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Anantha Divakaruni[1] Peter Zimmerman[2]

[1] University of Bergen.

[2] Federal Reserve Bank of Cleveland. This paper does not necessarily reflect the views of the Cleveland Fed or Federal Reserve System.

What is the paper about?

- Blockchain technology limits settlement. For example, Bitcoin can handle only about 7 transactions per second. This leads to congestion.
- Since the beginning of 2018, congestion has fallen dramatically. We show the Lightning Network, a means of settling payments off-chain, has driven this improvement.
- Can this allow cryptocurrencies to scale in the future?

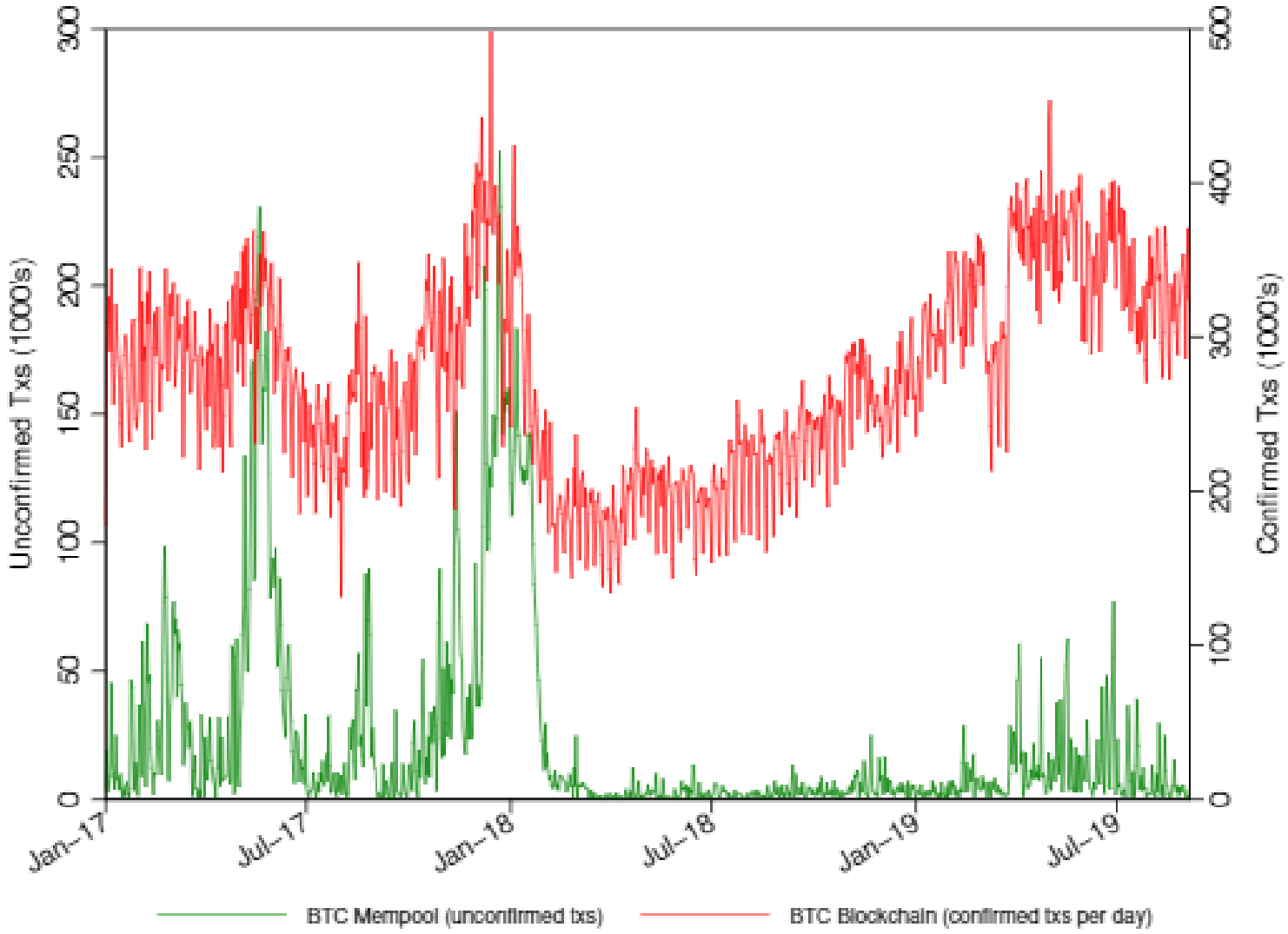
Limited settlement capacity of Bitcoin

- Bitcoin blocks arrive randomly, on average one every 10 minutes in long-run.
- Each block holds 1 MB of data, roughly 4000 payments. This limit allows communication between validators.
- Users can attach a fee to incentivise miners to prioritise their payment. But total expected supply is fixed, in long-run.

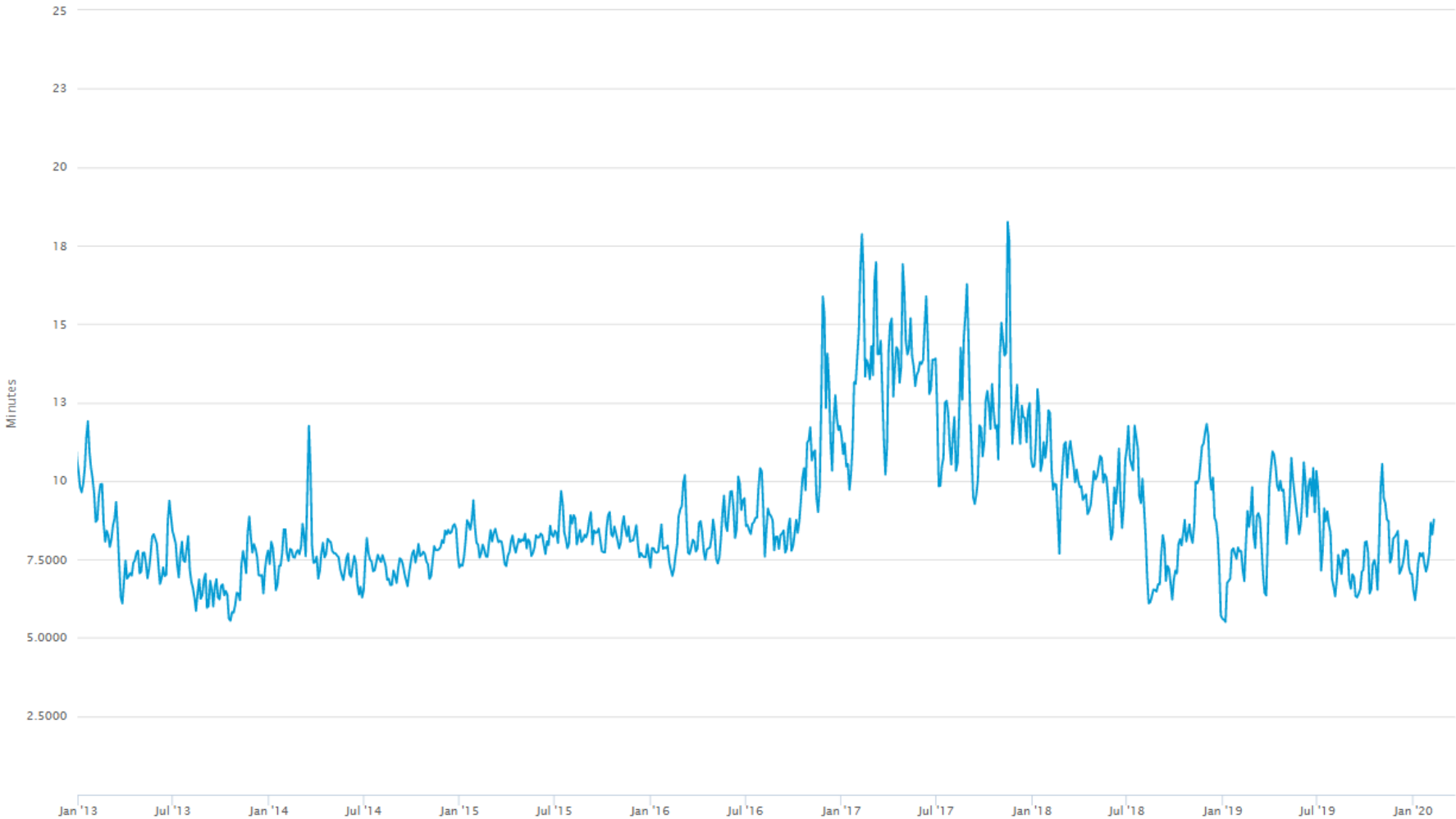
Block # 617216

Hash	ace36fe940f17700f66c29fad508ffe3f43f38c73845c686ddb8e3df...				2020-02-13 14:33
	196A5MsTViXACoFTyaLy1nMP4rByt523Rd	0.04500000 BTC	→	3CxZgQjZSrBQJ5qLjtJiYGndp3Eq4SfBNw	0.04440000 BTC
Fee	0.00060000 BTC (317.460 sat/B - 79.365 sat/WU - 189 bytes)				0.04440000 BTC 1 Confirmations
Hash	a0854ba63981237ce5136e42996851cd9a979dcf707d5219d58c79...				2020-02-13 14:29
	1NC5gELfDKqMtgfWuUAsCVStoTiGj3GV22	0.04900000 BTC	→	3CxZgQjZSrBQJ5qLjtJiYGndp3Eq4SfBNw	0.04840000 BTC
Fee	0.00060000 BTC (317.460 sat/B - 79.365 sat/WU - 189 bytes)				0.04840000 BTC 1 Confirmations
Hash	1b8210a8c60e304f687dc3805afca8e9190a3048e7fc9036e439a4...				2020-02-13 14:30
	3KWFdy66yW1ijrmc4yyVcUHUsCUJh4mZ4R	0.36932336 BTC	→	3HEPZ57yfmS2t3cnhJw1PK5WpN4c1DWLZN 33uvfuiCCCbiJ8smkKnKKbvCayuJycwAxU	0.00078000 BTC 0.36802017 BTC
Fee	0.00052319 BTC (129.183 sat/B - 61.192 sat/WU - 405 bytes)				0.36880017 BTC 1 Confirmations
Hash	6ce842e568dacd069ab2148472b643e61beb545ba6719ef83a705...				2020-02-13 14:33
	1D8hi1vrGxhChLNZ3usgBdfdWEsoaQsexb	1.45144032 BTC	→	1L7NMeNoLudVEoHEq4FXWQoi5MHQGDTmWj 14962oyGPM8hAvB9pGDWjV2rEzWvqabko5	0.02058363 BTC 1.43035669 BTC
Fee	0.00050000 BTC (221.239 sat/B - 55.310 sat/WU - 226 bytes)				1.45094032 BTC 1 Confirmations

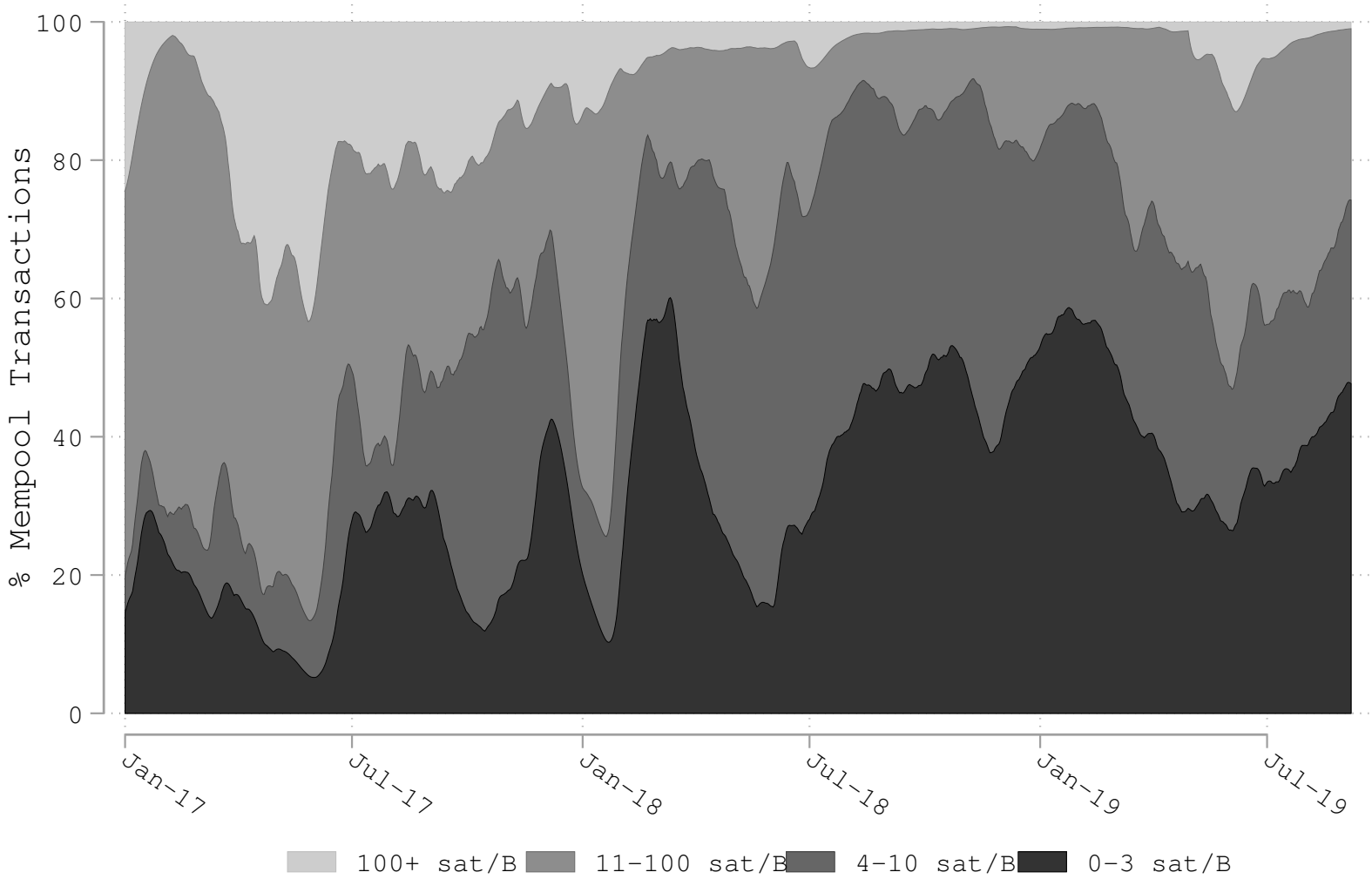
Congestion has fallen...



... along with settlement delays...



... and fees


% Mempool Transactions
100
80
60
40
20
0
Jan-17
Jul-17
Jan-18
Jul-18
Jan-19
Jul-19
100+ sat/B
11-100 sat/B
4-10 sat/B
0-3 sat/B

Why has congestion eased since the start of 2018?

- Not due to lower demand. Bitcoin is now handling a record number of transactions!
- Not due to mining incentives. Settlement capacity is fixed in long run.
- Possible technological innovations pushing out supply curve: **SegWit** and **Lightning Network**.

SegWit: an increase in block capacity

- Change to Bitcoin core protocol introduced 23 August 2017 (soft fork).
- Payments stored more efficiently: now up to $4\times$ as many can fit on a block.
- Upward shift in supply of settlement space, but bounded.

Lightning Network: a method for off-chain settlement

Days 1, 2 & 3: Alice pays Bob ₿1 each day;

Days 4 & 5: Bob pays Alice ₿1 each day

Without LN, 5 on-chain transactions required in total. Cost $= 5F$.

Lightning Network: a method for off-chain settlement

On day 0, Alice and Bob open a Lightning channel, and Alice locks in ₿3.

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On day 0, Alice and Bob open a Lightning channel, and Alice locks in ₿3.

Day 1: Alice balance vs Bob is - ₿1.

Day 2: Alice balance vs Bob is - ₿2.

Day 3: Alice balance vs Bob is - ₿3.

Lightning Network: a method for off-chain settlement

On day 0, Alice and Bob open a Lightning channel, and Alice locks in ₿3.

Day 1: Alice balance vs Bob is - ₿1.

Day 2: Alice balance vs Bob is - ₿2.

Day 3: Alice balance vs Bob is - ₿3.

Day 4: Alice balance vs Bob is - ₿2.

Day 5: Alice balance vs Bob is - ₿1.

Lightning Network: a method for off-chain settlement

On day 0, Alice and Bob open a Lightning channel, and Alice locks in ₿3.

Day 1: Alice balance vs Bob is - ₿1.

Day 2: Alice balance vs Bob is - ₿2.

Day 3: Alice balance vs Bob is - ₿3.

Day 4: Alice balance vs Bob is - ₿2.

Day 5: Alice balance vs Bob is - ₿1.

Channel is closed and coins distributed.
Only 2 on-chain transactions are required! Cost $= 2F$.

Literature

- **Economics of settlement latency:** Easley, O'Hara & Basu (2019); Hautsch, Scheuch & Voigt (2018); Huberman, Leshno & Moallemi (2017); Voigt (2020); Zimmerman (2020).

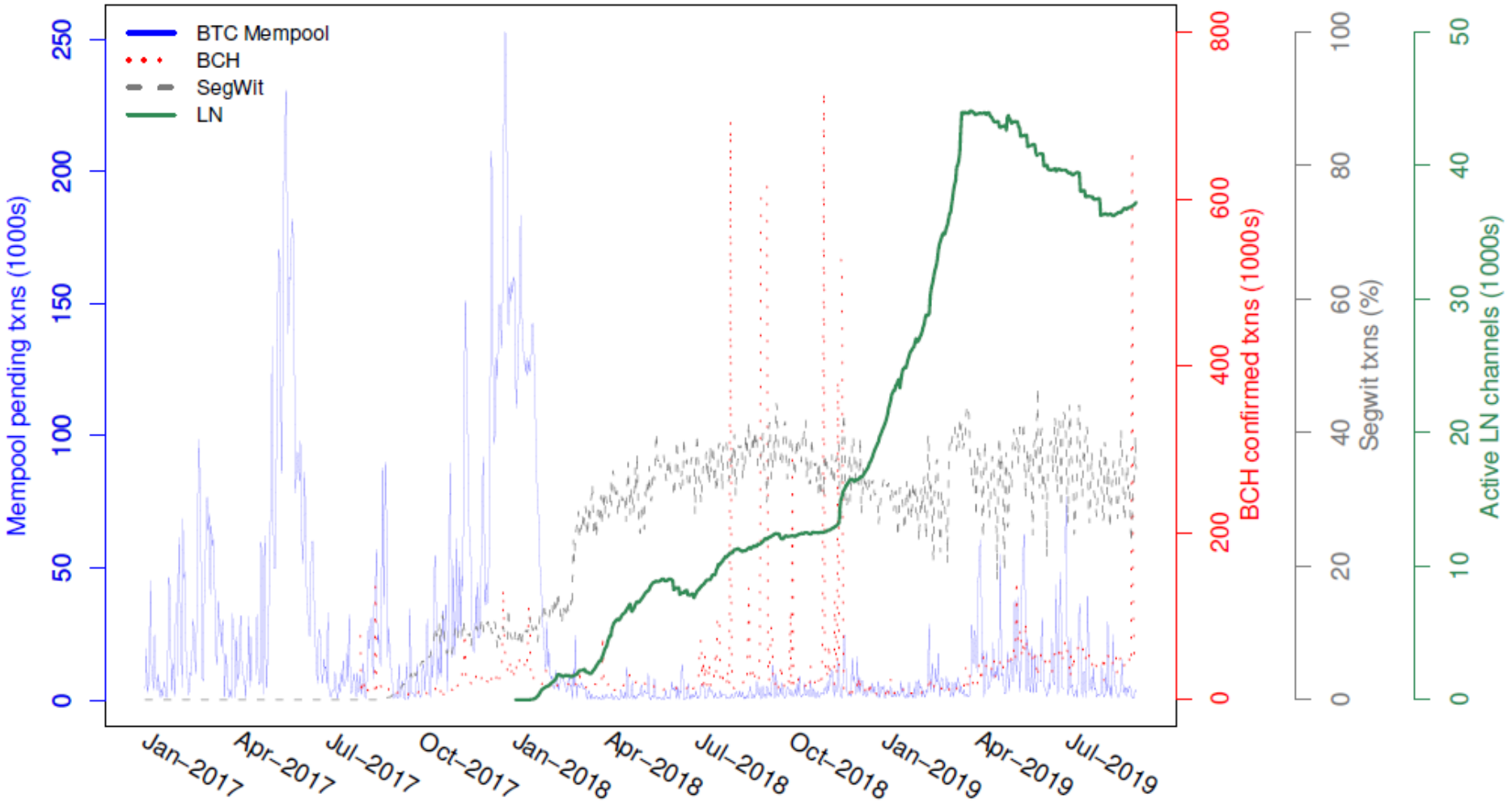
- **SegWit:** Brown, Chiu & Koeppl (2019); Lehar & Parlour (2020); Pérez-Solà, Delgado-Segura, Herrera-Joancomartí & Navarro-Arribas (2019).

- **Lightning Network:** Auer (2020); Bartolucci, Caccioli & Vivo (2019); Béres, Seres & Benczúr (2019); Bertucci (2020); Ersoy, Roos & Erkin (2019).

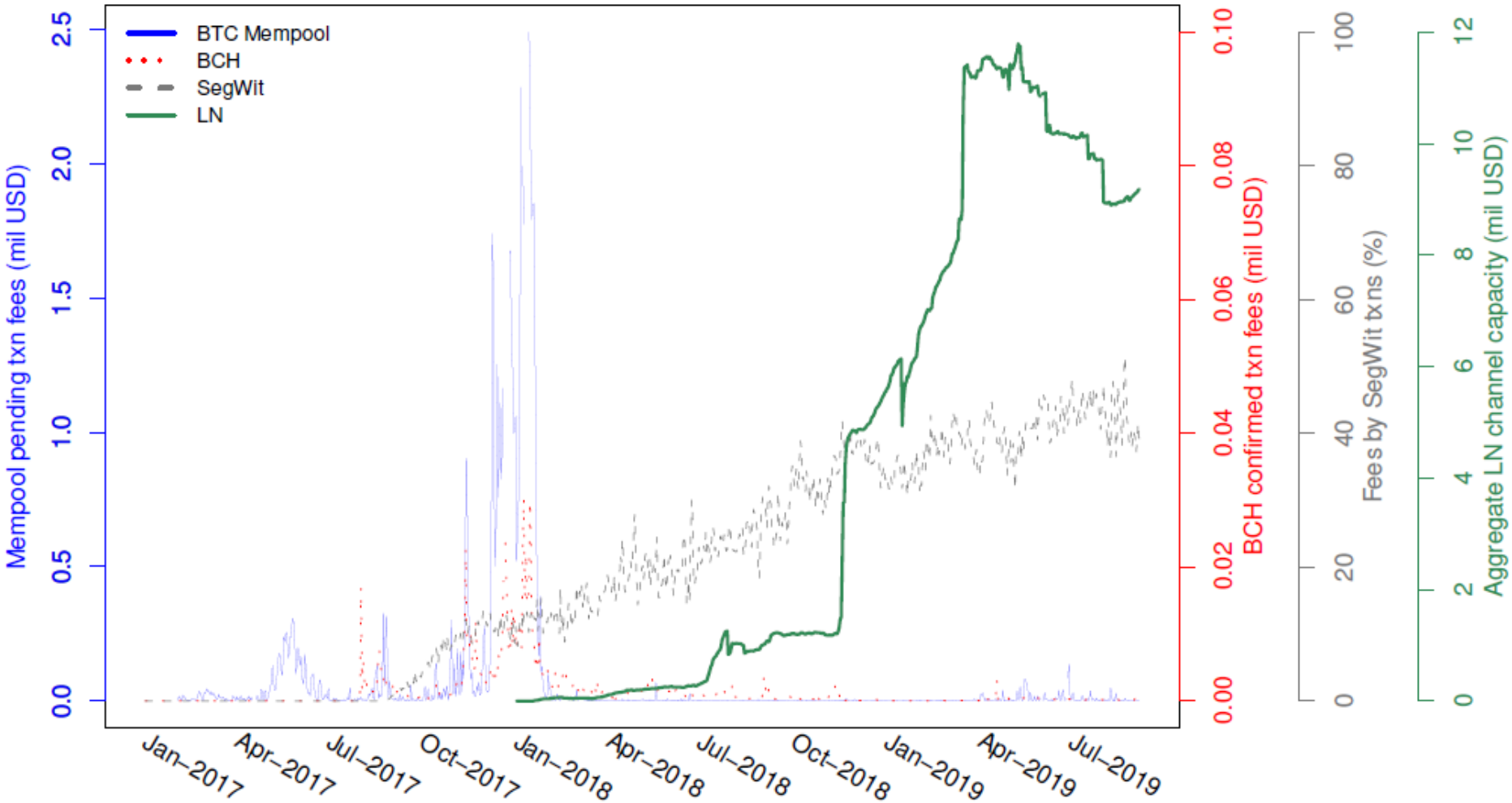
Data

- Daily data from 1 January 2017 to 5 September 2019.
- Congestion data from `jochen-hoenicke.de`: includes number pending and associated fees.
- Demand proxies: price change and volatility.
- Supply proxy: average rate of block creation per day.
- Indicators on usage of Lightning Network and SegWit.
  - **Lightning Network:** number of channels and total value of Bitcoin locked in.
  - **SegWit:** % of txns using SegWit, by volume and weighted by fee.

Adoption of innovations: by quantity



Adoption of innovations: by value



ARIMA model

$$\Delta y_t = \alpha + \beta \Delta X_t + \sum_{i=1}^{p} \gamma_i \Delta y_{t-i} + \sum_{j=1}^{q} \theta_j \epsilon_{t-j} + \epsilon_t,$$

where y_t is congestion, c a constant, ϵ_t error terms, X_t independent variables. Hyndman-Khandakar identifies p, q. Stationary with first-differences.

Results: % low fee txns (< 10 sat/vB)

	(1)	(2)	(3)
LN channels (log)	0.178***		0.180***
	(0.036)		(0.036)
Segwit txns (%)		-0.015***	-0.016***
		(0.004)	(0.004)
30-day volatility	-0.024	-0.037	-0.030
	(0.025)	(0.027)	(0.024)
1-day price change	0.047	0.051	0.058
	(0.224)	(0.223)	(0.222)
Mining intensity	0.041***	0.036**	0.034**
	(0.015)	(0.015)	(0.015)
Constant	-0.002	0.001	-0.001
	(0.002)	(0.002)	(0.002)
Observations	965	965	965

Results: mempool count (log)

	(1)	(2)	(3)
LN channels (log)	-0.273***		-0.260***
	(0.075)		(0.078)
SegWit txns (%)		0.017	0.017
		(0.012)	(0.012)
30-day volatility	-0.020	-0.014	-0.023
	(0.081)	(0.082)	(0.082)
1-day price change	-0.664	-0.681	-0.770
	(0.630)	(0.629)	(0.620)
Mining intensity	0.039	0.047	0.037
	(0.049)	(0.049)	(0.049)
Constant	-0.001	-0.004	-0.002
	(0.009)	(0.008)	(0.009)
Observations	965	965	965

Results: mempool fees

	(1)	(2)	(3)
LN capacity	-0.195**		-0.205**
(USD log)	(0.095)		(0.093)
SegWit txns		0.039*	0.041*
by fee (%)		(0.023)	(0.023)
30-day	0.090	0.077	0.077
volatility	(0.107)	(0.107)	(0.106)
1-day price	0.657	0.669	0.679
change	(0.445)	(0.443)	(0.442)
Mining	0.034	0.036	0.035
intensity	(0.059)	(0.059)	(0.059)
Constant	0.000	-0.005	-0.001
	(0.010)	(0.010)	(0.010)
Observations	965	965	965

Summary of results

- Lightning Network effect is robust: greater adoption of LN means lower congestion.
- Increase of 1 s.d. in LN adoption reduces mempool count by about one-third of s.d.
- Demand effects do not matter, though short-term increases in supply do help reduce fees.
- SegWit requires further investigation. 4 vB for SegWit = 1 vB for non-SegWit.

How much difference does Lightning make?

- If LN channels were at their end-sample level ($\sim 40,000$), peak mempool count would have been about 95% lower, and percentage of low fee txns about 6.6$\times$ higher.
- If LN capacity was at its end-sample level ($\sim$ 9.5m USD), peak fees would have been about 96% lower.

Implications

- Reduce barriers to arbitrage and improve liquidity between exchanges.
- But bid-ask spreads may rise as market makers face increased adverse selection (Voigt, 2020).
- Lessons for scalable decentralised currencies: Libra, CBDCs.