# Information-Centric Fog Network for Incentivized Collaborative Caching in the Internet of Everything

Junaid Ahmed Khan, Cedric Westphal, and Yacine Ghamri-Doudane

The authors propose a social-aware content caching and distribution scheme to model fog interactions allowing nodes to collaboratively cache content locally. They evaluate IS-Fog using realistic mobility traces of 2986 nodes. Results show that IS-Fog is a scalable and efficient content caching and distribution approach compared to existing schemes.


## Abstract

Current mobile network infrastructure has a hard time keeping up with the constant content demand by an increasing number of smart devices, in terms of both bandwidth and cost. At the same time, the advent of devices with relatively high resources (computing, communications, caching) allows offloading computation, control, cache, and communication near users, as in edge or fog networking. If we consider the caching resource, the basic challenges are: (i) How and who can form fogs for local content caching? (ii) How is interacting with the fog done for efficient content caching and retrieval? To address these, we leverage information-centric networking to propose IS-Fog, a social-aware fog network where the content is the first class citizen. We first classify a device's eligibility to provide content using novel content-based centrality. At the same time, we incentivize users to self-organize and share their devices' resources and cache in the fog. We then propose social-aware content caching and a distribution scheme to model fog interactions allowing nodes to collaboratively cache content locally. We evaluate IS-Fog using realistic mobility traces of 2986 nodes. Results show that IS-Fog is a more scalable and efficient content caching and distribution approach compared to existing schemes.


## Introduction

Future smart city applications are expected to generate and consume a large amount of data with intelligent devices related to connected transportation (smart vehicles), buildings (smart homes), industry and manufacturing, the energy sector (smart grid), e-health (wearables), surveillance, agriculture (sensors and actuators), and mobility-related applications (smartphones). The Internet of Everything (IoE) paradigm will allow every *thing* to connect to the Internet [1, 2]. At the same time, the soaring number of such connected things pose an alarming situation: Cisco predicts that by 2020, around 50 billion devices will be connected to the Internet [3].

It is challenging for current mobile network infrastructure to deal with such massive content delivery to users. For instance, different users requesting the same recently aired episode of a popular TV show on their mobile devices in an urban environment would result in lots of redundant requests in close proximity. Cloud-based solutions help a lot. However, they will be strained under current demand growth rates. Today, augmented/virtual reality (AR/VR) or vehicular automation applications require quick response under variable network connectivity and availability, while clouds incur long setup times, are leased for long times, and are oblivious to network connectivity.

*Fog* networking is a promising network architecture for devices at the edge (near users) to perform local decentralized resource pooling (computing, caching, and communication) as an ad hoc network, rather than using the infrastructure network [4, 5]. It addresses end users' requirements for real-time processing of content "now and here" while supporting rapid innovation and affordable scaling for increasing number of multimedia rich AR/VR-based applications in the upcoming fifth generation (5G) networks. We believe spatio-temporally co-located user devices with relatively high resource such as routers, small cells, and even vehicles can mutually orchestrate resources and act as surrogates for the infrastructure in the 5G networking architecture to compute, cache, and communicate locally near end users. Users in a neighborhood can enable their set-top boxes/wireless access points (APs) or vehicles' onboard units (OBUs) to mutually cache and share that popular TV show episode, thus limiting the backhaul connections to the service/content provider from other nearby users.

Two basic questions need to be addressed:

1. How do we identify and provide incentives to suitable candidate users with devices capable of composing, deploying, and managing a distributed fog network?
2. How do devices in a fog interact and collaborate to efficiently cache and retrieve content?

To address these questions, we present an information-centric social-aware fog (IS-Fog) networking, where information-centric networking (ICN) [6, 7] with its in-network caching [8] and content provider-consumer decoupling along "any-cast" routing support can be combined with fog networking. Additionally, we advocate a social aware approach where we redefine central-

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We suggest using ICN as a better suited architecture with its data centric approach along the support for in-network caching towards an integrated solution. However, the proposed collaborative caching is independent of the underlying layer 3 architecture and therefore, the current IPv4 based Internet infrastructure can still be used to implement our solution.

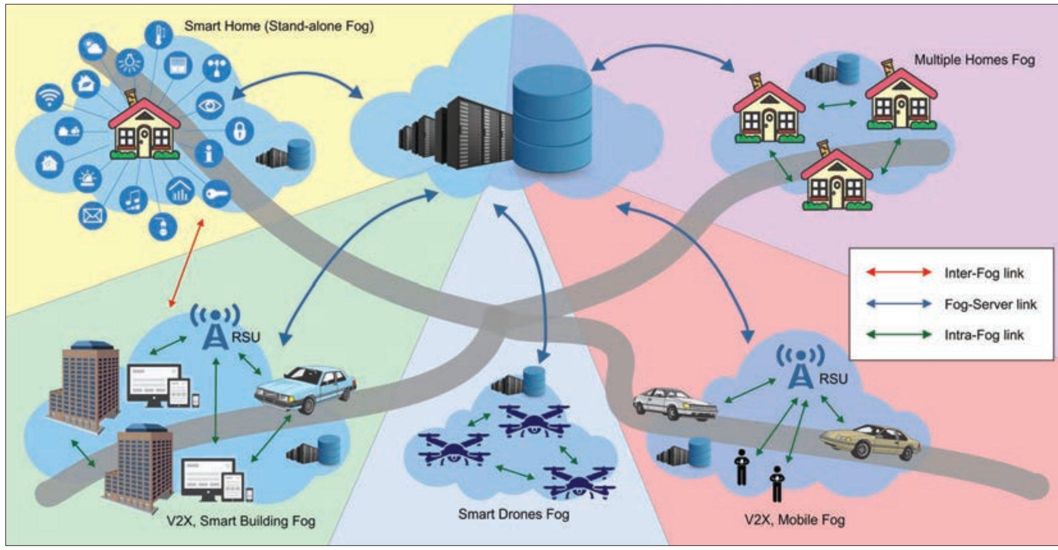


**Figure 1.** IS-Fog system overview.

ity, a measure used in network sciences to identify important nodes in a graph. Identification of influential users is required in social networks (and other graphs [9, 10]) for disseminating information.

Therefore, we first identify eligible candidate devices using a new content-based centrality scheme that classifies a device based on its ability to provide content to users instead of its topological connectivity. Such devices are viable candidates to provide their caching, computing, and communication resources to facilitate content delivery to nearby devices. Second, we target the fog formation, where we exploit game-theoretic concepts to motivate co-located devices to form a coalition and collaboratively cache maximum content locally in a distributed fog. Finally, we propose a social-aware content caching and distribution scheme modeling intra- and inter- fog interactions where ICN-enabled "any-cast" routing toward high centrality devices is used for cooperative content retrieval.

The goal is to provide a low-cost social-aware distributed caching, computing, and communication infrastructure at the edge that will complement the existing infrastructure and will offload network traffic, extend coverage, improve performance, and reduce the dependence on cloud-based solutions.

The next section presents the system overview of IS-Fog. We discuss the device identification phase where we redefine centrality scheme to classify a node. We then describe the incentivization phase for fog formation. We target the collaboration phase, where we describe the fog interactions in order to achieve efficient content caching and retrieval. An example discussing the joint identification, incentivization, and collaboration is provided. The performance evaluation and results are discussed. We highlight some open research issues toward IS-Fog. Finally, we conclude the article.

## IS-Fog: The Big Picture

We present IS-Fog as a framework that brings computing, control, caching, and communication near edge devices (locally) to complement the infrastructure network. We leverage fog networking as an architecture that uses nearby user devices to perform collaborative sharing of such resources. Figure 1 shows a system overview of different fog networks targeting different IoE applications in a smart city. Fogs can comprise different devices, such as connected smart vehicle automation, network of smart drones, smart and home automation [11]; even multiple houses and vehicles can collaborate to mutually form a fog in a neighborhood.

IS-Fog aims to use the ICN named data networking paradigm with any-cast routing for content caching and distribution in order to maximize content availability at the network edge. We suggest using ICN as a better suited architecture with its data-centric approach along the support for in-network caching toward an integrated solution. However, the proposed collaborative caching is independent of the underlying layer 3 architecture; therefore, the current IPv4-based Internet infrastructure can still be used to implement our solution.

The first step is to find the best possible candidates who can be motivated to be part of distributed fogs. Then such candidate devices can self-organize for efficient social-aware content caching and distribution in the network.

IS-Fog can scale from a standalone smart home with different connected devices (no mobility, indoor) to city-wide fleets of thousands of interacting autonomous vehicles (highly mobile, outdoor), although we concisely describe below two use cases where IS-Fog is applicable:

### Smart Home/Building Fog

An interesting fog use case is a smart home/building comprising different connected devices/sensors where their data should be collected, either periodically or in an event-based manner. Then pre-processing techniques need to be applied to the collected data, which requires sufficient computing power. Similarly, useful pre-processed data needs to be stored and communicated locally using low-cost resources for efficient access as its intended utilization lies locally. However, such data collection is challenging due to the heterogeneous resources over different devices, including constrained devices with limited resources. Similarly, subscribers requesting video streaming services from providers such as Netflix can be an example of large-scale traffic in a small building.

Thus, there is a need to find devices with relatively high computing, caching and communication capabilities to collaborate and offer resources to perform such actions. Moreover, we also need a controller or facilitator within the fog to decide how and when to perform efficient content caching and distribution based on user(s) interest. Such a controller is also required to deal with devices in the fog belonging to different manufacturers/owners, thus requiring efficient collaboration policies while ensuring fairness.

### Vehicular Fog

Another use case targets an outdoor urban environment with highly mobile devices such as smart vehicles and drones. For example, smart vehicles today, equipped with different heterogeneous sensor platforms, can collect, pre-process, store, and share data from urban streets due to their relatively high computing, caching, and communication capability [12]. However, it is challenging to collect data generated from, and consumed by, a large number of vehicles. To achieve scalable city-wide data collection and distribution, there is a need to find suitable vehicles with high inherent caching, computing, and communications capabilities to collaborate.

The aforementioned use cases require the availability of relevant content "now and here" for users regardless of the source IP address. Therefore, IS-Fog comprises a publish-subscribe ICN model allowing any user device (anything with a wireless communication unit supporting 5G, LTE, or Wifi) to subscribe to one (or more) of three roles: information provider, facilitator, and consumer.

We consider an application where different entities can subscribe to provide their resources, such as caches (in this case to the service provider) and in return be rewarded (e.g., with coupons or service discounts). Therefore, different owners can subscribe to smart home services and collaboratively share their resources, irrespective of their appliance vendors.

The three distinct roles are defined since certain user devices are able to be subscribed only as consumers or providers depending on the available resources, and thus not participating in facilitating other subscribers in the network, although devices with multiple roles can exist in IS-Fog.

## Identification: Redefining Centrality

It is nontrivial to find the devices available at the right time and place to form a fog in order to facilitate users in the network. We believe that among all the subscribed user devices, only a set of appropriate devices with sufficient resources can be considered important. However, the question is, how do we identify and select devices for content caching, distribution, and retrieval in a fog? To address this, we define a scoring/reputation system where high centrality user devices are considered the best candidates based on their ability to provide content. The ad hoc network connectivity between devices in a fog can be modeled by a graph, and therefore the well known *centrality* concept from network sciences can be used to identify important nodes in a graph.

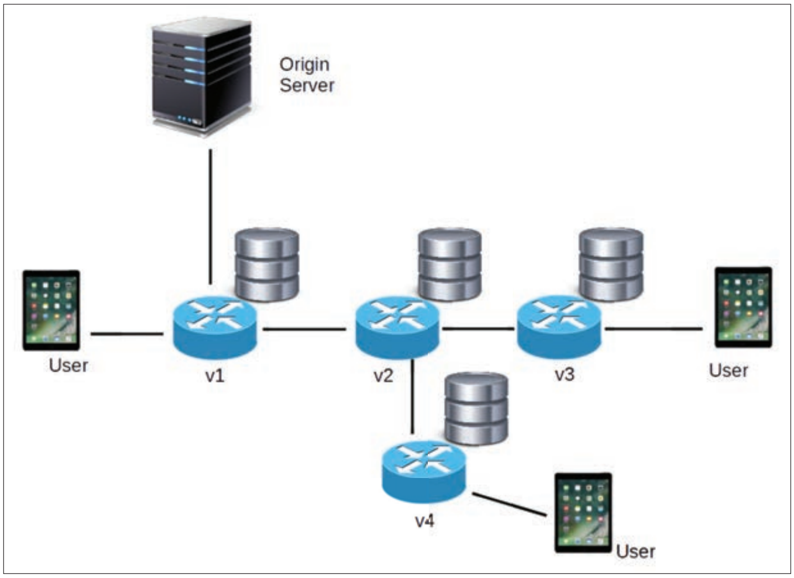


**Figure 2.** Content-based centrality example.

We allow high centrality devices to act as coordinators to create or merge/leave distributed fogs by collaborating with nearby devices while at the same time considering user interests. Incentives can be provided to motivate them [13].

A smart home can choose a set of relatively powerful devices, while a set of smart vehicles can self-organize with each other to form a distributed fog for efficient resource pooling in a neighborhood.

We define a novel content-based centrality measure as the sum of the ratio of the number of shortest paths in terms of number of hops from all users to all content that passes through the node to the total number of shortest paths between all the (user,content) pairs weighted by the popularity of the content. Figure 2 shows an illustration to explain the concept. Here node $v_1$ is on the path from the users to the content in the server, and requests will go through $v_1$; therefore, $v_1$ will have very high centrality. It is easy to see that the usual topological definition of centrality should therefore be modified as it varies in the type of content and where this content is cached.

Content that is popular will generate more traffic; therefore, the nodes that offer paths for this content should also have higher content-based centrality.

Once the device computes its centrality, it can consider itself to be part of a distributed fog by either:

- Creating a new fog in the case in which there is no existing fog in the vicinity
- Merge into an existing nearby fog created by high centrality devices

Nearby fogs may be formed by different owners. We also assume a monetary reward is paid to the owners of the devices forming such a fog. The users would prefer to merge into a fog with larger rewards formed by high centrality devices in order to gain a bigger payoff (say, proportional to the overall resources offered). However, the reward is based on the overall content delivered

The spatio-temporal coalitions formed thus reflect such social similarity among participants. Therefore, the reward offered by the content provider should be such that users caching content at their devices are themselves interested in the content and are not required to cache uninteresting content.

by the fog to which it belongs. We allow the identified high centrality user devices to cooperate in order to better manage and control distributed fogs due to their relatively high capabilities. To ensure fairness and provide incentives to caching nodes, a game-theory-based solution can be used. One such solution is discussed in the next section.

## Incentivization: Fog Formation

We incentivize users to collaborate and offer their devices' storage buffer to cache content locally where the process is referred to as fog formation for distributed caching. To manage this, we borrow the game-theoretic concept of coalition formation, where the goal is to offload a maximum amount of content from the service provider locally at the nodes subscribed to cache at different locations and times.

### Coalition Formation

Smart devices with caching capability can participate to form a coalition in a smart home/building. An optimization problem with the objective to cache a maximum amount of content locally near the end users can be modeled, while maximize the joint utility of nodes caching in the coalition for the users in the building/neighborhood. However, the constraints can differ between highly mobile devices such as connected vehicles,and stationary caching devices including routers, small cells, and so on.  However, common constraints such as *cost* require compensation for the resources spent such as the consumed energy and storage space of the participating devices. It can be in the form of a monetary reward, concurrency, coupons/fidelity points on subscription, or possible gift cards with a common goal of compensating users for their energy and storage. Another important constraint is the *social interest*, and the incentiviation takes into account owners/users with similar social interests based on their centrality score in the fog. Neighbors commonly interested in a particular TV series can collaboratively cache and share a recently aired episode. The spatio-temporal coalitions formed thus reflect such social similarity among participants. Therefore, the *reward* offered by the content provider should be such that users caching content at their devices are themselves interested in the content and are not required to cache uninteresting content.

### Solution Concept: The Grand Coalition Formation

The solution of the coalition game targets the formation of the set of fogs where we associate to each coalition $s$ a value $U_s(l,\bar{t})$ as the total reward available to players (caching nodes) in coalition $s$ at location $l$ and during time slot $\bar{t}$ in an urban environment. The coalition reward can be computed as the total amount of content delivered to the end users by the caching nodes in the coalition. To increase the coalition utility, we should allow high centrality nodes to form and manage the fogs and cache diverse content set in the coalition. Each individual node subscribed to cache prefers to merge to a nearby coalition with larger utility in order to increase its reward. Given two coalitions $s_1$ and $s_2$ in the node $v$ vicinity, $s_1 \succ s_2$ indicates that node $v$ prefers to merge with $s_1$ over $s_2$ assuming $s_1$ is initialized by a high centrality node along nodes caching diverse content sets. By joining $s_1$, it increases the coalition utility $U_{s_1}(l,t)$ since together with $s_1$, it can cache content, which will result in $s_1$ delivering a greater amount and more diverse set of content to the nearby users, and consequently increasing the node reward. Therefore, the more diverse set of content cached and subsequently delivered to the users by the nodes in coalition, the more the collective reward the nodes in the coalition receive.

The stable solution concept for the coalition game, namely *the core* can be achieved where each node subscribed for caching is motivated to participate towards forming the grand coalition of all nodes at a given location and time. It subsequently receives a share from the coalition reward proportional to the amount of content delivered altogether by the respective coalition. Under such conditions, a maximum amount of content will be efficiently cached at the nodes in coalition as stated in the above objective function while at the same time increasing diversity in the set of content available locally for the end users.

## Collaboration: Inter/Intra Fog Interactions

The focus of this section is the interactions between distributed fogs formed by the high centrality devices identified in the previous section to facilitate social-aware content caching and distribution. The interactions and collaborations are classified into two categories: intra-fog and and inter-fog.

### Intra-Fog Collaboration

This is the collaboration between different information facilitator devices in the fog to decide resource management for efficient content caching and distribution. High centrality user devices in each fog can collaborate with other nearby nodes to cache content. A content set is offloaded at a set of user devices while respecting each device's buffer threshold. The content placement process is initialized by the user with the highest centrality device in a neighborhood. It can announce itself as the responsible node for the neighborhood after a contention and start caching the most popular content while respecting its buffer constraints (i.e., the cached content should not exceed the available buffer space). The remaining contents are cached in a similar fashion in decreasing popularity at nearby devices with decreasing centrality where a maximum content is cached locally in decreasing popularity order. Finally, the set of content and devices in the fog are updated with the cached content. The coalitions described in the previous section can be applied where a device not merging with an existing nearby coalition formed by high centrality devices and greedily caching most popular content will in turn receive less payoff as the same popular content is already provided to the users by the high utility coalition comprising high centrality (content providing) devices.

### Inter-Fog Collaboration

Three types of interactions are possible in IS-Fog:
- *Fog-consumer* for user interests to be forwarded to nearby devices in the fog

- *Fog-provider* interaction for content retrieval from information providers
- *Fog-infrastructure* interplay where infrastructure assisted fog networking enables infrastructure to be used as a last resort resource in case content is not available locally

A consumer can forward its name-based interests using ICN inherent any-cast routing toward high centrality information providers. The idea is to let the user "pull" content of interest cached at important information facilitators on a local scope and reduce network overhead. We use the content-based centrality P-CBC to discover nearby information facilitators. A user interest can also specify a deadline to indicate the maximum threshold time to facilitate the requested content. Thus, if the interest cannot be satisfied by a local facilitator at a nearby fog by a threshold, the user interests can be forwarded to an infrastructure network to avoid high delays in content retrieval. The benefit of any-cast routing here is to enable multiple nearby facilitators to respond to the user interest in order to improve the content retrieval efficiency.

Figure 3 shows the fog interactions for the social-aware content distribution and retrieval where a consumer-generated interest in content is forwarded to a high centrality facilitator in the fog. A facilitator discovery process initializes and continues to search for the content at each intermediate relay fog by constantly discover the next highest centrality device in each intermediate relay fog since such a device has the ability to provide the content. If it is unable to find the content in the cache of all the member facilitators, it performs a facilitator discovery to find a device with higher centrality in the neighboring fog, and a pending interest table (PIT) entry is created. The process is repeated at each intermediate fog until either the desired content is found or there are no more facilitators to discover within the user specified deadline. Once the content is found, it is forwarded to the consumer device following a reverse path using breadcrumbs left in the PIT at each intermediate fog. Similarly, an intermediate fog subsequently populates the corresponding forwarding information base (FIB) entry for the content at its devices.

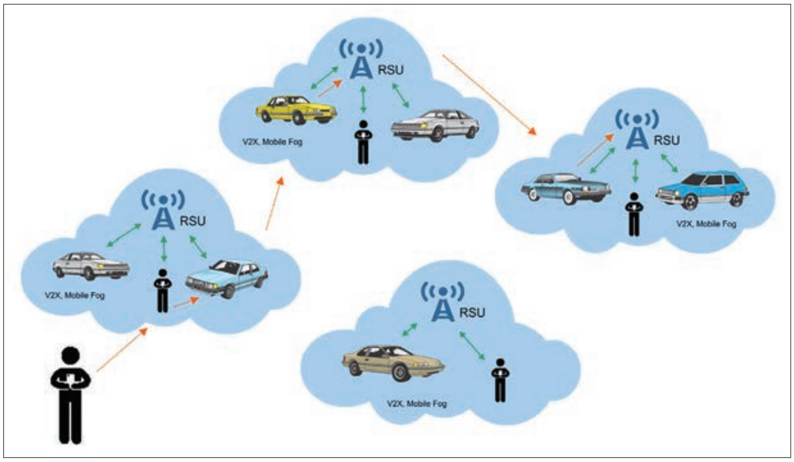


**Figure 3.** Facilitator discovery process.

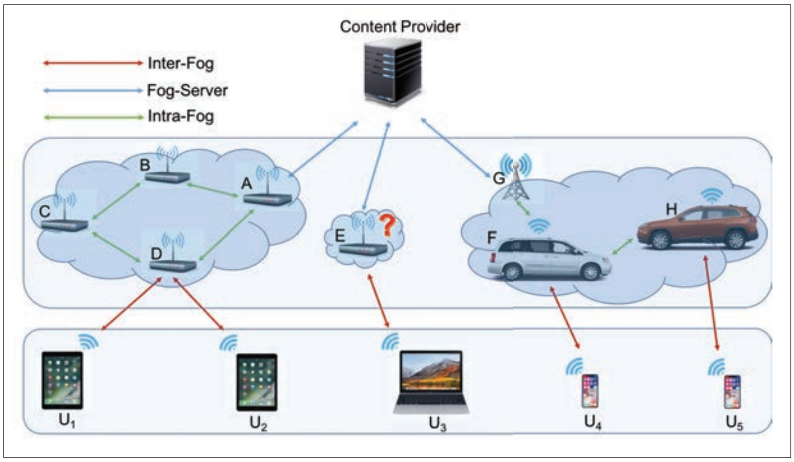


**Figure 4.** Example: IS-Fog summarized.

## Example: Identification, Incentivization, and Collaboration Summarized

Figure 4 summarizes the above identification, incentivization, and collaboration phases in IS-Fog. Nodes $A$–$H$ can be considered part of the fog network, while $U_1$–$U_5$ represent user devices. Nodes $A$–$D$ form the coalition to cache content that can typically be considered in a smart building scenario with node $A$ as the high P-CBC node due to its content provision capability. Similarly, nodes $F$–$H$ are in a coalition of connected vehicles in a typical urban environment with node $G$ as the high P-CBC gateway to provide content. Node $E$, on the other hand, prefers to form a standalone fog with self-coalition. It does not achieve high utility if there is already a high utility coalition ($A$ – $D$) nearby. Thus, it can be incentivized to merge into the high utility coalition to increase its reward as well as the overall amount of locally cached content. Finally, for any user device from $U_1$–$U_5$ can retrieve the desired content using the any-cast approach from the nearby coalition of nodes collaboratively caching the content.

*Self-Stabilization for Failure Recovery:* It is worth noting that fogs do not totally replace the infrastructure network, although they can complement the existing infrastructure. Highly time-sensitive interests are directly sent to infrastructure, of course at a higher content retrieval cost. For example, if the desired content is not found at a nearby fog within a certain deadline and no more high centrality devices can be discovered, the content is requested from the infrastructure. Similarly, parts of high resource consuming (computing, caching, etc.) tasks unbearable by user devices are offloaded at the infrastructure, thereby assisting the distributed fogs.

## Performance Evaluation

We evaluated IS-Fog on a scalable vehicular dataset using a realistic mobility trace from Köln, Germany [14]. The simulations are performed using NS-3. The total number of vehicles in our analysis are 2986 for a 1-h simulation duration with 1 s time granularity. The city center is simulated by clustering an area of 6 × 6 km$^2$. The number of neighborhoods can vary between different cities depending on the size, although we divide it into 36 neighborhoods (fogs).

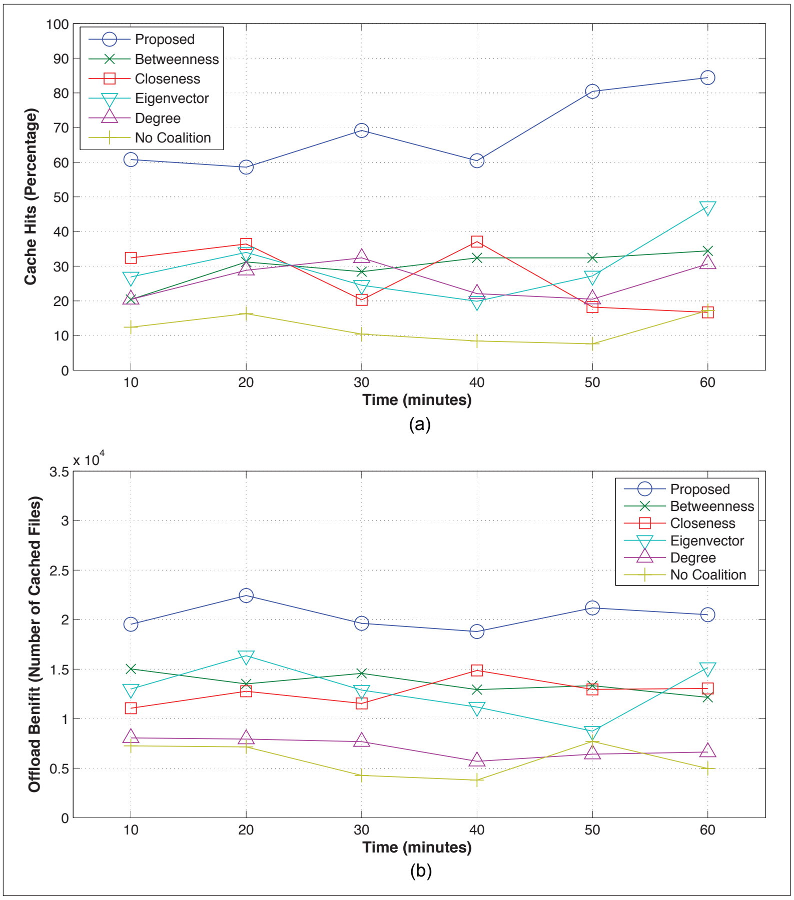


**Figure 5.** Comparison results of IS-Fog vs. no-fog-based caching: a) average cache hit rate; b) offload benefit (content cached locally).

## Simulation Scenario

The interests are generated by 900 nodes (approximately 30 percent of the 2986 nodes) as consumers in an urban environment using the Zipf distribution with skewness parameter $\alpha = 1$ for up to $10^6$ content chunks each of 1 kb size . We allow 900 (30 percent) of the nodes to perform in-network caching where uniform buffer sizes are assigned to each node, and the remaining nodes are intermediate nodes with no caching so that the nodes caching content can be evaluated efficiently. The corresponding coalition utility is derived for spatio-temporally co-located nodes in each fog. We use our social-aware routing protocol STRIVE [15] to forward the user interests and retrieve content from caching nodes.

The fogs formed using IS-Fog are compared to the following schemes:

- Centrality-based fog: This is a fog involving degree, closeness, betweenness, and eigenvector — a centrality-based fog.
- No fog: No coalition is formed; this is a greedy non-collaborative individual node LRU-based caching policy.

## Simulation Results

**Cache Hits:** Figure 5a depicts the average cache hit rate in percentage achieved by nodes in different coalitions (fogs) formed at different times, where the cache hits are shown after each 10 min. This analysis clearly shows that the coalitions formed at the nodes using IS-Fog outperform existing schemes with a minimum of 60 percent and up to 85 percent cache hits. Moreover, the case of no coalition between nodes results in the poorest performance in terms of cache hits reaching less than 10 percent during the entire simulation. Existing social metrics such as typical centrality schemes yield a cache hit rate of around 20–30 percent, thus validating IS-Fog's efficiency.

**Offload Benefit:** The benefit of offloading at mobile fogs is validated by finding the total number of files cached in the fogs. Figure 5b shows the offload benefit achieved by forming different coalitions at each 10-min interval of the simulation. The total number of content files made available for the user by caching at nodes by IS-Fog is higher than with all existing schemes as well as in the case of no coalition.

## Open Research Issues

IS-Fog is a caching solution in information-centric fog networking. Further research is needed regarding the issues below.

**Resource management:** There is a need to further study how to manage resources, in particular minimizing the *computing*, *caching*, *communications*, and *energy* resource usage of constrained devices in the IoE context. The data-centric model of ICN already helps in reducing the excessive resource used, although further measures are needed to enable scalable fog networking solutions.

**Delay:** Delay-sensitive applications such as video streaming, VR/AR, real-time multimedia, and safety in vehicular and industrial sensors. The basic question still needs an answer: how much delay is a delay for different applications?

**Limited and intermittent connectivity:** This is another key constraint that concerns distributed networking, and the heterogeneity and mobility experienced by vehicles, mobile phones, and so on. There is a need to deal with dynamic environments where the wireless access, devices, and resources in the fog are challenging to manage.

**Incentives to cooperate for resource pooling:** It is important to provide incentives to different users in order to join a fog and provide their resources. The fear of starvation still needs to be addressed as users are reluctant to "give" resources. We already addressed one aspect of incentivizing users with coalition game theory, although there is still a need for the development of efficient metrics with different game-theoretic tools to look after heterogeneity in resources of different users.

**Spatio-temporal social awareness:** There is a need for a user centric approach to study human behavior and social trends in order to be adaptable to user requirements for applications such as crowdsourcing. Also, it is important to focus on both space for location awareness and time for timeliness aspect of user(s) social interests.

**Cloud-fog interplay:** This deals with the interconnections and interactions in fogs. There is a need for efficient content distribution, especially over-the-top (OTT) content management. It is also important to define when to offload computation and caching from a fog to a cloud in order to facilitate big data analysis at the cloud, Furthermore, there is room to study the orchestration problem in a fog network.

**Security and Privacy:** Efficient trust models are needed to cater to the existence of malicious nodes along developing solutions to handle Byzantine environments in a fog network. Moreover, with the adaption of the General Data Protection Regulation (GDPR) by the European Union, novel data anonymization and encryption mechanisms are required to protect user privacy against any breaches in the data collected by various fog-based applications.

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## Conclusions

Despite the evolution toward 5G and beyond, it is challenging for the current infrastructure networks to cope with the bandwidth pressure from the increasing number of connected wireless devices. Existing cloud solutions do not scale well for efficient content provisioning and caching for future AR/VR-based multimedia-rich applications demanding content "now and here." We introduce IS-Fog as a novel paradigm of leveraging information-centric networking to coexist with fog networking in a social-aware approach. The idea is to allow edge devices with sufficient capabilities to collaboratively provide their caching, computing, and communications resources for local content provision to nearby users as a fog network. To do this, first we identify such devices using new content-based centrality, and model a coalition game to provide them incentives to self-organize and form a fog network to cache content near other user devices. Then we use both the inter-fog and intra-fog interactions to collaboratively cache and retrieve content from the locally formed fogs. The proposed IS-Fog framework is simulated using large-scale realistic traces comprising 2986 vehicles in an urban environment. Results show that the proposed framework is an efficient and scalable local content caching and retrieval scheme.

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## Biographies


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