Fog computing: A cloud to the ground support for smart things and machine-to-machine networks

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Abstract— **Cloud services to smart things face latency and intermittent connectivity issues. Fog devices are positioned between cloud and smart devices. Their high speed Internet connection to the cloud, and physical proximity to users, enable real time applications and location based services, and mobility support. Cisco promoted fog computing concept in the areas of smart grid, connected vehicles and wireless sensor and actuator networks. This survey article expands this concept to the decentralized smart building control, recognizes cloudlets as special case of fog computing, and relates it to the software defined networks (SDN) scenarios. Our literature review identifies a handful number of articles. Cooperative data scheduling and adaptive traffic light problems in SDN based vehicular networks, and demand response management in macro station and micro-grid based smart grids are discussed. Security, privacy and trust issues, control information overhead and network control policies do not seem to be studied so far within the fog computing concept.**

Keywords- Fog computing, Machine-to-machine networks

I. INTRODUCTION

Cisco [B, BMZA, C1] recently delivered the vision of *fog computing* to enable applications on billions of connected devices, already connected in the Internet of Things (IoT), to run directly at the network edge. Both cloud and fog provide data, compute, storage, and application services to end-users. The distinguishing fog characteristics are its proximity to end-users, its dense geographical distribution, and its support for mobility. Services can be hosted at end devices such as set-top-boxes or access points. Fog provides low latency, location awareness, and improves QoS for streaming and real-time applications (e.g., in industrial automation, transportation, networks of sensors and actuators), and supports heterogeneity (fog devices include end-user devices, access points, edge routers, switches, spanning multiple management domains). The fog computing paradigm is well positioned for real time big data analytics, supports densely distributed data collection points, and provides advantages in entertainment, advertising, personal computing and other applications. Existing fog computing based architectures can be modeled by a simple three level hierarchy as in Figure 1, where each smart thing is attached to one of fog devices, fog devices could be interconnected, and each of them is linked to the cloud.

Customers can develop, manage and run software applications on CISCO IOx framework of networked devices [C1], including hardened routers, switches and IP video cameras. Cisco IOx brings the open-source Linux and Cisco IOS® network operating system together in a single networked device (initially in routers). The open application environment encourages more developers to bring their own applications and connectivity interfaces at the edge of the network. This distributed computing infrastructure allows applications to run as close as possible to sensed actionable and massive data, coming out of people, processes and things. Such fog computing (a cloud computing close to the 'ground') concept creates automated response that drives the value.

II. SCENARIOS

Fog computing based systems are becoming important class of *cyber-physical systems (CPS)* [S-m2m]. We elaborate on the role of fog computing in several motivating scenarios: smart grids, vehicular networks, wireless sensor and actuator networks, smart building control.

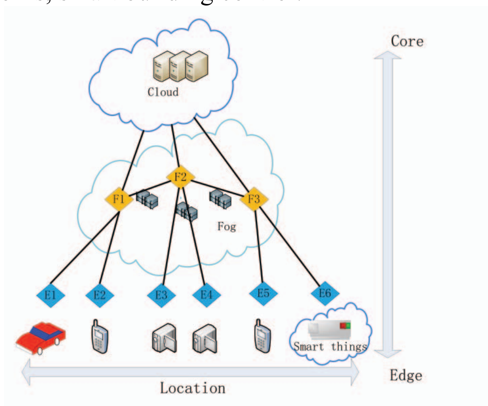

Figure 1 Fog between edge and cloud

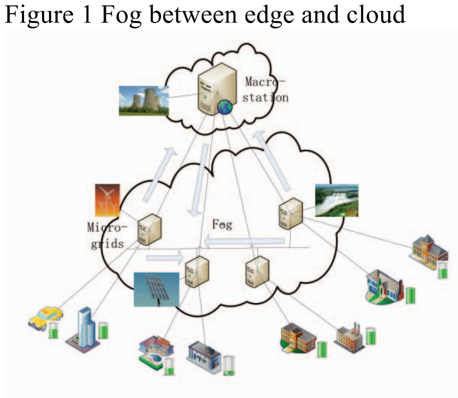

Figure 2. Fog computing in smart grid

In the *smart grid* (Figure 2), energy load balancing applications may run on network edge devices (e.g., smart meters, micro-grids) that automatically switch to alternative energies like solar and wind–based on energy demand, availability and the lowest price. Fog collectors at the edge process the data generated by grid sensors and devices, and

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issue control commands to the actuators [BMZA]. They also filter the data to be consumed locally, and send the rest to the higher tiers, for visualization and reporting for real-time or transactional analytics. Fog supports ephemeral storage at the lowest tier to semi-permanent storage at the highest tier. Global coverage is provided by the cloud, with business intelligence analytics.

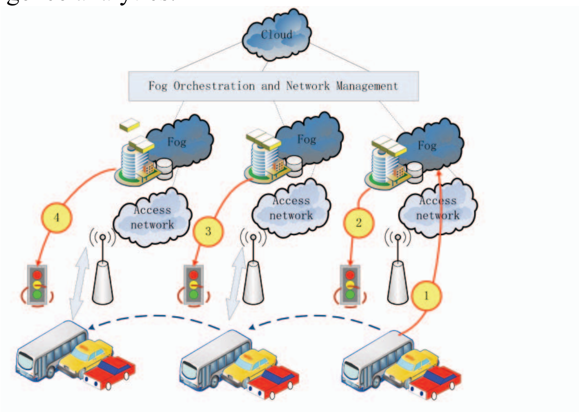

Figure 3. Connected vehicles scenarios

A *micro-grid decentralized smart grid* (Figure 3) was described in [WFKS]. Fog computing paradigm will provide novel smart grid model for essential applications such as demand response management. Micro-grids have recently emerged as a promising technology to integrate, with the main power grid, alternate echo-friendly distributed power generators such as wind farms, solar cells, micro turbines, waste to energy, plug-in hybrid electrical vehicles (PHEVs), and so forth. Macro station or micro-grids hosted fog devices greatly reduce communication overhead compared to existing centralized and fully distributed smart grid models, where each user handles its own power consumption with its own computing and communication resources, while individually frequently consulting power producers about the price, to optimize the cost.

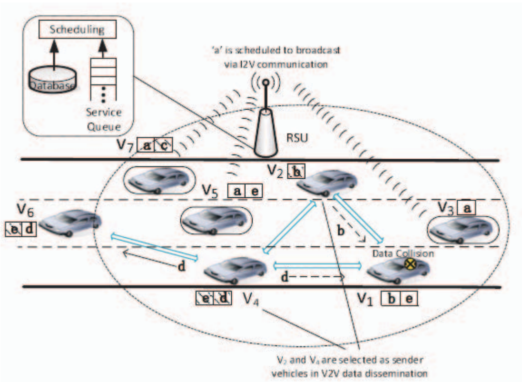

Figure 4. Data dissemination via the hybrid I2V/V2V

In the *smarter traffic lights and connected vehicles* scenario (Figure 3), video camera that senses an ambulance flashing lights can automatically change streetlights to open lanes for the vehicle to pass through traffic. Smart streetlights interact locally with sensors and detect presence of pedestrian and bikers, and measure the distance and speed of approaching vehicles. Intelligent lighting turns on once a sensor identifies movement and switches off as traffic passes. Neighboring smart lights (fog devices) coordinate to create green traffic wave and send warning signals to approaching vehicles [BMZA]. Vehicle-to-vehicle, vehicle to access points (Wi-Fi, 3G, LTE, road-side units, smart traffic lights), and access points to access points interactions enrich this scenario [BMZA].

Fog computing framework is applied to implement the first known software defined networks (SDN) concept for *vehicular networks* [LNLSS] (Figure 4). SDN is an emergent computing and networking paradigm and became one of the most popular topics in IT industry. It separates control and data communication layers. Control is done at 'centralized server', and nodes follow communication path decided by the server. 'Centralized server' may need distributed implementation. SDN concept was studied in WLAN, wireless sensor and mesh networks, but they do not involve multi-hop wireless communication, multi-hop routing, and there is no communication between peers. SDN concept will resolve the main issues in vehicular networks, intermittent connectivity, collisions, and high packet loss rate, by augmenting vehicle-to-vehicle (V2) with vehicle-to-infrastructure (V2I) communications, and centralized control.

We next describe *wireless sensor and actuator networks* scenario. Traditional wireless sensor networks fall short in applications that go beyond sensing and tracking, but require actuators to exert physical actions (open, close, move, focus, target, even carry and deploy sensors) [BMZA]. Actuators (fog devices) can control the system, the measurement process itself, stability and oscillatory behavior, by creating a closed-loop system. For example, in self-maintaining trains scenario, sensor monitoring on a train's ball-bearing can detect heat levels, allowing applications to send an automatic alert to the train operator to stop the train at the next station for emergency maintenance and avoid potential derailment. In lifesaving air vents scenario, sensors on vents monitor air conditions flowing in and out of mines and automatically change air-flow if conditions become dangerous to miners.

Decentralized smart building control is facilitated by wireless sensors deployed to measure temperature, humidity, or levels of various gases in the building atmosphere. Furthermore, the sensors will be able to exchange information (e.g., all sensors in a floor) and *coordinate* to combine their readings and arrive at reliable measurements, and use distributed decision making and activation at fog devices to react to data. The system components may then work together to lower the temperature, inject fresh air, or open windows. Air conditioners can remove moisture from the air or increase the humidity. Sensors can also trace and react to movements (e.g., by turning light on and off). Fog devices could be assigned at each floor and could collaborate on higher level of actuation. Networked buildings can maintain their fabric, external and internal environments, to conserve energy, water and other resources.

III. LITERATURE REVIEW ON FOG COMPUTING

A total of eight articles [B, BMZA, HLROK, HLOC, MBAP, NSTM, OKRR, ZC+] were identified on the fog computing concept, as described here, and labelled as such. The same name appeared in some more papers (not listed here) but refereed to other concepts. The literature review presented here therefore appears complete, and the topic is timely. However, some other concepts, not declared as 'fog computing', might fall under the same 'umbrella' e.g., cloudlets, elaborated in the next section.

Mobile Fog [HLROK] is a high level programming model for geospatially distributed, large-scale and latency-sensitive future Internet applications. In their logical structure (Figure 1), low-latency processing occurs near the edge while latency-tolerant large-scope aggregation is performed on powerful resources in the core of the network (cloud). Mobile Fog consists of a set of event handlers and a set of functions that an application can call. Two situation awareness applications were elaborated. In camera based vehicle tracking scenario, traffic cameras are used to help police identify and track certain vehicles. The programming model calls for functions to detect vehicles and read their license plates (possibly after zooming a chosen vehicle). In the traffic monitoring using mobility-driven distributed complex event processing (CEP) system, a sequence of similar movement and accelerator patterns from different vehicles on the same road can determine if an accident blocks the road. A separate programming model is described which calls on location multicast, range query, detection algorithms etc. Mobile Fog model is not presented as generic model, but is built for particular application, while leaving out functions that deal with technical challenges of, for instance, involved image processing primitives. The evaluation is based on network simulator where vehicle-to-vehicle video streaming is performed via cloud vs. intermediate fog computing nodes. Fog computing approach reduces latency and network traffic.

A placement and migration method for cloud and fog resources providers is presented in [OKRR]. It ensures application-defined end-to-end latency restrictions and reduces the network utilization by planning the migration ahead of time. They also show how the application knowledge of the CEP system can be used to improve current live migration techniques for Virtual Machines to reduce the required bandwidth during the migration. Network intensive operators are placed on distributed fog nodes while computationally intensive operators are in the cloud. Migration costs are amortized by selecting migration targets that ensure a low expected network utilization for a sufficiently long time. Their migration plan algorithm is based on the operator graph with operators, sources and consumers as nodes. This work does not optimize workload mobility because fog devices are also able to carry computationally intensive tasks. It also does not optimize the size of control information or mobility overhead, and does not describe network control policies for finding optimal paths for different applications.

An opportunistic spatio-temporal event processing system that uses prediction-based continuous query handling was proposed in [HLOC]. Their system predicts future query regions for moving consumers and starts processing events early so that the live situational information is available when the consumer reaches the future location. Historical events for a location are processed before the mobile user arrives at that location, so that live event processing begins at the moment the user arrives. Just-in-time computation is enabled by two 'black boxes': future location predictions for the mobile user placing the query, and processing time estimations for the CEP algorithms. To mitigate large speed of mobile user, authors propose using parallel resources to enable pipeline processing of future locations in several time- steps look-ahead. Further, they propose taking several predictions for each time-step look-ahead and opportunistically compute the events for all of those locations, parallel resources permitting. When the user arrives at that time, the prediction among those that is closest to truth (the user's actual position) will be selected and its events returned.

Existing methods for web optimization (minimizing HTTP requests, minimizing size of web objects, reorganizing the web page composition) were applied in [ZC+] in a novel manner, within fog computing context, such that these methods can be combined with unique knowledge that is only available at the edge (fog) nodes. More dynamic adaptation to the user's conditions (e.g., network status and device's computing load) can also be accomplished with network edge specific knowledge. As a result, a user's webpage rendering performance is improved beyond that achieved by simply applying those methods at the webserver.

In the mobile cloud concept [NSTM], pervasive mobile devices share their heterogeneous resources (e. g. CPUs, bandwidth, content) and support services. Neighbouring nodes in a local network form a group called a local cloud. Nodes share their resources with other nodes in the same local cloud. A local resource coordinator (fog device) is elected from the nodes in each local cloud. Authors [NSTM] proposed an architecture and mathematical framework for heterogeneous resource sharing based on the key idea of service-oriented utility functions. Normally, heterogeneous resources are quantified in disparate scales (e.g. power, bandwidth, latency). Authors presented a unified framework where all these quantities are equivalently mapped to "time" resources. They formulate optimization problems for maximizing the sum of the utility functions, and the product of the utility functions, and solve them via convex optimization approaches.

The reliability requirements of smart grid, cloud, and sensors and actuators are first reviewed in [MBAP], and then combined towards reliable fog computing. However authors only concluded that building fog computing based projects is challenging, and do not offer any novel concept for the reliability of the network of smart devices in the fog computing paradigm.

Several European union projects attempt to define M2M and Internet of Things. ETSI M2M and IoT-A proposed several architectures and standards. BETaaS (www.betaas.eu) proposed to replace cloud as the resident for M2M applications by 'local cloud' of gateways, the later being the devices that provide smart things with connectivity to the Internet (e.g. smart phones, home routers, road-side units). This enables applications that are limited in time and space, require simple and repetitive interactions, and respond in consistent manner.

IV. CLOUDLETS

Mobile devices may seamlessly integrate rich sensing (including human perception and cognition) and interaction capabilities with compute-intensive and data-intensive processing in the cloud. A major obstacle to this integration is the large and variable latency and intermittent connectivity between mobile device and cloud [S].

Cloudlets represent intermediate layers located between the cloud and each mobile device. The users connect to the nearest cloudlet through a wireless network, instead of accessing distant cloud. Cloudlets can be viewed as "data centers in a box" (owned by a local business with little or no professional attention) aimed to "bring the cloud closer" to few users at a time. They can provide the service and/or operate as offload elements. Cloudlet is a small cloud located nearby mobile users which will be connected through LAN network with clouds located far away. One of the cloudlet benefits is a possibility that mobile users can rapidly instantiate custom virtual machines (VMs) on the cloudlet running the required software in a thin client fashion [BG]. Instead of configuring software to service mobile device, a precisely preconfigured VM is delivered to the cloudlet. Cloudlet only contains soft state such as cache copies of code and data available elsewhere, and therefore cannot 'harm' mobile user. The usage of VM in cloudlets enables clean encapsulation of transient guest software environment and its clean separation from the permanent cloudlet host software environment. Chances of compatibility and cloudlet longevity are increased by such stable and narrow interface. Cloudlet can cache a copy of VM for future reconnections, and the same VM can be used for offloading by many mobile devices at the same time.

The main focus of recent papers is on the applications for image and voice recognition, natural language processing, mission planning, decision making, etc. For example, Apple's Siri enables the customer to use their voice in order to send messages, schedule a meeting, make a phone call, etc.

Experiments check the performance of the cloudlet concept, application processing and response and information distribution times. Face recognition is the most popular (e.g. [SMFKH] and Google's FaceLock) studied problem, and is used in most experiments involving offloading to the cloud. For instance, the mobile-cloudlet-cloud architecture named MOCHA performs task partitioning from mobile devices to cloud and distributes compute load among cloud servers (cloudlet) to minimize the response time given diverse communication latencies and server compute powers [SMFKH].

Cloudlets were introduced in [SBCD], before the fog computing concept. From its description, one can conclude that cloudlets are an important special case of the later concept. Both require us to rethink privacy, software licensing, business models and a myriad of other issues.

V. FOG COMPUTING IN VEHICULAR NETWORKS

When SDN concept is implemented with physically (not just logically) centralized control, it resembles the fog computing concept, with fog device acting as the centralized controller. Such SDN implementations were proposed for wireless sensor network [LTQ] and mesh networks.

We describe three implementations of SDN concept in vehicular networks. In the first one, independent fog devices serve as centralized coordinators and each serves nearby vehicles [LNLSS]. In the second, more general, fog devices are interconnected and implement 'logically centralized' coordinator in distributed manner. The third SDN implementation appears to be beyond the fog computing concept. Cloud could serve as the main centralized coordinator, and vehicles use V2I/3G/LTE to communicate to the base station, and base station may forward control information and download routing tables via cellular communications [C].

In the first SDN concept for vehicular networks and centralized control over V2V [LNLSS], traffic lights or road side units can serve as fog devices. The novel framework [LNLSS] abstracts all vehicles and roadside facilities as data plane routers in SDN. By leveraging the control plane in SDN, the system can effectively collect and maintain individual vehicle states to control and optimize V2V/V2I multi-hop routing in a logically centralized way.

Data communication in vehicular networks was traditionally done in decentralized manner. A survey of forwarding problems and methods in data dissemination and routing protocols for vehicular ad hoc networks is presented in [DSY].

SDN concept in vehicular networks was first studied and elaborated on a particular *cooperative data scheduling* problem in a hybrid vehicular communication environment [LNLSS], defined as follows. Vehicles are likely to request files of mostly common interest: road conditions, gas stations etc. In accordance with the specification of IEEE 1609.4, there is one control channel and two service channels. The control channel is used for disseminating management information, service advertisements and control messages. Two service channels are used for I2V and V2V data, respectively. Scheduling period consist of three phases. In the first phase, all the vehicles are set to the V2V mode and broadcast their heartbeat message, so that each vehicle is able to identify a list of its neighbouring vehicles. In the second phase, all the vehicles switch to I2V mode and each informs the RSU the list of its current neighbouring vehicles, and the identifiers of the retrieved and newly requested data items. In the third phase, each vehicle participates into either I2V or V2V communication based on the scheduling decisions. Multiple instances of data dissemination may be taken place simultaneously in this phase. For example, in Fig 4, RSU (fog device) transmits file a to V_7, V_5 and V_3, V_2 transmits file *b* to V_1, and V_4 transmits file *d* to V_6. Each vehicle has a set of requested files. Only one file can be transmitted/received in in one scheduling period. Each vehicle has a weight for being served. Objective in one scheduling period is to maximize weighted gain, which is the summation of the weight for each served vehicle in a scheduling period. Our objective is to prove that the problem is NP-complete and to describe fog computing based solution for optimal scheduling in one period, and to expand this solution and give an efficient algorithm for scheduling in all periods.

NP-completeness follows by reduction from weighted independent set problem in graph theory. A greedy algorithm [LNLSS] for scheduling transmission in one scheduling period optimizes weights to optimize number of received file over all rounds. SDN framework is compared, for quality and overhead, with some straightforward solutions, such as First Come First Serve, or Most Requested First. The solution [LNLSS] could be improved by allowing vehicles to store and forward items that they did not request, to assist other vehicles. The control overhead in SDN framework based solution could be reduced (while not loosing solution quality significantly) by techniques such as reducing update frequency by trajectory prediction. Further, interconnected fog devices can cooperate to improve their file delivery services to vehicles. If a vehicle does not receive requested file(s) from the current fog device, request will be migrated to neighboring one. Alternatively, cloud could become the coordinator (for all fog devices and all cars), and implement higher level SDN concept.

Fog computing concept may provide efficient traffic light control at much larger scale than existing solutions. After smoothing vehicles' travels, more vehicles can pass intersections with less waiting time and fewer short-time stops; therefore, the vehicles' CO_2 emissions can be reduced. [ZCW] studied adaptive traffic light control for smoothing vehicles' travel and maximizing the traffic throughout for both single and multiple lanes. [LS] proposed a three-tier structure. An electronic toll collection (ETC) system is employed for collecting road traffic flow data and calculating the recommended speed (tier 1). Radio antennas are installed near the traffic lights (tier 2). Road traffic flow information can be obtained by wireless communication between the antennas and ETC devices. Alternatively, [ZTD] presented the mathematical model and algorithms for traffic flow information detection based on proximity sensor networks; this real time information directly from the vehicular network may avoid the traffic congestion before its formation. A branch-and-bound-based real-time traffic light control algorithm is designed to smooth vehicles' travels (tier 3) [ZCW].

A fog computing paradigm based solution can accommodate variety of input: wireless communications with ETC as in [LS], RFID tags in cars with readers at traffic lights, cameras at traffic lights etc. with the corresponding localized analytics to derive traffic densities and flows. Summary traffic information from fog devices would be forwarded to the cloud for global coordination. Fog devices are decision makers, and naturally coordinate locally with neighboring fog devices along the same major roads.

To support logically centralized control of data dissemination, mobility between fog nodes, and between fog and cloud, state information of participating vehicles and IoT nodes needs to be collected and migrated efficiently. Vehicle's state information include real-time location, speed, heading, network capacity and load, QoS etc.

VI. FOG COMPUTING IN SMART GRIDS

Centralized demand response management algorithm [FQKS] can be implemented with a cloud computing approach, where each supplier and customer communicate directly with the cloud. Centralized algorithm will cause much bandwidth cost. Fully distributed implementation requires computing at each supplier and customer end, and extensive communication among them, due to distance between them.

Macro-grid or each micro-grid may act as fog devices. Customers communicate to nearby fog devices rather than remote cloud. Fog devices frequently communicate with customers, and occasionally with the cloud.

In the demand response management solution [WFKS], macro-station (as fog device) coordinates mutual power exchange among the micro-grid and between each micro-grid and macro station. To optimally reduce the total power losses in such a power grid system, a greedy coalition formation algorithm is proposed [WFKS]. The algorithm optimizes the total power losses across the entire power grid, including the cost of charging and discharging power storage devices, and power losses due to power transfers. The algorithm creates exchange pairs among micro-stations giving priority to pairs with higher power loss reduction per exchanged power unit.

Demand response management could be considered at several layers. One layer is a 'game' among consumers attached to the same fog device, based on the local information and the parameters provided by the fog device. The second layer is game between fog devices attached to the same cloud server and global information available therein. Further, fog devices could be interconnected. Partial information available in the fog devices (e.g., micro-grids) will enable them to form effective coalitions for minimizing the overall power losses and remarkably reduce the communication cost.

Decentralized online charging scheduling for large populations of electric vehicles is another example of possible application of the fog computing concept. The solution in [JWZL] is based on clustering that dynamically classifies heterogeneous electric vehicles into multiple groups and a sliding-window iterative approach that schedules the charging demand in each group in real time. Coordinated fog devices may provide an improved alternative solution.

VII. Conclusion

Security (e.g. authentication, misbehavior and anomaly detection, access control), privacy (privacy-preserving aggregation and demand response [LAWS], hiding details), trust, incentive [WCL] and fault tolerance [EC+] issues in the (explicit) context of fog computing were not studied so far. Existing methods need to be changed to accommodate two layer fog-cloud model. These issues were studied in the context of smart grids (e.g. [WZ]) and M2M communications (e.g. [LL]).

One can extend [OKRR] by improving workload mobility, observing that fog devices are also able to carry computationally intensive tasks. Optimizing the size of control information and mobility overhead, and network control policies for finding optimal paths for different applications can be investigated. Given state information, predicted network topologies, and data flows for different applications, how to design network control policies to find optimal routing paths for different operations, like routing, multi-casting, and broadcasting?

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