Energy-Efficient Softwarized Networks: Lessons Learned+

Highlighting patterns from a (literature) review

Iwan Setiawan[1,2], Binayak Kar[1], and Shan-Hsiang Shen[1]

[1]Computer Science and Information Engineering Dept.
National Taiwan University of Science and Technology

[2]Electrical Engineering Dept.
Universitas Jenderal Soedirman

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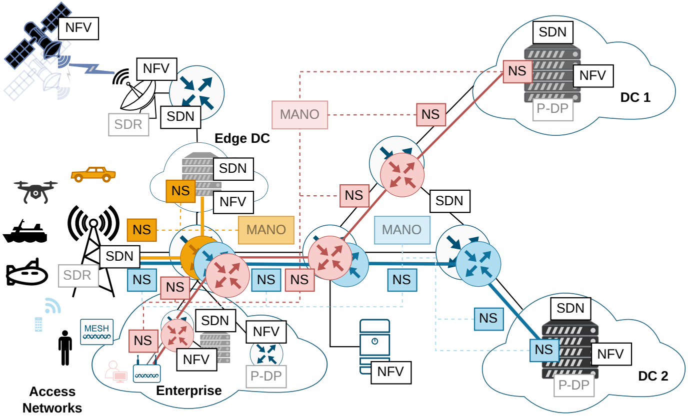
Outline

Softwarized Network Scenarios = Network Scenarios + NetSoft



Edge		Core	Cloud
Access Transport	Metro Transport	Core Transport	Central Cloud (DC)
Radio Access	Edge Cloud (Edge DC)		Hyperscalers

Motivation

Softwarized Network Scenarios

- Network scenarios from cloud to edge: resources, functions, topology, traffic (flows)
- Network softwarization: SDN, NFV, network slicing

Network Energy Efficiency

Energy consumption contributors, models, and energy-efficiency strategies

Research Questions

- How softwarized networks utilizing control and MANO layers accomodate energy efficiency in different network scenarios with energy-efficiency strategies?
- What kinds of attributes are considered in the literature?
- What challenges are arising from the state-of-the-art?

Review Methodology: Classification and Attributes

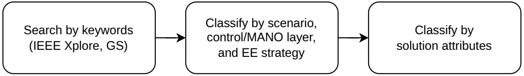
Classification

Mainly based on network scenarios[a] (types/settings): DC, transport, wireless, emerging.

[a] WSN was added in EE-SDN since we found multiple articles requiring a separated category.

Attributes

- Approaches: exact, heuristic, scheme
- Criteria: QoS, scalability, heterogeneity, mobility
- Metrics: energy, capacity, latency
- Evaluation: simulation, experimentation (emulation, testbed)



Review Methodology: Classified Articles and Venues

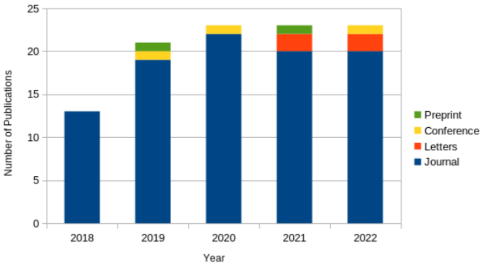


Fig. 3. Number of publications per year used in the survey with a total of 103 articles. It includes energy-efficient SDN (45), NFV (29), and NS (29).

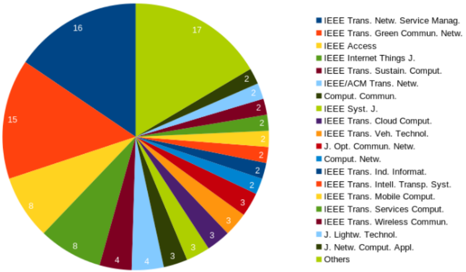


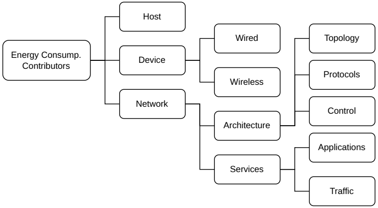
Fig. 4. Number of articles per journal used in the survey. They are primarily published by IEEE (or jointly with ACM and Optica) and Elsevier.

Energy Consumption Contributors and Models

Energy Consumption Models

- Based on energy consumption contributors[a]: static (baseline) and dynamic components
- Network devices: (considered) "non-proportional" for nodes, "proportional" for links[b]
- Depend on the network scenario, including technologies that power hosts, devices +links

[a] Not covered: other energy contributors in network infrastructure, e.g., cooling, mechanical, power distrib.
[b] Techniques: ALR (rate), IEEE 802.3az (low-power idle), cell zooming, etc.



$$P_{\mathrm{RAN}} = \sum_i P_{\mathrm{BS}_i} + \sum_j P_{\mathrm{FH}_j} + \sum_k P_{\mathrm{VBBU}_k}, \quad (1)$$

where P_{BS_i}, P_{FH_j}, and P_{VBBU_k} are the power consumption of the i-th gNB, the power consumption of the j-th fronthaul, and the power consumption of the k-th virtualized baseband unit (BBU), respectively. Depending on the specific RAN architecture, distributed or centralized, some of these components may not be considered.

D. López-Pérez et al., 2022, doi: 10.1109/COMST.2022.3142532

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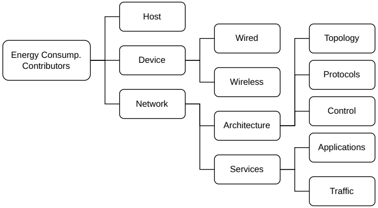

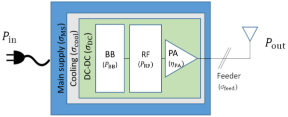

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Energy-Efficiency Strategies

Classification

- Focus on strategies that can be used with "softwarization": DA, SM, HT, EH, and ML
- Generalized HT to include heterogeneous resources/functions, including HetNet, accel.
- Generalized EH to include energy harvested from renewable and ambient sources

TABLE II
CATEGORIES OF EE STRATEGIES

Category	Host	Device*	Network
Hardware-based Improvements (HW)	●	●	○
Dynamic Adaptation (DA)	●	●	●
Sleep Modes (SM)	●	●	●
Heterogeneous Network (HT)	○	●	●
Energy Harvesting (EH)	○	●	○
Machine Learning (ML)	○	○	●

* Including wired and wireless, e.g. switches, base stations.

Network Softwarization

Network Softwarization: Network Management and Orchestration

- Network softwarization problems: SDN, NFV, network slicing +MANO
- Horizontal integration: multi segments or domains (technology, administrative)
- Vertical integration: control and MANO with hierarchical/centralized/distributed flavors

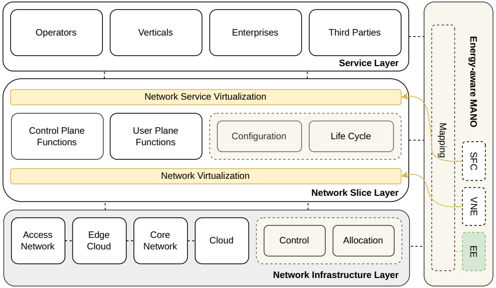


TABLE III
NETWORK SOFTWARIZATION LAYERS AND PROBLEMS

Technol.	Layer	Problem
SDN	C	CPP, multi-controller, hybrid, scenario-based
	M	TE, multimedia, security, scenario-based
NFV	RO	VNF-P, VNF-S, VNF-D, VNF-RC
	SO	VNF-TR
NS	NV	VNE, scenario-based (e.g., VDCE*, WNV)
	SV	SFC, scenario-based (e.g., Cloud)

* VDC Embedding, a variant of VNE in VDC

Results: Energy-Efficient SDN ①

Data center networks

- **State switching**: lighpath; "on" transition time; EAR+util. ratio; power-proport. ratio
- Multi-controller in intra-/inter-domain; transponder reconfiguration; VM placement; VM migration; multi-cloud with SD-WAN considering renewable energy+electricity prices

Transport networks

- **TCAM size:** number of flow rules (capacity) and compression; link utilization
- **Hybrid SDN**: EAR with tunneling; multi-stage migration considering budget per stage
- **Traffic prediction**: PCA+learning regression for threshold prediction; DL with GRU, traffic flows were monitored using adaptive intervals
- **Reliability**: dynamic topology switching; multi-agent RL considering QoE-fairness-power
- In-network caching; controller placement (minimal active controllers); utilization-based metric (RESDN); configuration prediction (LR/GA); traffic engineering; multimedia (QoE)

Results: Energy-Efficient SDN ②

Wireless networks

- **Heterogeneous networks**: cooperation of small cell BSs, partial connectivity; multi-hop device-to-device (D2D) source routing in WiFi/LTE networks
- **Mobility**: users' locations prediction+flow rule placement; blockchain-based 5G handover
- Interference in dense WLANs+channel selections+user-AP associations; multimedia QoE using deep RL (A3C)+playout buffer+adaptive bitrate+edge caching+video transcoding

WSNs

- **Network lifetime**: control node selection and cluster formation; multi-hop WSNs; RL; routing scheme considering energy, processing, memory, and trust
- **Load balancing**: control node placement; utilization-based metric (ECPUB), multi-path+secure routing, residual energy

Results: Energy-Efficient SDN ③

Emerging networks

- **Vehicular**: controller placement+switch assignment; RL for task offloading cooperation
- **Edge computing**: flow scheduling+geo-distributed edge DCs+cooperative resource sharing, service migration, caching; cooperative caching in MEC with content prediction based on neural network and service migration using deep RL
- Reactive routing in WBANs w/ fuzzy-based Dijkstra, signal-to-noise-ratio (SNR), battery level, hop count; blockchain-based IoT cluster arch. for efficient auth. +distrib. trust
- Single-hop maritime networks with sleep scheduling, opportunistic transmission, and renewable energy; routing in multi-modal underwater WSNs considering interference and parallel transmission; network topology generator considering link switching+inter-satellite link energy consump., DDoS mitigation based on deep RL in satellite networks; UAV-BS cooperation, UAV-user association, UAV hovering point

Results: Energy-Efficient NFV ①

Data center networks

- **Reliability**: server auto-scaling considering failure probability and different (less-)powerful servers; VNF migration and VNF backup with timers for high-availability
- State switching+VNF workload profiling; flow mapping and scheduling; reconfiguration, VNF sharing and migration; Cloud-native NFs+traffic prediction; CPU/GPU acceleration and GPU sharing among NFs

Transport networks

- **Load balancing**: VNF placement (VNF-P) +traffic steering in multi-domain SDNs; VoIP servers load balancing using VNFs+OpenFlow switches; VNF sharing
- VNF deployment in multi-domain SDNs; VNF-P with dynamic scalability of substrate networks; VNF-P considering security VNF types with requirements, including encryption acceleration; VNF-P with backup VNFs (off-site) for service availability

Results: Energy-Efficient NFV ②

Wireless networks

- **Functional splits**: central/remote sites w/ mid-haul bw. in a vRAN+UE-RRH switching; VM-based core and baseband NFs, backhaul/fronthaul config. and VM inter-traffic
- **E2E models**: VNF placement (VNF-P) in C-RAN, service differentiation with E2E latency+reliability; soft actor-critic-based DRL for radio and core resource allocation
- **Security**: security VNFs activation in multi-hop networks; blockchain-enabled NFV

Emerging networks

- **Satellite**: NFV-based services in sw.-defined LEO+S2S links; VNF-P+state switching
- **Edge computing**: VNF-P in multi-area edge considering latency; video streaming w/ dynamic caching+virtual BSs+compression; serverless/CNFs+NetFPGA accelerator
- Cyber-physical systems with sensor VNFs; NFV-based energy management in IoT; cloud-fog RAN+virt. BBUs+virt PONs; DRL-based optim. of radio+traject. in UAV

Results: Energy-Efficient Network Slicing ①

Data center networks

- **State switching**: minimum load-based activation; virtual network reconfiguration with a group-based virtual node migration; VNF sharing in SFCs+traffic processing capacity
- Node ranking+traffic grooming in optical DCs; VDC embedding+migration w/ DFS and ALR; network congestion+SR; constrained shortest path; resource reachability+renewable

Transport networks

- **Multi-domain networks**: geo-distributed substrate networks+energy prices and node ranking; carbon footprint+SFC migration+latency+renewable energy locations
- **State switching**: SFC+latency+flow table changes; adaptive shutdown delay of servers
- **Hybrid networks**: hybrid SDN/NFV; optical-electronic networks+wavelength manage.
- **Latency**: latency-constrained VNE; WAN+VNF sharing; sleep links+dynamic flow alloc.
- Active node reuse with dynamic regions of interest to map and reuse active areas

Results: Energy-Efficient Network Slicing ②

Wireless networks

- **Heterogeneous networks**: resource alloc. in virt. wireless networks with OFDMA and pricing decision; network selection (user association) in NR-U/WiFi networks; virtual network migration and state switching in virtualized fiber-wireless access networks (FiWi)
- **E2E network slicing**: power control and user's latency; E2E EE/latency in C-RAN
- Constrained DRL for resource alloc. w/ mixed action space both discrete (subchannel allocation) and continuous (energy harvesting duration) actions +battery+queue length

Emerging networks

- **State switching**: virtual resource allocation in a vehicle-assisted 5G network with an E2E system model; E2E latency+energy-aware models in SDN-based cloud-edge networks
- Distrib. netw. slicing in SDN-based LoRaWAN access netw. (dense IoT); extended SDN-based 5G network coverage w/ UAVs+SFC+VNF sharing; dynamic VNE in satellite

Lessons Learned: Network Infrastructure and Scenario

Network Infrastructure

- Different network scenario has different energy consumption model; accurate?
- Commonly used energy-efficiency strategies[a]: dynamic adaptation and sleep modes
- Mainly focus on data plane/infrastructure and physical (technologies)

[a] Need to be supported by hardware/infrastructure.

Network Scenario

- Multi-domain to inter-domain, e.g., inter-DC, intra/inter-domain routing, SD-WAN
- Technology- and topology-based energy consumption models, e.g., inter-DC EONs
- Dynamic scenarios with network topology and traffic (flows)[a]; e.g., flow energy consump.

[a] Delay-sensitive/-tolerant services, short/long flows, low-/high-load links, etc. affect EE mechanisms.

Lessons Learned: Energy-Efficiency Strategies

Dynamic Adaptation (DA)

- Computing: DVS (voltage), DFS (frequency), DVFS; energy/power proportional
- Networking: ALR (wired), "lightpath" (optical), "cell zooming" (wireless), traffic-based radio/transmission power (wireless), etc.

Sleep Modes (SM)

- **Multiple transition states**: off/sleep, idle (no-load), on (with-load)
  - Commonly combined with DA using varied "off/on" states and depend on the scenario
  - Technologies: combined bundled links (802.3ax) with low-idle/sleep links (802.3az), ...
- **State switching power**: a sudden power consumption when a device turned on
  - Reduce switching power consumption: energy cost, affects machine-wear (lifetime, reliability)
- **State switching time**: transition from on-to-off with "unfinished tasks" (energy consump. duration), off-to-on/sleep-to-on (wake-up delay), timers, microsleep

Lessons Learned: Applications and Network Softwarization

Energy-aware Applications

- **Traffic engineering**: rerouting, load balancing, congestion prevention, flow scheduling
- **Multimedia**: VoIP and (3D) video streaming with QoE/fairness/caching
- **Security**: DDoS, encryption, protection, and recovery functions
- **Reliability/availability**: failure handling, recovery, redundancy
- **Computing**: (E)DC resource management, workload scheduling, balancing, offloading

Network Softwarization

- Softwarized power/energy/resource control, management and orchestration (abstraction[a])
- Combined softwarization technologies: partial/hybrid SDN/NFV for network services
- Reconfiguration and optimization based on different and dynamic scenarios/services

[a] Global network view and resource management, including allocation, plus orchestration for efficient services.

Lessons Learned: Issues

Virtualizing Resources, Control, and Management: Abstraction+Consolidation

- Virtualization: virtualized resources, including virtual machines and containers
- Cloudification: service-based/elastic/on-demand virtualization (manage.) of hw. pools
- Softwarization: softwarized network control, virtualized functions, isolated services

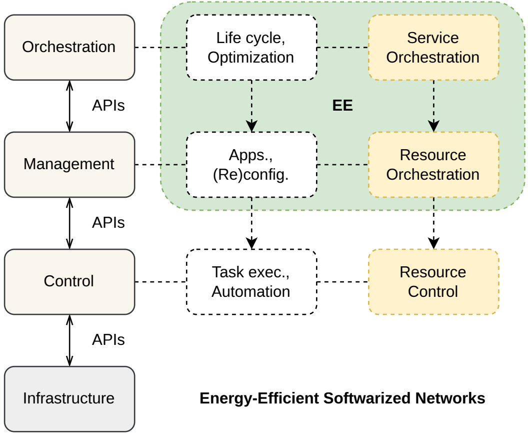
Maximizing Utilization

- Power-/energy-proportionality of network devices/infrastructure
- Maximizing utilization using already-on/-active nodes/links/paths/areas
- Utilization-based functions, ratios, and metrics

State Transition/Switching

- Reducing switching power and time/duration: min. load activation, off/on delay, sched.
- Reconfiguration of resources/functions/networks: scaling, aggregating, sharing, migration

Energy-Efficient Softwarized Networks



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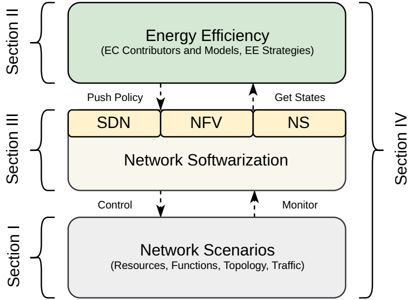


I. Setiawan, B. Kar, and S.-H. Shen, **Energy-Efficient Softwarized Networks: A Survey**

Preprint: https://arxiv.org/abs/2307.11301

Potential Challenges: Emerging Scenarios and Network Reconfiguration

Energy Savings at the Edge

- Emerging softwarized network scenarios at the edge
  - Various emerging scenarios from WBANs, IoT, to non-terrestrial, e.g., UAV and satellite
  - Edge networking (interconnection) converged with computing (collaborative cloud-edge)
- Multiple/massive end-devices and edge services with stringent latency +caching
- Edge wireless networks, e.g., dense RANs, D2D, NOMA, MEC, RAN/radio slicing

Network Reconfiguration and Sharing

- Dynamic network scenarios: scalability, e.g., green TE, video streaming, security defense
  - Techniques: consolidation/aggregation, resource/function migration, load shifting, etc.
  - Flexibility vs stability; is slow response better in terms of energy efficiency?
- Network (+compute) resource/function sharing, e.g., inter-DC resources, CNFs, serverless
- Prediction to anticipate utilization+power consumption. Reactive vs proactive reconfig.

Potential Challenges: Optimization and CMANO Energy Consumption

Optimization Approaches

- Schemes: machine learning-based optimization, multi-objective with Pareto, protocols
- Techniques: aggregation/grouping, segmentation/splitting, sorting/ranking, parallelization
- Criteria: QoS, scalability vs heterogeneity, mobility, reliability (redundancy)→availability
- Consideration: memory/cache/storage, e.g., joint comput., commun., caching (3C)
  - Max. memory util. & alloc., wildcard flow rules, flow placement, data compression, etc.
  - Other: temperature related to energy consumption, due to electrical resistance

Energy Consumption in Control and MANO Layers

- Considering including control and MANO (CMANO) layers in energy consumption model
  - Hierarchical/centralized/distributed styles and NetSoft problem types, e.g., SDN CPP
- Depends on the CMANO architecture in a netw. sce. (CMANO's resources, and so on)
- AI/ML energy consumption in the MANO, particularly orchestration layer

Potential Challenges: Network and Energy Heterogeneity

Network Heterogeneity

- Different requirements demand different resources/functions to be effective/efficient
- Orchestrate the demands and available heterogeneous resources/functions/networks
  - Domain-oriented: a specific domain in cloud to edge; functional splits→new segments
  - Performance: accelerators, e.g., SmartNIC, (Net)FPGA, GPU, DPU/IPU, P-DP
  - HetNet with small/macro cells, multi-access tech., e.g., optical/electrical, fiber/wireless
- Hybrid NetSoft: partial/hybrid SDN/NFV/P-DP, infra. migration to green+NetSoft

Energy Heterogeneity

- Grid, renewable, & ambient energy sources; EH strategy; Time/place-based load shifting[a]
- Combined resource slicing: virtualized network and energy (network+energy slice MANO)
- Carbon-aware MANO: focusing not only energy efficiency, but also carbon emissions

[a] Scheduling, "follow the sun/wind/etc.", availability; demand-response: adjusting energy demand/usage.

Potential Challenges: E2E EE, Measurements, and Evaluation

E2E Energy-Efficient Softwarized Networks

- Inter-domain nature, covers multiple segments or (administrative) domains, e.g., w/ SM
- E2E EE from RAN, core, to (edge/multi) cloud. Energy-efficient network slicing (services)
- Opportunities: E2E EE in private (5G) networks, industrial IoT, enterprise networks, etc.

Metrics and Measurements

- Softwarized metrics for energy efficiency: RESDN, ECPUB; do we need more?
- Generic metric: (successful) transferred bit per energy consumed; energy-related KPIs
- Measurement techniques, tools, supports (hardware, software, APIs); frameworks, data

Evaluation Environments

- Common evaluation environments, or "standardized"
- Simulating and realizing in physical testbeds, or collaboratively with federated testbeds

Closing Remarks

Conclusions

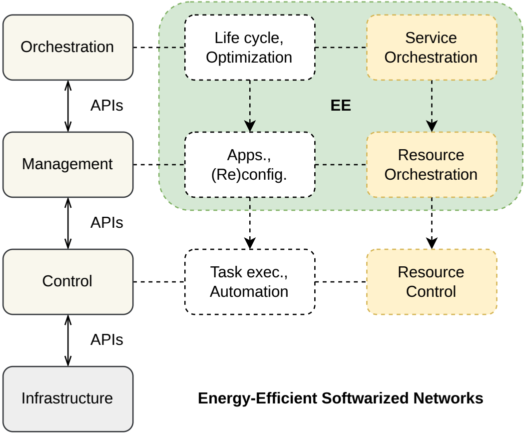
- Network softwarization provides programmability and flexibility to improve EE in various and dynamic scenarios, but demands efficiency on both infrastructure and CMANO layers
- EE can be accommodated in softwarized network scenarios using EE strategies via CMANO layers, supported by improved hardware[a] and software (Green+NetSoft infra.)
- EE optimization in CMANO layers, particularly orchestrator, needs energy consumption models/data and EE strategies that matched with the softwarized network scenario

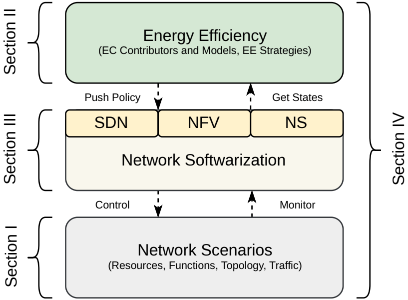
[a] "Green" supports (e.g., DA+SM), low-power (HW), if possible: reduced embodied carbon, e.g., manufact.

Notes

- Balancing network management, e.g., domains (edge/metro), layers ("enough" CMANO)
- Utilizing known technologies that support energy efficiency, e.g., PONs; Scheduling
- Energy-efficient protocols: control (via APIs), communications (network applications)

Energy-Efficient Softwarized Networks





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