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A Systematic Survey on the Recent Advancements in the Social Internet of Things

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ABSTRACT The social Internet of things (SIoT) is one of the emerging paradigms that can address the practical problems (e.g., massive object-to-object interconnection, service discovery, and scalability) of traditional IoT by exploiting object relationships and local navigability. This paradigm has an ability to integrate social networking aspects with the traditional IoT to build smart objects and services that have higher utility than traditional IoT-based systems. Recently, SIoT has attracted the attention of researchers, resulting in many studies related to technology and services provisioning mechanisms. In line with this trend, we provide a systematic survey of the most recent studies pertaining to six key aspects areas of SIoT. We classified these areas into service composition and discovery, network navigability, architecture and components, platform and tools, relationship and trust management, and presented a thorough review of studies in each area. Furthermore, we discuss network navigability and SIoT datasets categories in detail that are emerging research areas in the context of SIoT but remain unexplored in the previous studies. The holistic overview of SIoT integration with the other emerging technologies such as IoT, big data, cloud computing, and social network have also been demonstrated. Finally, we identify various research gaps and directions that enable researchers to conveniently grasp the research dynamics in SIoT. In this article, we intend to provide comprehensive knowledge about the subject matter (i.e., SIoT) from multiple perspectives.

INDEX TERMS Social Internet of Things, smart objects, network navigability, service discovery, Internet of Things, scalability, cloud computing, big data, social network.

I. INTRODUCTION

The Internet of Things (IoT) is a promising paradigm, which integrates a large number of pervasive and heterogeneous smart objects (e.g., sensors, smartphones, computers, and actuators) with different computing and connecting capabilities [1], [2]. These smart objects can communicate and interact with each other, and reach a common goal using different standards and communication protocols. These smart connected objects/things have demonstrated their effectiveness in different application areas such as smart home, energy, e-health, mobility, agriculture, and transportation, etc. [3]. Over time, many sectors are increasingly using IoT for improving the quality of service/people's life. We demonstrate the evolution in terms of technological advancement in IoT field in the past two decades in Figure 1. In line with trends, the new era of smart connected vehicles that has transformed the traditional vehicle Ad-hoc networks into Internet-of-Vehicle (IoV) has been observed across the globe [4], [5]. In this paradigm shift (e.g., IoT → IoV), a hierarchical relationship among the vehicles is established using smart objects. The emerging IoT technology has provided many advantages in IoV. However, the heterogeneity and the scalability are the key challenges that hinder the adoption

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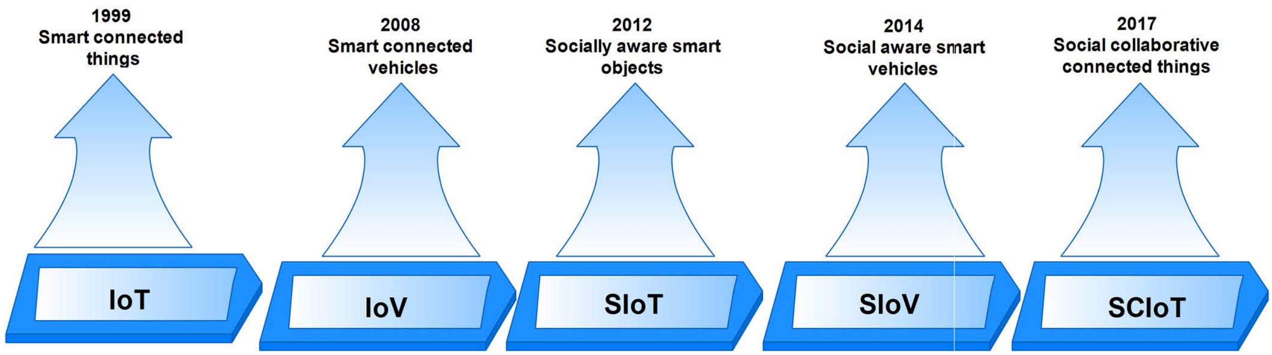

FIGURE 1. Evolutionary timeline of IoT and socially aware smart objects [3].

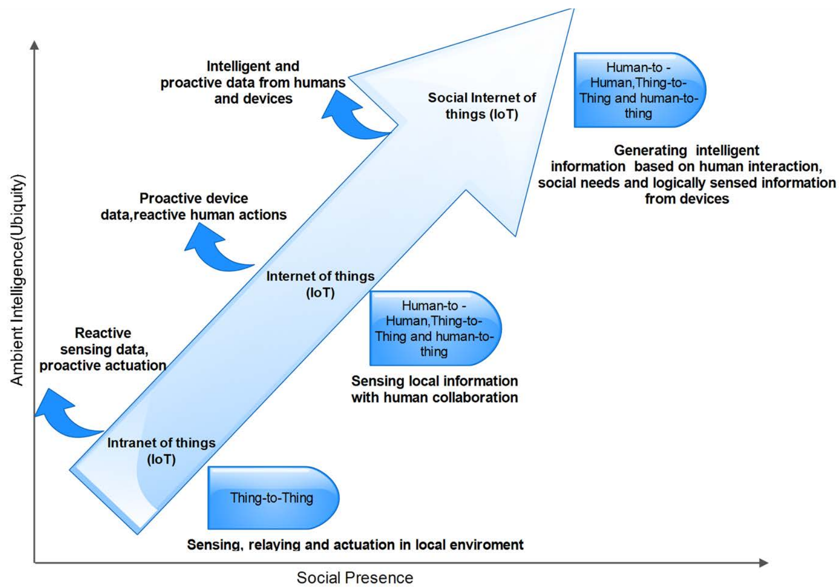

FIGURE 2. Evolution of SIoT from device and human interaction perspectives [1].

of large-scale IoT in any new application domain [6]–[8]. To successfully address the challenges of heterogeneity and scalability badly faced by the traditional IoT, a relatively recent development that mimics human relationship-building ability as a core principle has emerged, named social internet of things (SIoT) [9]. It refers to the convergence of IoT and social networking paradigms to create a network in which objects can establish social links, and can perform desired actions [10]–[12]. In SIoT, the objects can interact with each other and behave like social agents. They can request and provide the services in the network [1]–[13]. The induction of a social structure in the SIoT was inspired by Fisk's theory, which presented the social relationships among humans [14]. In the fourth phase, the Social Internet of Vehicle (SIoV) emerged as a new paradigm based on social objects that enhanced the services of traditional IoV [15], [16]. This cognizance enables these smart devices to socialize with each other based on shared context and mutual interests [17]. The Social Collaborative Internet of Things (SCIoT) is a most recent advancement based on SIoT in which social objects collaborate by interacting and sharing information to achieve a common goal [18], [19]. In these paradigms, social relationships have been extensively exploited to provide desired services in a distributed manner rather than relying on server-oriented architecture [3]. Hence, it is of paramount importance to cover recent developments in SIoT domain from multiple perspectives. Figure 2 demonstrates the evolution of SIoT from device and human interaction perspective [20]. In Figure 2, the horizontal axis demonstrates the evolution regarding social presence (e.g., human involvement in smart objects), and the vertical axis demonstrates the improvements in decision making by jointly using human and object data [21]. As shown in Figure 2, the SIoT has more potential regarding both social presence and intelligent decision-making [22]. Hence, it has become an active area of research in recent times [23], [24] and [25].

Until the present, a very limited survey regarding SIoT has been conducted and discussed SIoT classification [8]–[26].

A review of trust-specific aspects in SIoT was conducted by [3], [27]–[30]. Imran *et al.* [31] reviewed the SIoT, and highlighted only security privacy and the reliable data delivery aspects. Rho *et al.* in [10] discussed an editorial note and explained the protocol, architecture, and applications of SIoT; Ortiz *et al.* in [1] highlighted the current research in SIoT and emerging technologies and suggests an architecture for the SIoT. Atzori *et al.* in [32] discussed the social structure of objects using SIoT; they introduced the architectural model for the SIoT. Limited papers have covered major SIoT aspect areas such as platforms, network navigability, etc. Many of them covered security, and trust in [3]–[32]. Two studies such as Malekshahi *et al.* in [26] and Roopa *et al.* in [8] focused on key aspect areas such as SIoT platforms, relationship management, trust management and network navigability. Meanwhile, SIoT architecture and components have not been covered. In particular, the majority of surveys published so far have not covered interlinked aspects of SIoT such as service discovery and composition, SIoT platform management, and network navigability. Therefore, to address this gap, we present a systematic and comprehensive review concerning SIoT. The major contributions of this review article are summarized as follows.

- We discuss an emerging paradigm, named SIoT, including its distinctive features, core concepts, evolution, use cases and application, and basic functions.
- We identify six key aspects of SIoT including, service composition and discovery, network navigability, architecture and components, platform and tools, relationship, and trust management. These areas are becoming the focus of research in recent years to improve SIoT-based solutions. We systematically cover state-of-the-art and recent studies in each aspect. We analyzed and compared each study regarding its strength, weaknesses, and application areas.
- We discuss two emerging research areas such as network navigability and site platforms of SIoT that remained unexplored in the previous surveys.
- Our classification and analysis differ from previous studies since most studies have briefly covered the SIoT key aspects, and given detailed knowledge about the interlinked aspect has not been discussed explicitly.
- We discuss various unique challenges in the domain of SIoT that needs further research/development efforts from researchers/developers in the true realization of SIoT in coming years.
- The contents enclosed in this survey highlight recent developments in SIoT, and it provides a solid foundation for future research in this area.

The rest of the paper is organized as follows. In Section 2, we describe the basis related to SIoT and traditional IoT, and discuss the relationship between emerging technology, big data, and the cloud. In Section 3, we present the recent advancement in SIoT by proposing a classified catalog and reviewing various studies. In Section 4, we discuss open issues in SIoT and the latest research challenges. Section 5 concludes our study.

II. BACKGROUND AND THE BASIS

A. BASIS OF THE SIoT

In recent years, the concept of applying the SIoT to the traditional IoT ecosystem has gained popularity. The term SIoT was coined in 2012 [3]. Conceptually, it links two different domains: social networking and the traditional IoT to serve mankind effectively [33]. The practical example of SIoT is autonomous vehicles moving on the road, where embedded sensors in these vehicles can communicate with each other to avoid car accidents [17].

Table 1 illustrates the overview of the distinctive features of traditional IoT and SIoT paradigms [3]. In Table 1, the advantages, disadvantages, and interactive perspectives of both paradigms are presented. IoT devices are primarily used for connectivity between physical objects, whereas social technologies are responsible for collaboration and social interaction [3]. Smart Objects (SOs) can sense, process, store, and interpret information [27]–[34]. In IoT, SOs communicate with each other, but there is no notion of relationships between them. On the other hand, in SIoT, several types of social relationships exist between these objects [31]. In addition, the SIoT empowers the SO's to communicate without human intervention based on the specific rules set by the owners. The unique benefits of the SIoT are given below.

- The SIoT structure is navigable. This will make the object easily discoverable like to features of a human social network. Thence, scalability is also maintained [35].
- In SIoT, objects can establish social relationships with each other without human intervention for intelligent decision-making [36].
- SIoT contributes to increasing the security and trustworthiness of traditional IoT because services are accessed from nearby known objects [37].

B. SIoT APPLICATIONS AND USE CASES

The SIoT applications and practical use cases are given below.

1) TRAVEL AND TOURIST SERVICE MANAGEMENT

One of the interesting applications of the SIoT paradigm is tourism service management and cultural heritage [38], [39]. Let us suppose that David came to Seoul for the first time without any planning. It is not an easy task to find a hotel or room. To find the best possible location, he started to use a social mobility application (SMA). To do that, his mobile phone had already established a new social connection with a tourist application. By using that app, he could reach taxi stands and bus terminals. By using co-location and social connections, the social mobility app forwards a query to gather information on available transit networks. Also, a search is performed to find reasonable costs and projected schedules from separate items directly or indirectly linked to David's

TABLE 1. Overview of the distinctive features of IoT and SIoT [4].

	General architectural components	Features	Disadvantages	Challenges	Interactive perspective
IoT	☑ Smart devices. ☑ IoT. Connectivity. ☑ IoT Gateways.	☑ Intelligence. ☑ Connectivity. ☑ Sensing. ☑ Analyzing.	☑ Security and privacy.	☑ Interoperability. ☑ Scalability. ☑ Energy efficiency. ☑ Data management. ☑ Maintenance of IoT devices. ☑ Privacy management.	☑ Human to Human. ☑ Things to Things. ☑ Humans to Things.
SIoT	☑ Specialized devices. ☑ Social relationship manager.	☑ Scalability. ☑ Object discovery and navigability. ☑ Service composition. ☑ Dynamic nature and flexibility. ☑ Social interactions and social roles.	☑ Facilitates laziness. ☑ Ethical implication. ☑ Decreases face-to-face communica tion skills.	☑ Object relationship management. ☑ Compatibility. ☑ Selection of hardware. ☑ OS and platform.	☑ Human to Human. ☑ Things to Things. ☑ Humans to Things. ☑ Social network of objects. ☑ Relationship management.

TABLE 2. Summary and comparison of recent surveys with the proposed survey.

		The key aspects in SIoT					
Studies	**Year**	**Service Composition and Discovery**	**Network Navigability**	**SIoT Architecture and components**	**SIoT Platform, Tools and Datasets**	**Relationship Management**	**Trust Management**
This study	2021	☑	☑	☑	☑	☑	☑
Farhadi et al. [54]	2021	☒	☑	☒	☒	☑	☒
Malekshahi et al. [26]	2020	☒	☒	☑	☑	☑	☑
Ochoa et al. [55]	2020	☒	○	○	☒	☒	☒
Wang et al. [56]	2020	☒	○	☒	☒	☒	☒
W. Z. Khan [2]	2020	☒	☒	☒	☒	☒	○
Roopa et al. [7]	2019	○	○	☒	☒	○	○
Imran et al. [31]	2019	☒	☒	☒	☒	☒	○
Nitti et al. [8]	2016	☒	☒	☒	☒	☒	○
Antonio Ortiz et al. [12]	2014	☒	☒	○	☒	☒	☒

☑ Covered
☒ Not Covered
○ Briefly covered

mobile phone. In the social object network, questions and answers are treated hop-by-hop and are eventually stored on David's smartphone. Based on his preferences, he glances at the outcomes that are already ordered, e.g., the bus service. The social mobility feature initiates the buy request for a ticket. The bus terminal forwards its application to the mobile ticketing service. In this way, David can receive the e-ticket on his phone [33].

2) TRAFFIC MANAGEMENT

The SIoV [17] is a new term popular nowadays. In line with trends, the new era of smart connected vehicles has transformed the traditional vehicle ad-hoc networks into Internet-of-Vehicle (IoV) [40]. Therefore, the SIoV is a modern form of IoV. In SIoV, the objects behave socially and can share information such as road situations, weather conditions, vacant car parking slots, toll gates, and traffic information. The SIoV system is installed in the vehicle during manufacturing. These sensors can communicate with the manufacturing unit for providing various information. For example, when the vehicle is moving on the road, it maintains a social relationship list. In this way, it talks to the owner and the other vehicles using the On-Board Unit (OBU). The OBU is used for the sending and receiving of information such as navigation. When the vehicle is moving on the road, it may communicate to other vehicles by using the Road Side Units (RSU's).

3) HEALTH CARE MANAGEMENT

One of the promising fields in healthcare hospitals is smart health care [41]. A sensor can be used for saving a patient's life. For example, the heartbeat sensor is connected to the smartphone and cloud computing to diagnose dangerous diseases. It helps the doctors to care for and follow even patients

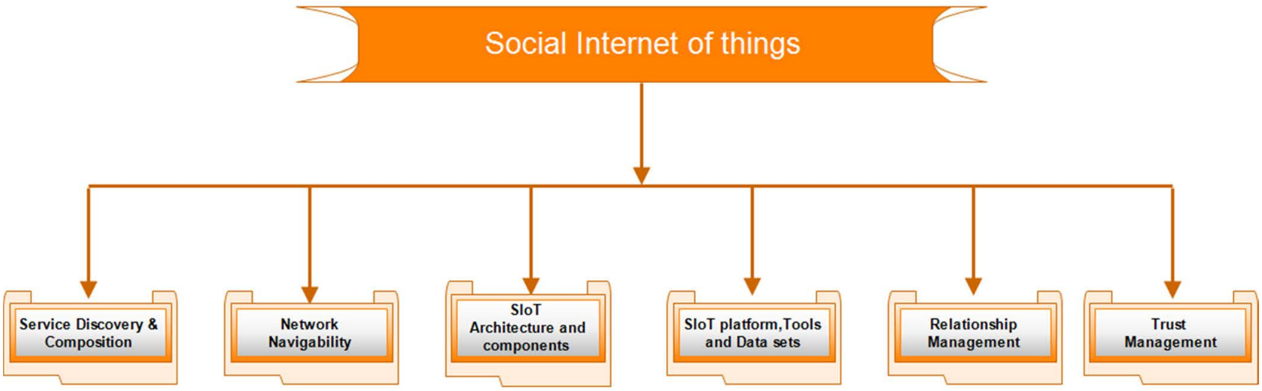

FIGURE 3. Proposed classification of key aspects of SIoT.

who live a thousand miles away [41]. Similarly, a smart sensor on highways and roads can alert the smart ambulance of an accident, and thus the smart ambulance can check the equipment required and reach to spot in the minimum possible time.

4) QUANTIFIED SELF-MANAGEMENT

The smartphone, big data, sensor visualization, and social propagation are already changing how individuals behave in society [42]. The fitness sensor devices made by Fitbit are a key example of the SIoT [43]. This application allows users to share their fitness data with their friends in the social network to receive feedback from others and motivate them to keep fit, similar to the zipper sensors [43] clipped onto golf clubs that carefully monitor movements, such as club swing angle and velocity. Later, it visualizes the data, and the device publishes the information to various social groups for their feedback.

III. RECENT ADVANCEMENTS IN SIoT

The recent advancement in SIoT has been illustrated in Figure 3. We classify the key aspects of SIoT into six categories: service discovery and composition, network navigability, SIoT architectures and platforms, relationship management, and trust management. We have reviewed the most recent state-of-the-art studies from the current literature. Table 2 shows a summary and a comparison of recent surveys with our survey. The most recent survey on friendship selection and relationship management is given by Farhadi *et al.* [44]. However, the authors did not discuss the service composition, SIoT architecture, components, etc. Malekshahi *et al.* [26] presented a survey on relationship management, trust management, SIoT architecture, and the SIoT platforms. However, discussion about key aspects of SIoT such as network navigability and the service composition and discovery are missing. Ochoa *et al.* [45] briefly surveyed network navigability and the SIoT architecture. Wang *et al.* [18] briefly reviewed network navigability. Trust management has been reviewed by Khan *et al.* in [3], but their discussion is limited to trust only. In contrast, our study covered most aspects related to SIoT. The details of our proposed classification shown in Figure 3 are explained below.

A. SERVICE DISCOVERY AND COMPOSITION

Service discovery allows the objects to discover the services automatically for the benefit of users and the network [46]. The service discovery uses a protocol called service discovery protocol (SDP) [47]. It is used to locate the objects, information, and services that match the discovery request [48]. The components related to object discovery are given below.

1) SMART OBJECTS

The physical objects are embedded with the sensors, RFID, actuators, etc. Smart objects can collect, process, and also interact with other objects.

2) OBJECT RELATIONSHIP

The discovery system establishes the various relationship between smart objects and hence autonomously discovers a target object that provides the required service.

3) DISCOVERY AREA

The discovery area is the collection of smart objects and their related data items over which the discovery algorithm finds the matching objects [49]. The service composition category provides a new dimension to select suitable friends for a specific task. The SIoT establishes the social structure among objects and people that intend to provide services. When a service request is initiated from a human/object, it is sent to the neighbor object. This can be initiated through the application programming interface (API). The received request is processed by matching with the available services on that object or nearby objects based on preferences and the history of interactions. A list of all relevant objects that exactly matched their requests and met their quality-of-service level is returned to the requester. Hereafter, we discuss the most recent state-of-the-art concerning service discovery and composition. George *et al.* [39] discussed the service composition of social objects in the context of providing tourist services in a certain area [50]. The authors in [39] proposed a SIoT-based approach to allow tourists to visit heritage services. The core objective of this research is to create and develop a model for providing services to users. In this model, the service composition and provision are performed mainly based on trustworthiness. The proposed model is divided into three layers (social awareness, geography, and service quality) by using the trustworthiness parameter.

Nitti *et al.* in [51] discussed the concept of service composition using cognitive radio (CR). The powerful feature of establishing social relationships and friendships was used by the authors in the development of the CR model. They used a distributed reference scenario with friendship management for achieving high scalability [51]. Sahraoui *et al.* in [22] introduced Artificial Social Intelligence (ASI) for tackling the problem of social relationships in SIoT. As far as we know, it is the first report in which artificial intelligence (AI) has been used for the SIoT. The advantage of ASI over traditional AI is that ASI is richer due to the integrated communication and computing methods. These enable it to deal with social relationship exploration derived from social computing. Finally, it improves the services offered to the user. Bahareh *et al.* [28] discussed the service composition and the selection problem using trust. Their proposed model is based on four components: relationship factor, performance assessment, global reputation evaluation, and punishment mechanism [28]. In this model, selfish objects are identified by using the punishment mechanism. For this, they consider the trustor's personal preference at the time of the trust calculation. To verify the accuracy, they used the CRAWDAD dataset. Xia *et al.* in [52] discussed a social-like semantic approach for the large-scale IoT. They had proposed a distributed search mechanism based on semantic relativity and semantic similarity. The fuzzy logic method calculates the correlation degree for device ranking. In most approaches, the use of AI has not been discussed which can be a valuable addition to each model's performance enhancement. Fan *et al.* [53] have discussed the service or resource discovery issue in SIoT. To solve this problem they had proposed an optimized efficient algorithm for searching Steiner Maximum Path-Connected Subgraph (SMPCS) [53]. They had extended the connectivity with novel meta-path-based edge-disjoint paths to heterogeneous information Networks (HINs) for cohesive subgraph search (CSS) and proposed the kpath-connected component (k-PCC) to measure the cohesiveness of subgraph in HINs.

B. NETWORK NAVIGABILITY

A network is navigable if there is a short path between all or almost all pairs of objects in the network [54]. The local network navigability is the key feature of SIoT. The SIoT is based on many objects, and generally, each object is connected to the others in a friendly manner. Due to a large number of objects, the search process in friendship networks is very slow. In this scenario, the finding of best friends among the set of friends imposes a computational cost and reduces the performance of the overall system [55], [56]. The state-of-the-art work listed on finding the short paths and the selection of a link to increase the network navigability are given below.

Nittie *et al.* [57] discussed friendship selection heuristics in the SIoT. These heuristics play an important role in establishing the social relations among objects in a social network. The proper selection of friends per node is very important. It increases network navigability and hence the scalability increases. The authors proposed five heuristics based on local network properties. The problem with this approach is that the authors did not use the trust parameter for the selection of the honest friends, and they also used a fixed number of friends per node. If the number of friends per node increases, it results in terms of a long path in the network.

Amin *et al.* [58] put their efforts into improving network navigability using the concept of small-world networks. They proposed an advanced link-selection model in which the selection of friendship among the friends has been established. The addition and the removal of specific friends or links are performed based on the removal of an old friend, a mutual friend, or some specific trust-based metrics. Moreover, they did not use trust in their proposed model for network navigability purposes. The static threshold for the selection of the right friends is also another problem in this approach. Amin et al [59] has presented an advanced service search model for SIoT. In this model, the objects can use the information by looking at the friends of friends. They had to use the centrality to compute the central node in the network. This distributed phenomenon helps the node to find a neighbor and hence the scalability is guaranteed in this way. Amin et al [60] presented an advanced service search model for the higher network navigation using small word networks. In this study, they have used the concept of the small world for efficient service search. Initially, the service search is initiated in different hops by using a service query message to the nearest object. If the requested object is identified immediately, a permanent link has been established between the service request and the service provider. Otherwise, the search procedure is repeated until the required service has been identified. This procedure is efficient because it is initiated only when an object asks for another object for a service. Similarly, Ramasamy *et al.* [61] presented advanced heuristics for the selection of the right friends in the SIoT. They proposed a model to improve the selected service and the composition problem. To solve this problem, they proposed heuristics for the selection of friends per object in the network. A strategy for the removal of old mutual friends was also discussed. They did not use trust-based metrics for the selection of the right friends in the network. Rajendran *et al.* in [62] proposed object recommendation-based friendship selection (ORFS) for achieving higher network navigability. They have used trust as a basic metric in the selection of friends from a social network. For establishing trust, they have designed a smarter ranking system based on the satisfaction rate and the SOR-based grey wolf algorithm (GFA). They used two real-world

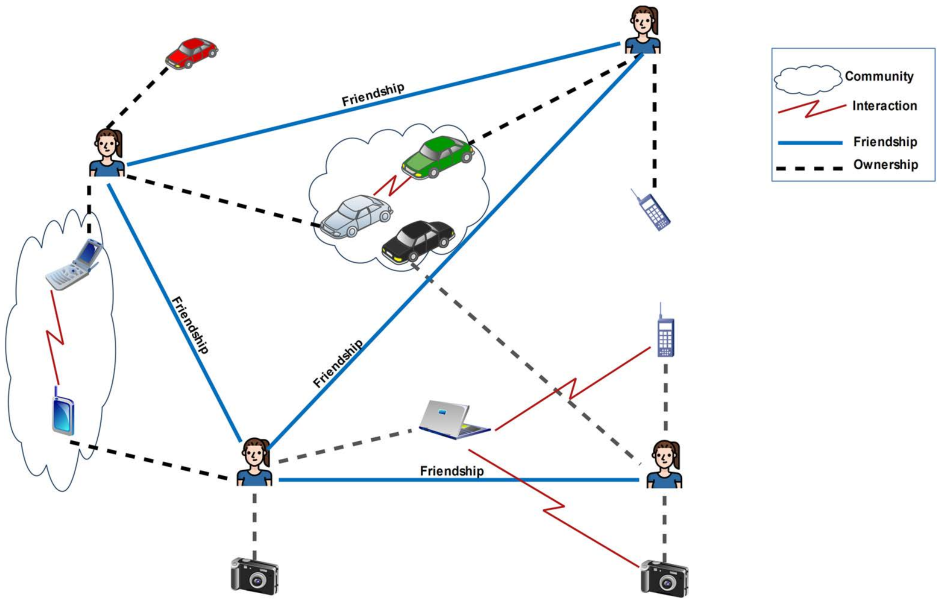

FIGURE 4. Social structure of the Internet of Things [73].

datasets to test the performance of their proposed model. The problem with this model is that they have used the undirected graph. Therefore, this model is not suitable to be used for directed graphs.

Pashaei *et al.* [63] have used the automata theory for gaining better network navigation. At first, they emphasize the importance of learning automata in the SIoT. The discovery of the desired service is made by using the centrality metric. The learning automata is embedded into each object, and hence, the selection of the most influential nodes is performed. The next-hop object is selected based on high centrality. The network is highly efficient, and the search for the object is completed in a limited time.

Figure 4 illustrates the social structure of the IoT and each user has a relationship with a device. These relationships are established based on friendship. If two users are friends, then the devices can cooperate. The friends are shown as a community. The type of relationship is established based on procedures outlined in [64]. These days, this newly derived concept is gaining more popularity because it provides various benefits, such as interpretability among different systems [54]. The benefits of the SIoT are not limited to the trustworthiness of objects, especially when providing various services and information to objects [48]. The SIoT is based on the assumption that each object can find the requested service using its friends [9]. To achieve this objective, the authors in [1] discussed the importance (and necessity) of improving the degree of connectivity between things and users. Things should be social and allow humans to establish relationships among them. The resulting conceptualization of the SIoT consists of people and devices. People are connected through their IoT devices, and they can improve the experience of realization by using smart services and applications. When dealing with the objects of the IoT framework, the idea is to exploit social awareness. It means turning the objects into autonomous decision-making entities. This new social dimension motivates the interaction among users and objects. The basic principle is to enable the objects to autonomously establish social links with each other in a way that objects exchange data in a distributed manner. The most recent model named SocIoTal was proposed by Bernabe et al [65]. It is a European FP7 project [66]. The key objective of this project are to provide a reliable and secure IoT environment through trust and transparency in the system, so that citizens can trust and exchange information with each other. The contribution of their research is to increase the level of user trust and also confidence on IoT systems. This module consists of various components, such as a security server, i.e., AAA, a web user environment, a context manager, and gateways. This module provides an opportunity for the construction of services for a greater good.

Khaled and Helal *et al.* in [67] presented an inter-thing relationships programming framework for building a distributed eco-system. This framework is comprised of various functions such as the service abstraction function, relationship abstraction function, and the recipe function. The recipe function is used to build a segment. This framework is based on filters, matches, and evaluations. The authors validated it by using a proof of concept (POC) and by building an App. Esfahani *et al.* [68] discussed an architectural model for the Mobile Social Internet of Things (MSIoT). This model was developed to overcome the challenges imposed by objects, especially concerning mobility. It has two main components, Service Forwarder (SF) and Mobility Management (MM). Through this mobility, they provide friendly social relationships. Nitte *et al.* in [69] have addressed the issue

TABLE 3. Publicly available datasets related to SIoT.

sr.no	Dataset	Provider	Feature	URL
1	SIOT Dataset	University of Cagliari	Complete dataset	http://www.social-iot.org/index.php?p=downloads
2	Snap	Brightkite	Location-based	https://snap.stanford.edu/data/loc-brightkite.html
3	Snap	Facebook	Social circles	http://snap.stanford.edu/data/egonets-Facebook.html
4	Massachusett s Institute of Technology	MIT Dataset: Reality Mining Data on human mobility.	Community-based	http://realitycommons.media.mit.edu/realitymining1.html
5	CRAWDAD	cambridge/haggle	Object relationships	https://crawdad.org/cambridge/haggle/20090529/
6	CRAWDAD	upb/hyccups	Social interaction	https://crawdad.org/keyword-social-network.html
7	CRAWDAD	cmu/hotspot	Location-based	https://crawdad.org/cmu/hotspot/20090415/

of a service search in IoT. The proper selection of friends impacts the search operation and hence the overall network navigability is achieved. In this study, they have proposed five heuristics based on local network navigability to have an impact on the overall network structure. Based on these heuristics, each node can accept or discard the relations in the network. In addition, they have suggested that restricting the number of friends will improve the search operation. They suggested a threshold to limit the number of friends in the network. The efficiency is measured in terms of the giant component, average path length, and local clustering coefficient [69]. Guo et al [70] have presented a social recommendation (SR) model. They proposed a deep learning deep learning-embedded social internet of things model. The objective of this architectural model is to guarantee reliable data management.

C. SIoT ARCHITECTURE MODELS AND COMPONENTS

The basic SIoT model was proposed by Atzori *et al.* [32], and we use the SIoT acronym to refer to their model. Generally, in the SIoT, each device has one or more owners who could own some other devices. Each device connects itself to other devices based on some predefined rules. These rules and mechanisms are inspired by humans. For instance, each user in the SIoT maintains a social relationship by considering the term friend. Figure 5 illustrates the basic architectural model discussed in [32]. It has three layers: the base layer, the component layer, and the application layer. Each layer can perform different functions. For example, the base layer provides the following functions: communication, semantics, and ontologies. This layer performs object services decomposition, ID management, and trust management. The application layer provides the interfaces for people and service API functions. The client-side layer performs different functions such as object-object interaction. The object abstraction layer acts as an interface between the attached devices. The service management and social agent functions are performed in the uppermost layer. Service management is used to control object behavior, and the social agent provides communication between objects and the SIoT server. In addition, it also provides an interface for the server-side connection. Voutyras *et al.* [71] proposed an architectural model for the SIoT by using the basic principles of the relational model. The Cultivate resilient smart Objects for Sustainable city applicatiOnS (COSMOS) [71] model can perform the services of the SIoT like recommending and sharing services between objects. Their design model includes basic elements, such as social monitoring, friend management, profiling and policy management, etc. Figure 6 illustrates the MSIoT architecture [68]. This model is quite similar to the model proposed by Atzori *et al.* in [33] except for the addition of two modules titled Mobile Object Relationship (MoR) and the Explorer Object Relationship (EoR). The EoR creates the relationships between moveable and static objects in the network. The ultimate objective is to discover the requested service. By using this type of structure, the clients can forward the requested services. The MoR is used to establish the relationship between mobile intelligent objects and the smart objects that travel among them. However, in this study, the proof of concept (PoC) of proposed architecture is not discussed.

D. SIoT PLATFORM TOOLS AND THE DATASETS

In this section, we discuss a comprehensive review of the most recent platforms and datasets for the SIoT. Amin *et al.* [72] proposed an integrated platform, named Social Pal for the IoT and social networks. The general architectural design of Social Pal is illustrated in Figure.7. The Social Pal is comprised of various components, including humans, Social Pal, interfaces, and the Internet. The actors interact with the Social Pal to get information using the interface panel. The actors in Social Pal can be humans or things [72]. Once the query is received by Social Pal, it decomposes the query by using service composition. The key features of Social Pal include application management, relationship management, recommendations, service search, and discovery. Moreover, the authors implemented a prototype and also provided a use case scenario. Beltran *et al.* in [73] presented a platform for the SIoT. In this proposal, they have investigated the semantic web services to develop automated services for SIoT networks. Their proposed platform includes a service creation environment in which users can dynamically create event-based actions by using their friends. Their proposed platform comprises three-layered structural modules that include communication, control, and an ontology-based layer. Girau *et al.* in [74] proposed Lysis, a cloud-based platform for IoT applications. The key features of this platform are to create social objects, social agents, and services. Similarly, [75] proposed a platform for the SIoT that is used for monitoring the coastal services. The authors

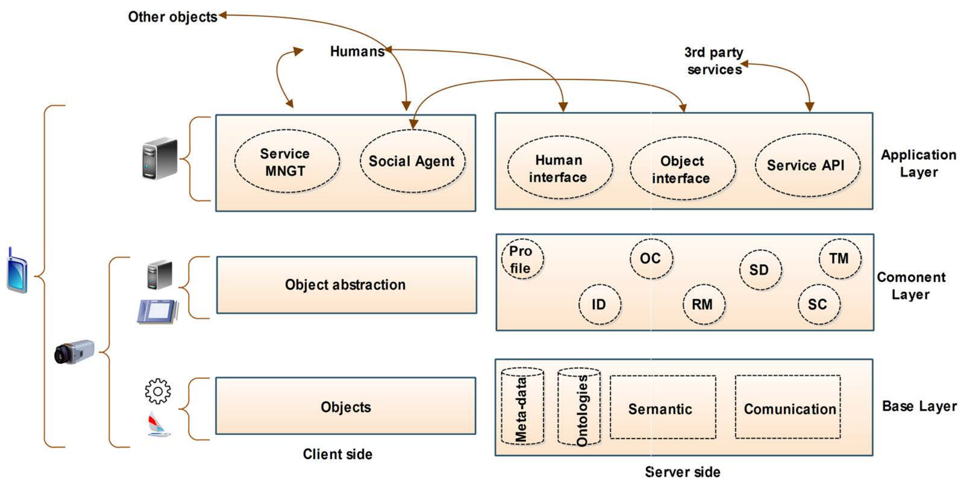

FIGURE 5. Fundamental three-layer architecture model of SIoT.

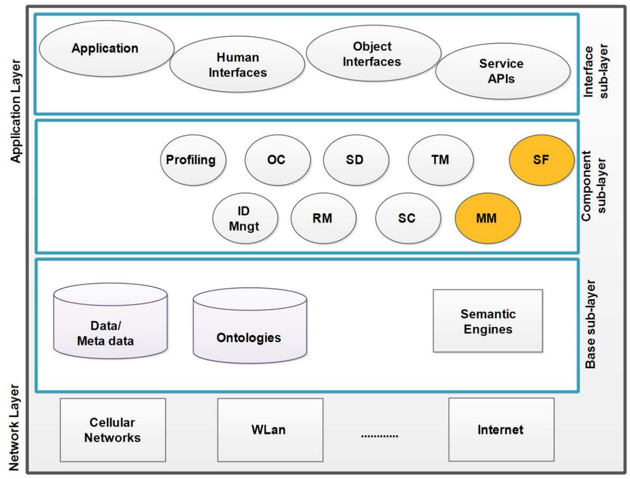

FIGURE 6. Workflow diagram of MSIoT architecture [81].

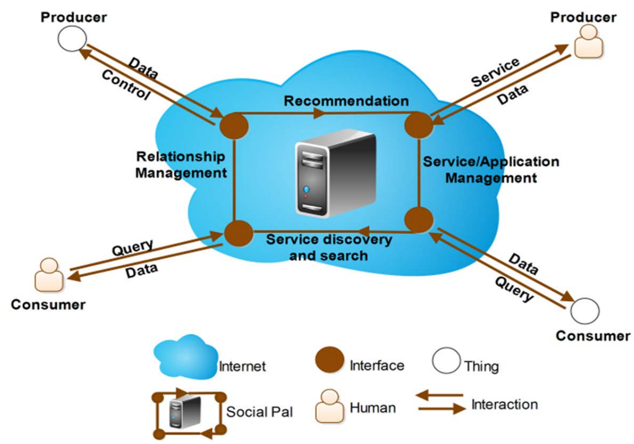

FIGURE 7. Overview of interactions among different entities in the social pal platform [1].

proposed a methodology in which each object can establish relationships with other objects. The proposed method was tested on a real dataset collected from the Poetto beach in Cagliari, Italy. The training and testing results are validated for the efficiency of the proposed model. Based on the extensive review of literature, we observed that there are still very limited datasets that are complete in most aspects such as 'Brightkite' [58]–[76] available to the research community. Therefore, Marche *et al.* in [6] for the first time created a suitable SIOT dataset. This dataset is based on real IoT objects. The objects, profiles, and resulting social interactions were collected from a smart city, i.e., Santander, a city in Spain. It is the most recent dataset to construct the SIoT networks. In addition, it is publicly available to the research community. According to the authors, they had tested it using different rules, such as OOR, SOR, etc., and it is proved that it is very useful in increasing the overall network navigability. Similarly, Alsaedi et al [77] proposed an IoT dataset for the research community. The objects and their profiles are also enclosed in this dataset. They incorporated the trust metric in it and employed machine learning and deep learning techniques for validation purposes. The details of publicly available SIoT-related datasets are given in Table 3. Moreover, there is no real and practical implementation publicly available for the researchers.

E. RELATIONSHIP MANAGEMENT

Relationship management (RM) is the key property of SIoT [78]. Several types of relationships co-exist between the objects and users in the SIoT [78]. The objects establish social relationships based on their movement, profiles, and interests [78]. These relationships can be established based on certain events and can be depicted between the users and the objects as shown in Figure 8 [18]–[78]. The rules are given below.

- Co-location object relationship (CLOR): This type of relationship exists where objects are in the same place.

TABLE 4. Inference rules used in relationship modelling between objects [8].

Object relation types	Rules
Social Object Relationship (SOR)	if ($x_a$and $x_b$belong to same community) then x_a has SOR with x_b
Co-Location Object Relationship (CLOR)	if (x_a.absoluteLocation∧ x_b. *absoluteLocation*==SameLocation) ∨x_a. (*relativeLocation* ==Same Location) ∨ Object has CLOR with Object
Co-Work Object Relationship (CWOR)	if ($x_a$and $x_b$offer same service) then x_a has CWOR with x_b
Ownership Object Relationship (OOR)	if ($x_a$and $x_b$have the same owner) then x_a has OOR with x_b
Parental Object Relationship (POR)	if ($x_a$and $x_b$belong to same community) then x_a has SOR with x_b

- Co-work object relationship (CWOR): This type of relationship may be established whenever objects collaborate to provide a common IoT application.
- Parental-object relationship (POR): A POR describes a parental relationship that may be related to objects belonging to the same production batch (e.g., the same model or the same manufacturer).
- Social-object relationship (SOR): A social relationship may be created when objects come in contact through social relationships, such as a relationship between a sensor and objects belonging to friends in a social network. An example is exchanging phone numbers with friends.
- Co-ownership (Co-ownership): This kind of relationship can be established among heterogeneous objects that belong to the same user.

The RM is an intelligent property that empowers the objects so that objects can easily recognize each other and make new friends. They can make/terminate relations based on this property. In the literature, various studies have covered this important concept in the context of SIoT and trust. For example, in [79] every object in the SIoT receives more responses based on their requests than in traditional IoT networks due to the distributed nature of SIoT network. Hence, these objects communicate with each other to yield services in a community-based manner. RM is vital to share resources, services, and information in the SIoT [26]. Roopa *et al.* [8] proposed a systematic review of the SIoT with emphasis solely on the importance of RM using friendship management. They have identified various rules for the definition of relationships in the SIoT. The inference rule is used to define the relationship between objects in the SIoT [8]. We have discussed these rules in an earlier section (POR, SOR, CLOR, etc.). The sample inference rules along with object description, object relation types are given in Table 4 [8]. Aljubairy *et al.* in [80] discussed a framework for predicting the relationships in the SIoT. This framework was developed to overcome the service search problems. The problem of predicting links over a certain time is handled with a future prediction relationships model. It is a three-step procedure. In the first step, the collection of raw data is accessed from an IoT device. In the second step, the general temporal network is developed using these devices. Finally, a prediction of relationships among these devices has been performed. Wu *et al.* in [81] developed a framework for IoT using cognitive networks (CNs). In this study, they presented a definition of CIoT (cognitive internet of things). They have discussed the enabling technologies involved in cognitive tasks. Kassis *et al.* in [82] discussed a friendship model for the CNs. The authors presented the idea using semantic web entities and smart software agents. They have proposed a theoretical framework using a use case scenario. Moreover, the validation and experimentation using real-world datasets were not reported by the authors. Wu et al in [83] has discussed the deep learning technique for the community detection in social networks. Their proposed model is threefold model. In this model at first a matrix is constructed. In the second step the feature has been extracted and the finally the community has been identified.

F. TRUST MANAGEMENT

Trust is a multidimensional concept in the context of SIoT [48], [84], [85]. The trust works as a unique solution when cryptography-based solutions are not available. In some cases, it ensures the reliability of the system in case of a malicious attack where the intruder can disturb the entire system. Khan *et al.* [3] presented a survey of trust management in the SIoT. Their contributions are twofold: introduction of the SIoT along with similarities and differences, and trust management in the SIoT. In a service-oriented environment such as the IoT/SIoT, trust plays an important role. It acts as a middle layer between the requester and the provider. The contribution of trust in resource management is to control the reliable service composition. In real life, trust plays an important role in relationship building/maintaining, especially when working in the same environment and for collaboration. The role of trust is crucial in the SIoT paradigm because it combines people and objects in the network. Trust in the SIoT-based environment is measured with the concept of reputation. The trust management life cycle is illustrated in Figure 9 and each phase is explained below.

- Observation: The social objects collect the information of objects from which they can provide the relevant services.
- Scoring: A weight is assigned to all objects in the network and is known as a reputation score. The reputation score is assigned by a centralized entity or an object. If multiple objects are available, these reputation scores are leveraged to prioritize the objects by ranking.
- Selection: When the process of scoring has been completed, the most suitable objects are selected for specific transactions.

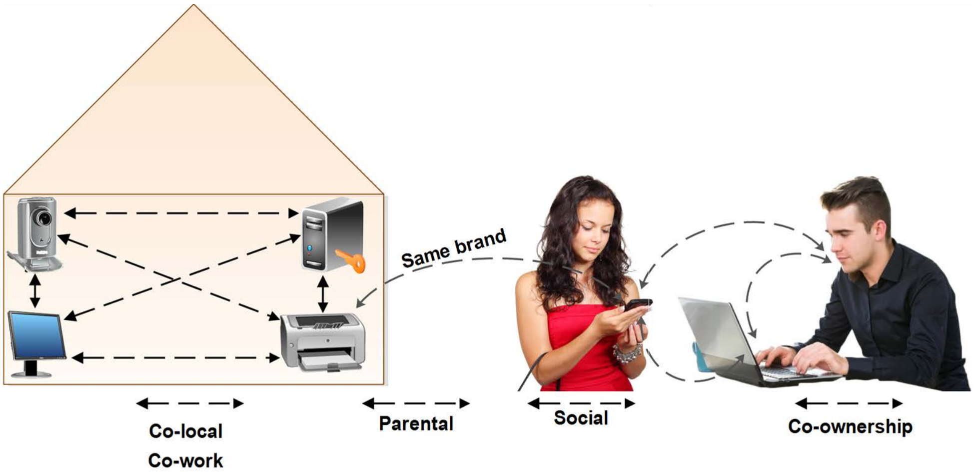

FIGURE 8. Types of social relationships among objects in the context of SIoT [90].

FIGURE 9. Overview of the trust management life cycle in SIoT.

- Transaction: After the selection of objects, the transaction takes place, and feedback is gathered and stored.
- Reward/Punishment: Finally, some functionality is leveraged to reward honest and cooperative objects that have a high reputation score, either locally or globally, in the network.

Trust management in SIoT has been discussed by various researchers such as Nitti *et al.* [29] discussed two trust management (TM) models for P2P and social networks. The first is subjective, and the second is an objective-based model. In the subjective model, each node can compute the trustworthiness of its friends based on its own experience and the opinions of friends. In the second model, each node stores the information in a distributed hash table (DHT). This table can be accessed by each object in the network. The limitation of this model is that it is based on a single entity [86]. Chen *et al.* in [87] worked on the improvement of this model. Therefore, each object in their model only updates the trust level towards other neighbors based on the occurrence of events. The trust level is updated by using indirect and direct observations and used to control the α and β parameters. These design parameters are used to control the trust propagation and aggregation and also to improve trust assessment accuracy in response to dynamic conditions. Here α is the weight on direct trust w.r.t (with respect to) experience and β is the weight on recommendation w.r.t experience. Lin and Dong [88] presented a TM model based on a goal, a trustee, and a trustor. The level of trust is achieved based on damage, gain, cost, and success rate. Khani *et al.* [89] presented a model named Mutual Context-aware Trustworthy Service Evaluation (MCTSE) in the SIoT. This model was developed to overcome the problems of providing the services using trust. The proposed model is used in three contexts: the environment, the type of task, and the devices. Talbi and Bouabdallah in [90] presented a TM model for SIoT networks. In this model, trust between objects is measured based on both direct and indirect interest. To measure the direct trust value, a global trust score is computed based on the assigning of a score obtained for each interest. To evaluate the indirect trust, the trustor looks for a recommendation from other potential recommenders [3]. Table 5 presents a comparison of the state-of-the-art trust models. In this table, we examine the models, trust metrics, relationships such as SoR, OOR, etc. The applications areas are also provided in this table.

IV. ANALYSIS: SUMMARY OF KEY CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Substantial efforts have been made toward converging social network concepts with the IoT; therefore, the SIoT appears to be the next step in the evolution of ubiquitous computing [45]. However, there exist various open research challenges that need further exploration from the research community for futuristic applications of SIoT [91], [92]. In this section, we pinpoint and discuss various promising future research directions for domain researchers and developers.

A. FRIENDSHIP: NETWORK NAVIGABILITY AND SCALABILITY

The objects in the SIoT have the ability to make or break relationships with other objects without human intervention [93], [94]. In addition, they can store and manage the information related to other objects [95]. The SIoT facilitates better navigation and an efficient search mechanism [57]. As stated earlier, the SIoT is very efficient at finding the desired services by utilizing different kinds of relationships [45]. However, with the increase in the number of objects, relationship management between these objects becomes tricky. The selection of the right friends and associated heuristics in the network is crucial to sustaining the network performance [58]. Right friends play an important role when selecting desired services in the SIoT applications. However, this research area still seeks the attention of researchers concerning different aspects (a few important aspects are listed below):

- The levels of the friendship.
- The kinds of tasks that can be accomplished by different types of friends.
- The right selection of friends in the network.

Future research directions and research questions are as follows. We should pay ample attention to the number of friends per object in the network because it directly impacts the performance of the entire platform. We should care about the friend classifications, i.e., selfish friends, malicious, and good friends [45]. The selection of good friends impacts the navigability and the scalability of the network. Therefore, devising low-cost and practical mechanisms for the selection of the right friends and associated friendship-based heuristics is an important research direction in the near future.

B. SERVICE MANAGEMENT (DISCOVERY AND COMPOSITION)

The service composition feature of SIoT provides a new dimension to select suitable friends for a specific task. In recent years, there exist many models and prototypes to discover and perform service composition-related tasks in traditional IoT [96]. The emerging SIoT demands new capabilities in the existing models and prototypes due to its unique nature of providing services. The development of advanced and intelligent models is inevitable for service discovery and composition. For example, the service-oriented architecture (SOA) [96] and the DPWS [97] are the famous service management architecture used in SIoT. Therefore, we may need robust mechanisms related to service discovery and composition for the futuristic applications of SIoT.

C. SIoT-POWERED APPLICATION DEVELOPMENT

The development of SIoT-based applications and the provision of desired functionalities in them is paramount in the near future amid the growing popularity of SIoT-based systems [1]. However, the application development process depends upon each situation, and scenario, and it involves what devices/services are required to meet the demand of users [1]. To this end, the open application programming interface (API) is very important to make SIoT-based applications widely accessible/ functional [1]. However, this area has been less focused by the researchers/developers, and there exist various development gaps such as building trust, service recommendation and management [98], and architectural design [31]–[45] that need a robust solution to make the SIoT services more functional/accessible [99], [100].

D. BUILDING NEW ACTOR-CENTERED BUSINESS MODELS

The SIoT provides various benefits to different actors such as developers, stakeholders, and users, to name a few. The dynamic and collaborative nature of the SIoT offers various business opportunities to these actors [1]. The current business model provides limited support to the SIoT. Hence, the development of attractive, low-cost, and useful applications and services is the key concern to augmenting SIoT-based services in the near future [1]. Therefore, the need of designing new business models has become more emergent than ever. The valuable avenues to rectify existing business models are given below.

- There is an increasing need to find non-conflicting business models that provide the help for collaboration and communication between actors.
- User-centered models that can invite the customers to participate and recognize the customer experience are paramount in futuristic SIoT applications.

E. FAULT TOLERANCE

In recent years, traditional IoT-powered infrastructures have badly failed to cope with the data abundance and device heterogeneity issues [3]. The failures often occur due to energy conservation, server-oriented architecture, and poor connectivity between IoT devices. These failures can lead to severe service disruptions, such as loss of data, latency, and recovery costs. Therefore, it is necessary to develop advanced fault-tolerant routing algorithms that work with minimal energy during communication. This will help to avoid network failures and will improve the connectivity among devices [101]. Despite many improvements, there is a significant lack of automated methods for fault tolerance in SIoT.

The SIoT is rooted in the IoT, and therefore, system-level failure detection and recovery from failure are very challenging tasks. IoT devices are developed by different manufacturers and therefore include a wide range of devices using different types of local connections. Owing to this heterogeneity, troubleshooting requires a large number of information sources that need to be explored to obtain information about node failures and consequences. Therefore, it is necessary to produce autonomic components that are capable of self-organizing and self-management. One study discussed a smart troubleshooting concept in which a set of activities and tools are used for collecting the failure information [102]. This information is generated by heterogeneous devices for analyzing the events and fault causes, respectively.

TABLE 5. Comparison of state-of-the-art trust models related to SIoT.

Study	Model	Trust metrics	Trust model	RELATIONSHIPS	APPLICATIONS
Khaled [74]	Friendship community of interest (CoI)	Direct	Objective and subjective	SoR	Traffic monitoring
[75]	Social similarity of friendship	Indirect and direct trust	Transaction, local	OOR	P2P, E-commerce
[76]	Similarity interest	Direct and indirect trust	Global, objective, and subjective	NA	

TABLE 6. The challenges research contributions and the future research directions in the SIoT.

Challenges	Research contributions	Future research directions
Friendship: network navigability and scalability in SIoT	W. Z. Khan et al. [61] M. Nitti et al. [68] F. Amin et al. [69]	• What are the strategies to develop appropriate friend relationships for the specific types of activities or tasks in SIoT? • How new friend ship relations can be established and used for gaining better services or completing the context of task. • The selection of Good friends is mandatory to achieve the higher network navigability in SIoT.
Service management (discovery and composition)	A. M. Ortiz et al. [1]	• The development of new service discovery models are necessary for the SIoT.
SIoT-powered application development	A. M. Ortiz et al. [1] Yang et al. [99] M. Nitti et al. [100]	• The building of new trust based models is mandatory for the SIoT application development. • The development of SIoT powered application development using device to device (D2D) communications is the mandatory right research direction.
Building new actor-centered business models	A. M. Ortiz et al. [1]	• The development of attractive, low-cost, and useful applications and services are the key concerns to augment SIoT. • The researchers should focus on the designing of new business models for SIoT.
Fault tolerance in SIoT	A. M. Ortiz et al. [1] W. Z. Khan et al. [61]	• It is necessary to develop advanced fault-tolerant routing algorithms that work with minimal energy during communication. • The robust solutions towards the identification of link failure in service provision, changes in sensor locations, or faulty devices identification are interesting research directions.
Context management in SIoT infrastructures	A. M. Ortiz et al. [1]	• We should focus on the development of low-cost mechanisms that can maintain context across the heterogeneous objects in SIoT environment in future.
Heterogeneity in SIoT	M. Malekshahi Rad [26] A. M. Ortiz et al. [1]	• The development of a new design that may efficiently deal with heterogeneous technologies will be of great importance for the successful deployment of SIoT is necessary.
Self-automation in SIoT	Roopa et al. [8] A. M. Ortiz et al. [1]	• More sophisticated self-automation methods are needed in SIoT for network management, service discovery, and navigability.
Trust, security, and privacy in SIoT	W. Z. Khan et al. [61] Roopa et al. [8] M. Malekshahi Rad [26]	• How to handle trust assessment of entities in the SIoT.
Energy management	A. M. Ortiz et al. [1] D. Wang et al. [111] Khanna et. [110] Marche et al. [111]	• The energy consumption in IoT devices is a common issue. The energy consumption in the SIoT devices should be low energy consumption. In this direction the new mechanisms for the utilization of energy should be considered. • Efficient energy management should be implemented at all levels; from M2M device communication to the interface design.
Data Management in SIoT	N. Gulati et al. [116] S. Peng et al. [46] V. Caballero et. [114]	• How to handle large amount of data in the SIoT is a challenging task. The development of new models for handling the large amount of data is required and the future research is needed.

Subsequently, the desired solutions are determined to correct the faults. The system can recover itself, and it becomes more resilient with the implementation of smart troubleshooting. It is a challenging task to develop a system that can repair itself to handle errors and faults. To do that, complex actions are required with the combination of both automatic and manual actions. Designing a generic fault-tolerant system that can work in most SIoT-based infrastructures is an important need of modern times. Hence, in the near future, robust solutions toward the identification of link failure in service provision, changes in sensor locations, or faulty device identification are interesting research directions [103].

F. CONTEXT MANAGEMENT IN SIoT INFRASTRUCTURES

The context-awareness is becoming an important feature in IoT and SIoT [3]. The SIoT is aimed to provide context-aware services, the set of devices is used to provide various data and services simultaneously. Therefore, the ability to correctly manage the current context across systems is very challenging because context can only be maintained via correct interpretation and unambiguous access to data. Thus, in the near future, the demand for context-aware services is likely to increase, leading to the adoption of SIoT on a large scale. Semantic approaches oriented to RDF and OWL [103] can be extended to include descriptors for SIoT users and device characteristics, facilitating the interpretability among all the components [1]. Therefore, we should focus on the development of low-cost mechanisms that can maintain context across the heterogeneous objects in SIoT environment in the future.

G. HETEROGENEITY

The actuators, sensors, ID tags, computers, tablets, and smartphones are the key components of SIoT [1]. These devices can have different manufacturers, brands, characteristics, embedded technologies, etc. These devices usually work together to achieve common goals for users [26]. They can communicate with each other through interoperable interfaces. Therefore, the SIoT-based systems should ideally be open to supporting a huge variety of applications/devices. Moreover, due to diverse characteristics regarding availability, reliability, bandwidth, and latency of each device, their integration is extremely complex [1]. In this scenario, the development of a new design that may efficiently deal with heterogeneous technologies will be of great importance for the successful deployment of SIoT in the coming years.

H. SELF-AUTOMATION

SIoT can connect trillions of objects and people via a single unified framework [1]. Therefore, the global management of huge platforms (with different devices) to realize self-operation is very tricky [8]. Therefore, different methods with self-organization, self-healing, and self-protection capabilities are vital in SIoT domain [31]. Therefore, more sophisticated self-automation methods are needed in SIoT domain for network management, service discovery, object replacement, cluster formation, navigability, and object response reading.

I. TRUST, SECURITY, AND PRIVACY

The relationships and links among objects in SIoT are established based on friendship and the corresponding trust level. The term trust is directly related to the privacy and security in objects, [104] and [105]. The current trust model does not provide any method for the calculation of an object's initial trust values [3]. It would lead to selecting dishonest nodes in the network and disturbing the functionality and the performance of the network. Storing a large history of transactions on resource-constrained objects can bring communication overhead and scalability issues. In addition, the mathematics involved in calculating trust may generate significant computational workloads. Since it is very challenging for constrained IoT devices with limited computation capabilities to calculate trust scores, thus the light weight and efficient trust management protocols are required for the computation of trust evaluation metrics. Thus, to ensure the trustworthiness among the social IoT objects leveraging a high degree of interaction among these objects is a huge demand in SIoT-based systems. Efficient identity management and privacy-enhancing technologies use are fundamental steps to increase user trust the SIoT applications. The ability to sense the data and compute the results is a challenging task. The main research questions are as follows: What trust assessment entities are available for the SIoT? How can we make trust management more efficient against misbehaving and dishonest recommendations in the SIoT? What efficient trust update models are available for SIoT objects? What efficient and robust algorithms are available for establishing trust? What are the tools and models available in this area for security and privacy? To answer these questions, robust techniques are needed that can exploit the SIoT dynamics and corresponding data modalities.

J. ENERGY MANAGEMENT

The SIoT is comprised of many prosumers (users) and smart devices [106]. While operating smart devices, a major portion of the energy is usually consumed during coordination [1]. Therefore, energy conservation is a coordinating factor in the design and the operation of SIoT [1], [107], [108], [109]. This research area is broad and attracting significant attention in recent times. In recent times, a new term such as social internet of energy (SIoE) is introduced that refers to the synergy that allows the physical devices that consume or produce energy to create social relationships to improve overall scalability [110]. It allows the users in the smart grid (SG) to create relationships to optimize their energy usage and improve overall scalability. The objective of SIoE is to enhance the relationships established between the devices and the users in the IoE by leveraging the technical aspects of SIoT. Moreover, integration of SIoE-based mechanisms with the SIoT environment is still very challenging. The social IoT is an emerging technology. It is a cluster between the Internet of things and the social networks. The energy consumption in IoT devices is a common issue [111] Efficient energy management should be implemented at all levels; from M2M device communication to the interface design [112] and [113]. All stages in the design of SIoT technologies have to be oriented to low energy consumption [1]. In this context, new mechanisms for energy management and utilization in an economical way is a vivid area of research in the near future.

K. DATA MANAGEMENT

The SIoT can generate a large amount of data on a daily basis. Data management or big data handling in SIoT is a challenging task [114]. In this regard, how to handle a large amount of data is a promising avenue for research [115]. The development of solutions that can draw a picture out of a huge amount of data, and provide actionable insights are important research directions for future endeavors. Table 6 briefly explains the research contribution, challenges and the future research directions in SIoT.

V. CONCLUSION

This study has analyzed and compared the recent studies related to SIoT from multiple perspectives including basic knowledge, related technologies, key aspect areas, and research dynamics (e.g., existing challenges and future research patterns). We provided a comparative analysis between traditional IoT and SIoT that enables researchers to understand this emerging technology from technical perspectives. We identified six key aspects such as service composition and discovery, network navigability, architecture and components, platform and tools, relationship and trust management, and systematically covered related studies. We analyzed and compared different studies regarding their strength, weaknesses, and application areas. We provided additional coverage about network navigability and platforms that are emerging research areas in the context of SIoT but have not been explained in detail in the previous studies. Based on the extensive analysis of previous studies and developed platforms, we discussed various research challenges, most of which have been investigated in the literature. But some issues such as "friendship: network navigability and scalability" and "service management" are still not investigated enough and need to be addressed in the near future by the research/development community.

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