Cloudlets

At the Leading Edge of Cloud-Mobile Convergence
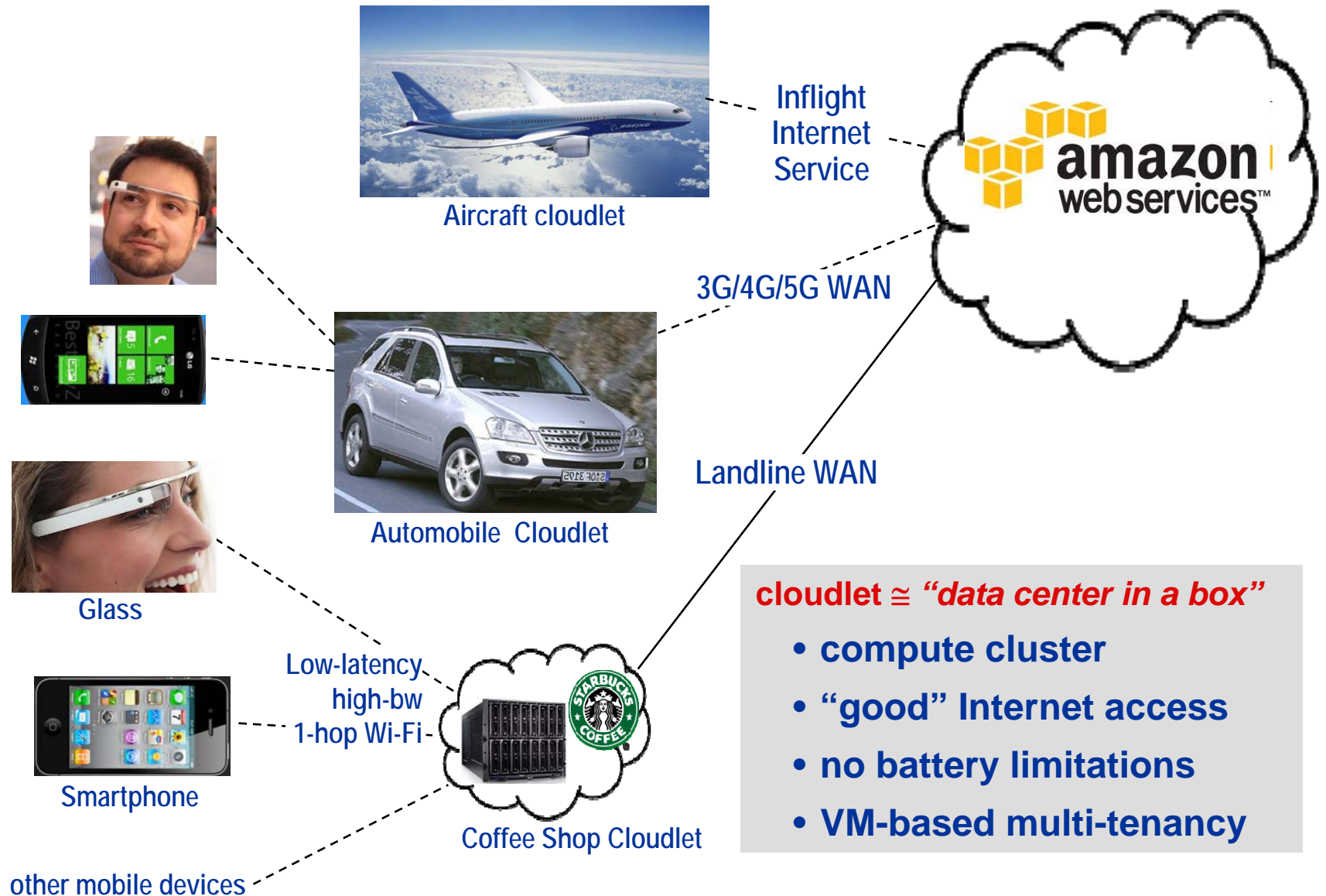
Mahadev Satyanarayanan

School of Computer Science

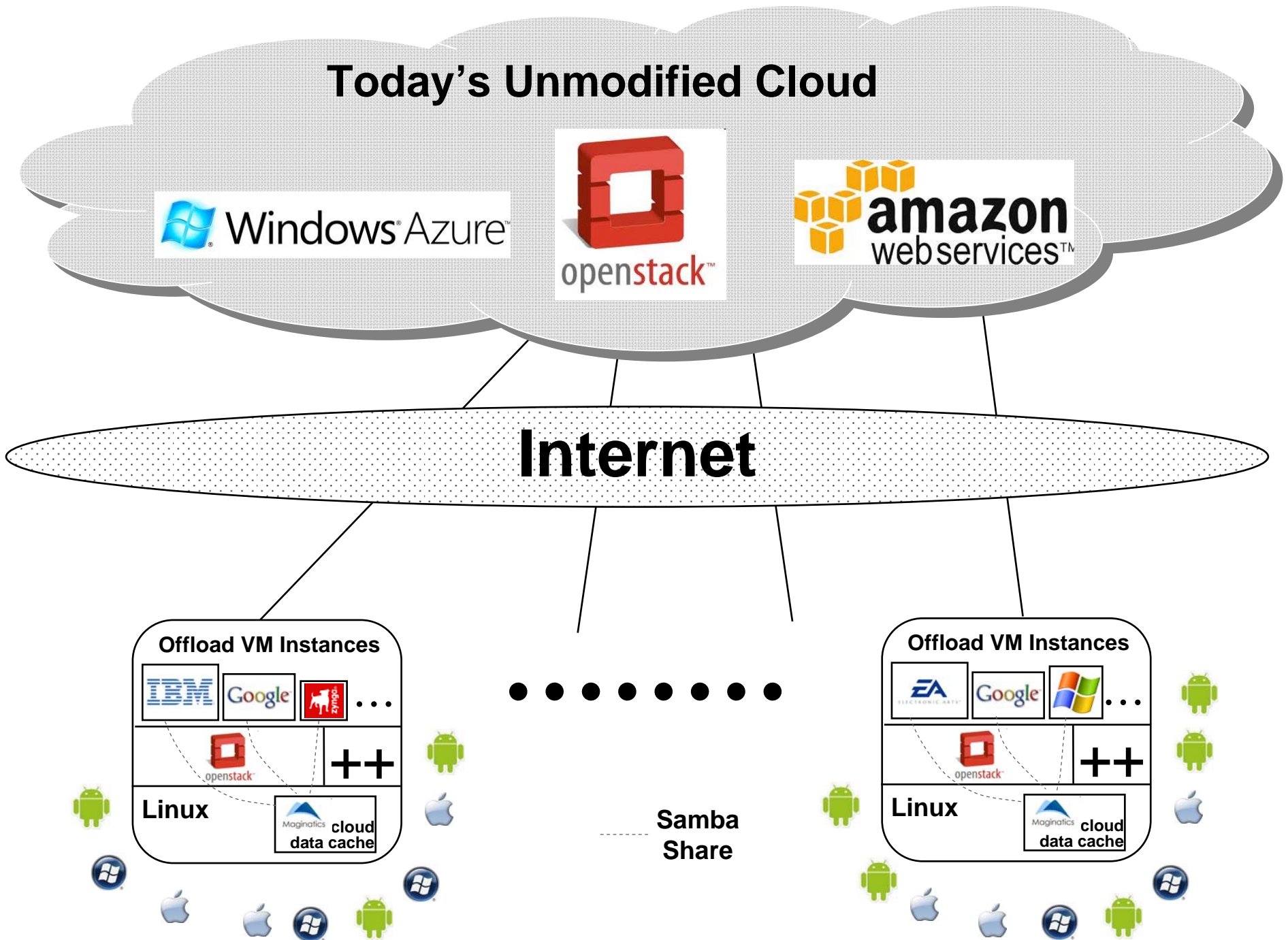**Carnegie Mellon University**

http://elijah.cs.cmu.edu

Bring the Cloud Closer

Create a Small Cloudlet Nearby

Aircraft cloudlet

Inflight Internet Service

amazon web services™

3G/4G/5G WAN

Automobile Cloudlet

Glass

Landline WAN

Smartphone

Low-latency high-bw 1-hop Wi-Fi

Coffee Shop Cloudlet

other mobile devices

cloudlet ≅ *"data center in a box"*

- **compute cluster**
- **"good" Internet access**
- **no battery limitations**
- **VM-based multi-tenancy**

November 7, 2013

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Three Questions

1. Does Latency Really Matter?

2. Can Cloudlets Self-Manage?

3. Can Cloudlets Reduce Bandwidth Demand?

1. Does Latency Really Matter?

"The Impact of Mobile Multimedia Applications on Data Center Consolidation"
Ha, K. Pillai, P., Lewis, G., Simanta, S., Clinch, S., Davies, N., Satyanarayanan, M.
IEEE International Conference on Cloud Engineering, San Francisco, CA, March 2013

"How Close is Close Enough? Understanding the Role of Cloudlets in Supporting Display Appropriation by Mobile Users"
Clinch, S., Harkes, J., Friday, A., Davies, N., Satyanarayanan, M.
Proceedings of the IEEE International Conference on Pervasive Computing and Communications (PerCom 2012), Lugano, Switzerland, March 2012.
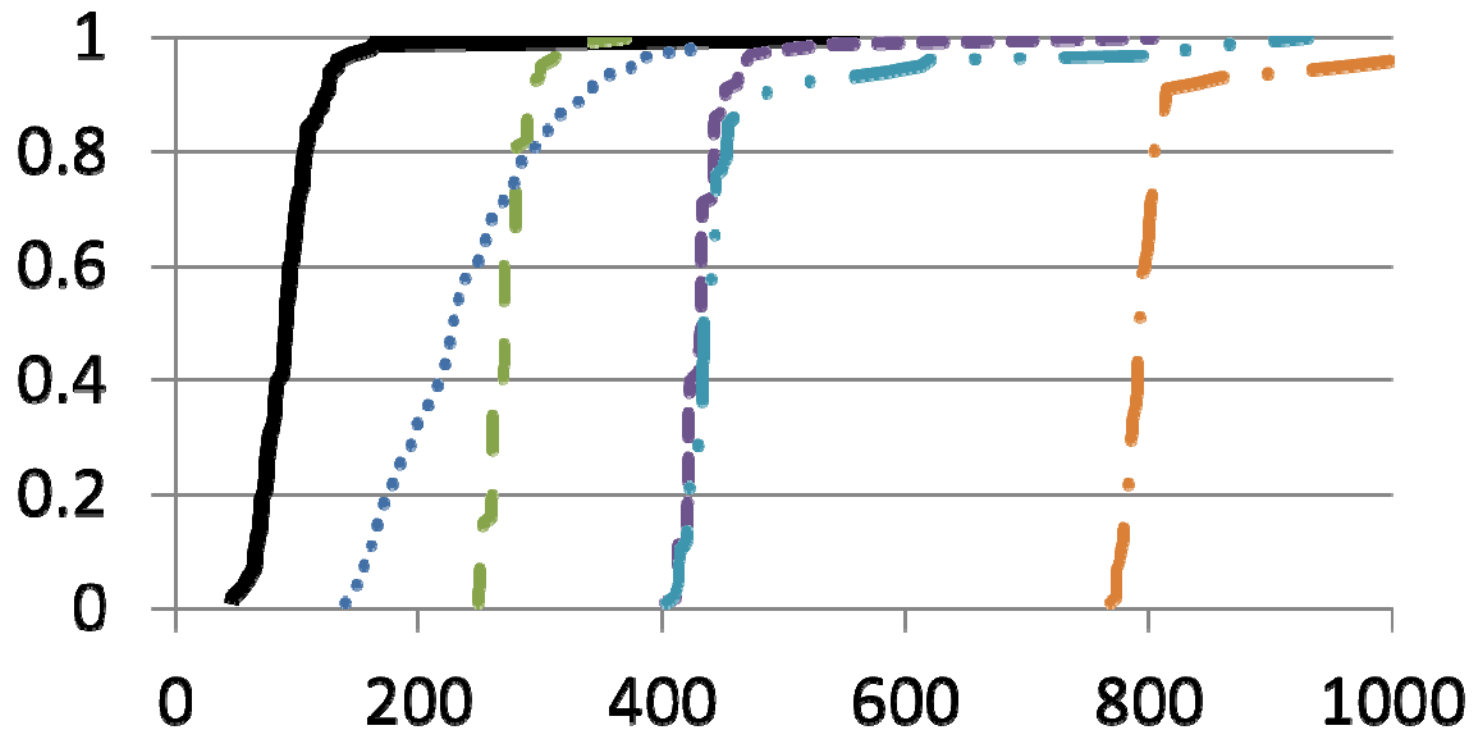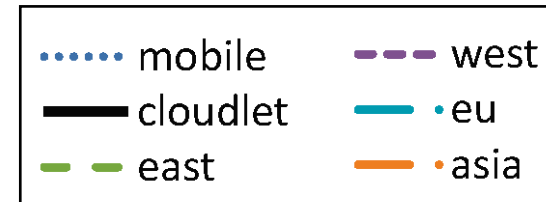
Face Recognition

CDF of Response Times (milliseconds)
Amazon EC2 offload
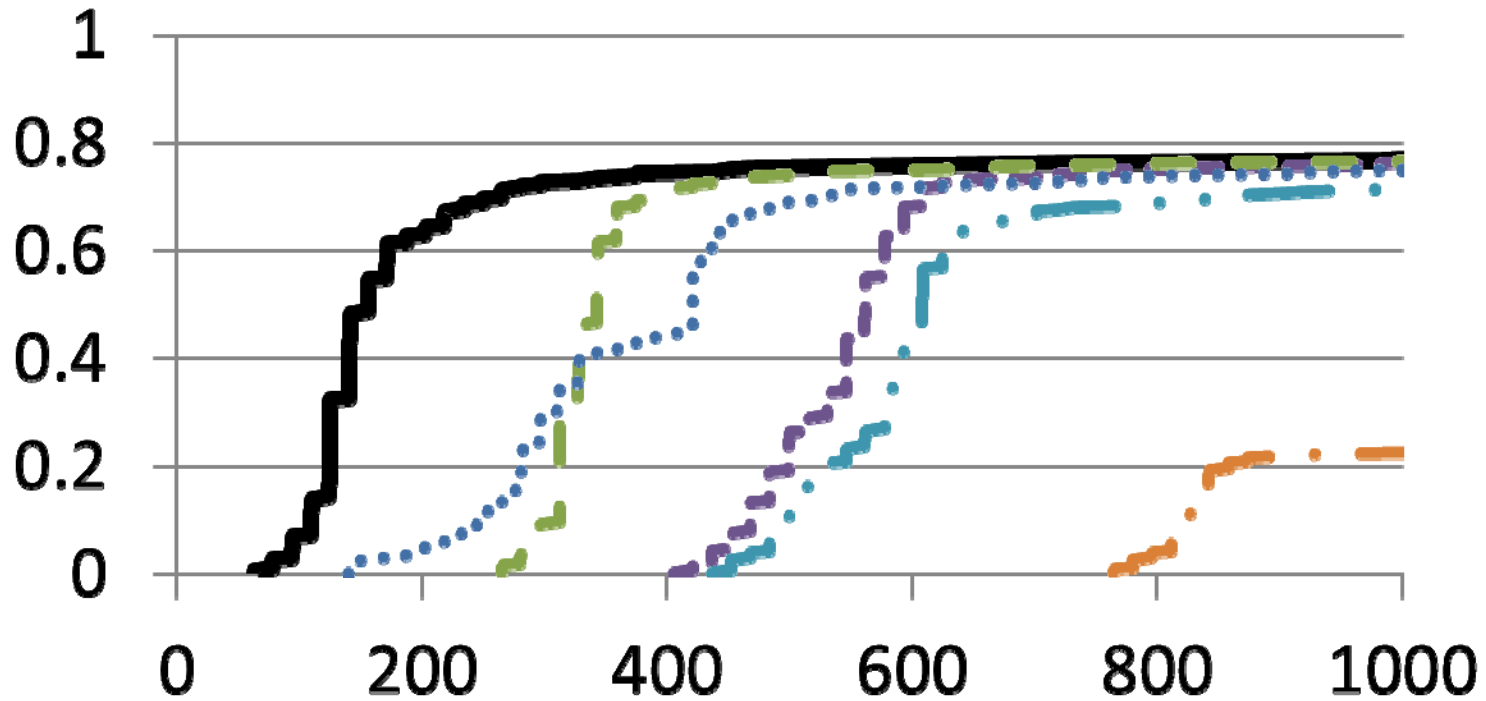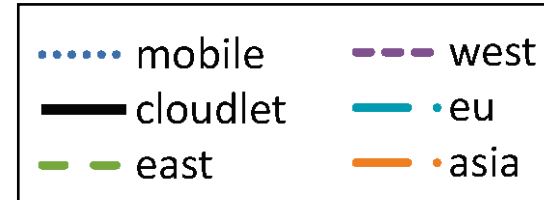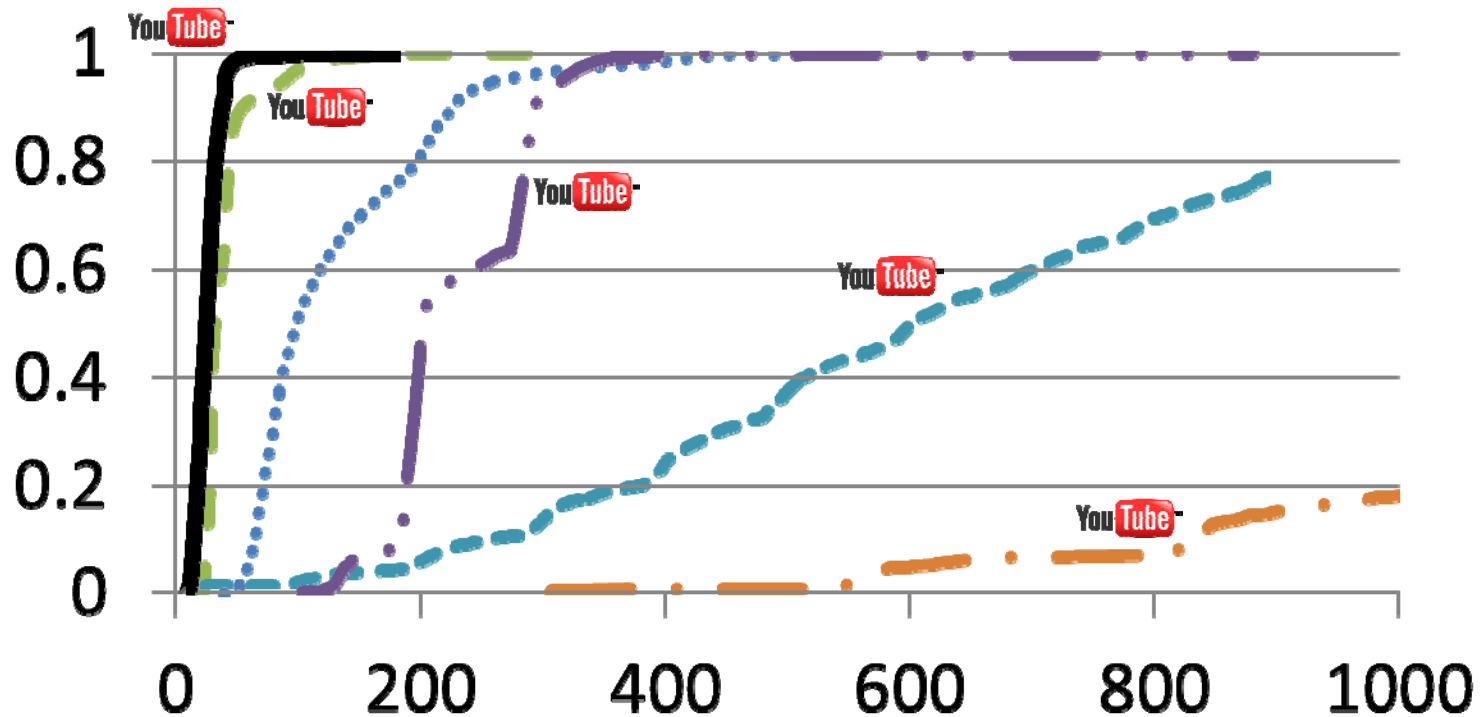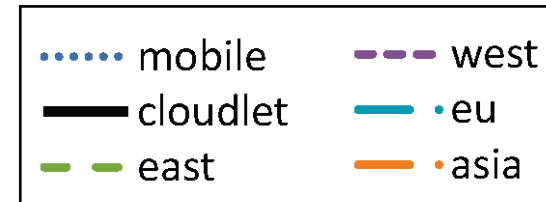
Augmented Reality

CDF of Response Times (milliseconds)
Amazon EC2 offload

Legend:
- ······ mobile
- —— cloudlet
- — — east
- - - - west
- —— eu
- —·— asia

Simulation-based Graphics

CDF of Response Times (milliseconds)
Amazon EC2 offload

Won't Mobile Devices Get Better?

Year	Typical Server		Typical Handheld or Wearable	
	Processor	Speed	Device	Speed
1997	Pentium® II	266 MHz	Palm Pilot	16 MHz
2002	Itanium®	1 GHz	Blackberry 5810	133 MHz
2007	Intel® Core™ 2	9.6 GHz (4 cores)	Apple iPhone	412 MHz
2011	Intel® Xeon® X5	32 GHz (2x6 cores)	Samsung Galaxy S2	2.4 GHz (2 cores)
2013	Intel® Xeon® E5	64 GHz (2x12 cores)	Google Glass OMAP 4430	2.4 GHz (2 cores)

Adapted from: J. Flinn, "*Cyber Foraging: Bridging Mobile and Cloud Computing via Opportunistic Offload.*" Morgan & Claypool Publishers, 2012.

Mobility demands a premium

- weight, size, battery life, heat dissipation, …
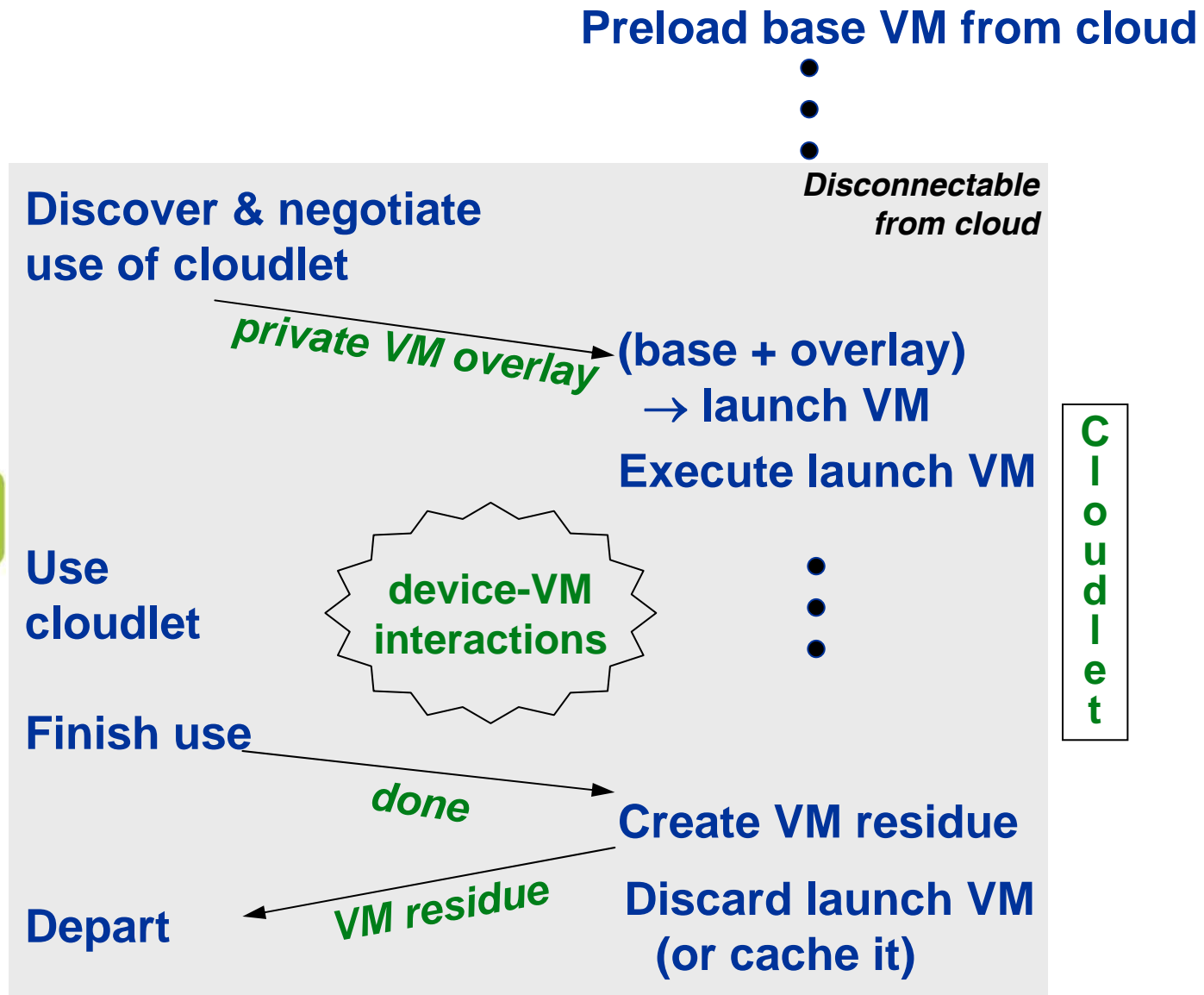- Moore's Law applied differently in this world

2. Can Cloudlets Self-Manage?

"Just-in-Time Provisioning for Cyber Foraging"

Ha, K., Pillai, P., Richter, W., Abe, Y., Satyanarayanan, M.

Proceedings of the Eleventh International Conference on Mobile Computing Systems, Applications and Services (MobiSys 2013), Taipei, Taiwan, June 2013

Dynamic VM Synthesis

Preload base VM from cloud

•
•
•

Disconnectable from cloud

Discover & negotiate use of cloudlet

private VM overlay

(base + overlay) → launch VM

Execute launch VM

Use cloudlet

device-VM interactions

C l o u d l e t

Mobile Device

Finish use

done

Create VM residue

Depart

VM residue

Discard launch VM (or cache it)

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Optimizations

Goal is to minimize "time to value"

- **(Overlay transfer + decompression + applying delta + VM resume)**

- **excludes time for association with cloudlet**

- **includes time to produce first result (1-2 minutes)**

4 optimizations

1. *Deduplication*

2. *Bridging semantic gaps*

  } Reduce overlay size
  (at overlay creation time)

3. *Pipelining*

4. *Early Start*

  } Expedite synthesis
  (at runtime)

Optimizations Win Big!
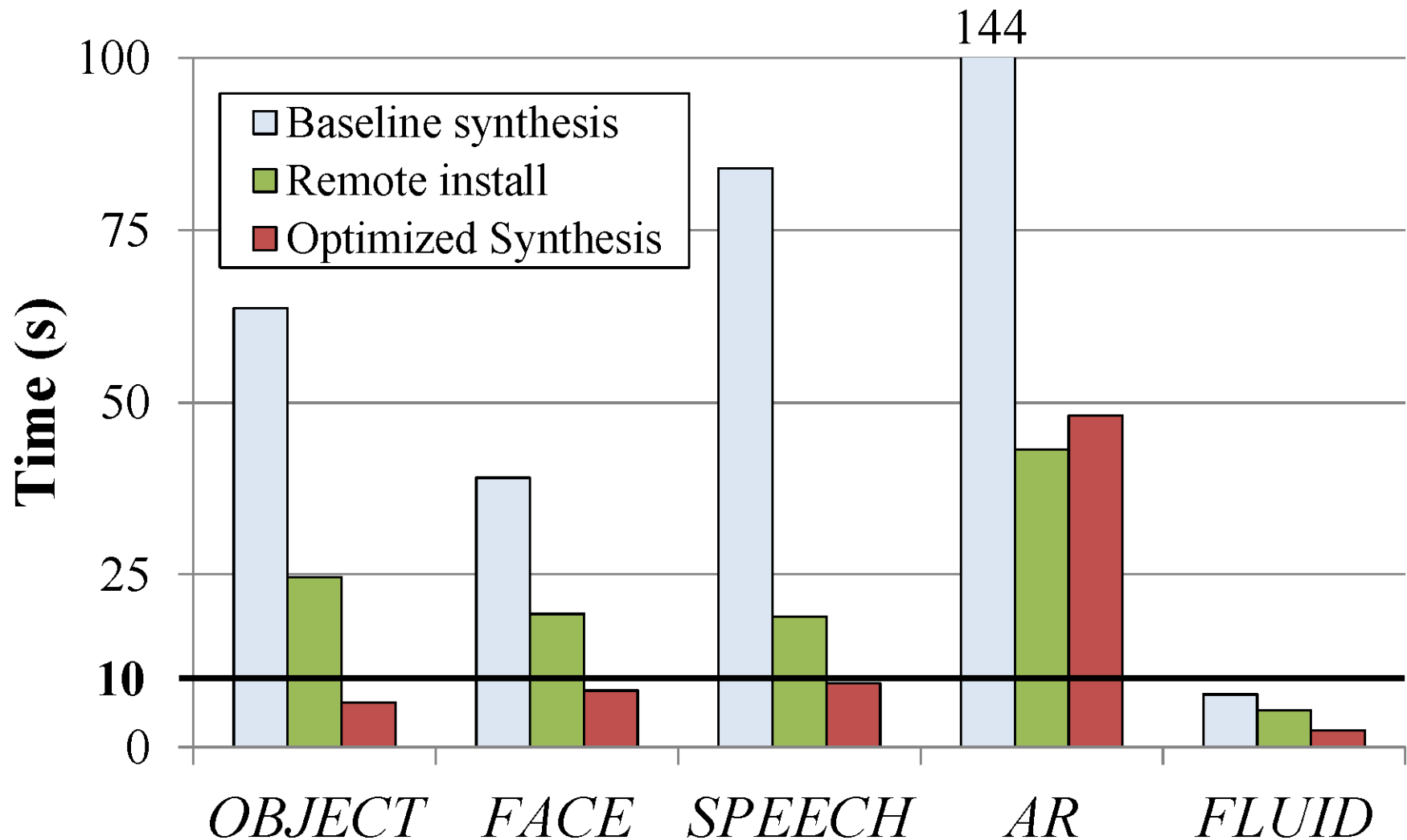
3. Can Cloudlets Reduce Bandwidth Demand?

"Scalable Crowd-Sourcing of Video from Mobile Devices"

Simoens, P., Xiao, Y., Pillai, P., Chen, Z., Ha, K., Satyanarayanan, M.

Proceedings of the Eleventh International Conference on Mobile Computing Systems, Applications and Services (MobiSys 2013), Taipei, Taiwan, June 2013

Effortless Video Capture

Google Glass Hits Runway At New York Fashion Week (PHOTOS)

Billy Farrell/BFAnyc/Sipa USA/Newscom

CARL FRANZEN - SEPTEMBER 10, 2012, 11:28 AM | 👁 3571

37

🐦 Tweet

👍 17

f Like

20

Updated 12:16 p.m. EDT, Monday, September 10

Google's experimental hi-tech glasses, "Google Glass," made an unexpected appearance at New York Fashion Week on Sunday when models for designer Diane Von Furstenberg (DVF)'s Spring 2013 collection took to the runway wearing the computerized specs, only to be joined later by the bespectacled designer herself and Google co-founder and Glass project leader Sergey Brin.

Opportunistic Sensing

Lost Child at Large Public Event

Found!

Challenge: Bandwidth

High cumulative data rate could overwhelm

- **metro area networks**

- **ingress Internet paths into centralized cloud infrastructure**

Today, 1 hour of video is uploaded to YouTube each second

- **equivalent of only 3,600 users simultaneously streaming**

- ***decentralization* essential for one million users or more**

Verizon recently upgraded metro area networks to 100 Gbps link

- **one link supports 1080p streams from only 12,000 users**
  (at YouTube's recommended upload rate of 8.5 Mbps)

- **supporting a million users will require 8.5 Tbps**

- ***even one YouTube data center per city may be too sparse!***

Challenge: Denaturing

One possible incentive model: like book publishing
     (royalties shared by service provider for images of value to others)

Continuous analysis and editing of privacy-sensitive parts of images

- **combines meta-data (e.g. location) and content (e.g. specific faces)**

- **automatic but user-specific, possibly context sensitive**

- **cannot require manual intervention by user (only exceptions)**
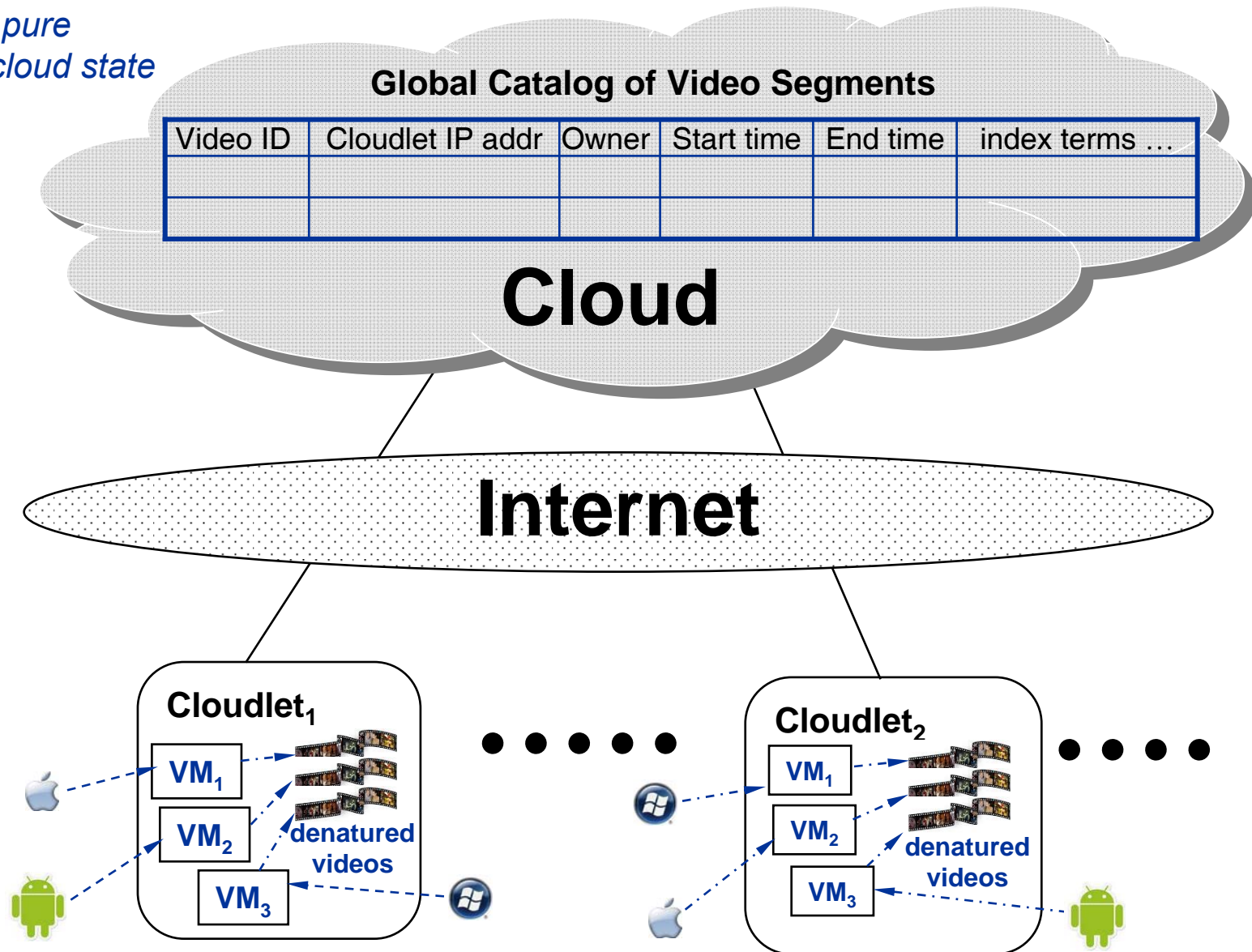 **(no incentive model can sustain continuous manual user effort)**
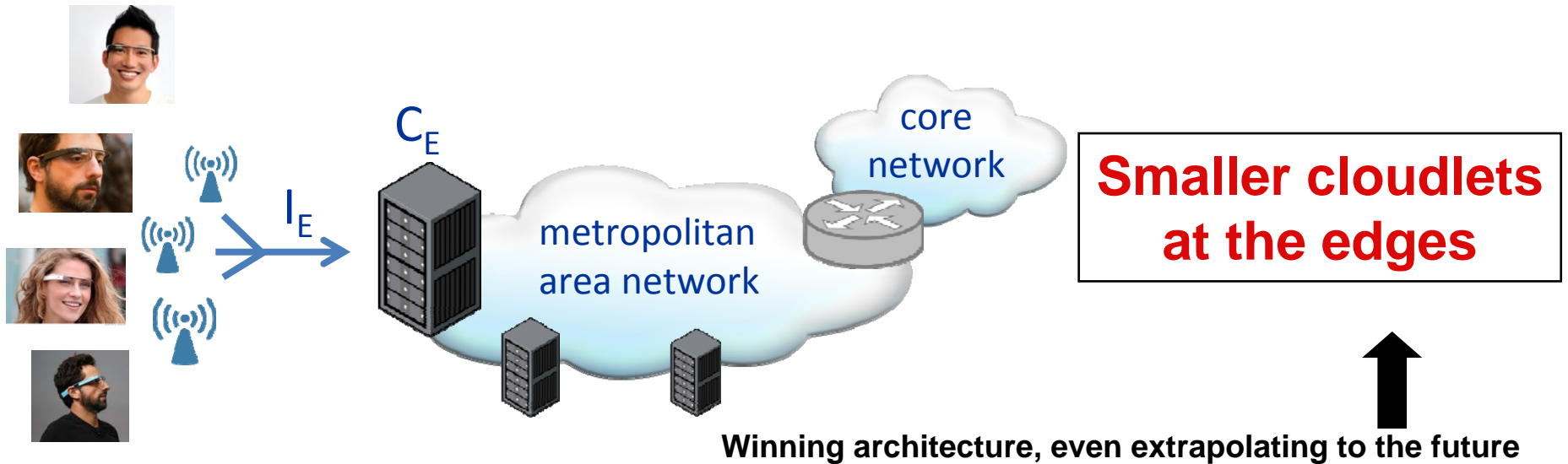
Image processing and denaturing is computationally expensive!
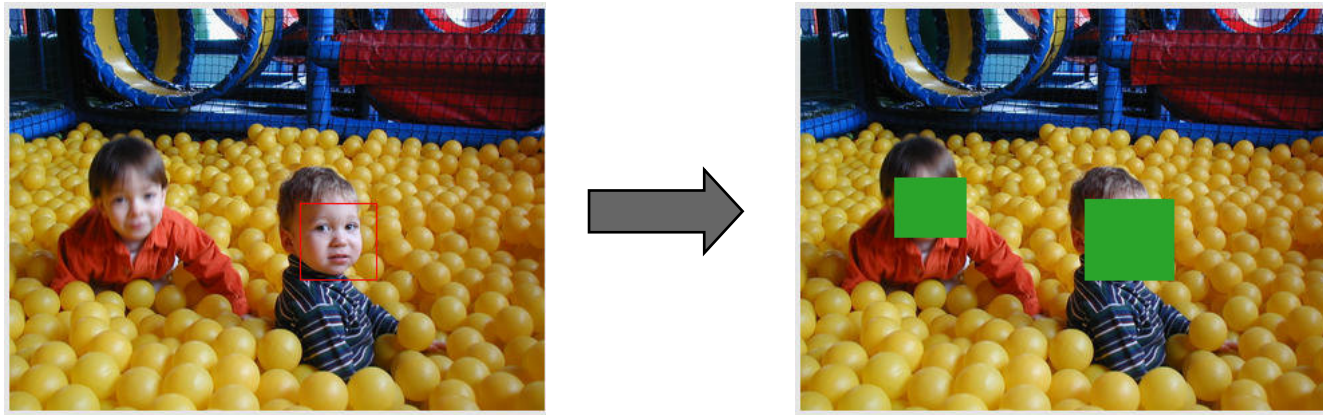
GigaSight Architecture

CDN in Reverse

Cloudlets now contain hard state – no longer pure cache of cloud state

Global Catalog of Video Segments

Video ID	Cloudlet IP addr	Owner	Start time	End time	index terms …

Cloud

Internet

Cloudlet$_1$

VM$_1$
VM$_2$
VM$_3$

denatured videos

Cloudlet$_2$

VM$_1$
VM$_2$
VM$_3$

denatured videos

Core versus Edge Deployment

C_E

I_E

core network

metropolitan area network

Smaller cloudlets at the edges

Winning architecture, even extrapolating to the future

Less scalable, even with future networks

Bigger cloudlet deep inside

metropolitan area network

core network

I_M

C_M

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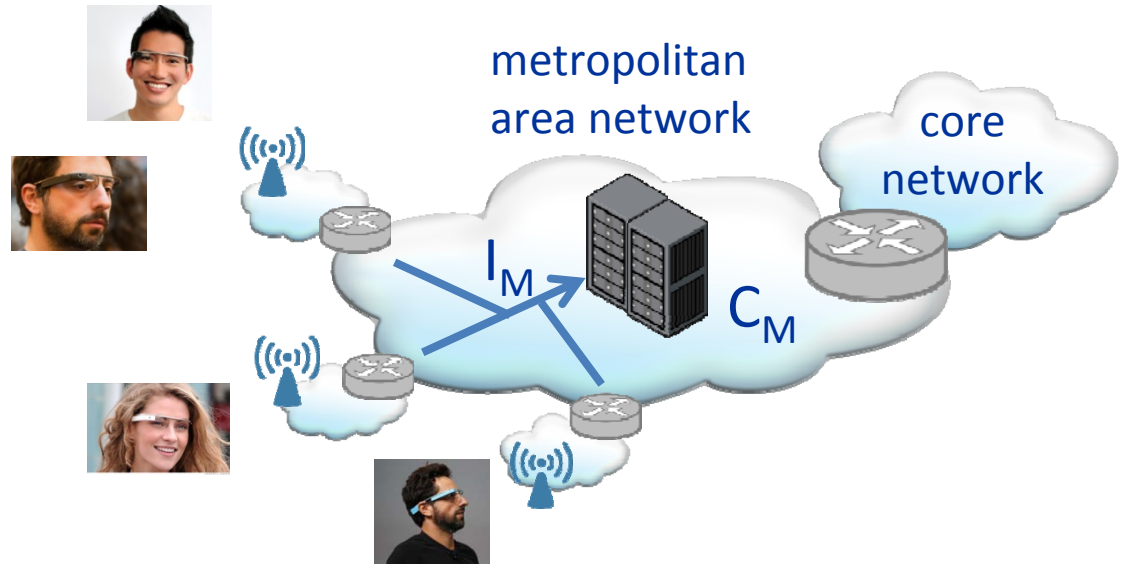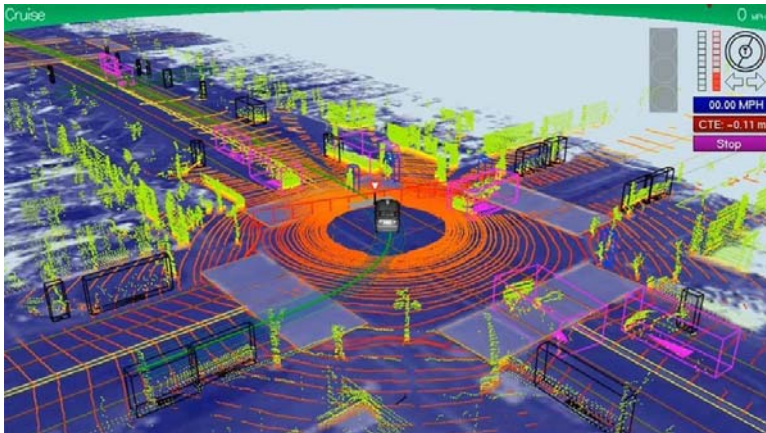
Broader Context of GigaSight

Near real-time edge analytics on high-data rate sensors

GE Aircraft Engines

1 TB/engine/day of sensor data

Google Car 750 MB/s

Boeing 787s to create half a terabyte of data per flight, says Virgin Atlantic

Internet of things will create a wide range of opportunities and challenges for airline

By Matthew Finnegan | Computerworld UK | Published 14:27, 06 March 13

The Path Forward

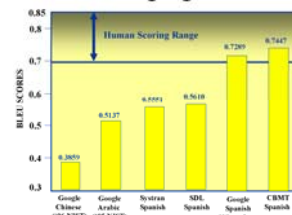|	
2008	**Early ideas on transient customization (Kimberley project at CMU)** **"Transient Customization of Mobile Computing Infrastructure",** Wolbach et al, **Proc. of the MobiVirt 2008 Workshop on Virtualization in Mobile Computing, June 2008, Breckenridge, CO** **Discussions leading to cloudlet concept for futuristic mobile apps** Satya, Victor Bahl (Microsoft), Ramon Caceres (AT&T), Nigel Davies (Lancaster), Roy Want (Intel)
2009	**"The Case for VM-based Cloudlets in Mobile Computing"** **published in October 2009** Very well received, over 370 citations in 4 years according to Google Scholar!
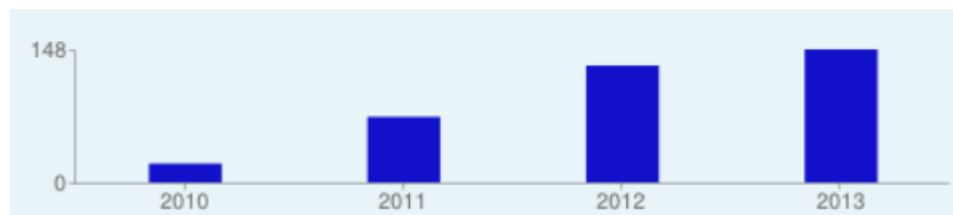
2010-2013 **Outside Carnegie Mellon**	**Research community embraces cloudlet concept** (many publications, partial list below) • **"Cloudlet-screen computing: A multi-core-based, cloud-computing-oriented, traditional-computing-compatible parallel computing paradigm for the masses"** Lin, T., IEEE International Conference on Multimedia and Expo (ICME 2009). July 2009 • **"Impact of Cloudlets on Interactive Mobile Cloud Applications"** Fesehaye et al, IEEE 16th International Enterprise Distributed Object Computing Conference, 2012 [Univ. of Illinois] • **"Cloud-Vision: Real-time face recognition using a mobile-cloudlet-cloud acceleration architecture"** Soyata, T., IEEE Symposium on Computers and Communication, (ISCC) July 2012 • **"Experimental framework of integrated cloudlets and wireless mesh networks"** Khan et al, Telecommunications Forum (TELFOR), Nov. 2012 • **"Tactical Cloudlets"** Keynote by Dr. Raju Namburu, Chief of Computational Sciences, US Army Research Laboratory, IEEE 20th International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems, Washington D.C., August 2012 • **"Optimal Admission Control Policy for Mobile Cloud Computing Hotspot with Cloudlet"** Hoang et al, IEEE Wireless Communications and Networking Conference (WCNC), April 2012 • **"Adaptive Application Configuration and Distribution in Mobile Cloudlet Middleware"** Verbelen et al, Mobile Wireless Middleware, Operating Systems, and Applications, Springer Lecture Notes, Volume 65, 2013 [Ghent Univ.] . . . *many others* . . .

Cloudlets now a mainstream concept in the research community

Industry Investment Has Begun

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
News

Nokia Siemens to merge cloud, base-station computing to boost performance

The company's Liquid Applications platform will use computing power in the cloud and in base stations, based on conditions

By Stephen Lawson, IDG News Service
February 24, 2013 04:06 PM ET

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IDG News Service - Nokia Siemens Networks will expand the role of cellular base stations with a new platform that will store and deliver some application data locally, while tapping into information about subscribers and traffic to improve the process.

The company announced the system, called Liquid Applications, at an event in Barcelona on the eve of Mobile World Congress. Liquid Applications can improve consumers' mobile experience but cutting delays as well as delivering more relevant content, CEO Rajeev Suri

United States [change]

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IBM and Nokia Siemens Networks Announce World's First Mobile Edge Computing Platform

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↓ News release   ↓ Contact(s) information
↓ Related XML feeds

Barcelona, Spain - 25 Feb 2013: Mobile World Congress: Nokia Siemens Networks and IBM (NYSE: IBM) announced today a collaboration to deliver the world's first mobile edge computing platform that can run applications directly within a mobile base station. This new platform allows mobile operators to create a truly unique mobile experience, relieve the ever increasing strain on network infrastructure and bring completely new solutions to market.

The new platform can accelerate the delivery of media-rich services by delivering content directly from the base station, ensuring enhanced quality of experience for consumers in the face of ever increasing data traffic growth. The platform also enables a new generation of

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cloudlet-based apps & services

early validation apps

An Open Cloudlet Ecosystem

open cloudlet API

early implementations

cloudlet infrastructure