Has poorer network performance due to over-the-air comms challenges

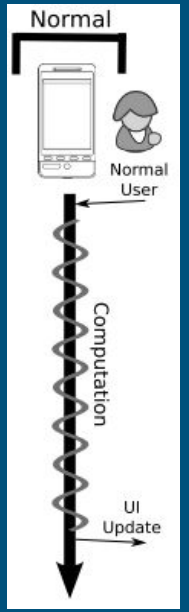
- Offloading computation could help with compute-intensive performance, but challenging to find good partitioning moments

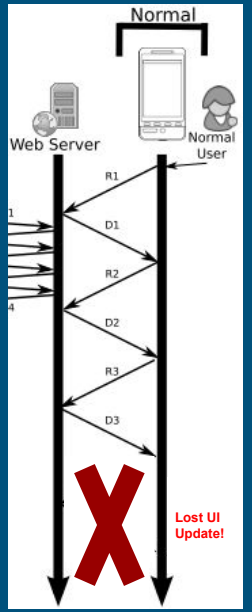




Mobile Computing Workload (2)

- Over-the-air comms with lost connectivity causes slower (or lost) UI responsiveness
  - In reality no datagram is sent as a single payload, so multiple request/response pairs are always needed
- The challenge is to find a dynamic way to support both of these problems



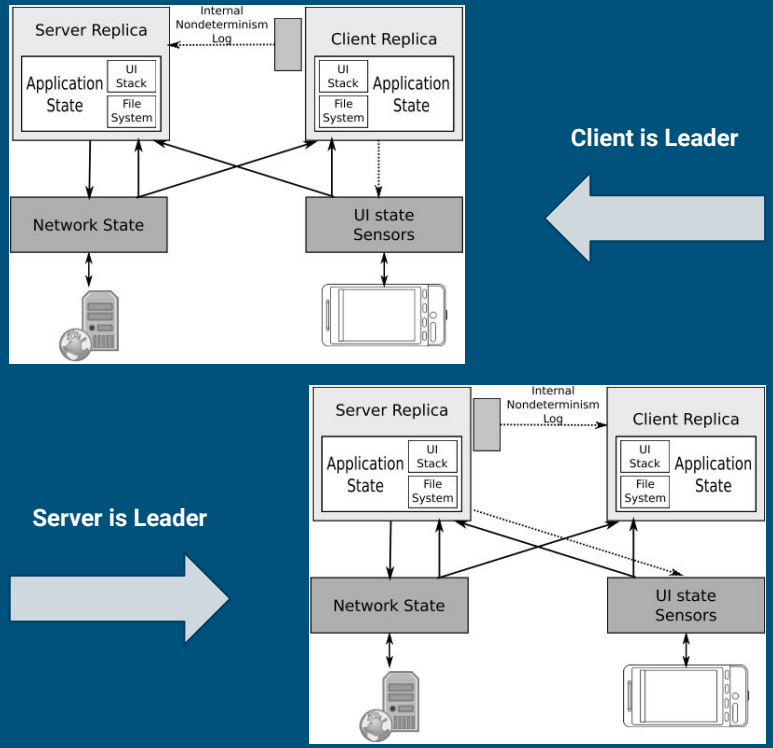


"The fundamental problem is that the right place to run a program depends on many factors."

How Tango Reduces Application Latency

1. Introduce a replica on both mobile & remote platforms, allowing either to send output to the user
2. Use *deterministic replay* to ensure the replicas perform the same computations & outputs
3. Share role of logging non-deterministic inputs from external sources & externalizing outputs
4. Replicate I/O sources to reduce amount of non-determinism
5. Allow replicas to log internal sources of non-determinism (thread & event scheduling, time queries, etc.)

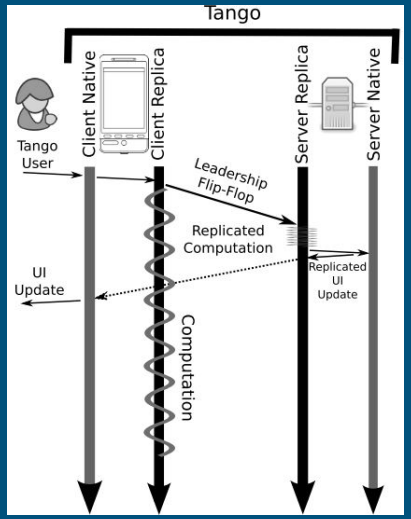
Architectural Overview



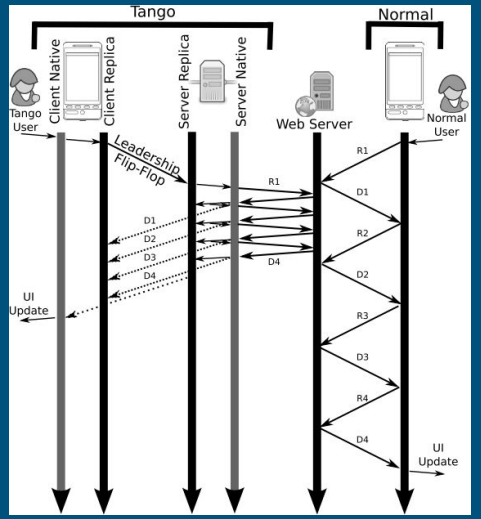
- Replicated targets run in Dalvik VMs executing the same application
  - Enforces deterministic co-execution independent of native ISAs; whatever source finishes first becomes “leader”
  - Supported by replicating native methods that the VM invokes (e.g., `java.math` functions)
  - Each application has frequent UI stack interactions; provides a “finish-line”
- External non-replicated parts (e.g., I/O) are executed on the replica first until native method is called; resulting state and return transferred to follower replica
- Internal non-replicated parts (e.g., scheduling decisions) are controlled by Tango itself to enforce determinism
  - Events elevate replica to leader status, thus state is transferred to follower replica

Example

- **User interacts with application UI; events are broadcast to both replicas**
  - Client replica is Leader because it receives UI inputs first
  - Server replica gets inputs as a pipeline before asking
- **Application enters compute-intensive phase**
  - Server replica quickly catches up to Client compute stage, flip-flops leadership
  - Server eventually calls UI methods, send results directly to client
- **Application enters network-intensive phase**
  - Server replica assumes leadership since it has faster comms (running at data center)
  - Responses sent in pipeline fashion like compute-intensive phase (one-way network delay!)
  - With small amount of computational burden, Client replica catches up, flip-flops leadership while waiting on remote responses



Compute Intensive Phase



Network Intensive Phase
(with & without Tango)

Implementation (1) - Threads & Native Methods

- Utilize *single managed threads* with a deterministic scheduling algorithm
  - Thread is managed any time it directly interacts with Dalvik VM state
  - Context switching of threads is round-robin

- When Java thread invokes a native method (via JNI), Tango moves thread to unmanaged execution; upon completion, thread is moved back to managed-mode
  - To prevent divergence, both replicas must agree on when an asynchronous event happens
  - Note, native method executions happen on *native threads*; Tango synchronizes these threads so they don't conflict

Implementation (2) - External Nondeterminism

- Proxy threads are run on both replicas to receive external inputs; Leader decides on *when* data arrives within replicated execution stream
- Network transmits are server-replica responsibilities; receives pushed to both replicas; leader decides on timing & results of `poll` & `select`
- UI handled similarly as network, but is client-replica responsibility
- Tango replicates application-specific portion of file system on both replicas by having each update their own local copies
  - External memory (e.g., SD card) are run by native thread on client, so server-replica gets copy
- Leader controls timestamp returns

Implementation (3) - Leadership & Server Faults

- Leader periodically messages Follower asking if it will accept leadership
  - Message contains current point of execution and pauses for response
  - Rejected leadership switch incurs a round-trip time (RTT) delay
- Since switching is cheap, requests are made when current leader has a dependency which incurs a RTT cost, but challenging to do when computation is significant
  - Prediction is supported by tracking how much computation has been completed since previous native method call
- When remote-leader is unable to communicate with client-follower, follower relies on a backup
  - A backup server located near the remote replica captures a log of non-deterministic operations
  - Will continue as non-replicated application when it’s caught up

Evaluation - Methodology

- Macrobenchmarks tested with & without tango on Samsung Galaxy S3 with Android 4.2.2
  - Network latency emulated via USB & netem rules for repeatability
  - No JIT support
- Sudoku & Poker selected as compute-intensive apps
- Hoot, TapTu, Email, Instagram, & Pinterest selected as network-intensive apps
- In addition to timely performance, energy consumption is also considered

Benchmark	Package	Network RTTs
Sudoku	de.georgwiese.sudokusolver	N/A
Poker	com.leslie.cjpokeroddscaculator	N/A
Hoot	com.hootsuite.droid.full	5
TapTu	com.taptu.streams	4
Email	com.android.email	4
Instagram	com.instagram.android	3
Pinterest	com.pintrerest	2-8

Evaluation - Compute Intensive Results

- Measured time from user input to screen update as perceived latency; 10 samples per configuration each
- Tango reduces perceived user latency in all cases compared with baseline
- Performance seems to bottleneck due to client-replica CPU contention

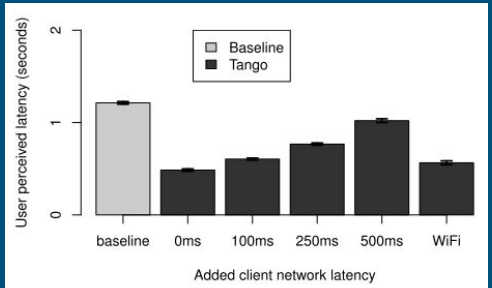


Figure 5: Sudoku performance

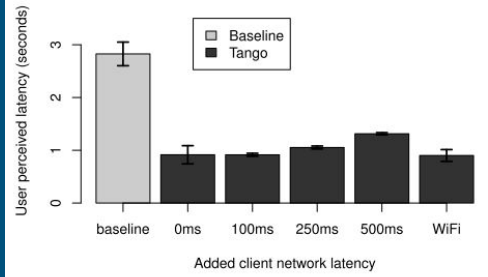


Figure 6: Poker performance

Evaluation - Compute Intensive Results

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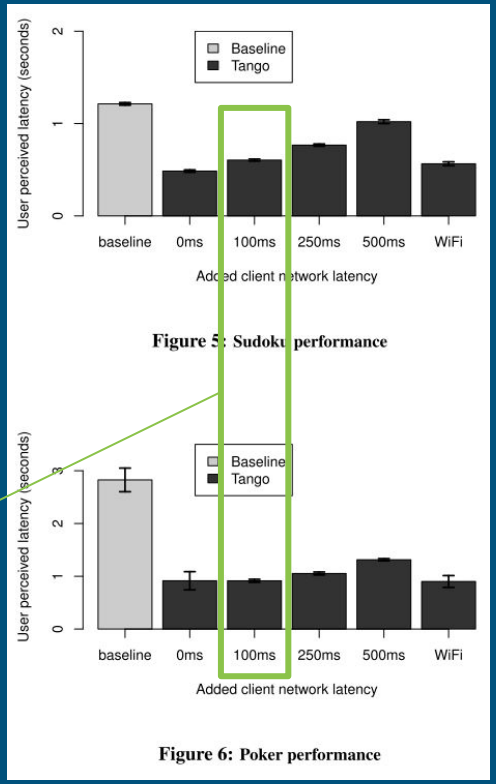
Typical LTE network delay!



Evaluation - Network Intensive Results

- Measured time from user input to screen update as perceived latency; 14 samples per configuration each
- Tango achieves latency speedup from 1.3-2.6x compared to baselines experiencing equivalent network delays
- Speedup can be attributed to needing fewer network request/response pairings (~1.03/sec compared to ~4.17/sec)

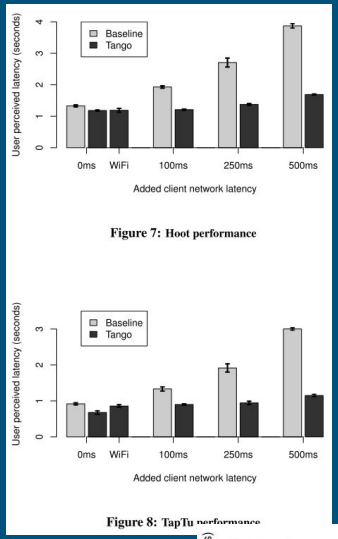


Figure 7: Hoot performance

Figure 8: TapTu performance

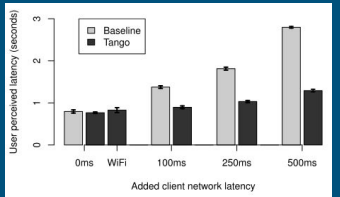


Figure 9: Email performance

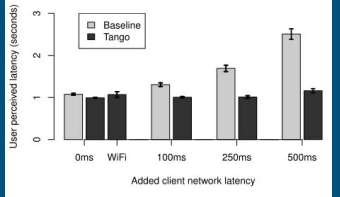


Figure 10: Instagram performance

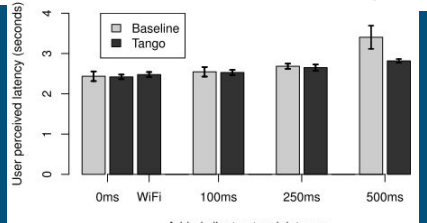


Figure 11: Pinterest performance

Evaluation - Energy Consumption

- Measurement assumes user pauses after screen update (3s for Poker, 1s for rest) plus time to finish all computation on both client & server; 10 samples
- Tango does offer an energy reduction in most cases, but not consistent
- Can be attributed to increased overhead adding to energy cost even though there is reduced completion times

Application	Baseline (J)	Tango (J)	%Change
Sudoku	2.47±.18	2.43±.17	-1.62%
Poker	7.14±.41	5.43±.22	-23.9%
Hoot	2.77±.15	2.46±.21	-11.2%
Taptu	2.14±.23	1.74±.21	-18.7%
Email	1.74±.12	1.78±.18	+2.30%
Instagram	2.26±.16	2.35±.20	+3.98%
Pinterest	4.16±.49	4.06±.30	-2.40%

Lessons Learned (1)

- Retrofitting platforms with Tango is not trivial
  - Using VMs did not always provide clean application partitioning
  - Supporting unmodified applications proved challenging, prevents many applications from gaining benefits
  - Effectively as complex as adding a deterministic hypervisor on top of a GPOS
- Most Android apps execute large numbers of native methods; trend seems to be increasing
  - Challenge is to identify & categorize (and possibly supply deterministic implementations) of appropriate methods
  - Heavy use of WebKit in many applications
- Supporting JIT and Ahead-of-Time compilation (ART) needs engineering effort and porting

Lessons Learned (2)

- Originally Tango was envisioned to support computation-heavy applications; surprisingly supports network-intensive applications!
  - Reduces developer workload because now they don't need to consider RTT costs as strongly in design

- Tango has limitations
  - Dealing with false dependencies among threads (e.g., one client thread sends, another receives) can hinder leadership decisions
  - Serialization of all managed threads impacts computation-heavy applications, prevents full client-side resource utilization
  - Leader-switch decision is still difficult to optimize

Advancements since Tango

- Many “direct” descendant applications!
- DeepWear (Xu2019)
  - Wearable devices have ***even less*** resources than cellular devices, but has DL needs; consider context-aware scheduling, partial offloading, and data streaming
- Web App Computational Offloading for ML (Jeong2018)
  - DNNs have huge computational costs; web app performance needs to contextually know when to schedule remote computation offloading
- Adaptive Cloud Offloading for Vehicles (Ashok2016)
  - Vehicles themselves are mobile devices, but have large sensory data inputs and extraordinary computational needs, so adaptive offload specific applications and decide when/which

Conclusion

- Tango provides a way to synergistically toggle client/edge resources by having both operate in parallel with appropriate synch-points
- Tango provides improvements to both computationally-intensive and network-intensive applications with little impact to SW devs
- Resounding focus has been to adaptively decide when to switch leadership/offloading and to apply it to other “traditionally not” mobile applications

Backup

References

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