The Art of Consistent SDN Updates

Stefan Schmid
Aalborg University
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Smart students in Berlin & Wroclaw:
Arne Ludwig, Jan Marcinkowski, Szymon Dudycz, Matthias Rost, Damien Foucard, Saeed Amiri
SDN: Algorithms *with a fundamental twist*!
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Applications and Control Plane

... and regarding decoupling / inter-connect!

Data Plane
SDN/OpenFlow is about **generality and flexibility**: in terms of how packets are matched (L2-L4 header fields and beyond), how **flows are defined** (fine vs coarse granular, proactive vs reactive), events can be handled **centrally vs in a distributed manner**, etc.

But there are also constraints and challenges: SDN is an inherently **asynchronous distributed system** (controller decoupled), switches are **simple devices** (not a Turing or even state machine!), IP-routing is prefix based, careful use of dynamic flexibilities: **don’t shoot in your foot!**
Applications: Algorithms with *a twist*!

- Let’s consider: Traffic Engineering
  - Circuit routing, **call admission**
  - Raghavan, Wolsey, Awerbuch, etc.

- **SDN twist:** more general/flexible!
  - **Non-shortest** paths and more
  - Enables **complex network services:**
    steer traffic through middleboxes i.e. **waypoints** (firewall, proxy etc.): paths may contain **loops**!
  - More than independent routing per segment: **none-or-all segment admission control**, joint optimization
  - E.g., LP relaxation (Raghavan et al.):
    how to **randomly round and decompose** complex requests?
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Optionally NFV twist: where to place NFV (or hybrid SDN)? Facility location / capacitated dominating set, but: not distance to but distance via function(s) matters!

Facility location / capacitated dominating set, but: not distance to but distance via function(s) matters!
Applications: Algorithms *with a twist*!

- **Levitating Dots**
- **SDN twist**
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**Online Admission Control and Embedding of Service Chains**
Tamás Lukovszki and Stefan Schmid.
22nd International Colloquium on Structural Information and Communication Complexity (SIROCCO), Montserrat, Spain, July 2015.

**Service Chain and Virtual Network Embeddings: Approximations using Randomized Rounding**
Matthias Rost and Stefan Schmid.
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Migration upon each new request undesirable: want incremental deployment! Related to submodular capacitated set cover and scheduling (Fleischer, Khuller), but end-to-end.

decompose complex requests?
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It’s a Match! Near-Optimal and Incremental Middlebox Deployment
Tamás Lukovszki, Matthias Rost, and Stefan Schmid.
Control Plane: Algorithms *with a twist!*

- **Reduce latency and overhead:** What can be computed locally?
  - Routing vs heavy-hitter detection?
  - LOCAL model! Insights apply: verification vs optimization

- **SDN twist: pre-processing!**
  - Hard in LOCAL: symmetry breaking! But unlike ad-hoc networks: no need to discover network from scratch
  - Topology events *less frequent* than flow related events
  - If links fail: subgraph! Find recomputed structures that are still useful in subgraph (e.g., *proof labelings*)
  - Precomputation known to help for relevant problems: *load-balancing / matching*
Control Plane: Algorithms *with a twist*!

- How to make control plane robust? **Software transactional memory** problem: network configuration = shared memory, updates = **transactions**, but *with a twist*: flows are uncontrolled, real-time transactions: do not abort! (And not only read!)

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*A Distributed and Robust SDN Control Plane for Transactional Network Updates*
Marco Canini, Petr Kuznetsov, Dan Levin, and Stefan Schmid. 34th IEEE Conference on Computer Communications (*INFOCOM*), Hong Kong, April 2015.
Control Plane: Algorithms *with a twist*

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Careful: independent flow spaces does not imply that controllers can *concurrently* update without *conflict*: e.g., due to *shared embedding*! Atomic read-modify-write?

relevant problems: *load-balancing / matching*
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Atomic read-modify-write relevant problems: load-balancing/matching

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In-Band Synchronization for Distributed SDN Control Planes
Liron Schiff, Petr Kuznetsov, and Stefan Schmid.
Data Plane: Algorithms with a twist!

- Even in SDN: Keep some functionality in the data plane!
  - E.g., for **performance**: OpenFlow local fast failover: 1st line of defense

- **SDN twist**: data plane algorithms operate under simple conditions
  - Failover tables are **statically** (proactively) preconfigured, w/o multiple failures knowledge
  - At runtime: **local view only** and **header space is scarce resource**
  - W/ tagging: **graph exploration**
  - W/o tagging: **combinatorial problem**
  - Later: **consolidate this with controller**!
Data Plane: Algorithms *with a twist*!

- With **infinite header space** ideal robustness possible. But what about bounded header space? And resulting route lengths?

- **Without good algorithms, routing may disconnect way before physical network does!**

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  - Operate under simple conditions.
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**How (Not) to Shoot in Your Foot with SDN Local Fast Failover: A Load-Connectivity Tradeoff**
Michael Borokhovich and Stefan Schmid.

**Provable Data Plane Connectivity with Local Fast Failover: Introducing OpenFlow Graph Algorithms**
Michael Borokhovich, Liron Schiff, and Stefan Schmid.
Decoupling: Algorithms *with a twist*!

- Decoupling already challenging for a single switch!

- Network *Hello World* application: MAC learning

- MAC learning has *SDN twist*: MAC learning SDN controller is **decoupled**: may miss response and keep flooding!

- Need to **configure rules** s.t. controller stays informed when necessary!
Decoupling: Algorithms with a twist!

- In-band control: cheap but algorithmically challenging!
  - Distributed coordination algorithms to manage switches?
  - Powerful fault-tolerance concept: self-stabilization

- **SDN twist**: switches are simple!
  - Cannot actively participate in arbitrary self-stab spanning tree protocols
  - Controller needs to install tree rules
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**Ground Control to Major Faults: Towards a Fault Tolerant and Adaptive SDN Control Network**
Liron Schiff, Stefan Schmid, and Marco Canini.
IEEE/IFIP DSN Workshop on Dependability Issues on SDN and NFV (DISN), Toulouse, France, June 2016.
Decoupling: Algorithms *with a twist*!

- Researchers proposed to *exploit SDN* rule definition flexibilities to solve growing FIB size problem
  - OpenFlow-based IP router: caching and aggregation
  - *Zipf law*: many infrequent prefixes at controller
  - Extremely distributed control 😊

- Online paging *with SDN twist*
  - Forwarding semantic: largest common prefix forwarding, i.e., dependencies: only offload root-contiguous set in trie
  - Can do *bypassing*
Decoupling: Algorithms *with a twist!*

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**Competitive FIB Aggregation without Update Churn**
Marcin Bienkowski, Nadi Sarrar, Stefan Schmid, and Steve Uhlig.
34th International Conference on Distributed Computing Systems (ICDCS), Madrid, Spain, June 2014.

**Online Tree Caching**
Marcin Bienkowski, Jan Marcinkowski, Maciej Pacut, Stefan Schmid, and Aleksandra Spyra.
Another challenge: asynchronous communication channel

He et al., ACM SOSR 2015: without network latency
Interconnect: Algorithms *with a twist*!

- Another challenge: asynchronous communication channel

Not only because of network latency, but also data structures!

He et al., ACM SOSR 2015: without network latency
What can possibly go wrong?

**Invariant:** Traffic from untrusted hosts to trusted hosts via firewall!
What can possibly go wrong?

Invariant: Traffic from untrusted hosts to trusted hosts via firewall!
Example 1: Bypassed Waypoint

Controller Platform

insecure Internet

secure zone
Example 2: *Transient* Loop

Controller Platform

insecure Internet

secure zone
Tagging: A Universal Solution?

- Old route: red
- New route: blue

2-Phase Update:
- Install blue flow rules internally
- Flip tag at ingress ports
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- Old route: red
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2-Phase Update:
- Install blue flow rules internally
- Flip tag at ingress ports

Cost of extra rules? Where to tag? Header space? Overhead?

Time till new link becomes available?
Alternative: Weaker Transient Consistency

**Idea:** Packet may take a mix of old and new path, as long as weaker consistencies are fulfilled transiently, e.g. Loop-Freedom (LF) and Waypoint Enforcement (WPE).

**Schedule** safe subsets in **multiple rounds**

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**Round 1**

Controller Platform

**Round 2**

Controller Platform

...
The Spectrum of Consistency

- **Strong**
  - **Correct network virtualization**
    - Ghorbani and Godfrey, HotSDN 2014

- **Weak, transient consistency**
  - (loop-freedom, waypoint enforced)
    - Mahajan and Wattenhofer, HotNets 2014
    - Ludwig et al., HotNets 2014

- **Per-packet consistency**
  - Reitblatt et al., SIGCOMM 2012
Going Back to Our Examples: LF Update?

insecure Internet → secure zone

secure zone → insecure Internet
Going Back to Our Examples: LF Update!

R1:
- Insecure Internet
- Secure zone

R2:
- Insecure Internet
- Secure zone
Going Back to Our Examples: LF Update!

R1: LF ok! But: WPE violated in Round 1!

R2:
Going Back to Our Examples: WPE Update?

insecure Internet → something → firewall → something → secure zone

Note: The diagram illustrates the flow from an insecure internet to a secure zone with a firewall in between. The text suggests a discussion on whether it's safe to go back to the examples with regards to WPE update.
Going Back to Our Examples: WPE Update!

R1:
- Insecure Internet
- Secure zone

R2:
- Insecure Internet
- Secure zone
Going Back to Our Examples: WPE Update!

R1: insecure Internet → ... → insecure Internet → secure zone

R2: insecure Internet → ... → insecure Internet → red square → secure zone

... ok but may violate LF in Round 1!
Going Back to Our Examples: Both WPE+LF?

insecure Internet → [ ] → [ ] → secure zone

- Dashed arrows indicate possible paths.
- Solid arrows show the primary flow.
Going Back to Our Examples: WPE+LF!

R1: R2: R3:
Going Back to Our Examples: WPE+LF!

R1: insecure Internet → secure zone

R2: insecure Internet → secure zone

R3: Is there always a WPE+LF schedule?
What about this one?
LF and WPE may conflict!

- Cannot update any **forward edge** in R1: WP
- Cannot update any **backward edge** in R1: LF

No schedule exists!
LF and WPE may conflict!

- Cannot update any **forward edge** in R1: WP
- Cannot update any **backward edge** in R1: LF

Good Network Updates for Bad Packets: Waypoint Enforcement Beyond Destination-Based Routing Policies
Arne Ludwig, Matthias Rost, Damien Foucard, and Stefan Schmid. 13th ACM Workshop on Hot Topics in Networks (HotNets), Los Angeles, California, USA, October 2014.
What about this one?
What about this one?

- Forward edge after the waypoint: safe!
- No loop, no WPE violation
What about this one?

- Now this backward is safe too!
- No loop because exit through 1
What about this one?

Now this is safe: 2 ready back to WP!

No waypoint violation
What about this one?

☐ Ok: loop-free and also not on the path (exit via 1)
What about this one?

- Ok: loop-free and also not on the path (exit via 1)
What about this one?
Back to the start: What if....
Back to the start: What if.... also this one?!
Back to the start: What if.... also this one?!

- Update any of the 2 backward edges? LF 😞
Back to the start: What if.... also this one?!

- Update any of the 2 backward edges? LF 😞
Back to the start: What if.... also this one?! 

Update any of the 2 backward edges? LF 😞
Back to the start: What if.... also this one?!

- Update any of the 2 backward edges? LF 😞
- Update any of the 2 other forward edges? WPE 😞
- What about a combination? Nope...
Back to the start: What if.... also this one?!
Back to the start: What if.... also this one?!

To update or not to update in the first round?
That is the question…
... which leads to NP-hardness!
To update or not to update in the first round? That is the question...
... which leads to NP-hardness!
Let us focus on **loop-freedom only**: always possible in $n$ rounds! (How?) But how to minimize rounds?
Example: Optimal 2-Round Update Schedules
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Clear: in Round 1 (R1), I can only update „forward“ links!

What about last round? Observe: Update schedule read backward (i.e., updating from new to old policy), must also be legal! I.e., in last round (R2), I can do all „forward“ edges of old edges wrt to new ones! Symmetry!
Optimal Algorithm for 2-Round Instances: Leveraging Symmetry!

- Classify nodes/edges with 2-letter code:
  - F, B: Does (dashed) new edge point forward or backward wrt (solid) old path?
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- Classify nodes/edges with 2-letter code:
  - F●, B●: Does (dashed) new edge point forward or backward wrt (solid) old path?

Old policy from left to right!
Optimal Algorithm for 2-Round Instances: Leveraging Symmetry!

Classify nodes/edges with 2-letter code:

- F○, B○: Does (dashed) new edge point forward or backward wrt (solid) old path?

Old policy from left to right!

New policy from left to right!
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New policy from left to right!

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Old policy from left to right!

New policy from left to right!
**Insight 1**: In the 1st round, I can safely update all forwarding (F•) edges! For sure loopfree.

- F•, B•: Does (dashed) new edge point forward or backward wrt (solid) old path?

- •F, •B: Does the (solid) old edge point forward or backward wrt (dashed) new path?
Optimal Algorithm for 2-Round Instances: Leveraging Symmetry!

**Insight 1:** In the 1st round, I can safely update all forwarding (F•) edges! For sure loopfree.

**Insight 2:** Valid schedules are reversible! A valid schedule from old to new read backward is a valid schedule for new to old! Old edge point forward or backward wrt (dashed) new path?
Optimal Algorithm for 2-Round Instances: Leveraging Symmetry!

**Insight 1:** In the 1st round, I can safely update all forwarding (F•) edges! For sure loopfree.

**Insight 2:** Valid schedules are reversible! A valid schedule from old to new read backward is a valid schedule for new to old!

**Insight 3:** Hence in the last round, I can safely update all forwarding (●F) edges! For sure loopfree.
Optimal Algorithm for 2-Round Instances: Leveraging Symmetry!

**Insight 1:** In the 1st round, I can safely update all forwarding (F•) edges! For sure loopfree.

**Insight 2:** Valid schedules are reversible! A valid schedule from old to new *read backward* is a valid schedule for new to old!

**Insight 3:** Hence in the last round, I can safely update all forwarding (•F) edges! For sure loopfree.

**2-Round Schedule:** If and only if there are no BB edges! Then I can update F• edges in first round and •F edges in second round!
**Optimal Algorithm for 2-Round Instances:**

**Leveraging Symmetry!**

- **Insight 1:** In the 1st round, I can safely update all forwarding (F●) edges! For sure loopfree.

- **Insight 2:** Valid schedules are reversible! A valid schedule from old to new *read backward* is a valid schedule for new to old!

- **Insight 3:** Hence in the last round, I can safely update all forwarding (●F) edges! For sure loopfree.

**2-Round Schedule:** If and only if there are no BB edges! Then I can update F● edges in first round and ●F edges in second round!

That is, FB *must be* in first round, BF *must be* in second round, and FF are *flexible*!
Intuition Why 3 Rounds Are Hard

Structure of a 3-round schedule:

- Round 1: FF, FB
- Round 2: FF, FB, BF, BB
- Round 3: FF, BF

W.l.o.g., can do FB in R1 and BF in R3.

Boils down to:

FF
Intuition Why 3 Rounds Are Hard

Structure of a 3-round schedule:

- **Round 1**: FF, FB
- **Round 2**: FF, FB, BF, BB
- **Round 3**: FF, FB, BF, BB

Moving forward edges does not introduce loops, nor does making the graph sparser.

W.l.o.g., can do FB in R1 and BF in R3.

Boils down to:

- FF
A hard decision problem: when to update FF?

- We know: BB node $v_6$ can only be updated in R2
- When to update FF nodes to make enable update BB in R2?
Intuition Why 3 Rounds Are Hard

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- But only if FF-node $v_3$ is not updated as well in R1: potential loop

No exit from loop!
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- Smells like a gadget: which FF nodes to update when is hard!
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Being greedy is bad!
Don’t update all FF!
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A hard decision problem:

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- When to update **FF nodes** to make enable update BB in R2
- E.g., updating FF-node $v_4$ in R1 allows to update BB $v_6$ in R2
- But only if FF-node $v_3$ is not updated **as well** in R1: potential loop
- **Smells like a gadget:** which FF nodes to update when is hard!

Devil lies in details: original paths must also be valid! I.e., to prove that such a configuration can be reached.

Being greedy is bad! Don’t update all FF!
It’s Good to Relax: How to update LF?
LF Updates Can Take Many Rounds!

Invariant: need to update $v_2$ before $v_3$!
LF Updates Can Take Many Rounds!

Invariant: need to update $v_3$ before $v_4$!
LF Updates Can Take Many Rounds!

Induction: need to update $v_{i-1}$ before $v_i$ (before $v_{i+1}$ etc.)!

$\Omega(n)$ rounds?! In principle, yes...: Need a path back out before updating backward edge!
It is good to relax!

But: If s has been updated, nodes not on (s,d)-path!
It is good to relax!

But: If s has been updated, nodes not on (s,d)-path!

Could be updated simultaneously!
It is good to relax!

Finally put back on path!

But: If $s$ has been updated, nodes not on $(s,d)$-path!

Could be updated simultaneously!
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```plaintext
Finally put back on path!

But: If s has been updated, nodes not on (s,d)-path!

Could be updated simultaneously!

3 rounds only!
```
A log(n)-time Algorithm: Peacock in Action
A log(n)-time Algorithm: *Peacock in Action*

**Shortcut**

**Greedily choose far-reaching (independent) forward edges.**

**Prune**

**Prune**
A log(n)-time Algorithm: *Peacock* in Action

R1 generated many nodes in branches which can be updated simultaneously!
A log(n)-time Algorithm: *Peacock* in Action

Shortcut

Prune

Shortcut

Prune

Line re-established! (all merged with a node on the s-d-path)
Peacock orders nodes wrt to distance: edge of length $x$ can block at most 2 edges of length $x$, so distance $2x$. 

A log(n)-time Algorithm: *Peacock* in Action
A log(n)-time Algorithm: *Peacock* in Action

At least 1/3 of nodes merged in each round pair (shorter s-d path): logarithmic runtime!
A log(n)-time Algorithm: *Peacock in Action*
A log(n)-time Algorithm: *Peacock* in Action

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**Shortcut**

**Prune**

**Shortcut**

**Prune**

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Scheduling Loop-free Network Updates: It's Good to Relax!
Arne Ludwig, Jan Marcinkowski, and Stefan Schmid.
Remark on the Model

Easy to update new nodes which do not appear in old policy. And just keep nodes which are not on new path!
Loop-Freedom: Summary of Results

- Minimizing the **number of rounds**
  - For 2-round instances: polynomial time
  - For 3-round instances: NP-hard, no approximation known

- Relaxed notion of loop-freedom: $O(\log n)$ rounds
  - No approximation known

- Maximizing the **number of updated edges** per round: NP-hard (dual feedback arc set) and bad (large number of rounds)
  - dFASP on simple graphs (out-degree 2 and originates from paths!)
  - Even hard on bounded treewidth?
  - Resulting number of rounds up to $\Omega(n)$ although $O(1)$ possible

- Multiple policies: aggregate updates to given switch!
  - Related to **Shortest Common Supersequence Problem**
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Extension: Multiple Policies

At least one node needs to be **touched** twice: otherwise at least one flow will have a temporary loop:

Worst case: \( k \) policies require \( k \) touches!
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On the positive side: given individual transiently consistent schedules, can optimally combine them using dynamic programming! Independently of the consistency property.
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Can't Touch This: Consistent Network Updates for Multiple Policies
Szymon Dudycz, Arne Ludwig, and Stefan Schmid.
46th IEEE/IFIP International Conference on Dependable Systems and Networks (DSN), Toulouse, France, June 2016.
Conclusion

Applications and Control Programs

E.g., distributed control but also MAC learning (Jen@Dagstuhl)!

... and regarding inter-connect!

E.g., robust failover.

Data Plane

E.g., admission control and routing with waypoints.

E.g., network updates or self-stabilizing in-band control network.
Own References

Can't Touch This: Consistent Network Updates for Multiple Policies
Szymon Dudycz, Arne Ludwig, and Stefan Schmid.
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Michael Borokhovich, Liron Schiff, and Stefan Schmid.