Combating WMD Attacks in Multi-Layer Mesh Networks: From Analytical Studies to Prototype

High-Altitude Electromagnetic Pulse (HEMP) and Satellite Networks

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Outline

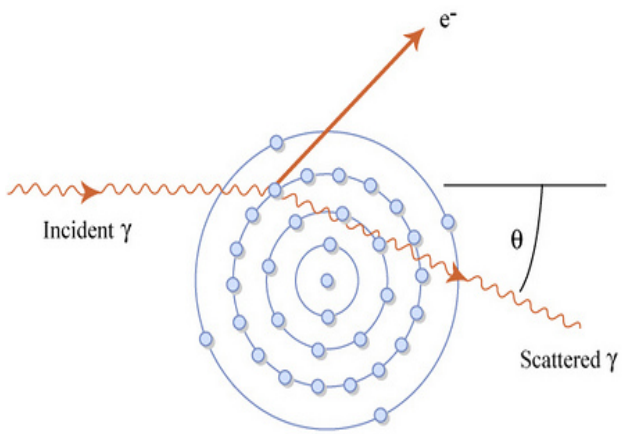
- EMP Basics and Weapons
- Nuclear HEMP Properties and Effects
- Satellite Networks Basics
- HEMP's Impact on Satellites
- Proposed Research: Post-HEMP Restoration with Satellite Assistance

EMP Weapon Types

- **Nuclear High-Altitude Electromagnetic Pulse (HEMP):** Nuclear detonation at high altitude provokes Compton Scattering which combined with Earth Magnetic Field generates coherent pulse [1];

- **High-Power Microwaves (HPM):** High-frequency pulse from non-nuclear device. Might destroy electrical equipment. Suitcase-sized device could disrupt equipment a mile away [2];

- **Electromagnetic Bombs:** Explosives destroy special electric circuit;
  - **Explosively Pumped Coaxial Flux Compression Generator (FCG):** Oldest e-bomb, low frequencies (< 1 MHz), most micro electronics invulnerable;
  - **Virtual Cathode Oscillator (VirCatOr):** More complex, provides higher frequencies.



Compton Scattering: Gamma rays + air => high-energy free electrons at 0.9 *C* speed.

[1] Miller, Colin R. "Electromagnetic pulse threats in 2010." (2005)
[2] Wilson, Clay. "High-altitude electromagnetic pulse (HEMP) and high power microwave (HPM) devices: Threat assessments." (2008)

EMP Weapons' Properties

Weapon [1]	Probability of Use [1]	Lethal Range [1]	Vulnerable Targets [1]	Potential Attackers [1]	Shape [2]
Nuclear HEMP	Moderate	Up to 1,500 mile radius (Texas size damages are more probable)	Electronics, computer chips, sensors, communications, vehicles, power transmission systems, civilian infrastructure	Nuclear powers with ballistic missile technology, Rogue states HPM Low See note Integrated circuits, circuit cards, relay switches US, UK, Australia, Russia, Sweden	Semi isotropic, rounded U-shaped "smile"
FCG	High	175 meters	Unprotected systems connected to long-run wires longer than 250 feet, possibly people	Modern militaries	Dependent on coil/structure, non-isotropic
VirCatOr	Moderate	150 meters	Integrated circuits, circuit cards, relay switch, possibly people	Any information age adversary	Dependent on coil/structure, non-isotropic
Current HPM systems don't generate enough power to guarantee destruction of integrated circuits on a large scale.					Dependent on antenna

[1] Miller, Colin R. "Electromagnetic pulse threats in 2010." (2005)
[2] Wilson, Clay. "High-altitude electromagnetic pulse (HEMP) and high power microwave (HPM) devices: Threat assessments." (2008)

Nuclear HEMP Properties

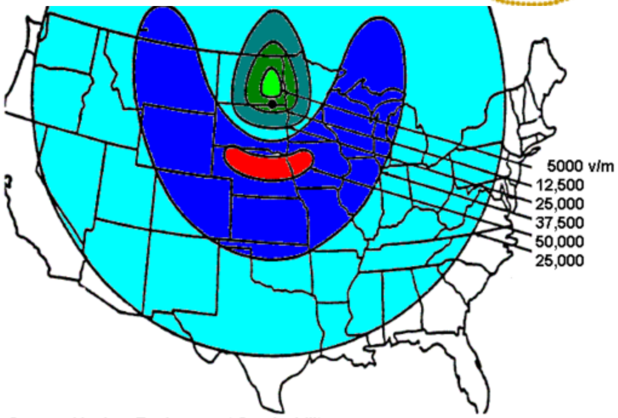
"In the past, the threat of mutually assured destruction provided a lasting deterrent against the exchange of multiple high-yield nuclear warheads. However, now even a single, low-yield nuclear explosion high above the United States, or over a battlefield, can produce a large-scale EMP effect that could result in a widespread loss of electronics, but no direct fatalities, and may not necessarily evoke a large nuclear retaliatory strike by the U.S. military." [2]

[2] Wilson, Clay. "High-altitude electromagnetic pulse (HEMP) and high power microwave (HPM) devices: Threat assessments." (2008)

Nuclear HEMP Properties

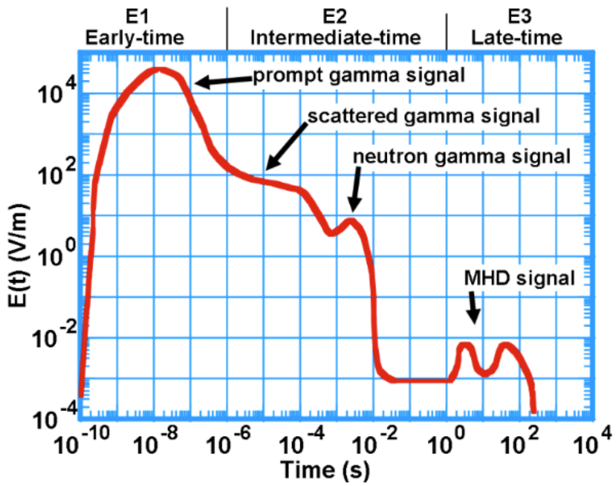
Altitudes > 30 km (22 g/cm^3 air), line-of-sight, too fast to harm humans, composed of cumulative consecutive pulses [4]:

- **E1:** nanoseconds, coherent, induces extremely high voltages burning electro/electronics, too fast for surge protectors:
  - Mid-stratosphere ionization convert region into electrical conductor;
  - 1.44 MT at 0.1 % gamma efficiency => 2 MeV gamma rays => Peaking 50 MV/m at floor level;
  - 10 kT bombs might get 40 % efficiency [4];
- **E2:** microseconds to seconds, less than 1 s after E1, similar to lightning;
- **E3 (Solar EMP):** temporary distortion of Geomagnetic field, lasts tens to hundreds of seconds, similar to Geomagnetic Storm, induce currents in long conductors (power lines).



Source: Nuclear Environment Survivability, U. S. Army, report AD-A278230 (1994)

Downward tilt of Earth's magnetic field at high latitudes shapes area of peak strength into a smile pointing to the Equator [3, 5].



[3] Min, Gyung Chan, et al. "Development of the HEMP Propagation Analysis and Optimal Shelter Design, Simulation Tool." (2013)
[4] Longmire, Conrad L. "Justification and Verification of High-Altitude EMP Theory, Part I." (1987)
[5] "The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid." (2010)

Nuclear HEMP Test Cases

- **USA, Johnston Atoll, 1962 (codename Starfish):** 1.4 MT nuclear test, 400 km altitude, effects in Hawaii (1450 km away): 1-3 % street lights failed, circuit breakers tripped, burglar alarms triggered, and telecommunications relay damaged [6];
- **Russia, 1962 (Soviet Project K):** 300 kT nuclear test, altitudes 300 km, 150 km, and 60 km included: damage to underground cables 600 km far buried 90 cm deep; above ground telecom lines; surge arrestor burnout; spark-gap breakdown; blown fuses; and damaged Military generators and substations. <u>Earth's magnetic field there is greater than at Johnston Atoll</u> [7];
  - ➢ Soviet scientist (*A*) interviewed by American scientist (*Q*) after end of USSR [7]:

    "Q: Would you make a judgment on whether early or late EMP caused the damage?
    A: The air line was damaged by early EMP and the cable by late-arriving EMP. (…)
    Q: Were the military generators damaged by early or late EMP?
    A: Early. (…)
    Q: Is the north-south and east-west orientation of lines important?
    A: Definitely yes. They are unambiguously tied to the geomagnetic field."

[6] Foster Jr, John S., et al. "Report of the commission to assess the threat to the united states from electromagnetic pulse (emp) attack." (2004)
[7] US-Russian meeting "HEMP effects on national power grid & telecommunications." (1995)

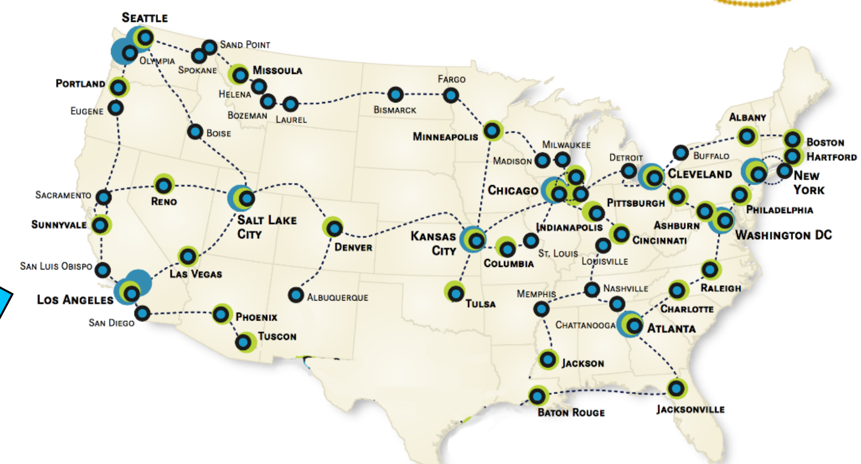
HEMP's Effects on Devices

- Integrated circuits with short-signal paths => high-frequency EMP;
- Large electrical systems => low frequency EMP;
- Pulses higher than 10 kV/m sufficient to cause widespread damage [8];
- Wires running through affected area serve as antennae [9];
- Hardening: protective metallic shielding, special surge protectors, wire termination procedures, screened isolated transformers, spark gaps, etc.;
- Hardening increase electronic resistance to EMP [7].

[7] US-Russian meeting "HEMP effects on national power grid & telecommunications." (1995)
[8] House Military Research & Development Subcommittee, "Threats Posed by Electromagnetic Pulse to U.S. Military Systems" (1997)
[9] Carlo Kopp, "The Electromagnetic Bomb: A Weapon of Electrical Mass Destruction." (1996)

Possible HEMP Effect on the Connectivity

Internet2 Topology [10].



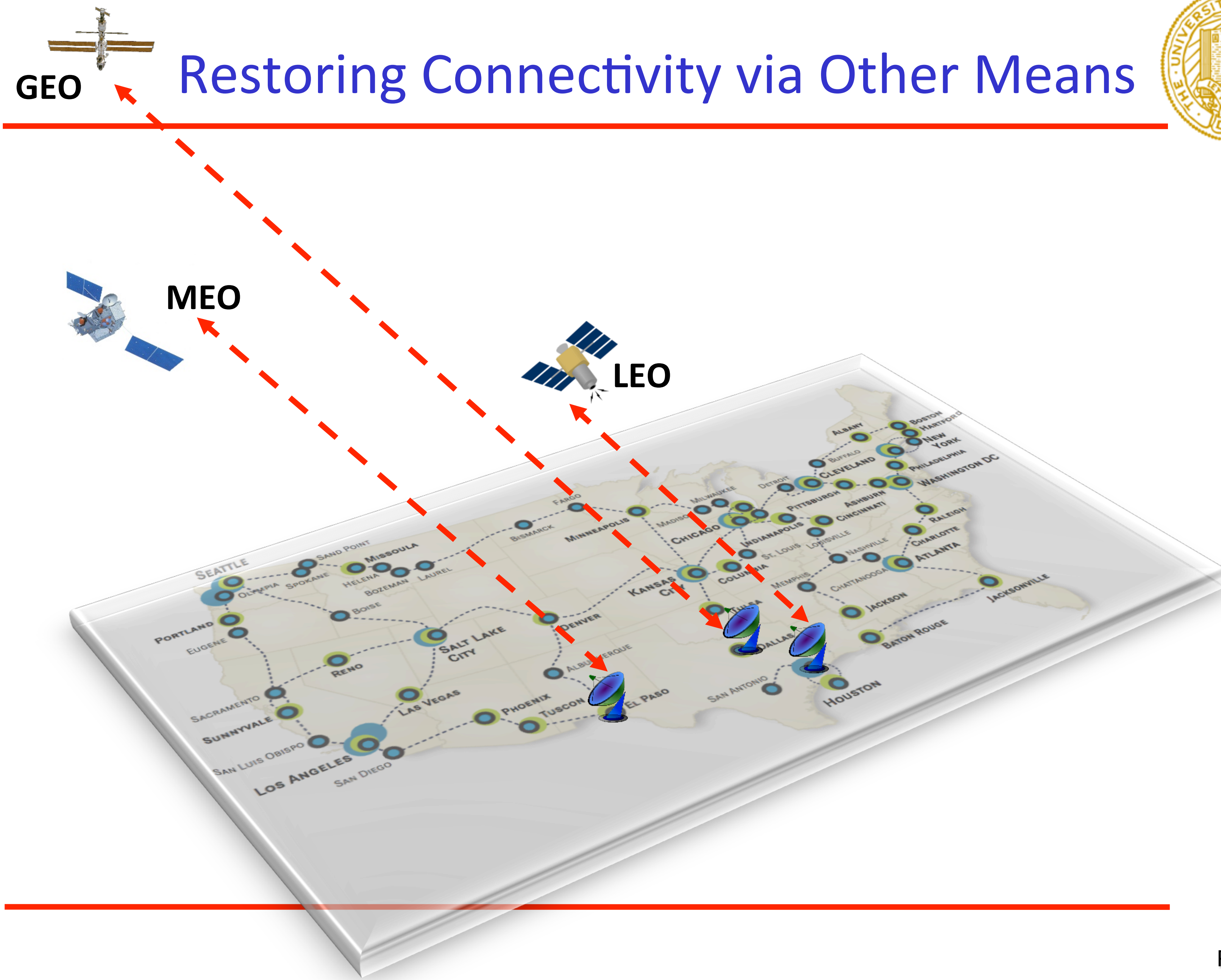
(A) Texas is fully compromised.

(C) Still some connectivity in Texas.

(B) Texas is partially compromised.

[10] Internet2 Network Infrastructure Topology (2015)

Restoring Connectivity via Other Means



Satellites

Satellite Quick Facts [11]:

i. Operating Satellites by Country

USA	Russia	China	Other	Total
549	131	142	483	1305

ii. American Satellites by Owner/Operator

Civil	Commercial	Government	Military
21	250	126	152

iii. Satellites by Type of Orbit

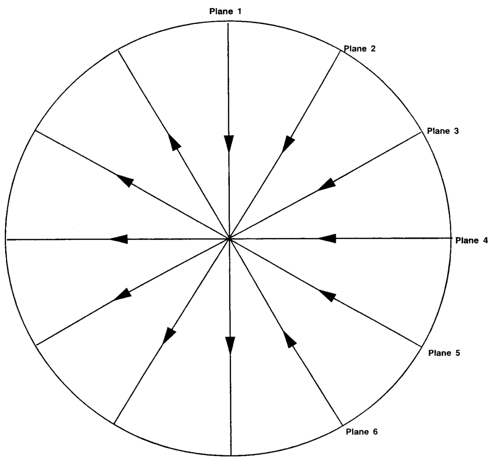
LEO (160-2000 km)	MEO (2000-35000 km)	HEO (Highly Elliptical)	GEO (35786 km)
696	87	41	481

[11] Union of Concerned Scientists (2015)

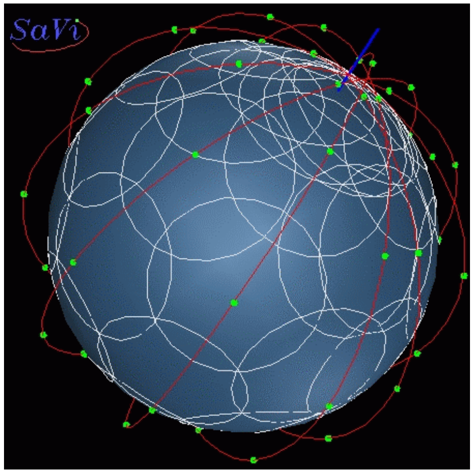
Satellite Constellation Example: Iridium

- Each IRIDIUM satellite maintains up to four Inter Sat Links each (except for planes 1 and 6) [12];
- 6 orbits, 11 satellites per orbit, each 4400 km apart, 100.3 minutes period [12].

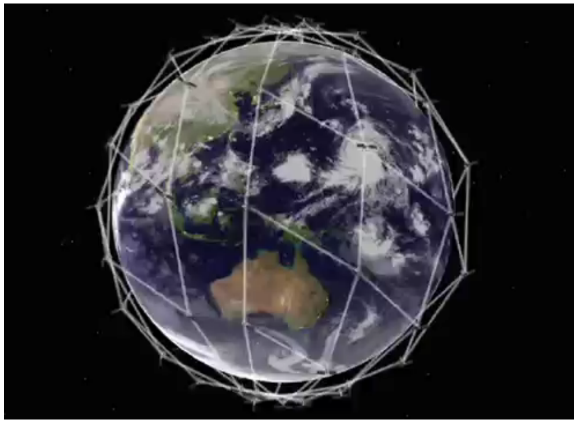
(A) Orbits (planes) seen from Pole.



(B) Footprint of each Satellite.



(C) Iridium's orbital motion [15].



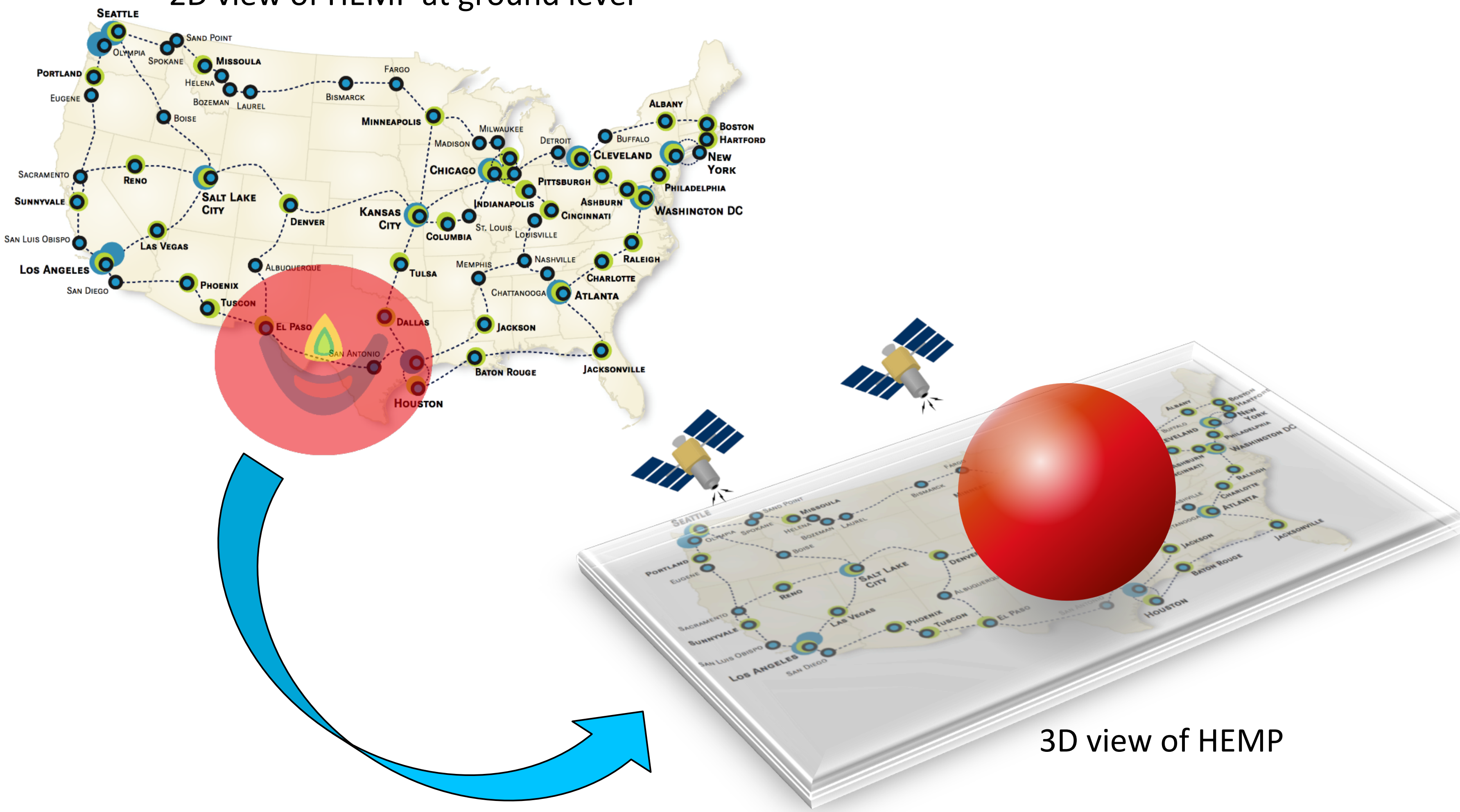
(D) Average end-to-end delays.

No. of Satellites in Path	2	4	6	8	10	12	14
End to End Delay (sec)	0.071	0.098	0.125	0.152	0.179	0.206	0.232

[12] Pratt, Stephen R., et al. "An operational and performance overview of the IRIDIUM low earth orbit satellite system." (1999)
[15] Global Telesat Communications, "Iridium Satellite Constellation." (2012)

HEMP's Impact on Satellites

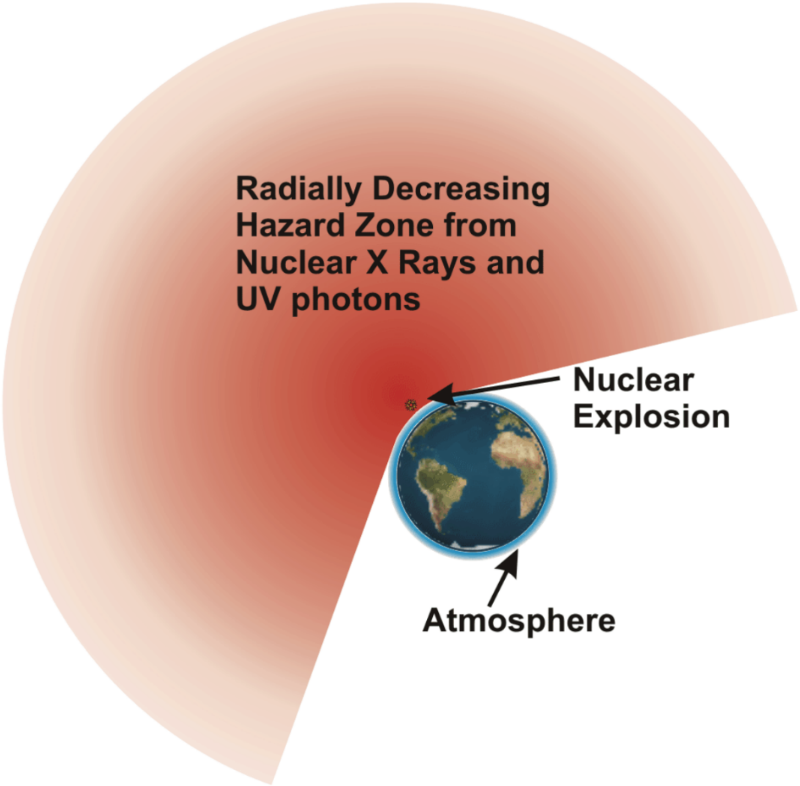
2D view of HEMP at ground level



3D view of HEMP

HEMP's Impact on Satellites

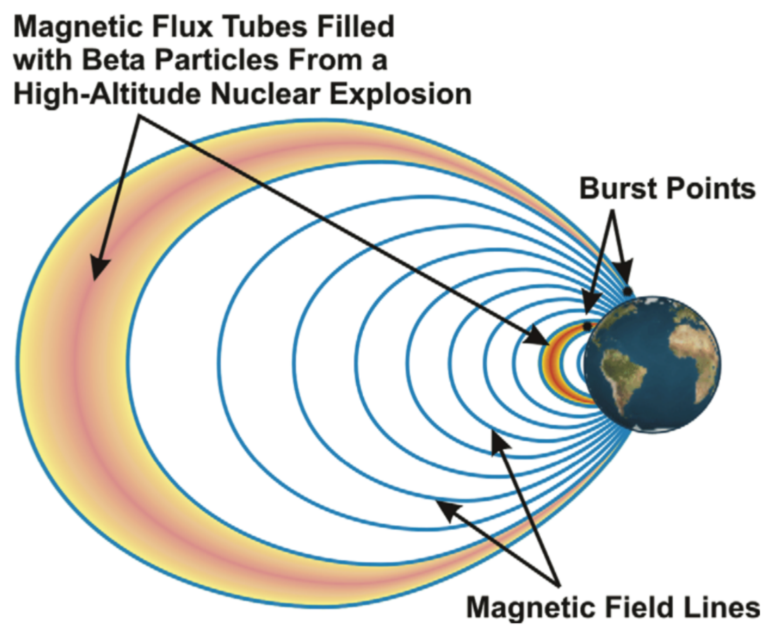
- Immediate direct, line-of-sight exposure to nuclear radiation pulses:
  - X-ray, ultraviolet, gamma-ray, and neutron pulses;
- Size of hazard zone depends on weapon yield, detonation altitude, and the degree of satellite hardening against disruption or harm [13];
- Damage:
  - **Structures and coating**: solar panels and sensor optics if X-ray and UV fluxes too high;
  - **Electronics**: X-ray and Gamma radiation induce destructive currents.



[13] Foster Jr, John S., et al. "Report of the commission to assess the threat to the united states from electromagnetic pulse (emp) attack: Critical national infrastructures." (2008)

HEMP's Impact on Satellites

- Earth has naturally occurring radiation belts;
- EMP belts are caused by free electrons released in detonation;
- Impact depends on repeated passages through belt cumulatively;
- Characterization of spatial and temporal properties is complex;
- Intensities of radiation belts depend strongly on burst latitude [13].



[13] Foster Jr, John S., et al. "Report of the commission to assess the threat to the united states from electromagnetic pulse (emp) attack: Critical national infrastructures." (2008)

HEMP's Impact on Satellites: Belt exposure effects

Time-to-failures of satellites due to different simulated HEMP events [13]:

Event	Time-to-failure (days)		
	NOAA (LEO 800 km)	TERRA (LEO 700 km)	ISS (LEO 322 km)
5 MT @ 200 km	0.1	0.1	0.1
0.8 MT @ 368 km	1	1	0.5
0.8 MT @ 491 km	1	1	1
4.5 MT @ 102 km	0.1	0.2	0.2
4.5 MT @ 248 km	0.1	0.2	0.2
0.03 MT @ 500 km	40	100	150
0.1 MT @ 200 km	10	17	20

- NOAA, TERRA and ISS are all hardened, specifically built satellites (which may not be the case for commercial satellites)

[13] Foster Jr, John S., et al. "Report of the commission to assess the threat to the united states from electromagnetic pulse (emp) attack: Critical national infrastructures." (2008)

HEMP's Impact on Satellites: Line-of-sight effects

Risk of immediate damage of satellites due to different simulated events [13]:

Satellite	Event	Probability of Damage (%)		
		Thermo-mechanical	SGEMP/burnout	Latch-up/burnout
ISS (LEO 322 km)	4.5 MT @ 248 km	1.7	4	4.2
	1 MT @ 300 km	0	5	5
	0.1 MT @ 120 km	0	3	4
	5 MT @ 200 km	1.7	5	5
NOAA (LEO 800 km)	1 MT @ 300 km	0.2	19	20
	0.1 MT @ 120 km	0	3	5
	5 MT @ 200 km	1	7	8
TERRA (LEO 700 km)	1 MT @ 300 km	0.3	18	18
	0.1 MT @ 120 km	0	2	5
	5 MT @ 200 km	1.2	7	7

* The likelihood that one specific satellite will be in line-of-sight of the explosion ranges from 5 to 20%, reducing a lot the probabilities above. In fact, any satellite that is in direct line-of-sight and relatively close (LEO) will almost certainly fail immediately [13].

[13] Foster Jr, John S., et al. "Report of the commission to assess the threat to the united states from electromagnetic pulse (emp) attack: Critical national infrastructures." (2008)

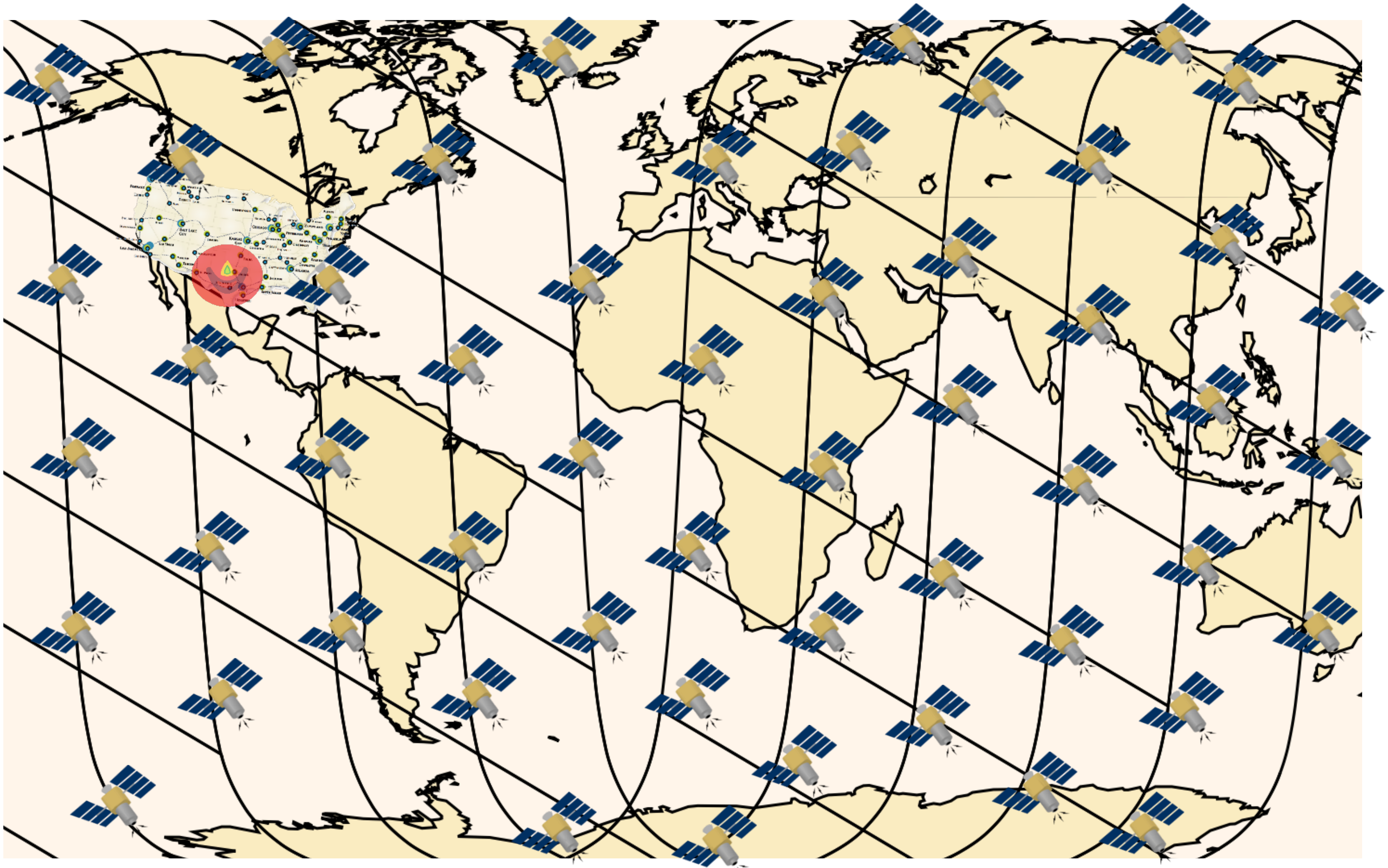
HEMP's Impact on Satellites

- Satellites in LEO are much more susceptible to damage from both direct and persistent radiation;
- Satellites at GEO are typically hardened to a greater extent than LEO;
- Line-of-sight exposure of LEO to explosion => immediate loss of many operational capabilities, as well as loss of power generating capacity;
- **Weapons from 10 kT to 100 kT:** EMP attacks over the Northern continental US or Canada indicates lesser risk to LEO satellites [13];
- Satellites in orbit already depleted a portion of their anticipated service life;
- **1962, Starfish Prime:** 21 satellites in orbit (or launched in the following weeks, consisting of *20 LEO + 1 MEO*), 8 were damaged and <u>compromised or terminated their missions</u> [14];
  - Information about the other 13 is not publicly available.

[13] Foster Jr, John S., et al. "Report of the commission to assess the threat to the united states from electromagnetic pulse (emp) attack: Critical national infrastructures." (2008)
[14] Brown, W.L. et al, "Collected Papers on the Artificial Radiation Belt From the July 9, 1962, Nuclear Detonation." (1963)

Post-HEMP Restoration with Satellite Assistance

Possible HEMP effect on Iridium constellation [12] include impairment/destruction of satellites:

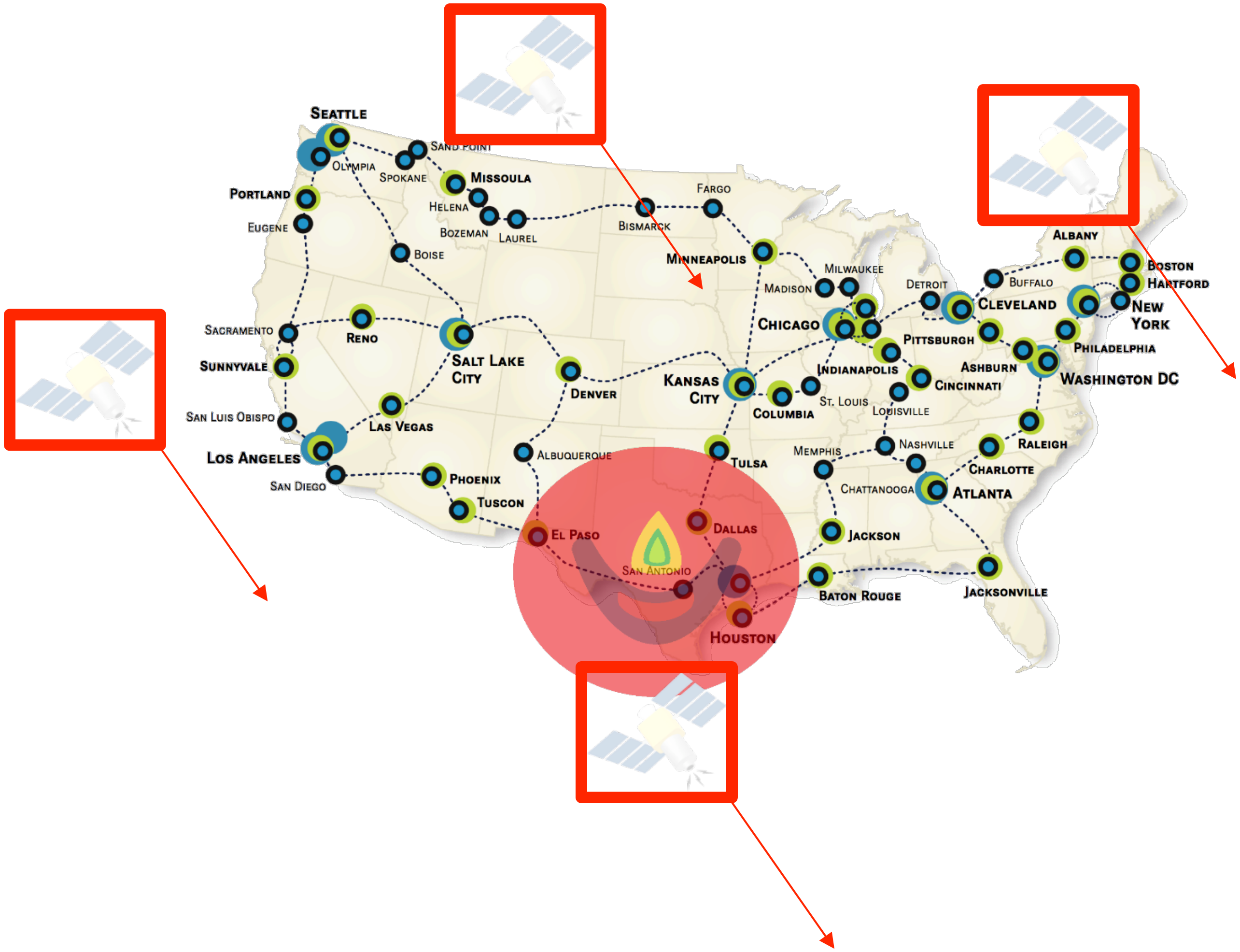


[12] Pratt, Stephen R., et al. "An operational and performance overview of the IRIDIUM low earth orbit satellite system." (1999)

Post-HEMP Restoration with Satellite Assistance

Initially, LEO satellite coverage would be lost:

t = 0 min



Post-HEMP Restoration with Satellite Assistance

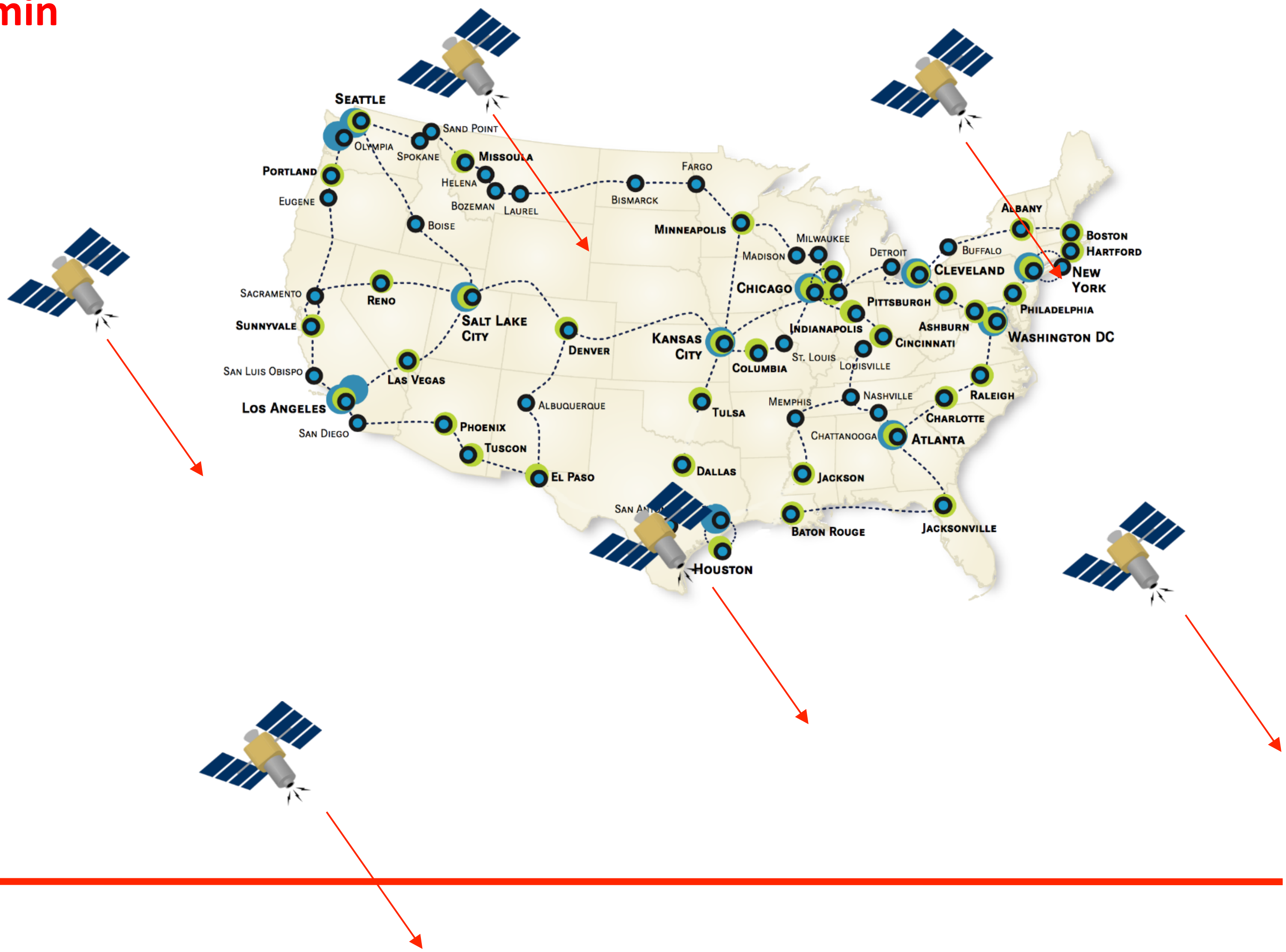
As orbits rotate, LEO coverage would be regained after some time from still functioning satellites:

t = 15 min

Post-HEMP Restoration with Satellite Assistance

Complete LEO coverage would be achieved after some more time:

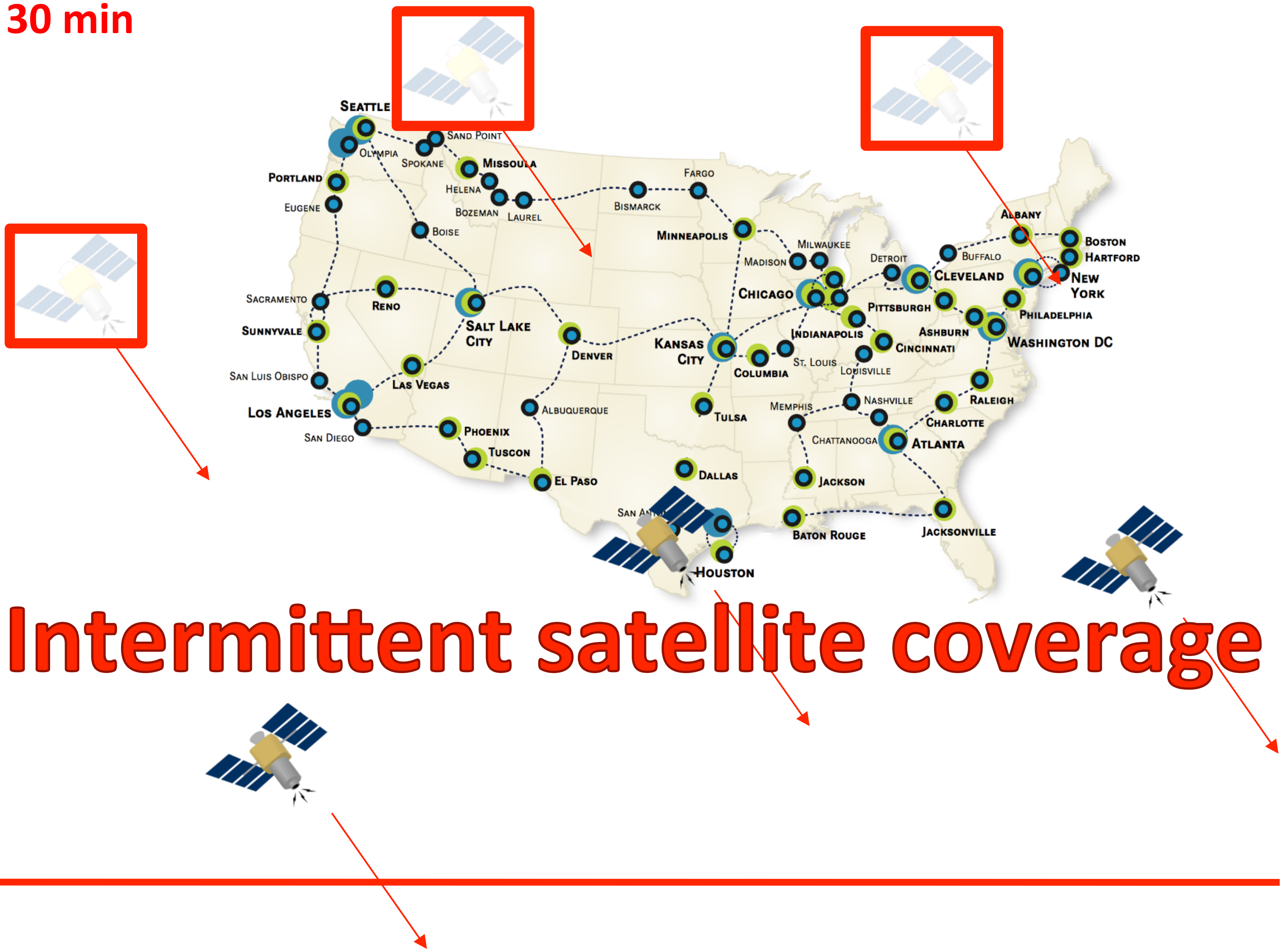
t = 30 min



Post-HEMP Restoration with Satellite Assistance

With the orbital movement, defective LEO satellites would periodically come back:

t = 1 h 30 min



Intermittent satellite coverage

Post-HEMP Restoration with Satellite Assistance

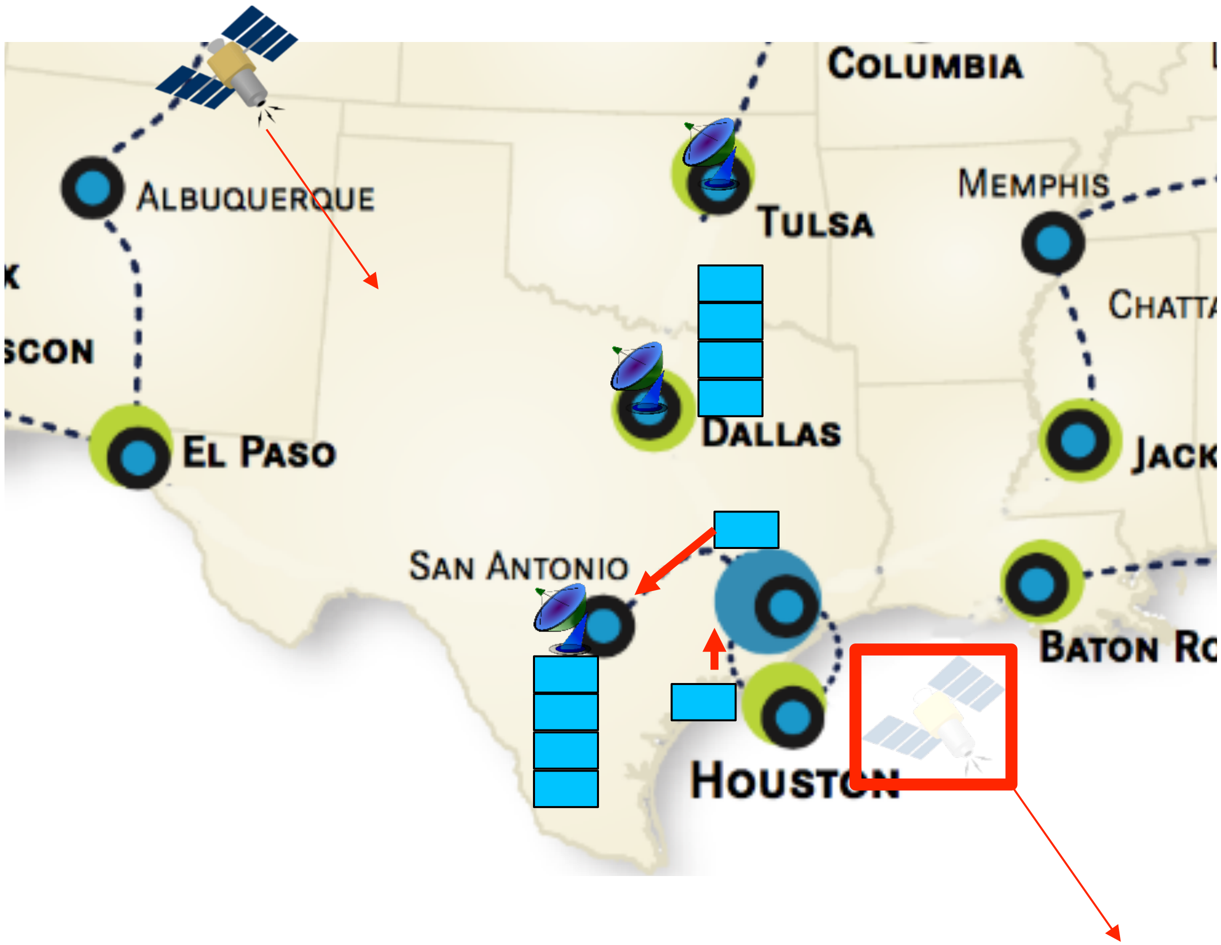
Challenges	Opportunities
Determining exact impact on satellites constellation is complex	Satellite orbits are known, periodic, and well defined
Better hardened constellations (likely survivors) are military/government and will probably be overflowed by military/high-priority traffic	Traffic scheduling can be used to send traffic flows through connected parts of the constellation, intermittently
GEO imposes a high delay, limiting some types of 2-way communications	Delay Tolerant Networks might help ensure that packets arrive at their destinations in badly disrupted networks through several Land-Satellite-Land hops
Since GEO satellites would like survive, the majority of traffic would be routed through them whenever possible (possible bottleneck)	State of the art High Throughput Satellites (HTS) offer up to 134 GBps in GEO (Via Sat1 [16]) and more than 10 Gbps per satellite with guaranteed latency below 150 ms in LEO (O3b [17], launched in 2014)
Commercial LEO constellations (provide smaller delays) are likely to suffer big "holes" in coverage	

[16] Amos, Jonathan, "Viasat Broadband 'super-satellite' Launches." (2011)
[17] O3b Networks, "O3b Technology - O3b Networks." (2015)

Proposed Solution:
Post-HEMP Restoration with Satellite Assistance

Survived nodes buffer the traffic to be sent outside of the damaged area once there is LEO satellite connection:

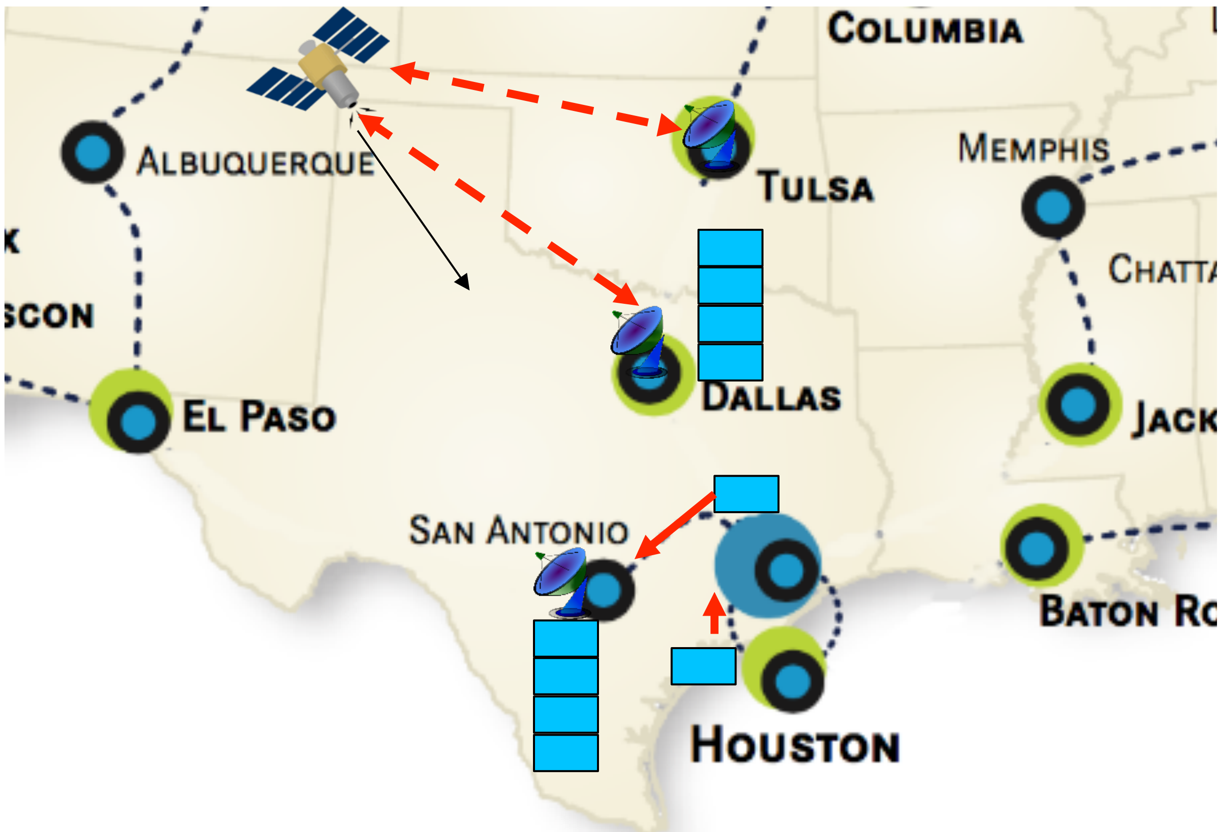
t = 15 min



Proposed Solution: Post-HEMP Restoration with Satellite Assistance

As coverage is slowly regained, buffer nodes begin evacuating queues to nearest (minimum delay) LEO satellite land station of main network:

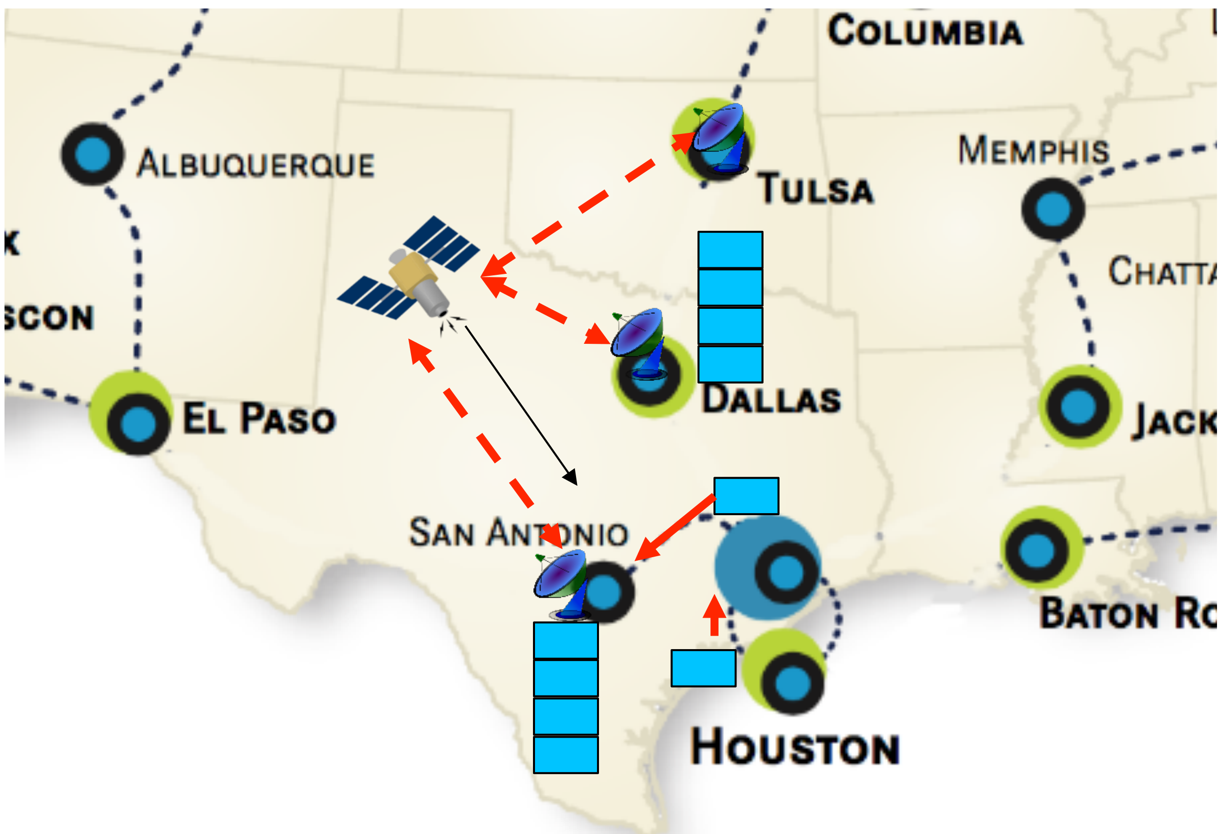
t = 30 min



Proposed Solution: Post-HEMP Restoration with Satellite Assistance

While having LEO satellite connection, queues are evacuated based on the priority of emergency communication:

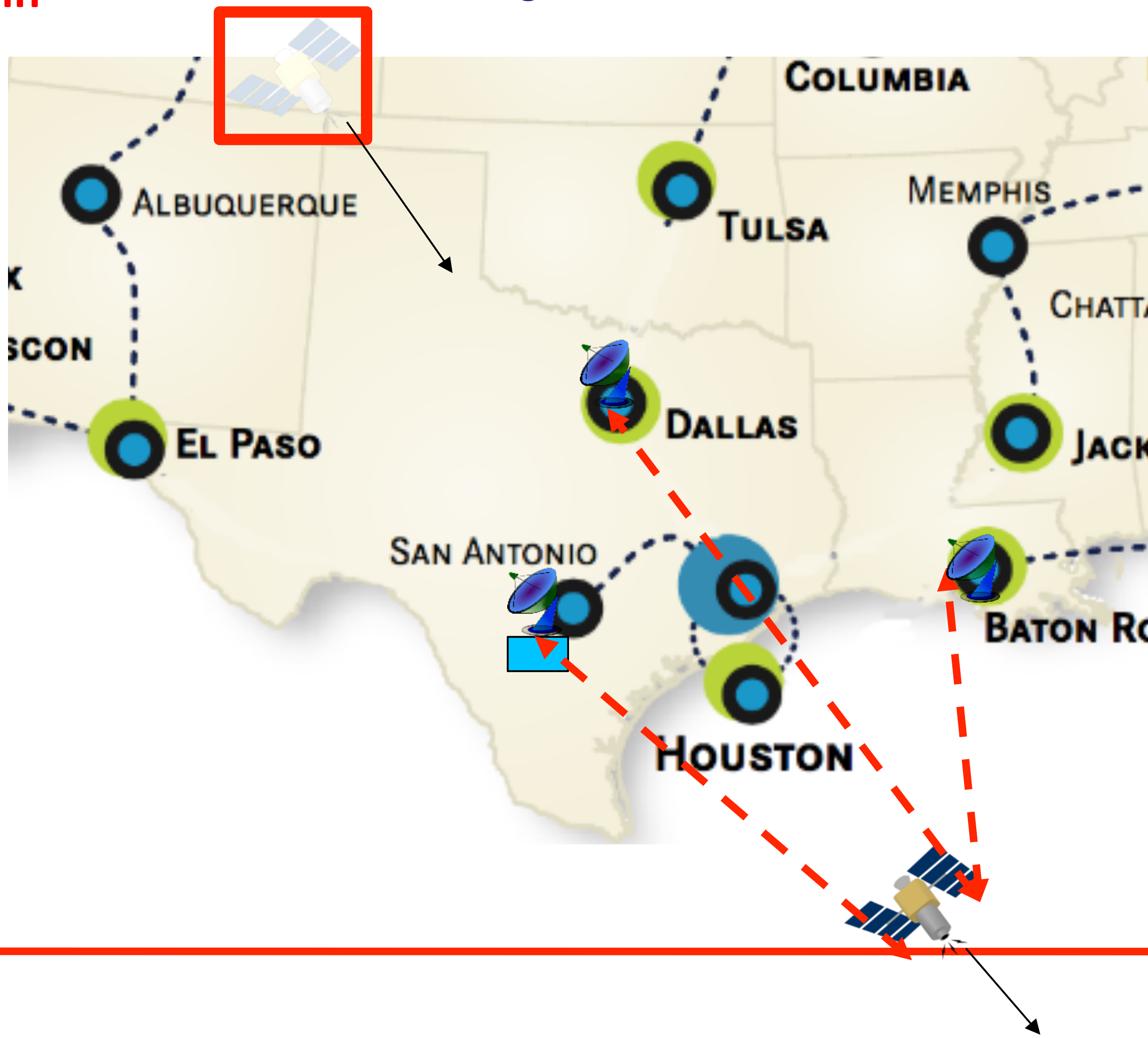
t = 35 min



Proposed Solution:
Post-HEMP Restoration with Satellite Assistance

As LEO constellation "hole" approaches, main network is informed and scheduling starts again:

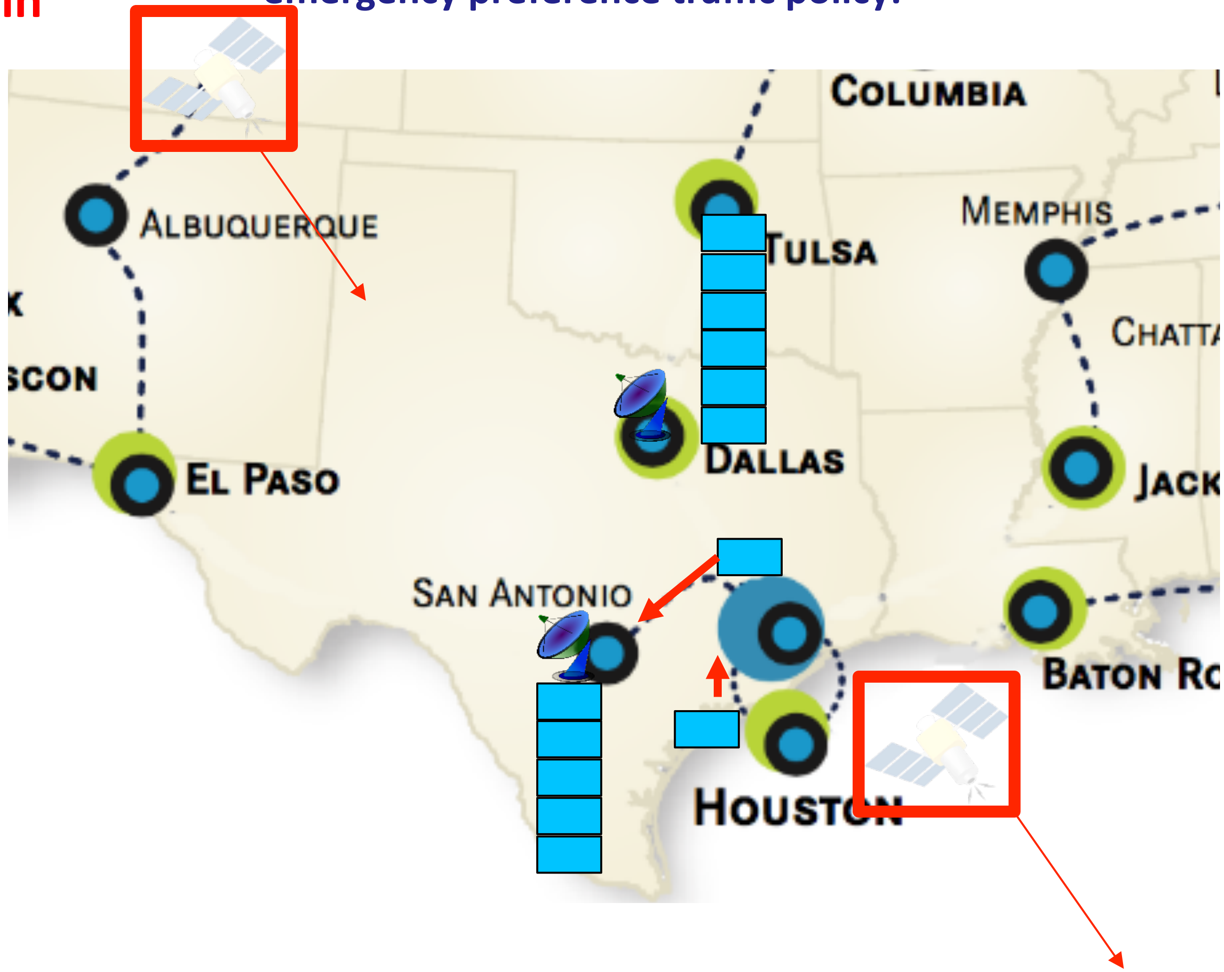
t = 1 h 10 min



Proposed Solution: Post-HEMP Restoration with Satellite Assistance

During lack of LEO coverage period, flows are buffered according to an pre-determined emergency preference traffic policy:

t = 1 h 25 min



Proposed Solution: Post-HEMP Restoration with Satellite Assistance

Objective

Maximize the continuity of mission-critical services considering their QoS requirements (delay-tolerant, degraded-service tolerant) with undamaged terrestrial and non-terrestrial communication infrastructure after a HEMP attack;

- **Given**
  - Network topologies (original and post-HEMP sub-network)
  - Buffering capabilities of network nodes;
  - Knowledge of unaffected satellites and their orbits/positions/speed/throughput;
  - Traffic priority (Telecommunication Service Priority *TSP* [18], emergency data, and other highly important traffic, as SCADA data)
- **Constraints**
  - Throughput and delays of satellite network;
  - Degraded-service tolerance and latency sensitivity of traffic being queued;
  - Buffering capability of nodes;

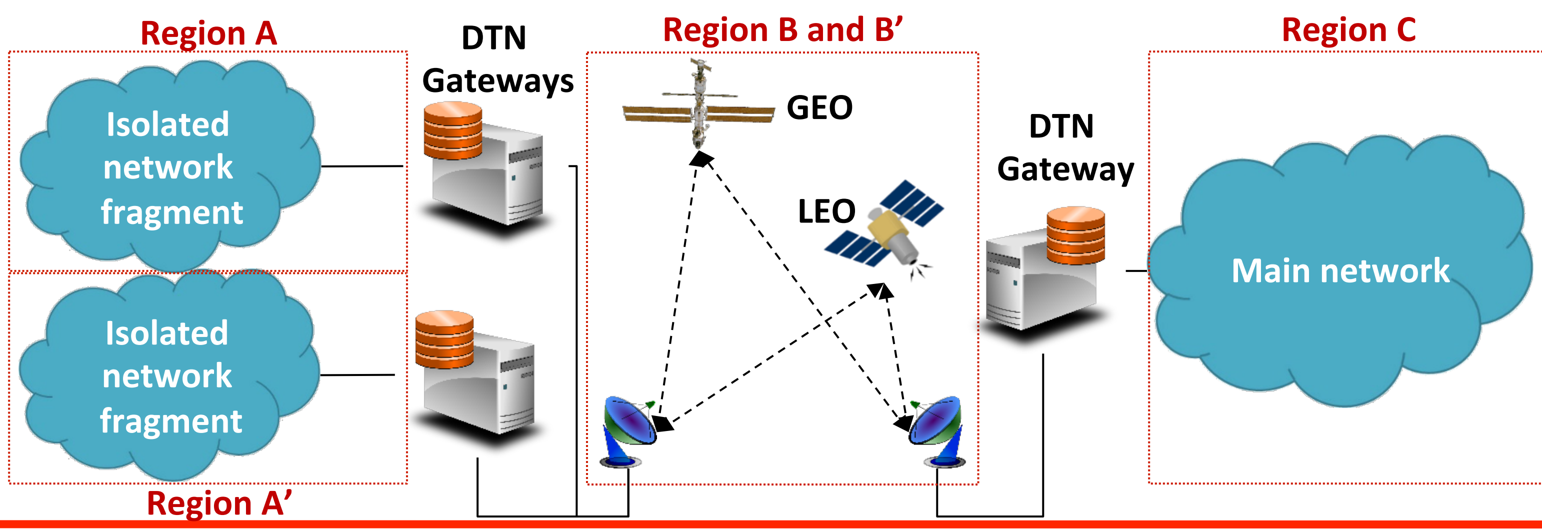
Expected Output

Intelligent QoS-aware traffic scheduling method to maximize throughput while providing mission-critical services at least their minimum requirement in terms of delay and throughput.

[18] Homeland Security, "Telecommunications Service Priority (TSP)." (2013)

Delay/Disrupt Tolerant Networks (DTN)

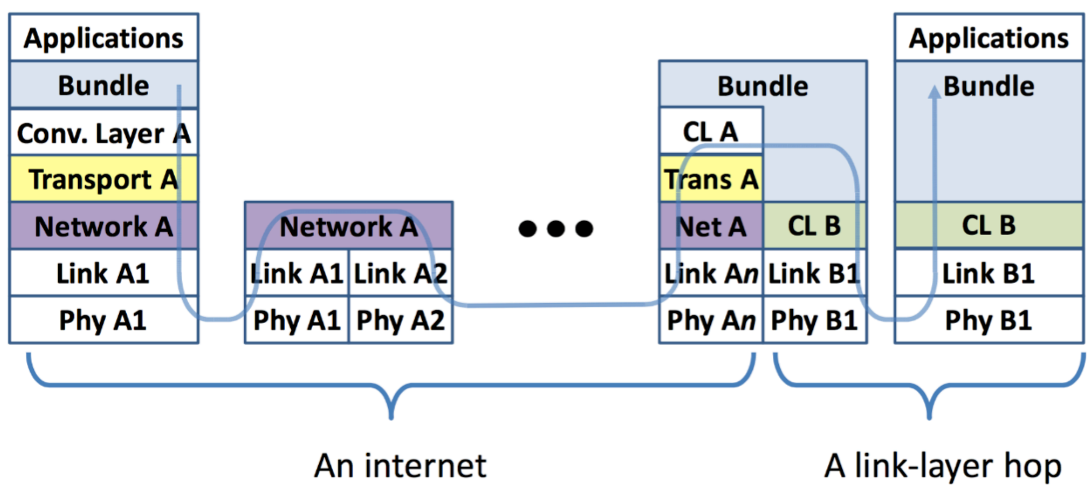
- Challenged Internetworks: latency, bandwidth limitations, system connectivity, error probability, node longevity, and/or path stability substantially worse than typical networks (Internet);
- Bundle Protocol, "overlay" architecture: operates above existing protocol stack, providing store and forward gateway function between "bundle forwarders";
- Opportunistic or predictable contacts, parameterized by: start/end times, capacity, latency, endpoints, direction;



[19] Fall, Kevin. "A delay-tolerant network architecture for challenged internets." Proceedings of the 2003 conference on Applications, technologies, architectures, and protocols for computer communications. ACM, 2003.

Delay/Disrupt Tolerant Networks (DTN)

- Traffic vs Data: whatever has higher priority and can cope with the latency, transmission delays, intermittent behavior may get queued (simplification);
- BP key unit of transfer is the bundle: can be stored in multiple nodes and fragmented;
- Routing: ranges from zero knowledge of network (only on opportunistic contacts) to total knowledge of network (only deterministic contacts);



[20] Araniti, Giuseppe, et al. "Contact graph routing in DTN space networks: overview, enhancements and performance." Communications Magazine, IEEE 53.3 (2015): 38-46.

Contact Graph Routing

- Dynamic routing paradigm that computes routes through time-varying topology of scheduled communication contacts in a DTN architecture (only planned/scheduled topology changes);
- Each node exchanges with every other node Contact Plan Messages, two types:
  - Contact message: beginning and end of time interval for the message; transmitting and receiving nodes; planned tx rate;
  - Range message: beginning and end of time interval for the message; transmitting and receiving nodes; anticipated distance between the nodes during the interval;
- With the Contact Plan, each node builds a routing table listing all routes from it to all other nodes (each destination node containing possibly multiple routes, one for each local neighbor). Also, each route entry shows:
  - All other nodes of the route;
  - Latency of the route;
  - The latest time the route is available;
- To perform the above, a Contact Graph is generated. This graph needs to be updated as nodes go out of range and transmit stop times are reached.

[20] Araniti, Giuseppe, et al. "Contact graph routing in DTN space networks: overview, enhancements and performance." Communications Magazine, IEEE 53.3 (2015): 38-46.
[21] Seguí, S., and Esther H. Jennings. "Contact Graph Routing." NASA Tech Briefs (2011): 15.

Contact Graph Routing

- **Well-formed routes**: sequence of contacts, no loops;
- **Expiration time**: creation time + TTL of bundle;
- **One Way Light Time margin**: max distance variation during transmission;
- **Last moment**: deadline to receive – (OWLT + OWLT margin) [if contact moment is smaller than last moment, no transmission];
- **Contact capacity**: tx rate * duration;
- **Estimated capacity consumption for a bundle**: includes overhead;
- **Residual capacity of a contact**: (total contact capacity) – (ECC of higher priority bundles);
- **Plausible opportunity**: contact whose residual capacity greater than bundle's ECC;
- **Plausible route**: sender to destination series of plausible opportunities;
- **Forfeit time**: moment a bundle has to be sent in order to follow a plausible route;
- **Excluded nodes**: list of nodes through which bundle won't go through;
- **Critical bundle**: highest priority bundle.

[20] Araniti, Giuseppe, et al. "Contact graph routing in DTN space networks: overview, enhancements and performance." Communications Magazine, IEEE 53.3 (2015): 38-46.
[21] Seguí, S., and Esther H. Jennings. "Contact Graph Routing." NASA Tech Briefs (2011): 15.

Contact Graph Routing: The Algorithm

Initialization:

Set destination D to bundle's final destination node; set deadline X to bundle's expiration time; create empty Routing Table; set forfeit time to infinity for every destination; and create a list of Excluded Nodes.

Contact Review Procedure:

In this step, each node creates/updates a DAG "Contact Graph". Its root is a virtual self-to-self contact and the other vertices are all other contacts that might contribute to reach some other node. Virtual ending vertices representing contact from nodeA-to-nodeA are also included. For each destination D, Dijkstra is run iteratively (each time removing the initial contact) until no more routes are found.

Each best route for each contact is added to the Routing table in the entry of the respective destination node. Each of these routes need not be continuous at every instant (all nodes are capable of storing).

Forwarding Decision:

Among the available routes, choose the one with the lowest cost and queue the bundle for transmission in that route's entry node. If any route forfeit time is reached and there's still bundles in its queue, look for a new route for those bundles.

[20] Araniti, Giuseppe, et al. "Contact graph routing in DTN space networks: overview, enhancements and performance." Communications Magazine, IEEE 53.3 (2015): 38-46.
[21] Seguí, S., and Esther H. Jennings. "Contact Graph Routing." NASA Tech Briefs (2011): 15.

Contact Graph Routing: Pros & Cons

PROs	CONs
High confidence due to accurate information	Consider all nodes able to store and forward
Even though the current topology doesn't necessarily reflect the routes being calculated, it eventually will.	Consider nodes only have one contact at a time (no one P2M downlink, nor M2M uplink)
Changes to topology can be multicasted so that all nodes can update their DAGs	No opportunistic contacts considered
Delay of other bundles in the outbound buffer: Contact Graph Routing - Earliest Transmission Opportunity [20]	No advantages of periodicity of contacts
	No established initialization protocol to exchange Contact messages
	Routing decisions only based on local knowledge might not maximize traffic

[20] Araniti, Giuseppe, et al. "Contact graph routing in DTN space networks: overview, enhancements and performance." Communications Magazine, IEEE 53.3 (2015): 38-46.
[21] Seguí, S., and Esther H. Jennings. "Contact Graph Routing." NASA Tech Briefs (2011): 15.

Initial Approach

Objective

Maximize the bundle traffic sent from/to the isolated networks to the main network;

Given

- Network topologies (original and post-HEMP sub-network);
- Initially single isolated network;
- Buffering capabilities of network nodes (unlimited on the ground, zero on satellites);
- Knowledge of unaffected satellites and their orbits/positions/speed/throughput;
- Bundle priority (Telecommunication Service Priority *TSP* [18], emergency data, and other highly important traffic, as SCADA data);
- Single satellite ground stations per isolated network;

- **Constraints**
  - Throughput, delays, contact times of satellite network;
  - Degraded-service tolerance and latency sensitivity of traffic being queued;

Expected Output

Traffic scheduling method to minimize the total unused capacity of the Earth to satellite, satellite to satellite, and satellite to Earth links while respecting bundle priorities.

Overall Approach

1. **Immediately before/during the EMP attack (very small window):** try to evacuate data according to Sifat/Carlos proposals;
2. **After the EMP attack:**
   1. **Initialize:** Communicate all affected nodes through whatever GEO satellites available in order to exchange their locations, priorities, and get to know where are the possible traffic evacuation points in the main network;
   2. With knowledge of LEO/MEO/GEO orbits and what portion of them were destroyed (also their throughput capacities and latency):
      1. Send high priority/high latency elasticity to GEO
      2. Send medium/low priority and medium/high latency elasticity to MEO, using specific routing approach
      3. Send low latency elasticity traffic when with LEO coverage and infinite elasticity traffic always (to be queued when without LEO coverage)

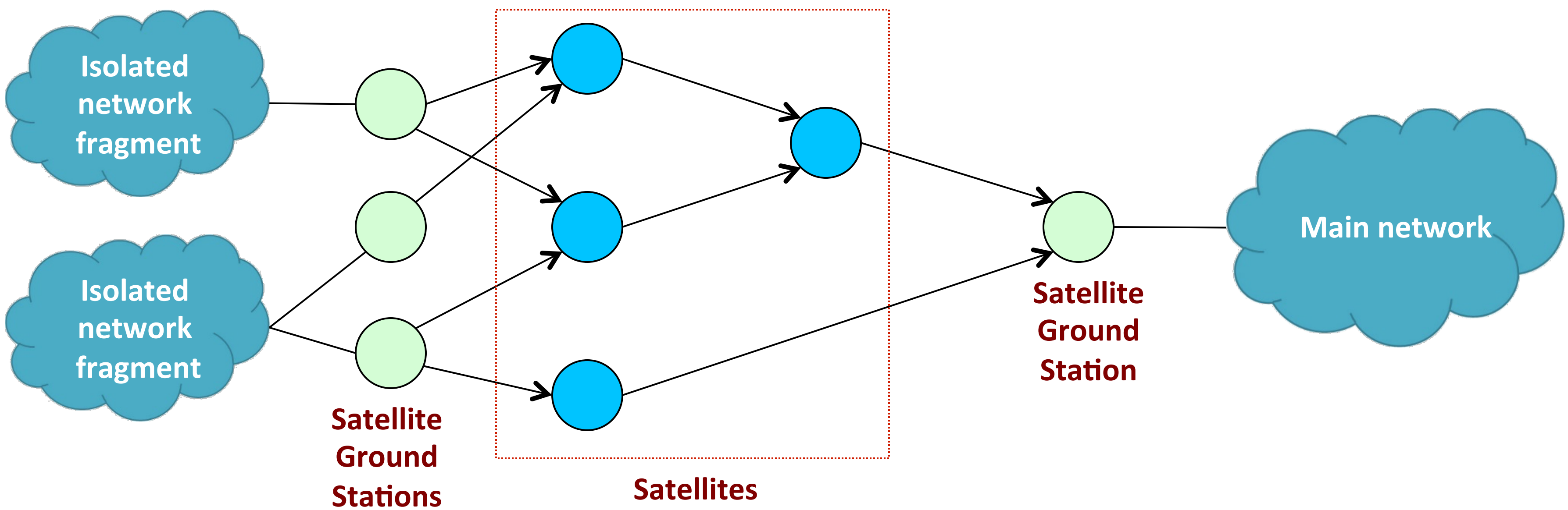
Initial Approach

Routing Approach 1:

Modify CGR to account for the objectives and specific scenario. (Still a local knowledge situation).

Routing Approach 2 (Possibly):

Implement variation of Max-Flow algorithm in carefully elaborated graph where edges encompass contact start/end times, capacities, and latencies.



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Thank you!