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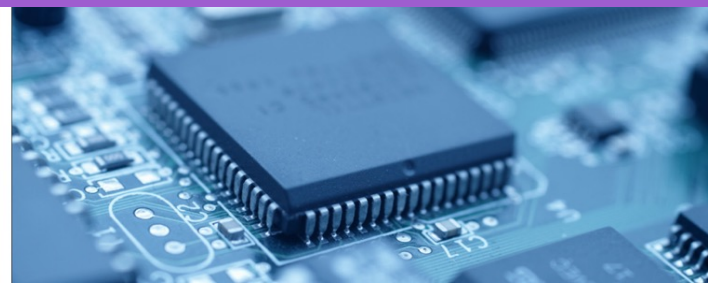

Revisiting Temporal Storage I/O Behaviors of Smartphone Applications: Analysis and Synthesis

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Outline

- Background
- Motivation
- Auto-correlation & Self-similarity
- Synthesis
- Conclusion

Background

- Storage subsystem of Smartphone:
  - ✓ eMMC or UFS flash memory
  - ✓ SQLite, F2FS/Ext4, and …
- Mobile I/O traces:
  - ✓ **Nexus5** from San Diego State University: BIOtracer, 18 common applications [33];
  - ✓ **AppDedupe** from Xiamen University: MobileCT, 15 typical applications [21].

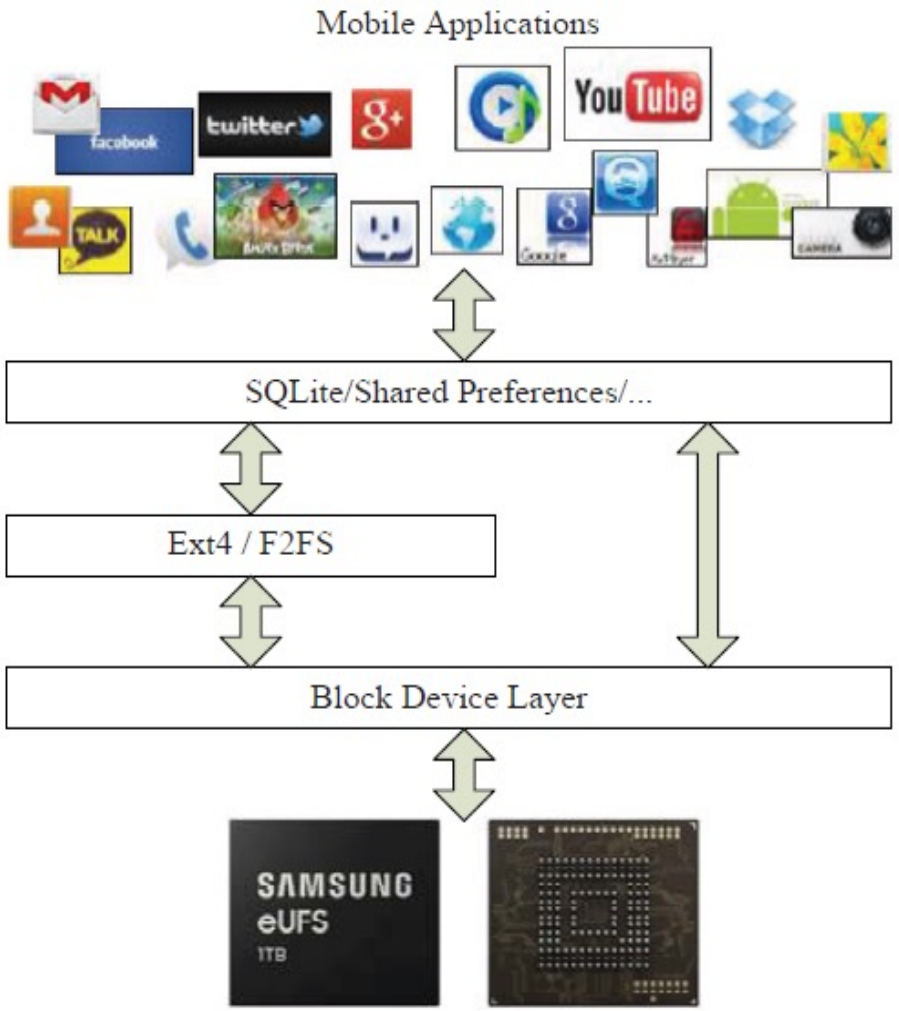


Figure 1: Storage subsystem of Smartphone.

TABLE 1: WORKLOAD DESCRIPTIONS.

Workload	Application	Category	Read/Write Ratio	Description
Nexus5	Email	Web	1/2.37	Execute Email, log in and receive/send/view emails
	Amazon	Web	1/1.70	Execute Amazon, search goods by any keyword, and have an online shopping
	WebBrowsing	Web	1/4.18	Execute WebBrowsing, search by any keyword, View results and search again
	Movie	MM	17.52/1	Select a movie file, play the movie, and change volume
	Music	MM	1/1.12	Select a music file, play the music, and change volume
	CameraVideo	MM	2.39/1	Execute CameraVideo and record a video clip
	GoogleMaps	MM	1/6.56	Execute GoogleMaps, search road map and navigate
	YouTube	MM	1/39.00	Execute Youtube, search a video by any keyword and view the video
	Radio	MM	1/74.76	Execute Radio, select a channel and change volume
	Facebook	SNS	1/2.91	Execute Facebook, view new messages or pictures, add comments, etc
	Twitter	SNS	1/7.68	Execute Twitter, read new tweets, and post tweets
	AngryBirds	Game	1/5.46	Execute the AngryBirds application, select a level, and play the game
	Idle	DU	1/8.04	Smartphone in idle state
	Booting	DU	2.02/1	Smartphone booting process
	Installing	DU	1/56.47	Execute the Android market and select one application to install
	CallIn	Basic	1/1427.57	Answer an incoming call
	CallOut	Basic	1/91.59	Scroll lists, search a person by name, and Make a phone call
	Messaging	Basic	1/36.04	Execute Messaging and receive/send/view messages
AppDedupe	58City	Web	1/2.27	Execute 58City and search messages by any keyword
	MojiWeather	Web	1/1.73	Execute Moji Weather and check the weather at various times and places
	OperaBrowser	Web	1/1.35	Execute Opera Browser, search by any keyword, View results, and search again
	SohuNews	Web	1/5.33	Execute Sohu News, select and view news
	YoudaoDict	Web	1.84/1	Execute Youdao Dict, search by any keyword, and view results
	XiamiMusic	MM	1.54/1	Execute Xiami Music, search/select a music file, play and change volume
	Meitu	MM	1.39/1	Execute Meitu, select a target, and make a nice picture
	Qiu	SNS	1/7.26	Execute Qiu, view new messages/pictures/videos, add comments, and etc
	BaiduTieba	SNS	1/7.77	Execute Baidu Tieba, view new messages or pictures, add comments, and etc
	Wechat	SNS	1/9.42	Execute Wechat, view new messages or pictures, add comments, etc
	Weibo	SNS	1/7.70	Execute Weibo, view new messages or pictures, add comments, etc
	Tencent	SNS	1/20.74	Execute Tencent, view new messages or pictures, add comments, and etc
	FruitCool	Game	1.12/1	Execute Fruit Cool, select a level and play the game
	PeaPod	Game	1/2.11	Execute Pea Pod application, select a level and play the game
	Game2048	Game	1/8.26	Execute Game2048 application, select a level and play the game

Motivation

- **Observations**:
  - ✓ To approximate temporal I/O features, the traditional distributions are used, such as Poisson [28], Normal [25], and Uniform [20].
  - ✓ Real I/O activities contain **burst** [8] and even present the heavy-tailed feature [34].
  - ✓ The traditional distributions do not specialize in accurately describing I/O burstiness

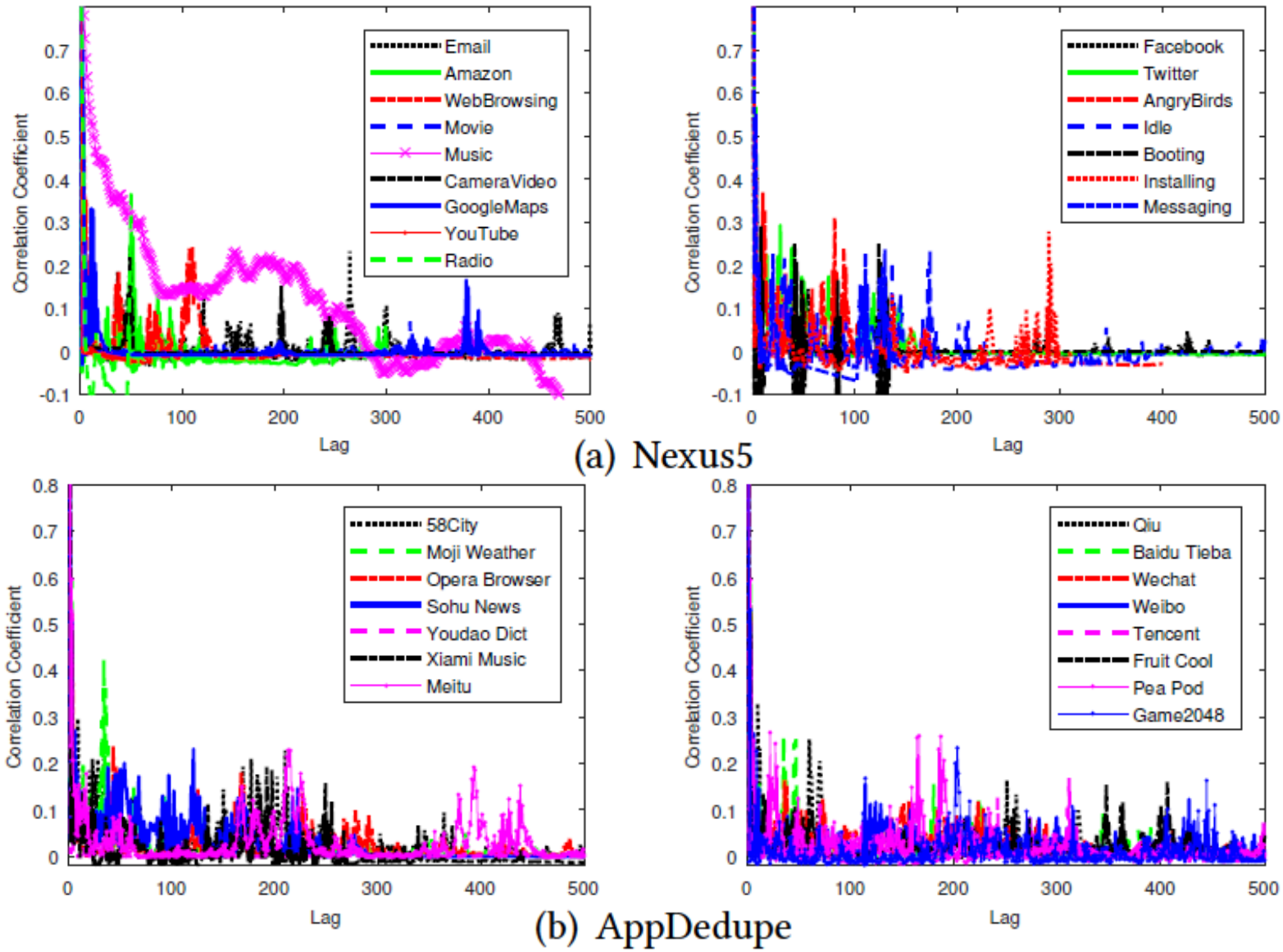
- **Issue**: Is it still appropriate to use traditional methods such as Poisson to describe I/O activities with burstiness in mobile application workloads?

Auto-correlation & Self-similarity

- Tool: Auto-Correlation Function (ACF)
  - ✓ For a time series $S = \{S_t : t = 1, 2, \ldots, n\}$, $\mu = E[S_t]$, $s_t = S_t - \mu$
  - ✓ Correlation coefficients: $ACF(k) = \frac{E[s_t \cdot s_{t+k}]}{E[s_t^2]}$, *for* $k \geq 0$.
  - ✓ A correlation coefficient forms a mapping relationship with a time interval (also called lag) k
- For I/O requests in mobile applications:
  - ✓ If the correlation coefficients of arrival intervals decrease rapidly with the increase of lag and approach 0, there is almost no correlation.
  - ✓ Otherwise, there is a certain degree of correlation.

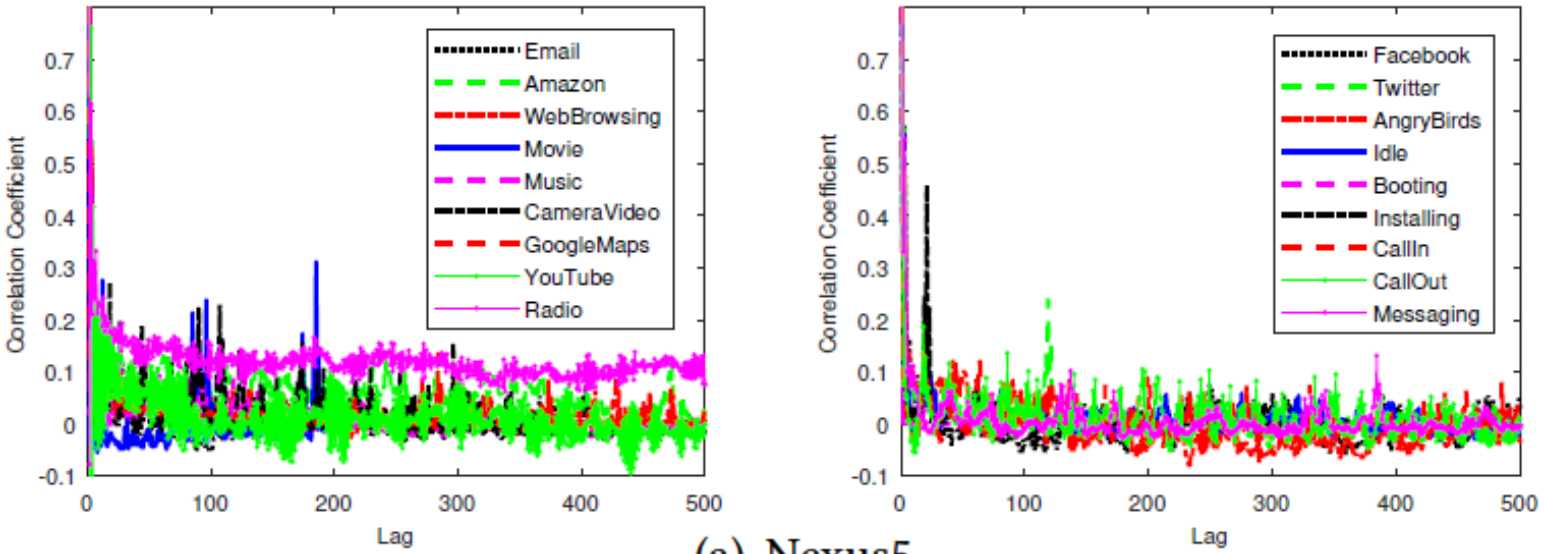
Auto-correlation & Self-similarity

- Figure 2: ACFs of ***read*** requests in Nexus5 and AppDedupe
- Evident correlation:
  - ✓ Email, Music
  - ✓ other 9 AppDedupe apps.
- Almost no correlation:
  - ✓ Movie, YouTube
  - ✓ YoudaoDict
- Certain degree correlation:
  - ✓ remaining 12 Nexus apps.
  - ✓ MojiWeather, Qiu, BaiduTieba, WeChat, Tencent

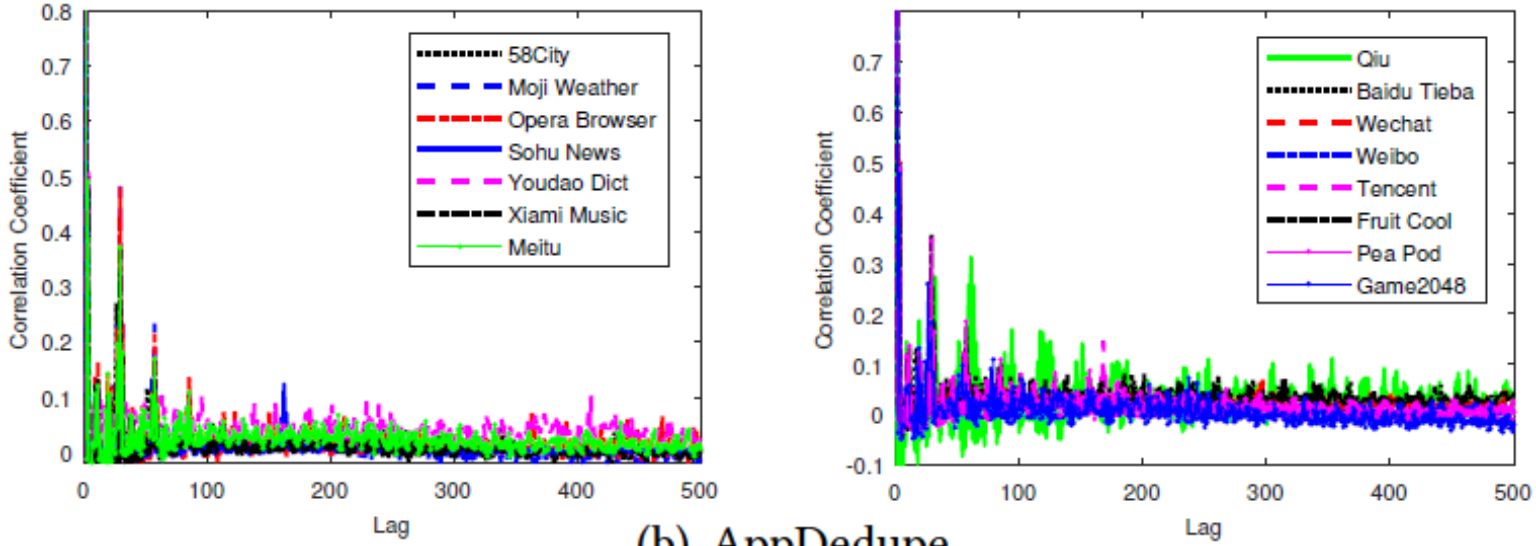


Auto-correlation & Self-similarity

- Figure 3: ACFs of ***write*** requests in Nexus5 and AppDedupe
- Evident correlation:
  - ✓ Radio
  - ✓ N/A
- Almost no correlation:
  - ✓ Booting
  - ✓ WeChat, Weibo, Tencent
- Certain degree correlation:
  - ✓ Remaining 16 Nexus apps
  - ✓ Other 12 AppDedupe apps



(a) Nexus5



(b) AppDedupe

Auto-correlation & Self-similarity

TABLE 2: COMPARING THE CORRELATIONS OF INTER-ARRIVAL TIMES OF READ AND WRITE REQUESTS IN SMARTPHONE APPLICATIONS.

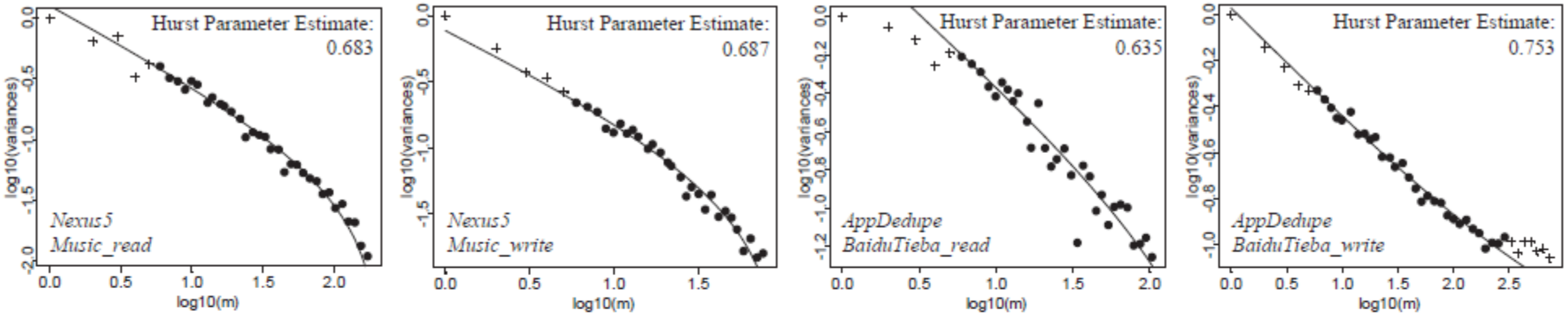
Category	Nexus5			AppDedupe		
	Application	Auto-correlation		Application	Auto-correlation	
		Read	Write		Read	Write
Web	Email	Evident	Certain degree	58City	Evident	Certain degree
	Amazon	Certain degree	Certain degree	MojiWeather	Certain degree	Certain degree
	WebBrowsing	Certain degree	Certain degree	OperaBrowser	Evident	Certain degree
				SohuNews	Evident	Certain degree
				YoudaoDict	Almost no	Certain degree
Multimedia	Movie	Almost no	Certain degree			
	Music	Evident	Certain degree			
	CameraVideo	Certain degree	Certain degree	XiamiMusic	Evident	Certain degree
	GoogleMaps	Certain degree	Certain degree	Meitu	Evident	Certain degree
	YouTube	Almost no	Certain degree			
	Radio	Certain degree	Evident			
SNS	Facebook	Certain degree	Certain degree	Qiu	Certain degree	Certain degree
	Twitter	Certain degree	Certain degree	BaiduTieba	Certain degree	Certain degree
				Wechat	Certain degree	Almost no
				Weibo	Evident	Almost no
				Tencent	Certain degree	Almost no
Game	AngryBirds	Certain degree	Certain degree	FruitCool	Evident	Certain degree
				PeaPod	Evident	Certain degree
				Game2048	Evident	Certain degree

Auto-correlation & Self-similarity

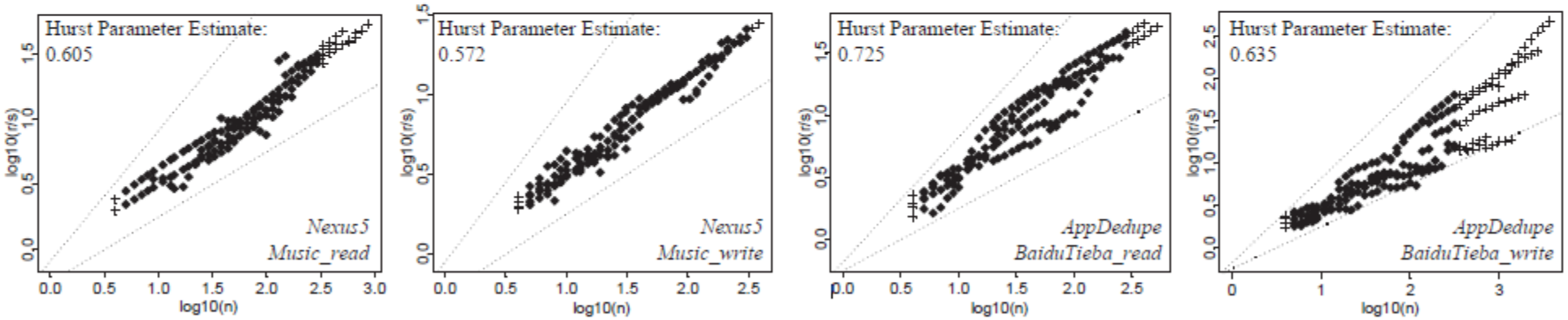
- What is self-similarity?
  - ✓ The characteristics of a certain process are similar from different time scales
  - ✓ Obtain an intuitive impression of the self-similar nature in data traffic through the literature [15]
  - ✓ How to measure?---the Hurst parameter ($0.5<H<1$)
- Tools to estimate the Hurst Parameter:
  - ✓ Variance-time plot (VTP) [15]
  - ✓ R/S (rescaled adjusted range) analysis (also called Pox plot) [4]

Auto-correlation & Self-similarity

➢ Estimation of the Hurst parameter for the Music and BaiduTieba applications



(a) The Variance-time plots



(b) The Pox plots

Figure 4: Estimating Hurst parameter: Plot (a) gives the variance-time plots, and Plot (b) shows the Pox plots for read and write requests in the Nexus5 and AppDedupe applications, respectively.

Auto-correlation & Self-similarity

- Estimation of the Hurst parameter for Smartphone applications

TABLE 3: ESTIMATING HURST PARAMETER.

	Type	Application	Estimates of Hurst parameter			
			VTP		R/S analysis	
			Read	Write	Read	Write
Nexus5	Web	Email	0.972	0.599	0.589	0.507
		Amazon	0.687	0.701	0.502	0.634
		WebBrowsing	0.601	0.614	0.637	0.589
	Multi-media	Movie	N/A	0.785	N/A	0.578
		Music	0.683	0.687	0.605	0.572
		CameraVideo	0.506	0.932	0.517	0.686
		GoogleMaps	0.935	0.613	0.583	0.605
		YouTube	N/A	0.615	N/A	0.577
		Radio	0.516	0.995	0.558	0.698
	SNS	Facebook	0.505	0.536	0.670	0.589
		Twitter	0.776	0.663	0.767	0.647
	Game	AngryBirds	0.900	0.834	0.700	0.722
	Syst.	Idle	0.963	0.516	0.537	0.537
		Booting	0.993	N/A	0.656	N/A
		Installing	0.983	0.647	0.504	0.656
	Basic	CallIn	N/A	0.518	N/A	0.547
		CallOut	N/A	0.567	N/A	0.554
		Messaging	0.501	0.549	0.598	0.587

	Type	Application	Estimates of Hurst parameter			
			VTP		R/S analysis	
			Read	Write	Read	Write
App-Dedupe	Web	58City	0.996	0.694	0.898	0.663
		MojiWeather	0.993	0.603	0.935	0.718
		OperaBrowser	0.988	0.569	0.784	0.708
		SohuNews	0.994	0.588	0.771	0.615
		YoudaoDict	N/A	0.736	N/A	0.727
	Multi-media	XiamiMusic	0.906	0.525	0.695	0.622
		Meitu	0.997	0.576	0.801	0.638
	SNS	Qiu	0.991	0.859	0.682	0.690
		BaiduTieba	0.635	0.753	0.725	0.635
		Wechat	0.755	N/A	0.736	N/A
		Weibo	0.849	N/A	0.779	N/A
		Tencent	0.740	N/A	0.575	N/A
	Game	FruitCool	0.997	0.772	0.856	0.693
		PeaPod	0.992	0.627	0.876	0.680
		Game2048	0.609	0.573	0.695	0.627

Synthesis

- Read and write requests:
  - ✓ Appear to be IID in a minority of Smartphone applications.
  - ✓ Present self-similarity in most mobile applications.
- So, a versatile I/O request generator is needed:
  - ✓ To flexibly synthesize both the IID and self-similar request series.
- The alpha-stable model used in Ref. [35] does specialize in.
  - ✓ Including 5 characteristic exponents, i.e. α, β, σ, μ and H.

Synthesis

TABLE 4: ESTIMATES OF THE PARAMETERS OF ALPHA-STABLE MODEL BASED ON MAXIMUM-LIKELIHOOD ESTIMATE.

	Category	Application	Alpha-stable parameter							
			Read				Write			
			α	β	σ	μ	α	β	σ	μ
Nexus5	Web	Email	0.753	1.000	1.69336	1.65897	1.492	1.000	4.26704	1.76417
		Amazon	1.259	1.000	1.86528	2.83142	1.055	1.000	1.15262	0.481945
		WebBrowsing	0.722	1.000	1.07085	1.30469	1.576	1.000	0.476345	6.71386
	Multi-media	Movie	2.000	N/A	2.09666	5.00000	1.732	1.000	1.84897	1.97764
		Music	0.810	1.000	0.230783	0.33578	1.392	1.000	2.46264	3.68941
		CameraVideo	1.105	1.000	11.0188	7.35920	1.251	1.000	1.40482	1.95681
		GoogleMaps	0.857	1.000	4.97107	1.58223	1.065	1.000	2.93415	3.94645
		YouTube	2.000	N/A	7.07621	7.00000	1.048	0.650	0.413874	1.87462
		Radio	0.582	1.000	0.187590	0.600699	1.015	1.000	0.599205	1.52030
	SNS	Facebook	1.046	1.000	2.18949	1.75500	1.403	1.000	2.77890	3.28988
		Twitter	0.495	0.679	0.496075	1.73237	2.103	1.000	74.4216	109.563
	Game	AngryBirds	0.779	1.000	1.37965	0.309696	1.358	1.000	1.65876	0.352857
	System	Idle	1.391	1.000	5.75139	0.281383	1.088	1.000	0.630747	1.50039
		Booting	2.000	N/A	133.138	142.000	0.965	1.000	15.4338	14.7975
		Installing	1.135	1.000	0.926981	1.01511	1.214	1.000	8.37532	3.99068
	Basic	CallIn	N/A	N/A	N/A	N/A	0.774	0.943	0.505572	1.64573
		CallOut	N/A	N/A	N/A	N/A	1.057	1.000	0.802666	1.12361
		Messaging	0.651	1.000	0.484863	0.612074	1.142	1.000	7.92939	0.371500
App-Dedupe	Web	58City	1.243	1.000	9.92369	1.51147	0.702	0.478	1.36847	8.66558
		MojiWeather	1.068	1.000	43.8725	49.7752	0.564	0.379	0.612295	9.90113
		OperaBrowser	0.917	1.000	7.23940	5.82955	0.734	0.348	1.19161	9.82263
		SohuNews	1.183	1.000	5.65366	2.84954	0.588	0.410	0.619861	9.88300
		YoudaoDict	1.405	1.000	2.49634	0.819159	1.320	1.000	8.52834	7.09163
	Multi-media	XiamiMusic	1.468	1.000	4.12785	4.62793	0.687	0.255	0.822920	9.92455
		Meitu	1.237	1.000	11.6244	3.40332	0.913	0.549	2.78354	9.25005
	SNS	Qiu	1.135	1.000	5.41833	2.88988	1.203	0.282	1.48739	9.84817
		BaiduTieba	0.990	1.000	2.94737	3.64542	1.306	0.663	5.14837	11.2792
		Wechat	1.237	1.000	3.29481	2.14703	1.083	1.000	5.58413	7.66937
		Weibo	1.012	1.000	3.58972	4.12543	1.091	0.584	3.49948	9.11128
		Tencent	0.986	1.000	1.32137	1.66474	1.438	1.000	10.0201	13.7350
	Game	FruitCool	1.302	1.000	11.9668	0.939637	0.876	0.558	2.68281	9.24305
		PeaPod	1.989	1.000	24.5416	10.8361	0.543	0.396	0.574609	9.90076
		Game2048	1.238	1.000	4.94893	2.71991	0.665	0.430	1.01914	8.78944

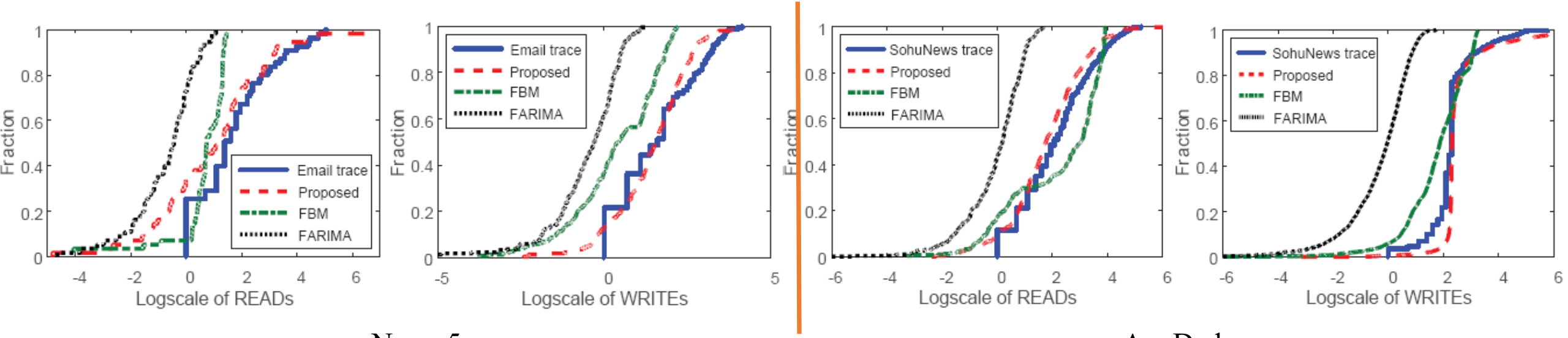
- Error estimation for the self-similar mobile application workloads.

TABLE 5: TRIMMED MEANS OF ERRORS FOR SYNTHESIZING SELF-SIMILAR REQUEST SEQUENCES.

	Category	Application	FARIMA		FBM		Proposed		Improvement (%)			
									vs FARIMA		vs FBM	
			Read	Write	Read	Write	Read	Write	Read	Write	Read	Write
Nexus5	Web	Email	14.05	7.81	21.37	9.64	11.47	6.36	46	18	18	34
		Amazon	4.65	4.01	5.90	3.92	5.18	3.69	21	8	10	6
		WebBrowsing	15.65	4.70	11.28	5.58	9.51	3.02	39	36	15	45
	Multi-media	Movie	N/A	4.81	N/A	4.01	N/A	3.64	N/A	24	N/A	9
		Music	2.02	5.48	15.73	7.94	1.29	4.39	36	20	91	44
		CameraVideo	24.48	3.79	37.16	4.96	21.96	2.71	10	29	40	45
		GoogleMaps	35.99	7.18	26.81	18.98	25.75	7.26	28	-1	3	62
		YouTube	N/A	2.04	N/A	11.53	N/A	0.87	N/A	57	N/A	92
		Radio	5.19	3.34	4.88	74.63	4.41	1.49	15	55	10	98
	SNS	Facebook	10.85	6.52	13.66	5.72	8.45	6.25	22	4	38	-9
		Twitter	35.35	22.80	11.57	32.82	9.94	15.38	71	32	14	53
	Game	AngryBirds	10.71	3.81	11.33	16.23	10.80	3.11	-0.8	18	5	81
	System	Idle	15.09	2.31	14.84	24.65	12.83	1.58	15	32	13	93
		Booting	166.97	N/A	217.74	N/A	165.10	N/A	1	N/A	24	N/A
		Installing	4.58	19.85	4.08	46.28	2.79	16.33	39	18	32	65
	Basic	CallIn	N/A	4.62	N/A	3.71	N/A	3.26	N/A	29	N/A	12
		CallOut	N/A	3.67	N/A	7.88	N/A	3.74	N/A	-2	N/A	53
		Messaging	10.07	21.34	8.97	30.48	9.01	19.35	10	9	-0.4	37
App-Dedupe	Web	58City	22.05	9.20	45.93	20.94	16.85	5.64	23	39	63	73
		MojiWeather	79.61	9.86	37.44	24.33	24.56	4.67	69	53	34	81
		OperaBrowser	26.20	9.70	33.83	14.78	19.31	5.24	26	46	43	65
		SohuNews	13.51	9.50	14.83	12.91	9.45	4.26	30	55	36	67
		YoudaoDict	N/A	17.00	N/A	26.66	N/A	17.67	N/A	-4	N/A	34
	Multi-media	XiamiMusic	10.04	9.30	10.38	13.27	8.93	4.10	11	56	14	69
		Meitu	18.30	10.34	24.44	19.18	15.41	7.33	16	29	37	62
	SNS	Qiu	17.00	9.27	14.79	17.89	15.47	2.58	9	72	-4.5	85
		BaiduTieba	9.79	11.52	15.14	15.68	8.97	9.06	8	21	41	42
		Wechat	6.56	N/A	31.49	N/A	7.19	N/A	-9	N/A	77	N/A
		Weibo	14.44	N/A	18.54	N/A	11.45	N/A	21	N/A	38	N/A
		Tencent	6.56	N/A	6.70	N/A	4.95	N/A	24	N/A	26	N/A
	Game	FruitCool	24.29	10.63	39.44	25.98	15.11	7.32	38	31	62	72
		PeaPod	25.75	10.02	35.87	19.99	22.39	4.96	13	50	37	75
		Game2048	16.79	8.97	14.15	8.93	13.02	3.98	22	56	8	55

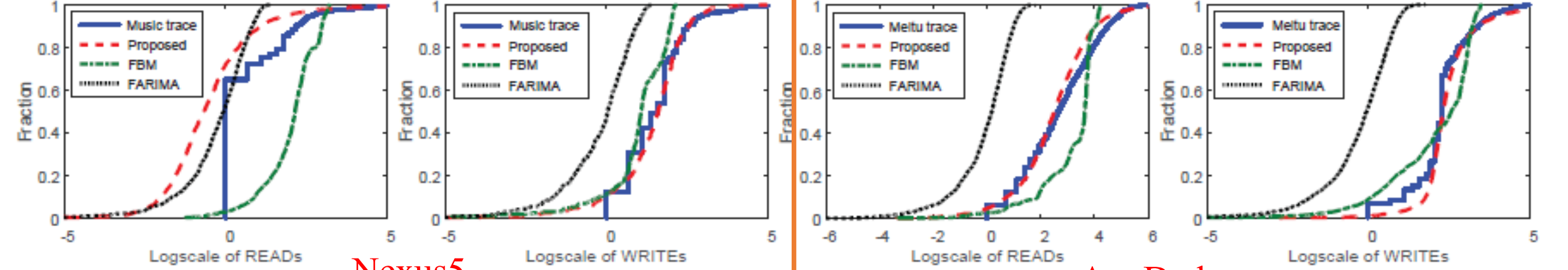
Synthesis

- Empirical Study (CDF: Cumulative Distribution Functions):
  - ✓The Figure shows the comparison of the empirical distributions of the logscale of the number of read requests (READs) or write requests (WRITEs) per second, for the *web* type of Nexus5 and AppDedupe applications, e.g., *Email, SohuNews*

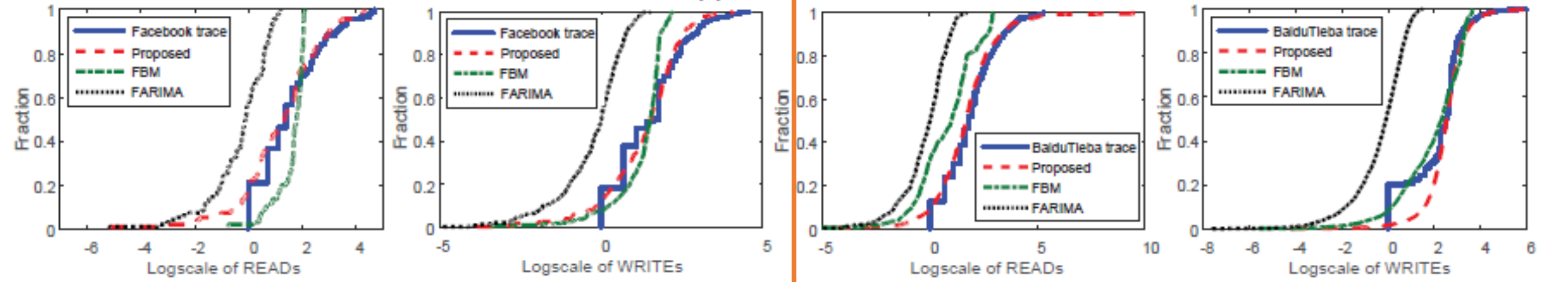


Nexus5 AppDedupe

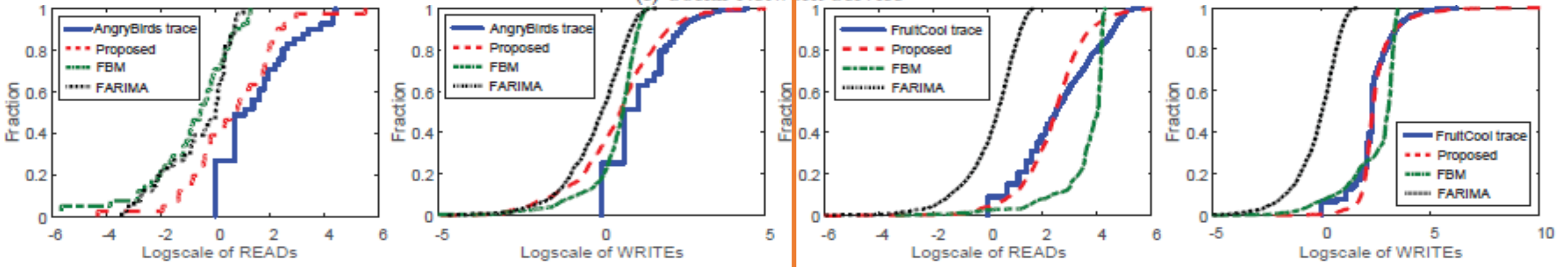
Fig. 5



(b) Multimedia



(c) Social Network Service



(d) Game

Synthesis

- Error estimation for the IID mobile application workloads
- Empirical Study:
  - ✓ Fig. 6 shows the empirical distributions of the synthetic and actual request sequences for *read requests in Movie and write requests in Wechat*

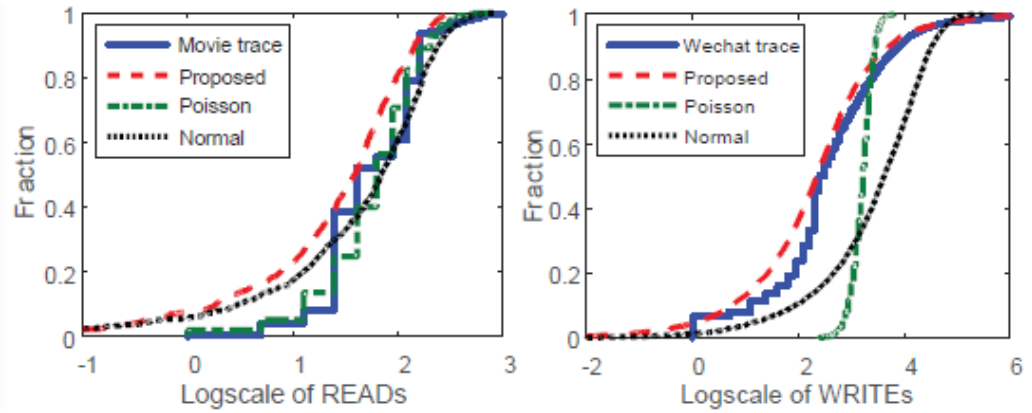


Figure 6: Comparison of the CDFs of the synthetic and real sequences for the IID Nexus5 (e.g. Movie) and AppDedupe (e.g. Wechat) application workloads.

TABLE 6: TRIMMED MEANS OF ERRORS FOR SYNTHESIZING IID REQUEST SEQUENCES.

	Category	Application	Normal		Poisson		Proposed		Improvement (%)			
									vs Normal		vs Poisson	
			Read	Write	Read	Write	Read	Write	Read	Write	Read	Write
Nexus5	Multi-media	Movie	3.30	N/A	3.12	N/A	2.81	N/A	15	N/A	10	N/A
		YouTube	13.40	N/A	9.20	N/A	8.09	N/A	40	N/A	12	N/A
	System	Booting	N/A	102.39	N/A	67.85	N/A	60.82	N/A	40	N/A	10
App-Dedupe	Web	YoudaoDict	9.02	N/A	5.48	N/A	5.78	N/A	36	N/A	-5	N/A
	SNS	Wechat	N/A	38.37	N/A	15.60	N/A	12.26	N/A	59	N/A	21
		Weibo	N/A	16.49	N/A	7.52	N/A	7.41	N/A	55	N/A	1
		Tencent	N/A	24.51	N/A	18.77	N/A	15.18	N/A	38	N/A	19

Conclusion

- Characterizing mobile I/O workloads is critically important for the design and performance optimization of the mobile storage subsystem.
- This paper studies the correlation of inter-arrival times of read or write requests in 33 Smartphone applications, and shows the existence of self-similarity in both Nexus5 and AppDedupe workloads.
- Based on the parameters measured from Nexus5 and AppDedupe traces, we deploy a flexible mobile I/O request generator to accurately synthesize mobile storage workloads.

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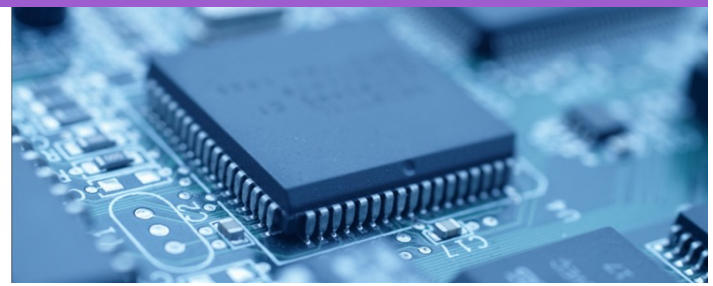

Revisiting Temporal Storage I/O Behaviors of Smartphone Applications: Analysis and Synthesis

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Thank you!

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