Layered MPC

Perfect MPC over Layered Graphs

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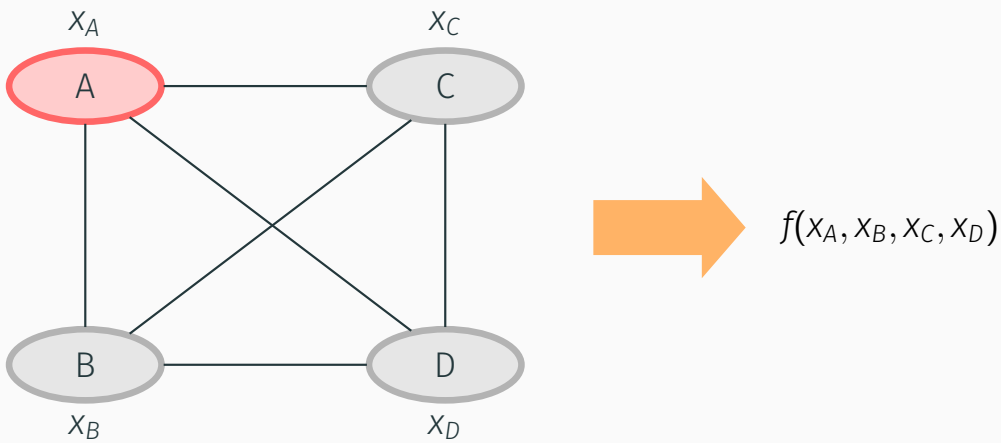
Motivation

Brief History

- [BGW88]: general MPC with perfect, full security and optimal threshold ($t < n/3$).



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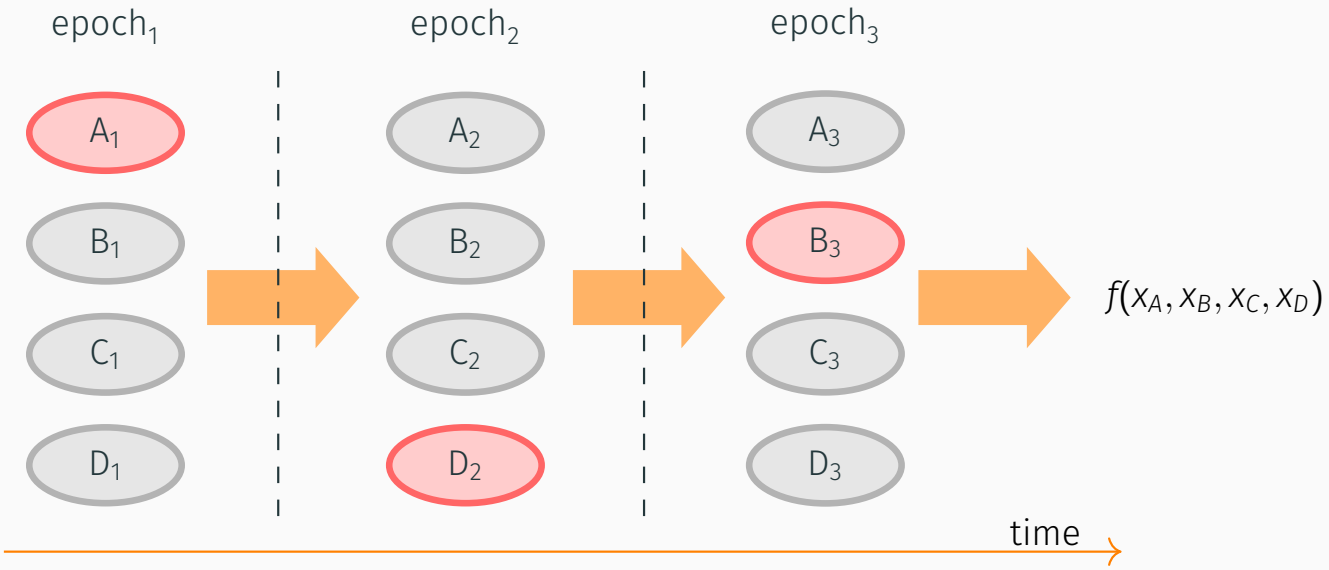
- [BGW88]: general MPC with perfect, full security and optimal threshold ($t < n/3$).
- [OY91]: feasibility result of general MPC with **mobile adversary**
  - Show feasibility of general IT MPC [BGW88, RB89].
- [HJKY95, BELO14, CH01]: **Proactive** Secret Sharing & MPC.



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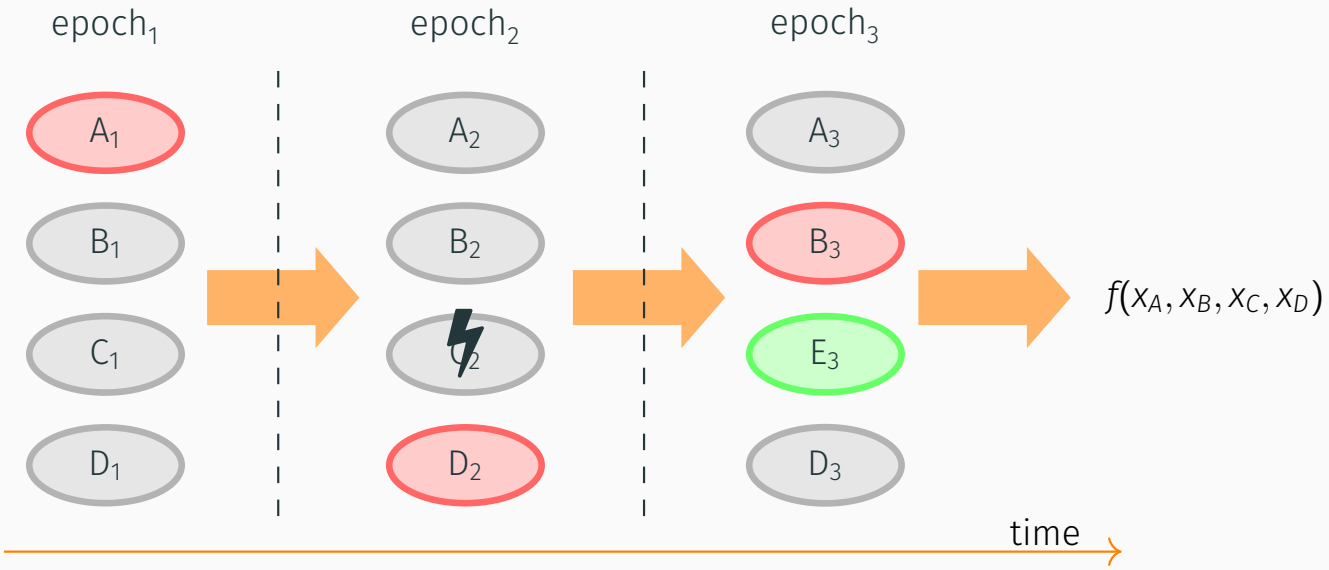

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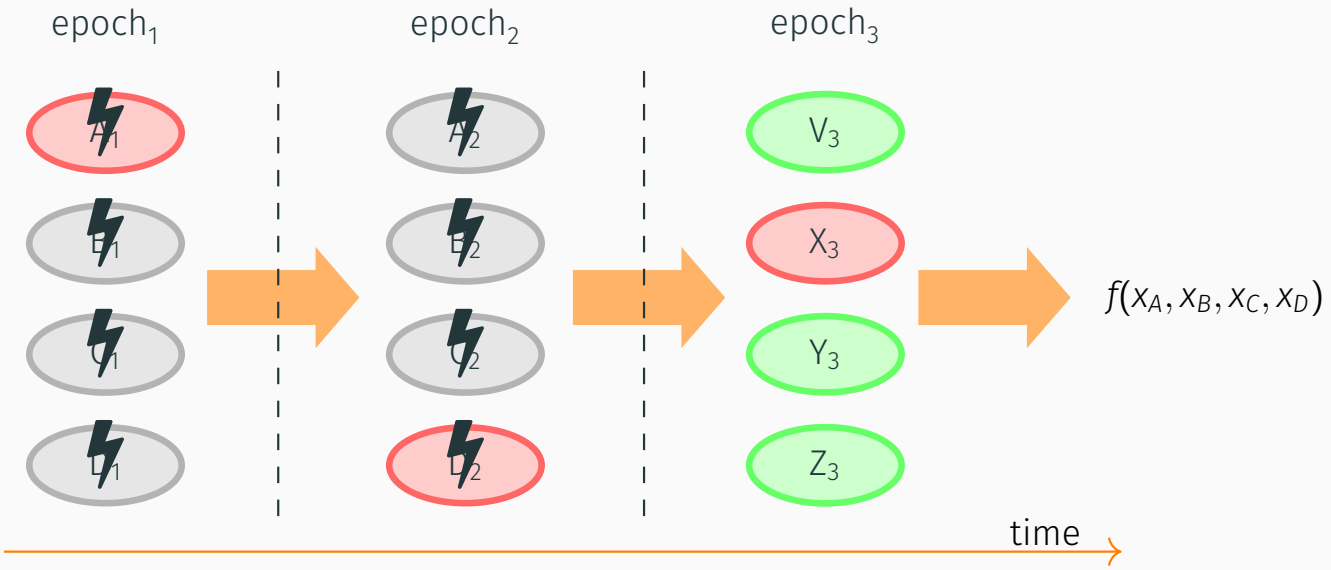
- [GHM+17, BGG+20, GHK+21, CGG+21]: Secret sharing and MPC using **ephemeral committees** (YOSO, Fluid).



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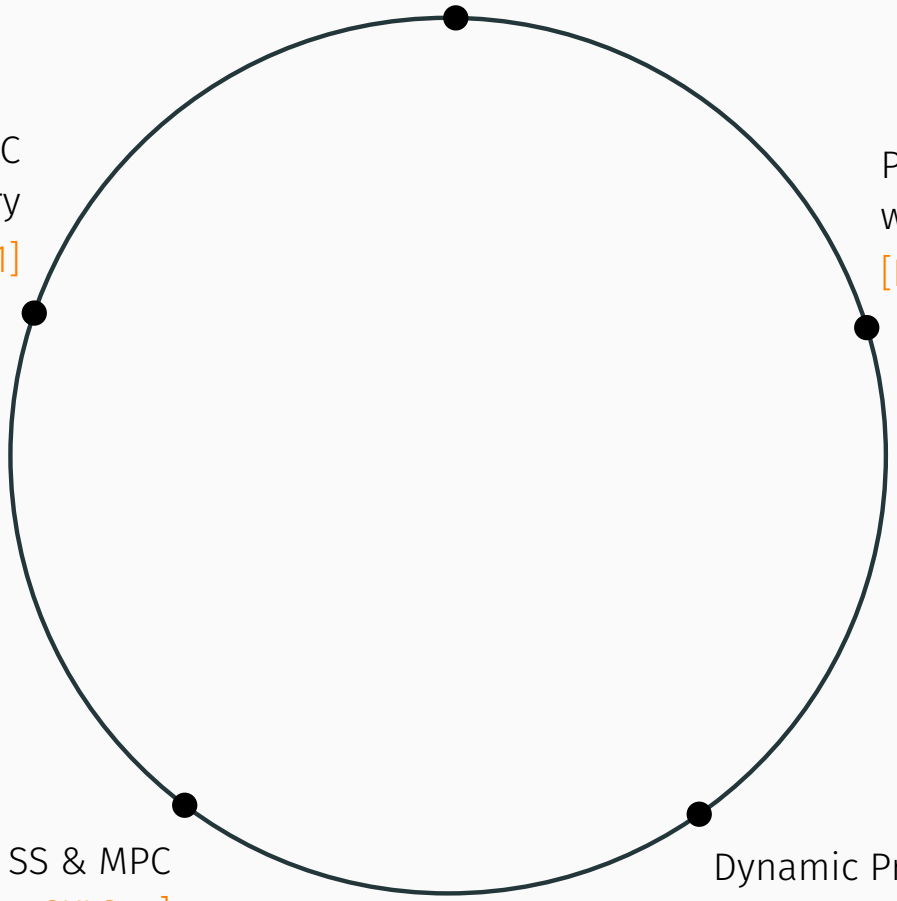

Perfect General MPC, $t < n/3$
[BGW88]

Proactive SS and MPC
w Ephemeral Committees
[BGG+20, GHK+21, CGG+21]

Dynamic Proactive SS & MPC
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Perfect General MPC
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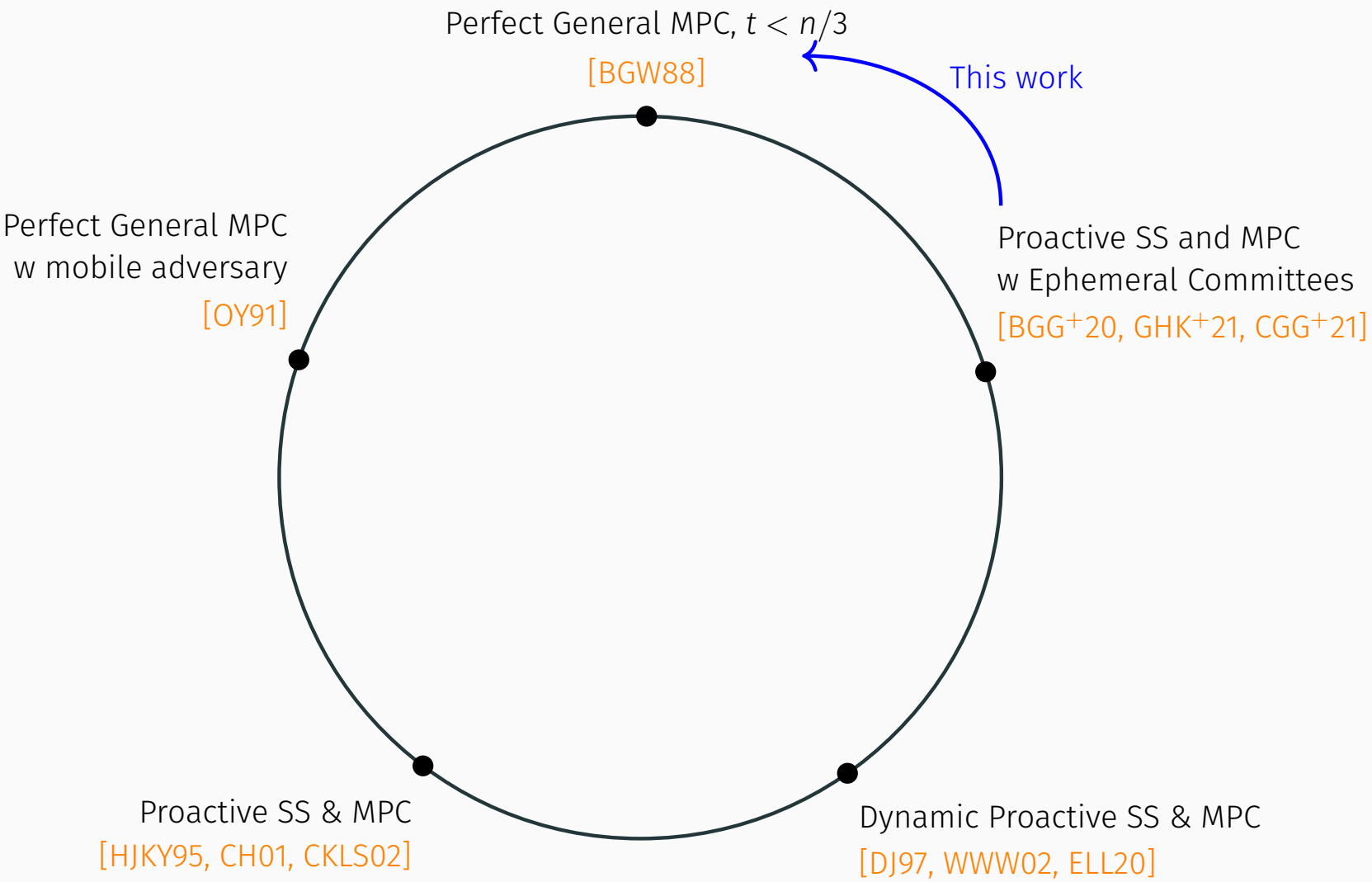

Motivation

Is it possible to construct MPC with **ephemeral committees** *achieving* **perfect full security** *against a* **maximally mobile adversary*** *while maintaining* **optimal corruption threshold***?*

*An epoch contains a single round, $|\text{epoch}| = 1$

Contributions

Area	Reference	|epoch|	Security	Corruption	Setup (BC+Chan.)
Proactive MPC	[HJKY95]	>1	Comp (full)	$t < n/2$	Next Round
	[OY91]	=1	Stat (full)	$t < n/c$[†]	Next Round
Ephemeral Committees	[GHK+21] (YOSO)	=1	Stat (full)	$\mathbb{E}[t] < n/2$	Any Future Round
	[CGG+21] (Fluid)	=1	Stat (abort)	$t < n/2$	Next Round

[†]The adversary may corrupt at most a constant fraction of parties.

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	This work	=1	Perfect (full)	$t < n/3$	Next Round

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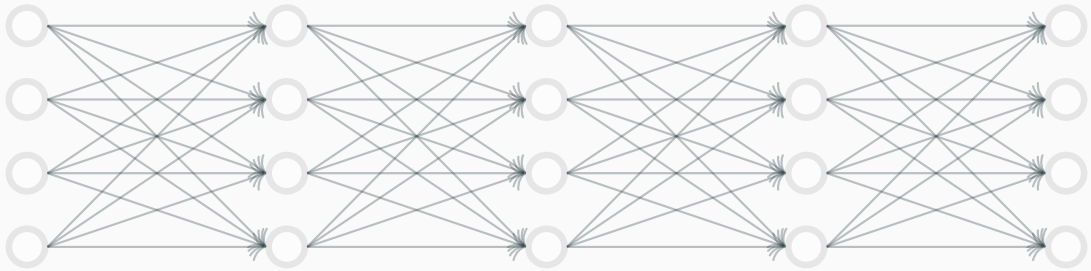
Contributions

Layered MPC is an instance of standard MPC [Can00, Gol09, HM00] with restricted interaction pattern [HIJ+16] induced by a graph G.



Use the setting of layered MPC to (indirectly) study protocols for maximally proactive MPC [OY91].

Lemma 1

Secure Layered MPC $\Rightarrow^*$ Secure Maximally Proactive MPC

* assuming secure erasures

Contributions

Main Contribution:

- Formalize the model of **Layered MPC**—standard MPC with special interaction pattern and adversary structure.

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- Present layered MPC protocols for general functionalities with **perfect, full security** and **optimal corruption threshold** $t < n/3$.
  - CNF (Replicated) Secret Sharing based protocols [GIKR01, Mau06].
  - Shamir Secret Sharing based protocols (efficient) [BGW88].

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- Improve on existing results on **maximally proactive** MPC protocols [OY91] and on new work on MPC with **ephemeral committees** [GHK+21, CGG+21].
- Present layered MPC protocols for general functionalities with **computational, full security** and $t < n/2$.

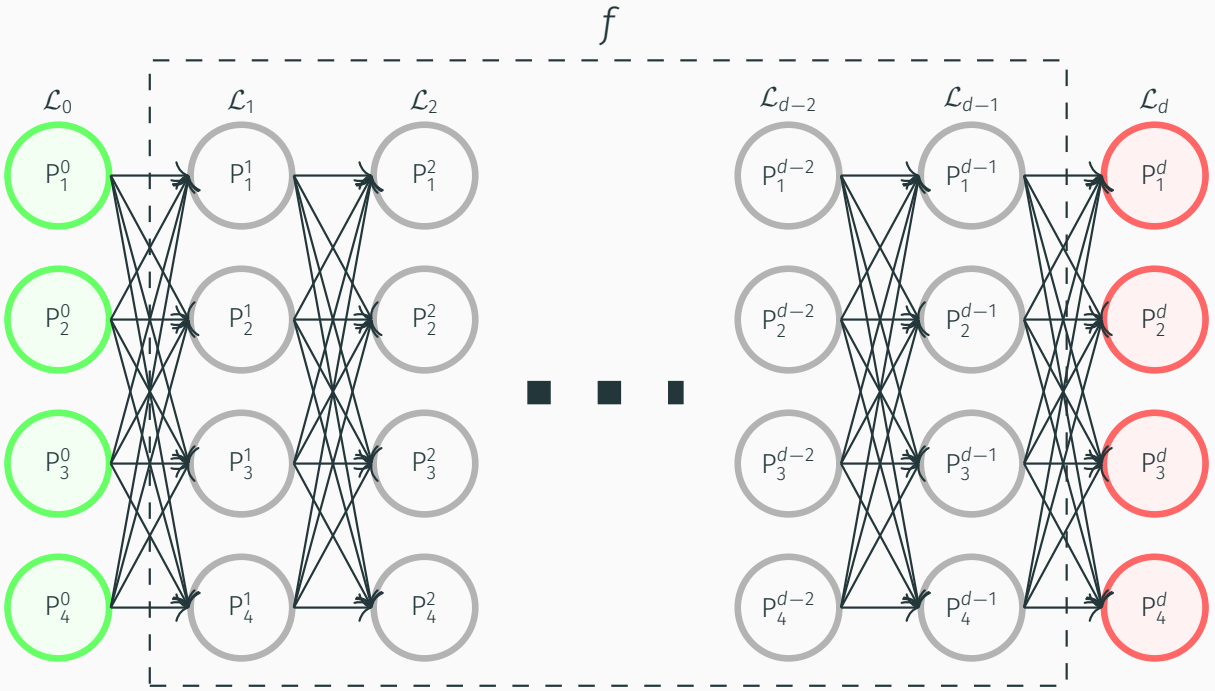
Layered MPC

Layered MPC

An (n, t, d)-**layered protocol** has the following properties:

Parties. $N = n(d+1)$ parties partitioned into $d+1$ layers $\mathcal{L}_i$, $0 \leq i \leq d$, where $|\mathcal{L}_i| = n$.

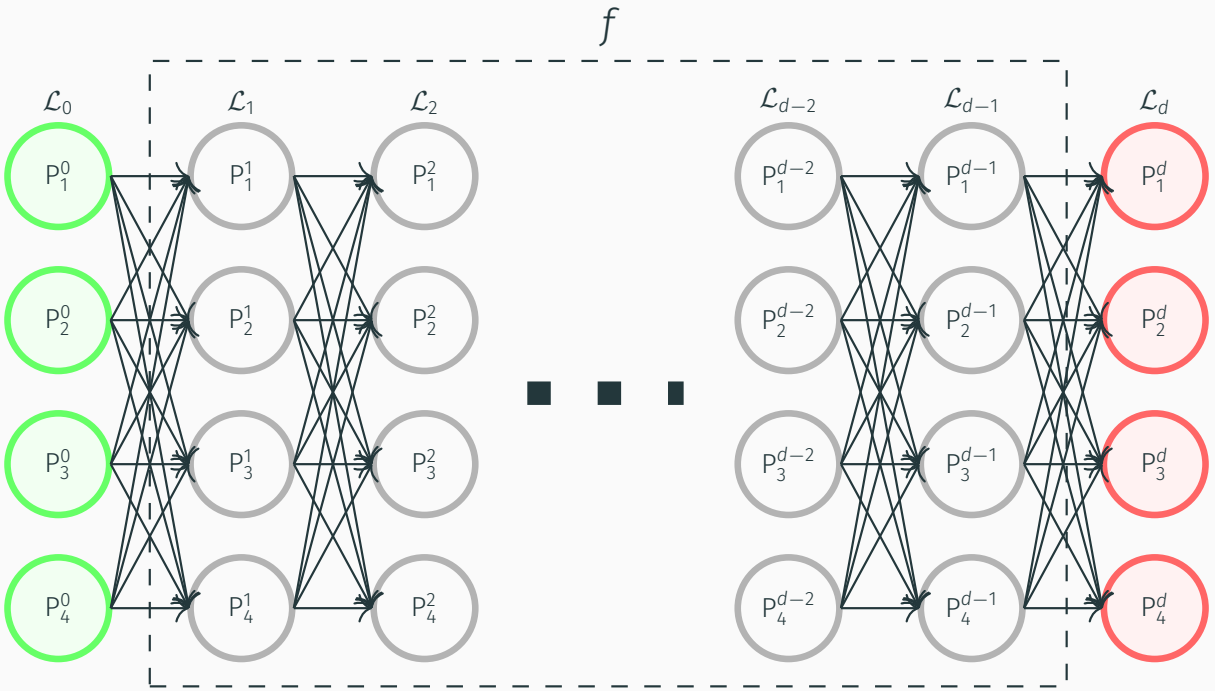
Interaction. d synchronous rounds where parties in $\mathcal{L}_{i-1}$ may send messages to parties in $\mathcal{L}_i$ over secure channels and broadcast.



Layered MPC

Functionalities. We consider functionalities f that take inputs from input clients and deliver outputs to output clients.

Adversaries. We consider active, rushing, adaptive adversaries who may corrupt any number of input/output clients, and t parties in layers $\mathcal{L}_i$, $0 < i < d$.



Layered MPC

A note on Layered Broadcast

- The model of layered MPC assumes layer-to-layer broadcast.
- Deterministic Broadcast is impossible in the layered setting.
- Derived from the result of [Gar94] on reaching agreement in the mobile setting.

Lemma 2

Deterministic Broadcast is possible iff $t = 0$.

Basic Primitives

Future Messaging

Future Messaging functionality f_{FM}

PUBLIC PARAMETERS: Sender $\mathsf{S} \in \mathcal{L}_0$, receiver $\mathsf{R} \in \mathcal{L}_d$ for $d > 0$ and message domain M.

SECRET INPUTS: S has input $m \in M$.

f_{FM} receives m from S, and delivers m to R.

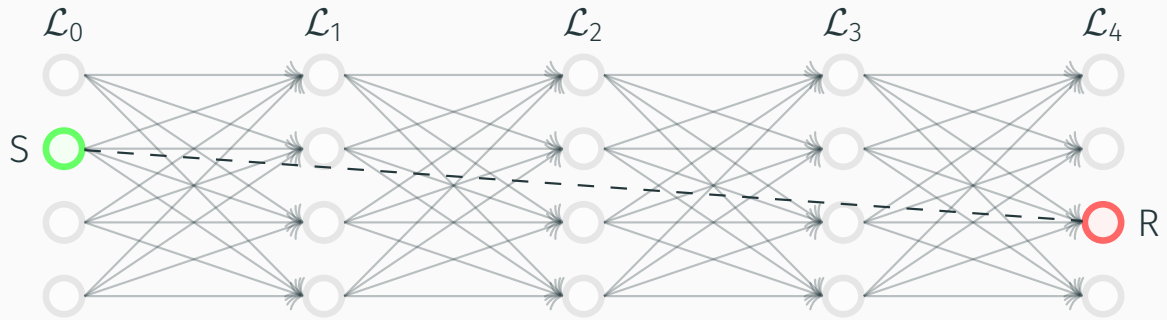
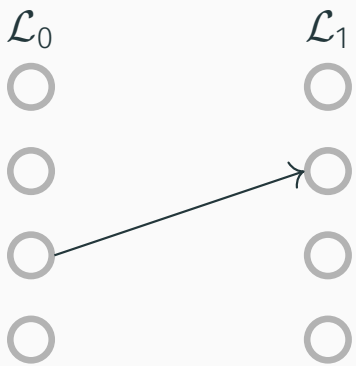


Figure 1: Π_{FM} from S of m to R

Future Messaging

Π_{FM} from $\mathcal{L}_0$ to $\mathcal{L}_1$:

Use the secure point-to-point channels from layer to the next layer.



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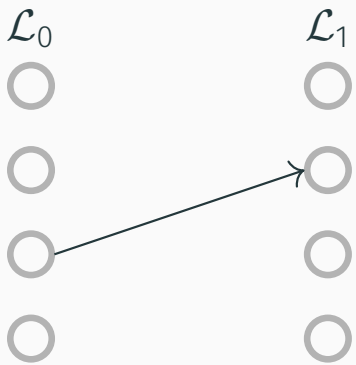
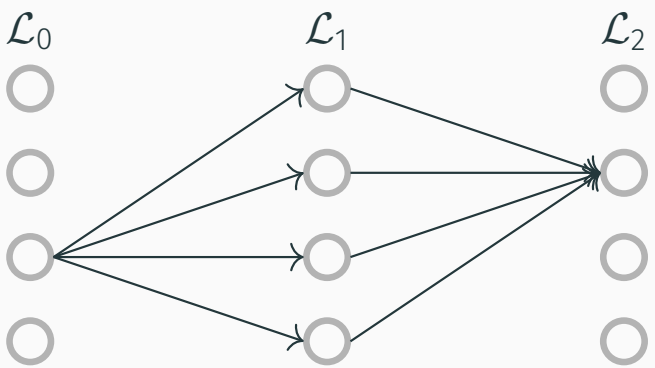


Π_{FM} from $\mathcal{L}_0$ to $\mathcal{L}_2$:

1. S does $\mathrm{Sh}(m) = (s_1, \ldots, s_n)$ and sends s_j to P_j^1.
2. P_j^1 forwards s_j to R and R obtains $\hat{m} = \mathrm{Rec}(\hat{s}_1, \ldots, \hat{s}_n)$



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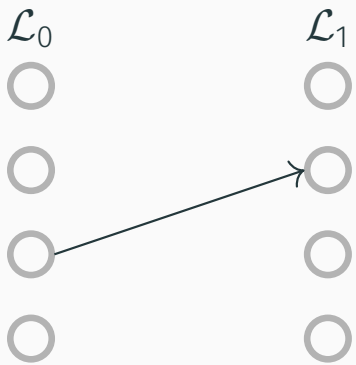

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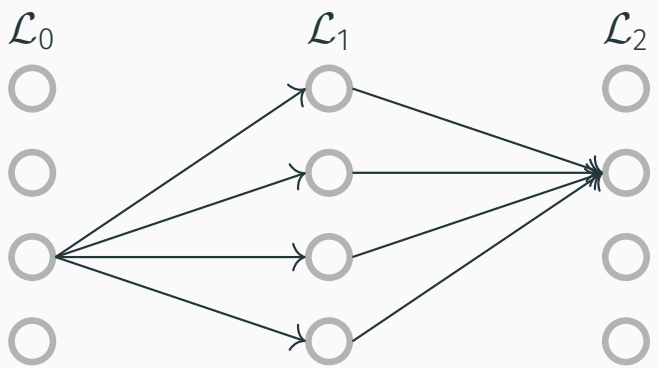
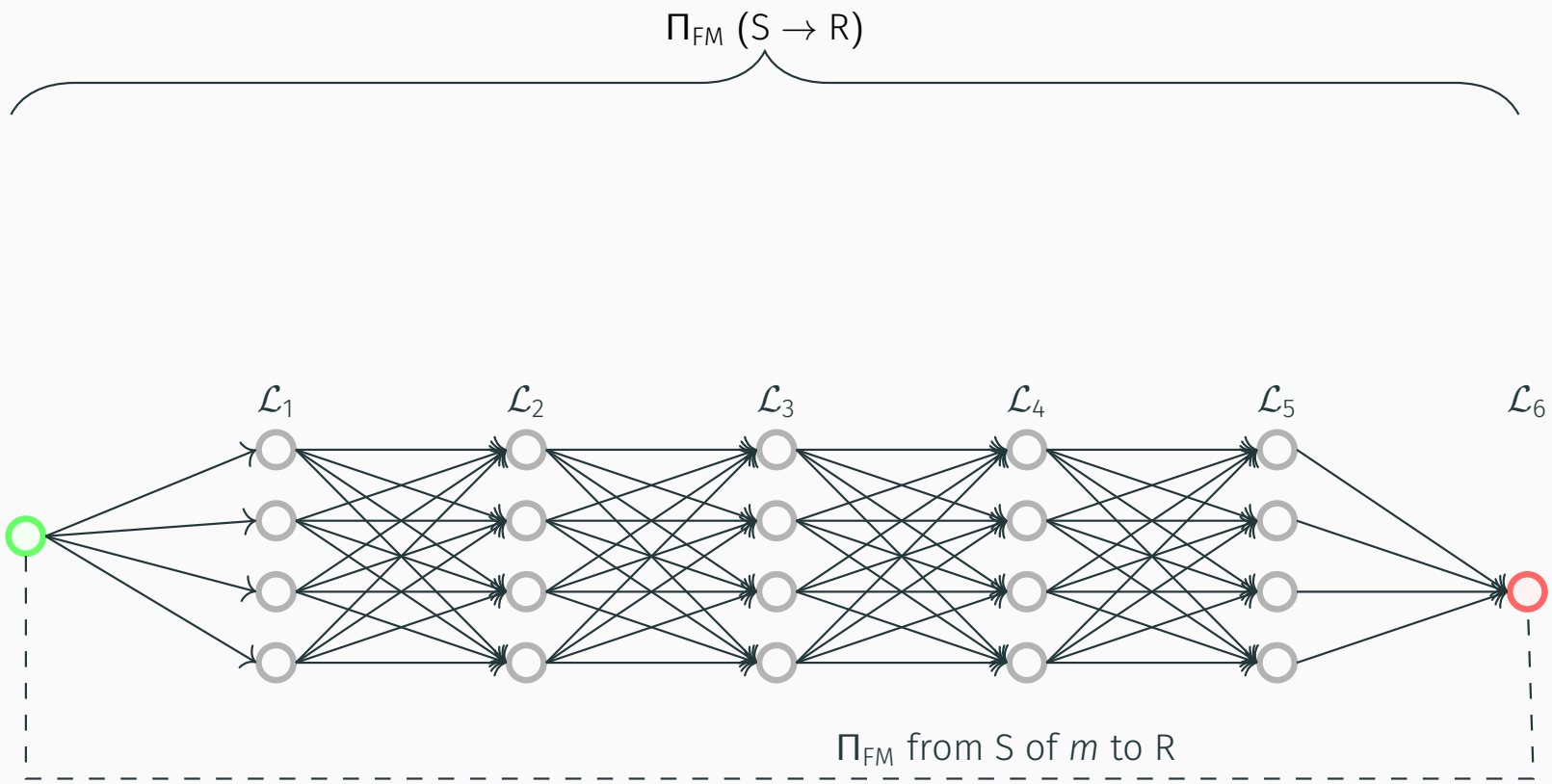


(Equivalent to perfect malicious 1-way SMT [DDWY93])

Future Messaging



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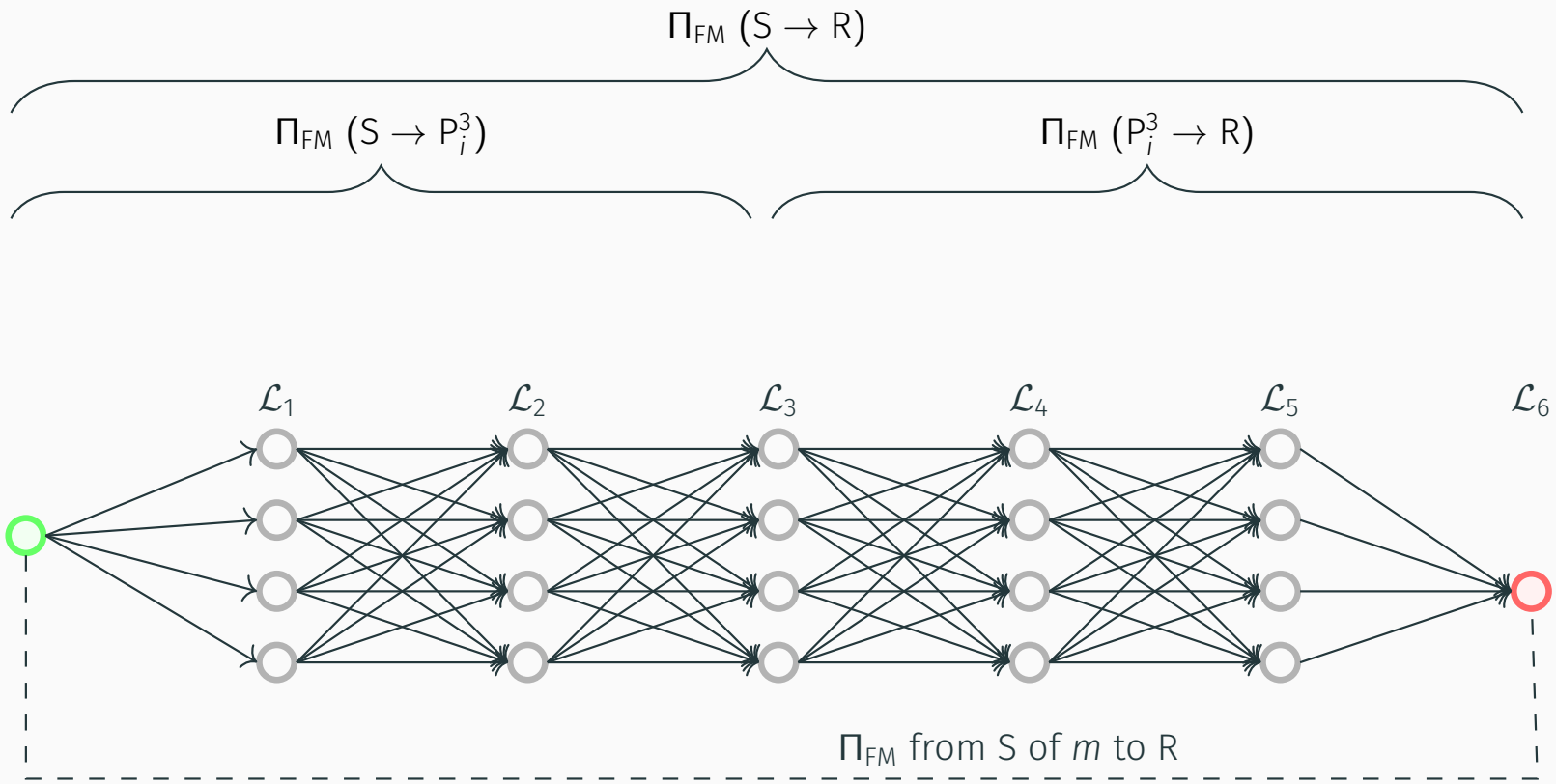

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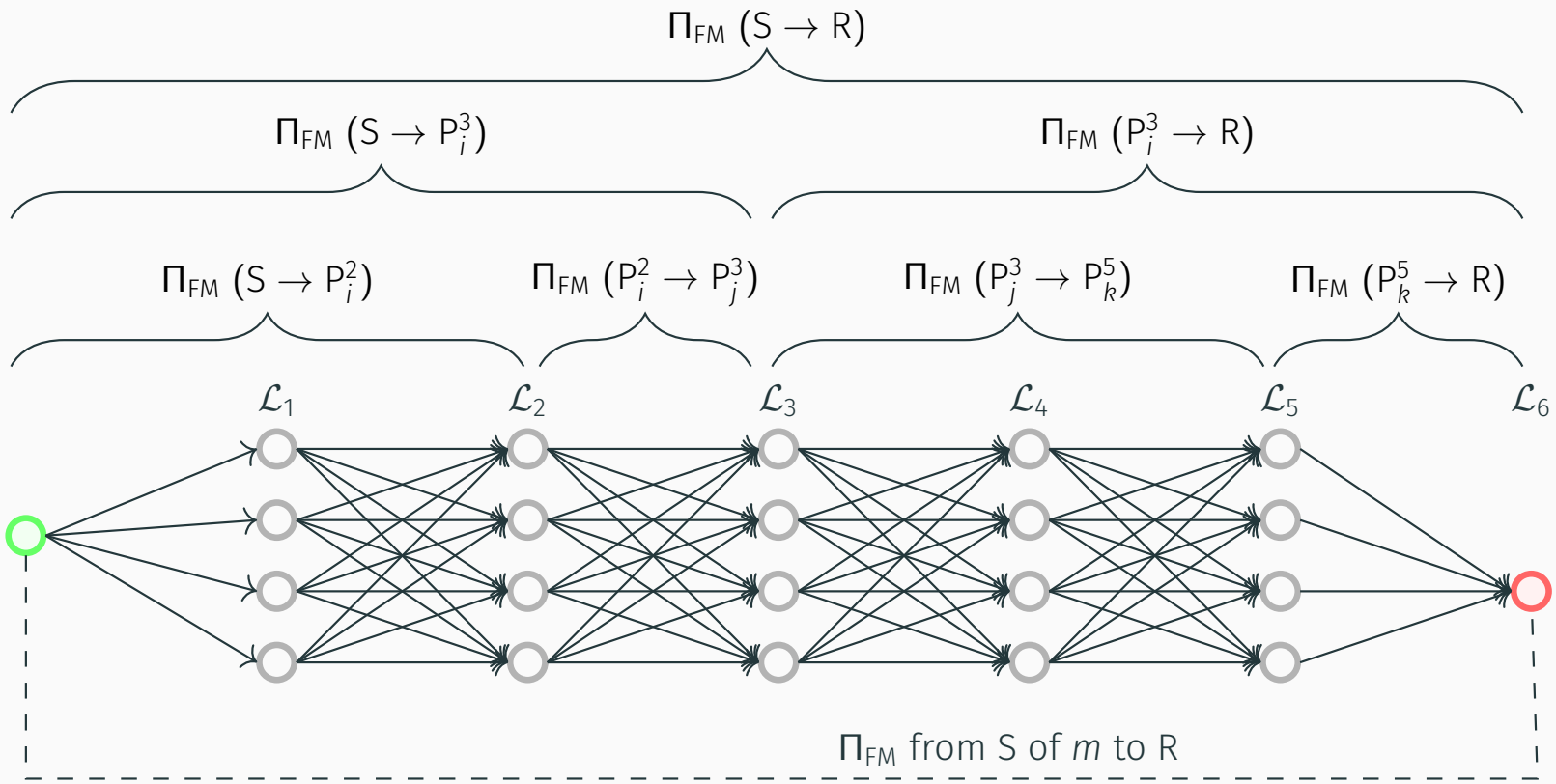
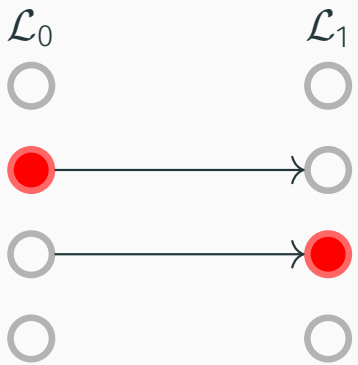


Future Messaging (and Rushing)

Dishonest Sender and problems with rushing

Parallel Invocations f_{FM}^{n}:

- When invoking multiple f_{FM} in parallel, the adversary can cause a **correlation attack**.
- Model the parallel functionality as **corruption-aware**.



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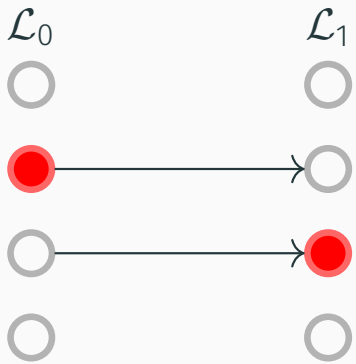
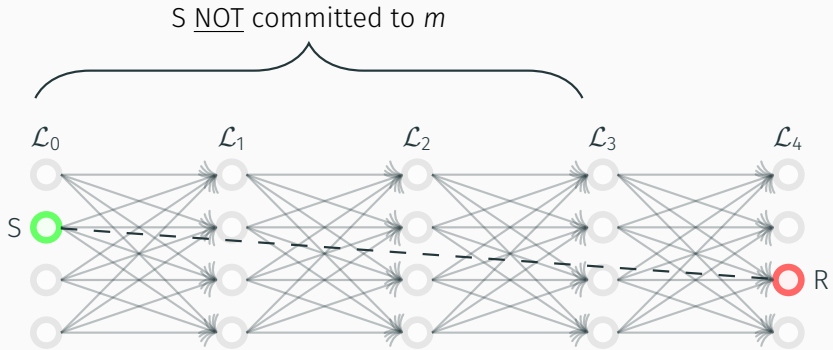


Non-committing Primitive:

- The adversary can change the message m to a message of its choosing m' in f_{FM} until the last round.
- Where YOSO assumes ideal **committing** communication to future rounds.

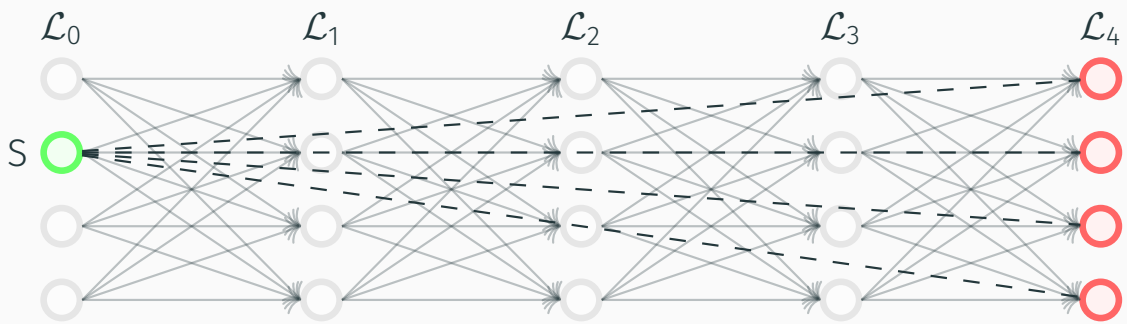


Future Broadcast

(Conditional) Future Broadcast

- Future Broadcast:
  Invoke f_{FM} where parties in $\mathcal{L}_{d-1}$ are instructed to broadcast their shares instead of sending to a recipient R.

- Conditional Disclosure:
  Conditioned on some event E, honest parties in $\mathcal{L}_{d-1}$ reveal their shares.



Future Messaging

Summary of Future Messaging

Complexity Assuming a linear secret sharing scheme, Π_{FM} is a recursive protocol realizing f_{FM} with communication complexity $O(n^{\lceil \log d \rceil} \log |M|)$.

Security Honest sender reduces to an instance of SMT
Dishonest sender is challenging with rushing.
Especially, when composing protocols.

Extension Future Messaging can be extended to (Conditional) Future Broadcast.

Towards Layered MPC

Layered CNF-VSS Protocol

Design Approach

CNF-VSS of [GIKR01]

Weak Future Multicast $\Pi_{\text{weak-FMcast}}$

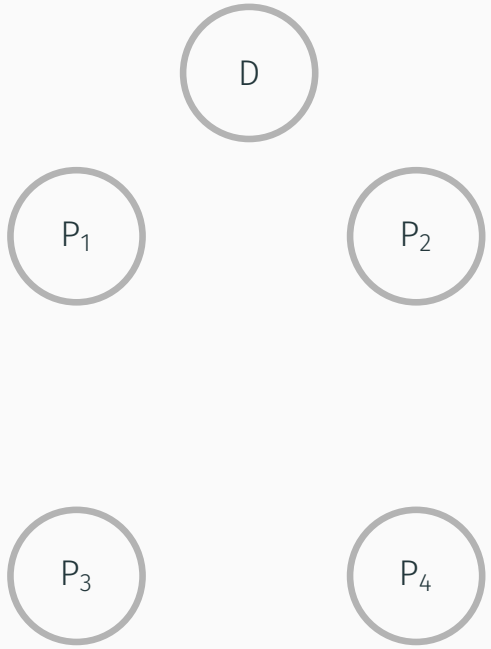
Future Multicast Π_{FMcast}

Verifiable Secret Sharing Π_{VSS}

Techniques from [GIKR01]

4-round perfect CNF VSS

D (dealer) holds a secret $s \in \mathbb{F}$ and obtains $\mathrm{Sh}_{\mathrm{CNF}}(s) = (s_1, \ldots, s_n)$.



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4-round perfect CNF VSS

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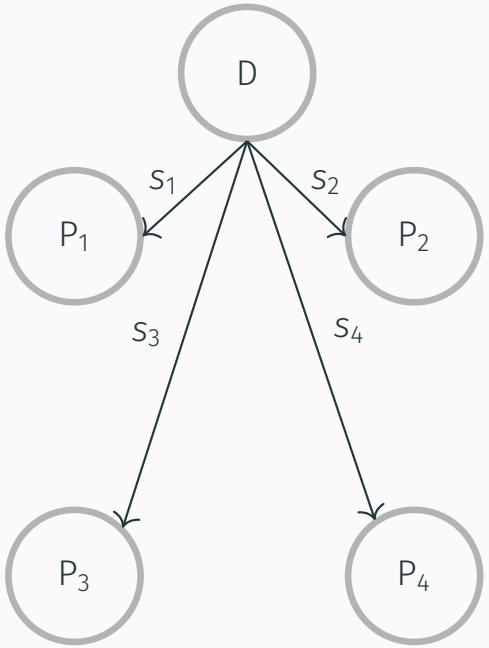
1. D sends $s_j = (r_T)_{T \ni j}$ to P_j.



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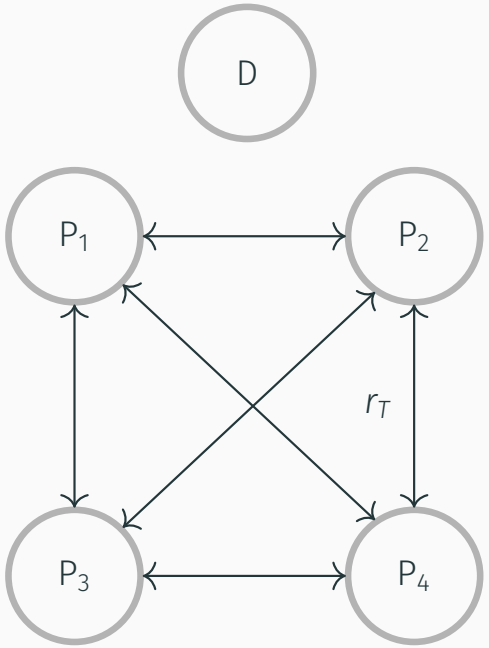
2. Each pair $(\mathrm{P}_j, \mathrm{P}_{j'})$ exchange share r_T (if $j, j' \in T$).



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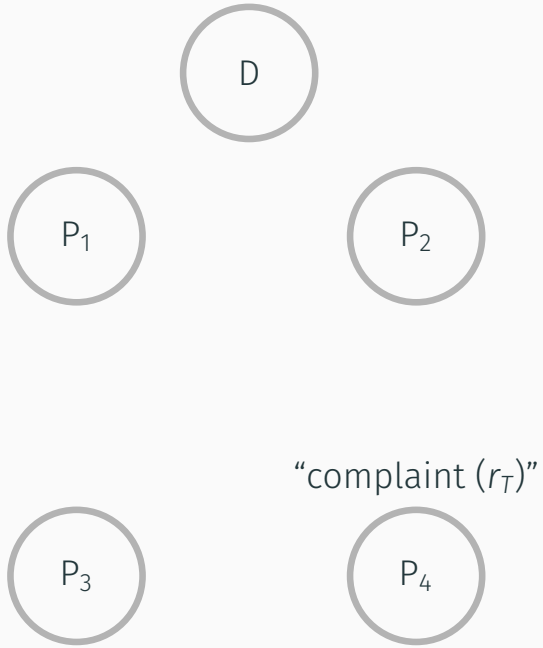

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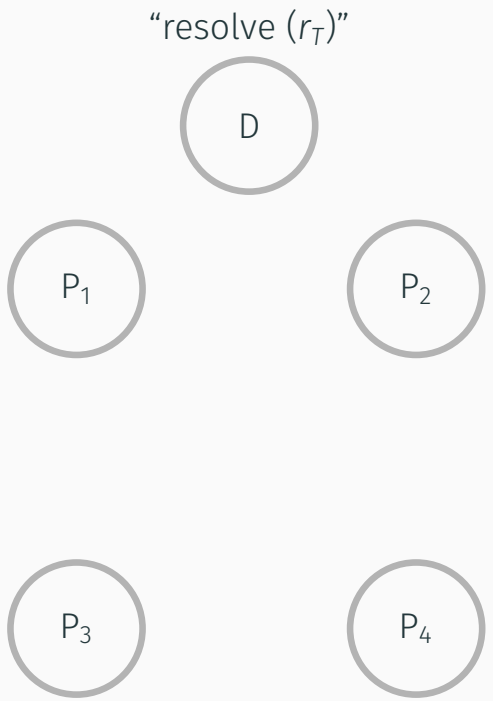
2. Each pair $(\mathrm{P}_j, \mathrm{P}_{j'})$ exchange share r_T (if $j, j' \in T$).
3. If disagreement, involved parties broadcast "complaint (r_T)".
4. D then broadcasts "resolve (r_T)", if any complaints received from P_j or $\mathrm{P}_{j'}$.



Techniques from [GIKR01]

Challenges with layered [GIKR01]

- Dealer speaks more than once (round 1 and round 4).

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- P_j and $P_{j'}$ exchange additive shares.

  Solution:
  Invoke a Distributed Equality Check with Π_{add} for each pair (j, j').

Future Multicast

Future Multicast functionality f_{FMcast}

PUBLIC PARAMETERS: Sender $S \in \mathcal{L}_0$, receiving set of parties $R \subseteq \mathcal{L}_d, d \geq 5$, message domain M.

SECRET INPUTS: S has input $m \in M$.

f_{FMcast} receives m from S, and delivers m to all parties in R.

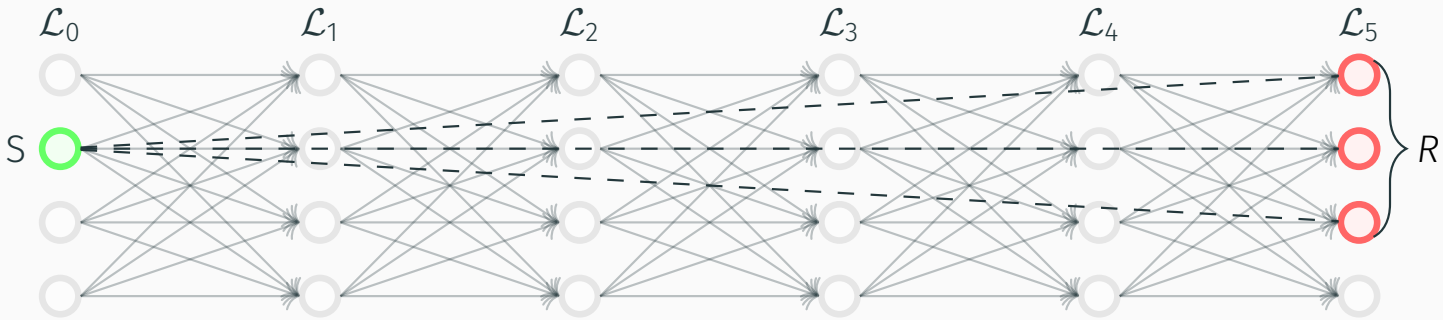
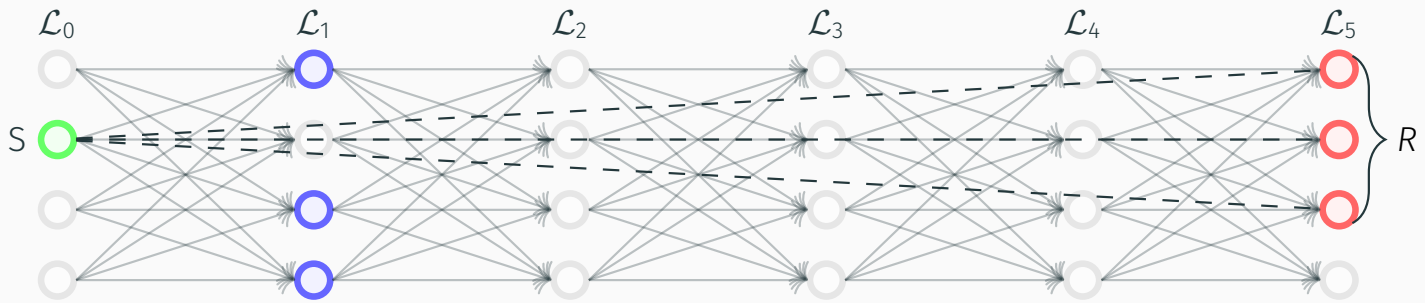


Figure 3: Π_{FMcast} from $S \in \mathcal{L}_0$ of m to $R \subseteq \mathcal{L}_5$

Future Multicast

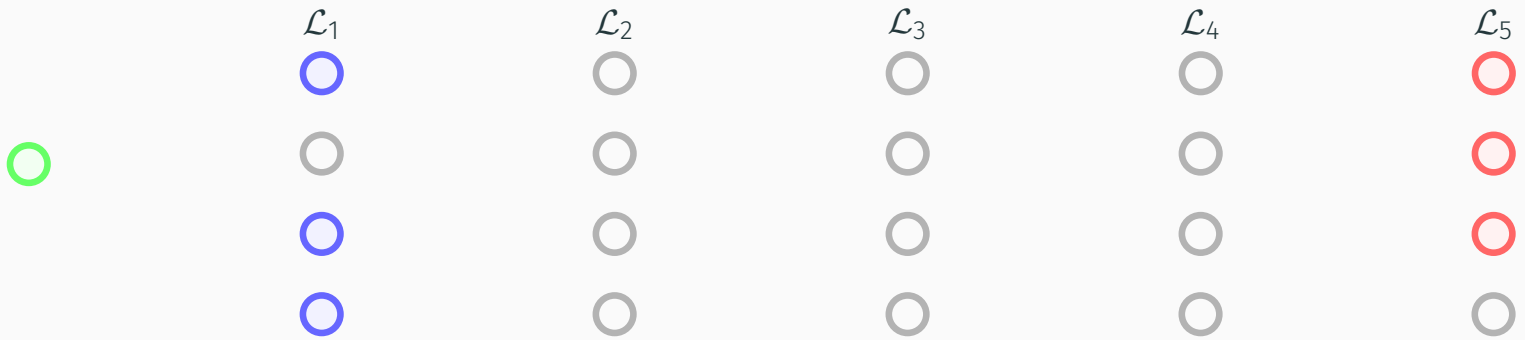
Sketch of Π_{FMcast}

1. S samples additive shares $\{r_T\}_{T \in \mathcal{T}}$ of m.
2. S sends each r_T to $R \subseteq \mathcal{L}_5$ using $\Pi_{\text{weak-FMcast}}$.
   Using a different set of intermediaries $U_T \subset \mathcal{L}_1$ where $|U_T| = n - t$.
3. Parties in $R \subseteq \mathcal{L}_5$ do $\hat{m} = \sum_{T \in \mathcal{T}} \hat{r}_T$.



Weak Future Multicast

$\Pi_{\text{weak-FMcast}}$ of $r = r_T$ from $S \in \mathcal{L}_0$ to R using U_T as intermediaries.



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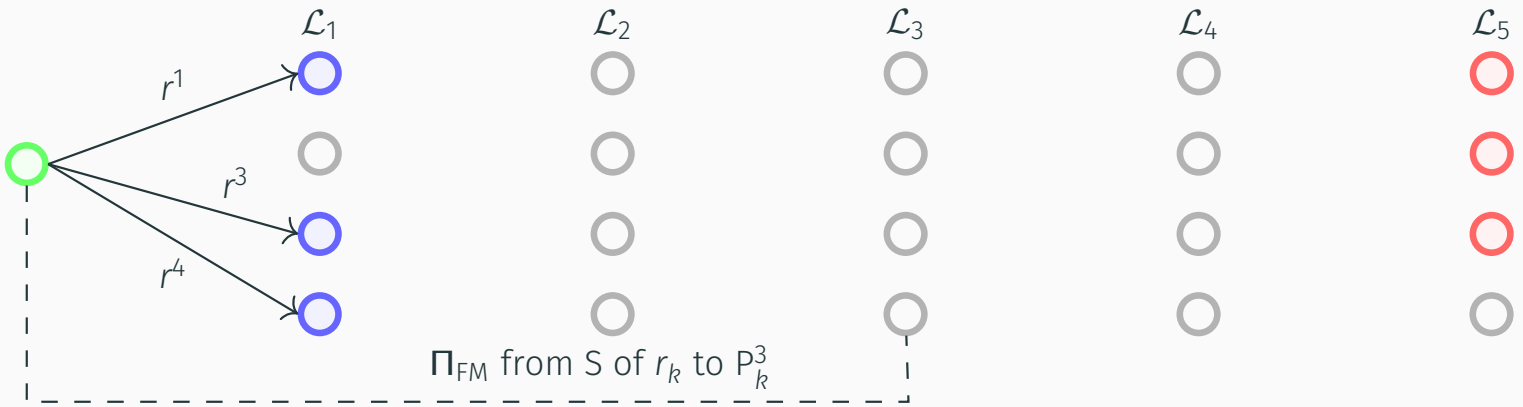

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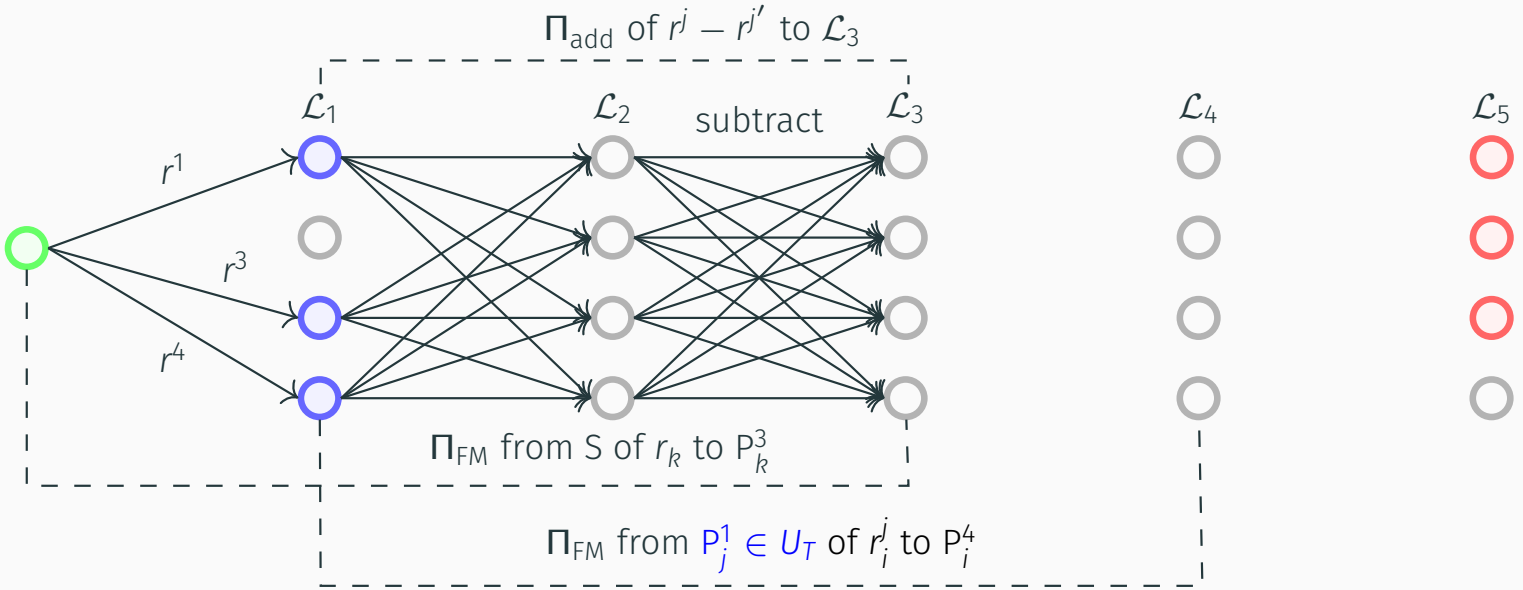

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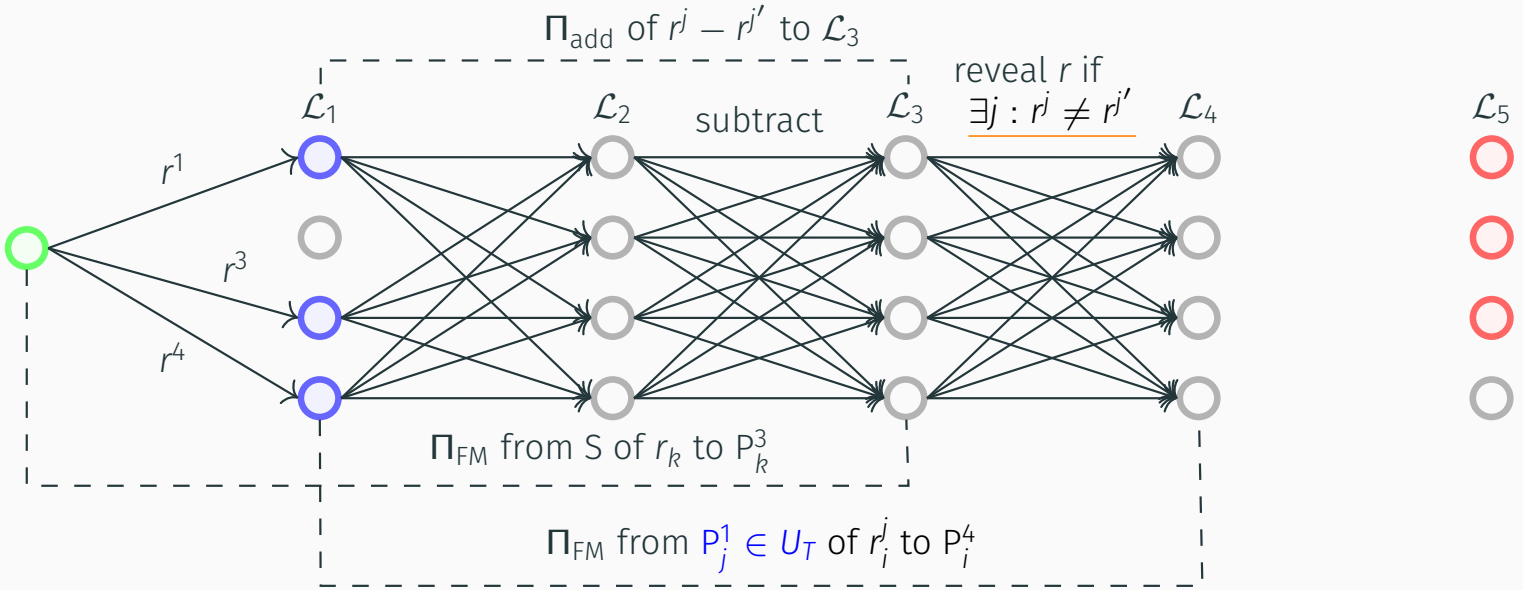

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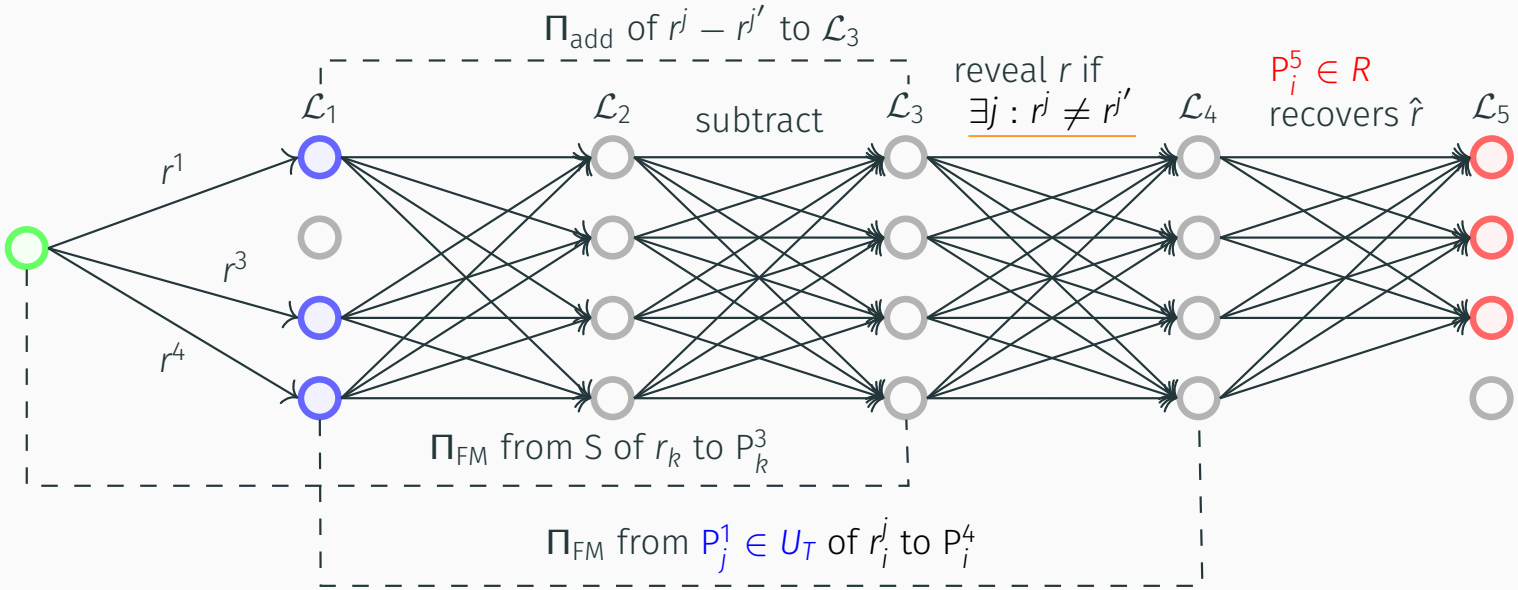


Layered VSS

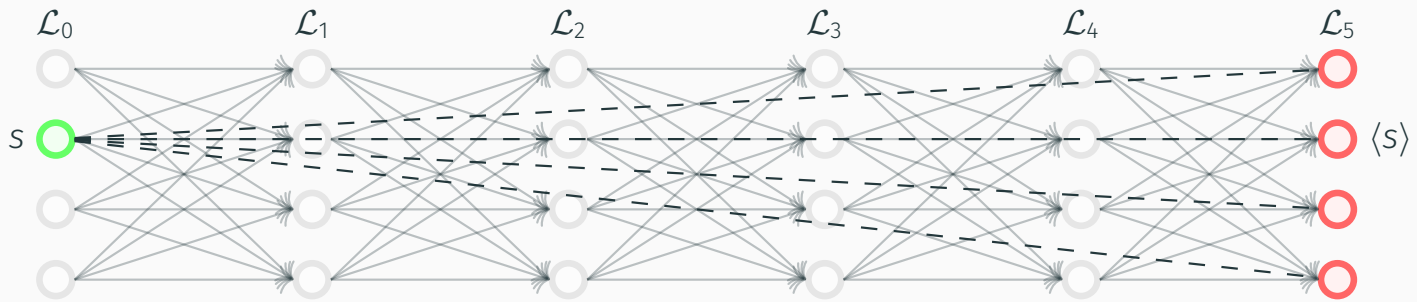
An $(n, t, 5)$-layered protocol Π_{VSS} realizing f_{VSS} where $t < n/3$.

From $\Pi_{\text{weak-FMcast}}$ to Π_{FMcast}:

- Each additive share r_T is transferred to R using U_T.
- Since at least one set (U_T) is comprised of only honest parties the message $m = \sum_{T \in \mathcal{T}} r_T$ remains secure if S and R are honest.

From Π_{FMcast} to Π_{VSS}:

- S samples $\{r_T\}_{T \in \mathcal{T}}$ as additive secret sharing of secret s.
- For each $T \in \mathcal{T}$, execute Π_{FMcast} with S as sender with input r_T and $\{\mathrm{P}_i^5 : i \in T\}$ as receivers.



Results

CNF-based Layered MPC [GIKR01, Mau06]

Theorem 1: CNF-Based Layered MPC

Let f be an n-party functionality computed by a **layered arithmetic circuit** C over a finite ring, with D **layers** and M gates. Then, for any $t < n/3$, there is an $(n, t, O(D))$**-layered MPC protocol** for f. The communication consists of $2^{O(n)} \cdot M$ ring elements.

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Corollary 1: Secure Maximally Proactive MPC

Let f be an n-party functionality computed by a layered arithmetic circuit C over a finite ring, **with** D **layers**. Then, for $t < n/3$, there is a **maximally proactive MPC protocol** computing f in $r = O(D)$ **rounds**.

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- May be concretely efficient for small n.
- Use techniques from [CDI05] to amortize the communication overhead by sending k-bit seeds and let the receivers generate most shares locally.
- This technique makes use of black-box access to PRG (computational security).

Efficient Layered MPC [BGW88]

Theorem 2: Efficient Layered MPC

Let f be an n-party functionality computed by a **layered arithmetic circuit** C over a finite field, with D **layers** and M gates. Then, for any $t < n/3$, there is an $(n, t, O(D))$**-layered MPC protocol** for f. The communication consists of $O(n^9) \cdot M$ field elements.

Efficient Layered MPC [BGW88]

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Corollary 2: (Efficient) Secure Maximally Proactive MPC

Let f be an n-party functionality computed by a layered arithmetic circuit C over a finite field, **with** D **layers**. Then, for $t < n/3$, there is an efficient **maximally proactive MPC protocol** computing f in $r = O(D)$ **rounds**.

- Extending the techniques for Distributed Equality Check and Conditional Future Broadcast to the [BGW88]-setting.

Maximally Proactive MPC and Dynamic Committees

f	Reference	Level	Security	Comm.	Threshold
FM	This work	perfect	full	poly(n)	$t < n/3$
VSS	[BGG+20]	comp.	full	poly(n)	$t < n/4^*$
	This work	perfect	full	$2^{O(n)}$	$t < n/3$
	This work (Sec. 5)	perfect	full	poly(n)	$t < n/3$
MPC	[GHK+21] (YOSO)	statistical	full +setup†	poly(n)	$t < n/2^*$
	[CGG+21] (Fluid)	statistical	abort	poly(n)	$t < n/2$
	[OY91]	perfect	full	poly(n)	$t < n/d$
	This work	perfect	full	$2^{O(n)}$	$t < n/3$
	This work (Sec. 5)	perfect	full	poly(n)	$t < n/3$
	This work (Sec. 6)	comp.	full	poly(n)	$t < n/2$

Table 1: Protocols realizing primitives in the most extreme proactive settings. (*protocol security relies on the adversary only doing probabilistic corruption, †assumes access to ideal target-anonymous channels for future messaging)

Conclusion

Summary:

- Definition of MPC over layered graphs (layered MPC).
  - Instance of standard MPC with restricted interaction patterns.
  - Implications for maximally proactive protocols [OY91].
- Reviewed CNF-based layered protocols for f_{VSS}.

Conclusion

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- Definition of MPC over layered graphs (layered MPC).
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- In Section 5 we describe **efficient** (but more involved) layered protocols for general MPC based on [BGW88].

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- In Section 6 we present layered protocol for general MPC with **computational** security for $t < n/2$.

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- In Section 6 we present layered protocol for general MPC with **computational** security for $t < n/2$.

Future Work:

- Identify a **compiler** from a class of protocols secure in the standard setting to secure layered protocols.
- Investigate the **statistical setting** ($t < n/2$) and possibly obtain a full characterization of layered MPC.

Thank You!

Check out the eprint:
https://ia.cr/2023/330 & https://ia.cr/2023/415

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