Received February 3, 2019, accepted March 4, 2019, date of publication April 1, 2019, date of current version April 12, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2906880

Data Aggregation in Massive Machine Type Communication: Challenges and Solutions

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This work was supported in part by the National Science and Technology Major Project under Grant 2018ZX03001029-004, in part by the Beijing Natural Science Foundation under Grant L182038, in part by the National Natural Science Foundation of China under Project 61631005, and in part by the 111 Project of China under Grant B16006.

ABSTRACT Machine type communication (MTC) is a fundamental technology to realize the concept of fully connected world in fifth generation (5G) Internet of Things (IoT). The massive roll out of the MTC devices is a serious challenge for cellular networks from operational and management perspective, including massive access and network congestion. Many proposals have been put forward by the research community to cater to the nuisance of massive MTC (mMTC) access in cellular networks. Recently, data aggregation has attracted a lot of research attention owing to its robust ability to resolve the above-mentioned challenges. In this paper, we review the recent development in data aggregation techniques, including their application scenarios, design, and limitations. Commencing with the application scenarios and current challenges in the MTC network, the classification of various proposed solutions for massive access along with the family of data aggregation techniques is discussed in detail. By doing so, it provides an insight about the future design trends that can propel the current research efforts to curb the mMTC access in a cellular network.

INDEX TERMS 5G networks, cooperative aggregation, D2D, data aggregation, Fog, hybrid aggregation, IoT, machine-to-machine communication, MTC, resource allocation, survey, UAV.

I. INTRODUCTION

The communication industry has seen a tremendous growth over the last two decades. From first generation (1G) analog systems to fourth generation (4G) all−IP based systems, the fifth generation (5G) of cellular networks is now observing heterogeneity in terms of devices, technologies and techniques. Due to this heterogeneity of devices and services, a multi-tier architecture is expected in 5G networks [1]. Contrary to previous generations, which were developed to cater bandwidth craving applications from people; 5G is about connecting people and devices [2] and thus requires several technologies and services to fulfill the traffic demands from massive number of these connected devices [3] and people. The key enabling heterogeneous technologies and techniques include: machine-to-machine communication [4], device to device communication (D2D) [5], unmanned aerial vehicles (UAVs) [6], cloud computing [7], mmwave communication [8], fog computing [9], and internet of things (IoT) [10].

Internet of thing is revolutionizing the physical world around us by transforming it into information sources [10] i.e. digitalization of the physical world around us through pervasive presence of uniquely addressable things or objects [11]. Machine to machine communication (M2M) is an essential building block of IoT [12], and is termed as machine type communication (MTC) by third generation partnership project (3GPP) [13]. It encompasses algorithms, mechanisms, and technologies that enable services and networked devices to exchange information or control data seamlessly, without explicit human intervention [14]. In other words, an MTC enables objects to *talk* to each other through any of the communication network (wired or wireless).

The proliferation of MTC devices (MTCDs) propels serious challenges to the current cellular networks due to its huge number [15], particularly in ultra-dense scenarios like stadiums, concerts [2], hotspots and flash crowds [16]. MTCDs are connected with each other to form MTC network to

The associate editor coordinating the review of this manuscript and approving it for publication was Ibrar Yaqoob.

facilitate intelligent consumption of commodities such as water management [17], smart metering [18], environment, structure and asset monitoring [19], on-body sensors, remote diagnostics, smart agriculture and surveillance systems [20], [21]. The traffic per MTC device is not significant but the simultaneous and unpredictable number of access from these devices causes congestion and signaling overhead at the radio access network (RAN) and core network (CN).

To throttle the massive access at the base station (BS) several techniques are proposed such as pull-based schemes [22], MTC clustering [23] and data aggregation [24]. Among these, data aggregation has gained much attention recently due to its potential benefits. Data aggregation is a technique to collect, store, process and transmit data to the BS from resource-constrained MTCDs [24]. This causes effective reduction of MTC-BS transmission distance, thus becomes an energy-efficient solution. Furthermore, it also improves the spatial spectrum reuse, reduces the number of direct connections to the BS, and the RAN congestion [25]. The data aggregation techniques are equally useful in MTC cellular and capillary networks. In capillary MTC networks, the MTCDs utilize a short-ranged communication technology such as 802.15 or 802.11 to accomplish communication among one another or to a central gateway. In contrast to cellular MTC network, capillary networks uses license free band that helps reduce the communication cost in terms of limited resources and devices' complexity.[1]

Over the last few years, several survey papers have been published covering various aspects of MTC and massive MTC (mMTC). However, despite its usefulness, the existing literature lacks a comprehensive survey of data aggregation schemes in MTC network that critically discusses its limitations to envisage the future direction. A comparison of surveys on MTC networks since 2014 is listed in Table 1 in chronological order. The authors in [17], [24], [26]–[33], presented comprehensive surveys covering general aspects of MTC including technologies, opportunities and objectives. Since one of the major issues with mMTC is the massive signaling and severe congestion at the radio access and core networks, therefore, much attention is given to radio resource management and other physical (PHY) and medium access (MAC) layer issues. As a consequence, several surveys covering various aspects of PHY and MAC layers can be found in literature including [12], [19], [34]–[40]. The next generation networks involve ultra dense networks (UDNs), therefore, Chen *et al.* [41] presented a survey on critical issues and methods to implement MTC in UDNs. Since security of MTC devices is a serious issue, therefore, Barki *et al.* [42] presented a comprehensive survey of security issues and discussed the related challenges. Wang and Fapojuwo [43] presented survey on three major low power and long range MTC enabling technologies including low power wide area (LPWA) network, IEEE 802.11ah and cellular MTC. For industrial MTC, Perera *et al.* [14] presented a survey with focus on context aware computing, while Chen *et al.* [44] presented survey on recent developments of home MTC networks. MTC traffic issues are discussed by Soltanmohammadi *et al.* in [45] while energy efficiency issues are reviewed by Ali *et al*. [46]. Since cellular networks are quite overloaded by MTC and human type traffic (HTC), therefore alternate solutions are required. In this vein, Aijaz and Aghvami [47] presented survey on cognitive MTC while Pereira and Aguiar [48] presented feasibility study for using user equipments (UEs) or smartphones as gateways for MTC devices.

Several survey papers are also available in the literature covering various aspects of data gathering schemes in wireless sensor networks (WSNs) [49]–[53]. Some authors have used the same concepts of data gathering in WSNs and termed them as data aggregation in MTC [54]. However, the recent advancements in MTC call for novel data aggregation techniques that are suitable for their challenging scenarios. More recently, Ashrafuzzaman and Fapojuwo argued that in current MTC networks, there is nearly no scope for traditional redundancy-oriented data gathering techniques developed for WSNs [55]. The main reason of this notion is the MTCDs' ability to interact effectively not only for sensing but also working according to the instructions from an application server. Furthermore, the WSNs are infrastructure-less networks in which sensor nodes work mainly in adhoc manner. On the other hand, MTC networks have a defined architecture by European Telecommunications Standards Institute (ETSI) [56] and MTCDs transmit/receive data through capillary/cellular connections. From these reasons, we can infer that the survey papers on data gathering techniques in WSNs do not encompass the novel data aggregation proposals presented for MTC networks. This motivates us to fulfill this need and to survey data aggregation schemes in MTC networks.

This paper aims to provide a survey of the different data aggregation schemes that have been proposed over the last years to resolve the challenges induced by massive access. A comprehensive discussion about the different schemes is provided, identifying strengths and weaknesses of each one of them, while drawing future trends to steer the efforts along the same line.

A. CONTRIBUTION AND ORGANIZATION

The aforementioned survey papers on MTC have provided valuable insights into the high-level network architectures, communication technologies, standardization efforts, service platforms, and key applications supported by MTC networks. However, the present literature lacks any serious effort to survey data aggregation schemes or to investigate other effective solutions to resolve the nuisance of massive access in MTC network. To the best of our knowledge, this is the first effort to generally categorize the massive access solutions and to provide a detailed review on data aggregation for managing MTCDs in heterogeneous 5G network. The main contributions of this paper are following:

[1] further detail in Section IV-A

TABLE 1. Summary of survey papers on MTC.

Reference	Year	RAT	MTC Aspect	Contribution
Bockelmann *et al.* [19]	2018	Both*	mMTC	Review and analysis of performance of access schemes and multi-user decoding techniques for massive MTC in a multi-service air interface through a common evaluation framework.
Akpakwu *et al.* [17]	2018	Both*	cMTC and mMTC	Extensive survey on emerging and enabling 5G technologies for both massive and critical MTC applications.
Xia *et al.* [40]	2018	Both*	RRM	Comprehensive survey on RRM in cellular, capillary and HETNETs
Chen *et al.* [41]	2017	Both*	MTC in UDN	Survey on critical issues and methods to implement MTC in UDN
Zhao *et al.* [26]	2017	Both*	General	Survey on state-of-the-art MTC technologies, challenges and opportunities
Dawy *et al.* [24]	2017	Cellular	mMTC	Requirements and challenges of mMTC applications in cellular networks
Ali *et al.* [27]	2017	Both*	General	State-of-the-art communication technologies, architectures and development platforms for supporting MTC applications
Wang and Fapojuwo [43]	2017	Both*	LPWA MTC	Survey of three major low power and long range M2M solutions.
Cao *et al.* [28]	2016	Both*	General	Categorization of contemporary MTC solutions on the basis of context, task and objective.
Bockelmann *et al.* [12]	2016	Cellular	mMTC	PHY and MAC layer solutions for massive and energy-efficient MTC access
Soltanmohammadi *et al.* [45]	2016	Cellular	MTC traffic	Traffic issues of MTC and their solutions for LTE/LTE-A networks
Verma *et al.* [29]	2016	Both*	General	Comprehensive review of MTC in terms of architecture proposed by 3GPP, ETSI and oneM2M.
Ali *et al.* [46]	2016	Both*	Energy efficiency	Explored and analyzed the current proprietary protocols and techniques for MTC energy efficiency and classification of these protocols on OSI model
Palattella *et al.* [30]	2016	Both*	General	Investigation of emerging 5G technologies to enable global IoT and consideration of both the standardization and technological scenarios.
Barki *et al.* [42]	2016	Both*	Security	Survey of security issues and related challenges in MTC networks
Biral *et al.* [34]	2015	Cellular	mMTC	Survey on problems of RRA related to massive MTCDs and their solutions
Ghavimi and Chen [31]	2015	Cellular	General	review of architectures, service requirements, challenges, and applications of MTC in 3GPP LTE/LTE-A networks
Rajandekar and Sikdar [35]	2015	Cellular	MAC layer	Different MAC layer issues and protocols for MTC networks
Aijaz and Aghvami [47]	2015	Cognitive radio	Cognitive MTC	Review on emerging standardization efforts and the protocol developments for cognitive MTC networks
Lee *et al.* [32]	2014	Both	General	Survey of existing MTC service platforms and proposed new service platform architecture
Lee *et al.* [36]	2014	Cellular	RRM	Requirements of RRM functionality and current research on different RRM algorithms to support carrier aggregation in LTE-A.
Pereira and Aguiar [48]	2014	Cellular	Mobile MTC	Survey on ETSI standards and protocols and feasibility study on smartphones as gateways for MTC
Laya *et al.* [37]	2014	Cellular	RAN overload	PHY and MAC layers solutions for managing RAN overload in mMTC
Perera *et al.* [14]	2014	Both*	Industrial MTC	Industrial and market perspectives of MTC with focus on context aware computing
Chen *et al.* [44]	2014	Both*	Home MTC	Survey on recent developments in home MTC networks; analyzing related security issue for both cellular and capillary networks
Kim *et al.* [33]	2014	Both*	General	Architectures,issues, and enabling technologies for MTC service platforms
Islam *et al.* [39]	2014	Cellular	Access management	Survey and classification of existing access management techniques for MTC networks.
Abu-Ali *et al.* [38]	2014	Cellular	Uplink scheduling	Survey on uplink scheduling algorithms in LTE/LTEA networks.

*Both cellular and capillary networks

1) *Classification of proposed solutions in literature for mMTC access:* There are variety of solutions proposed to address various challenges of massive access of MTCDs in cellular networks. In this article, we classify and briefly review current proposals that encounter the massive access of MTC in the 5G networks.

2) *Comprehensive categorization of state-of-the-art data aggregation solutions:* On the basis of type and technology of aggregating device, we have categorized the existing data aggregation proposals. A comprehensive discussion is rendered to signify the advantages and limitations of each technique along with the future direction.

3) *Identification of current challenges and open issues:* More generally, the challenges induced by massive access of MTC in 5G networks are also identified such as privacy and security, caching, cognition, cooperation and energy harvesting to provide current issues and direction for future research.

The article is organized as: Section II presents the applications scenarios and challenges due to massive MTC access along with traffic pattern. Section III provides the categorization of existing solutions to cope massive access along with cellular enhancements proposed by 3GPP. Data aggregation along with its ETSI architecture is discussed in Section IV. The effects and categorization of different aggregation scheme is also discussed along with its challenges. Section V provides a critical discussion on different aggregation schemes to highlight their advantages and limitations. Section VI discusses the role of data aggregator as resource scheduler to handle the nuisance of limited resources. Future research directions are presented in Section VII. Section VIII concludes the paper.

II. MASSIVE MACHINE TYPE COMMUNICATION: APPLICATION SCENARIOS, TRAFFIC PATTERN AND CHALLENGES

In this section, we begin with a concise introduction of application scenarios of mMTC followed by a briefly description of the various induced challenges.

A. MASSIVE MTC APPLICATIONS AND TRAFFIC CHARACTERISTICS

Machine type communication devices enable real-time monitoring and control of any physical environment. The interconnections and communications among the objects around us enable several MTC applications for the realization of smart world [57]. The massive MTC application scenarios include: smart cities [58], smart environment [59], smart grid [60], [61], smart metering [18], smart animal farming [14], connected appliances [62], public safety [63], medical / health care [64] and structure / asset monitoring [19]. Figure 1 depicts some of the application scenarios of MTC applications, which require massive deployment of MTCDs in an area.

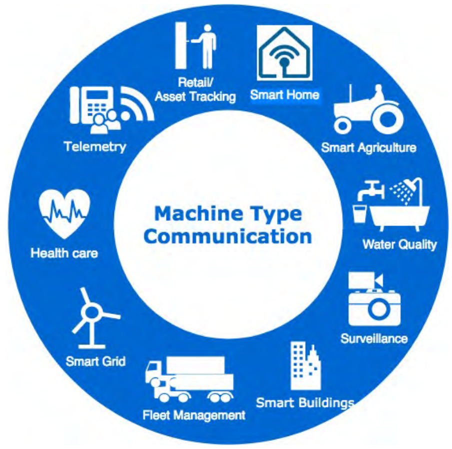


FIGURE 1. Application scenarios of machine type communication.

Although, MTCDs usually access the network sporadically to transmit small data payloads [19], however, it may vary due to diversity in the application scenarios. For example, smart metering devices send few bits of data periodically or when triggered by an MTC server [41], while video surveillance or connected goggles like applications consume high bandwidth [65]. In an effort to characterize MTC and human type communication (HTC) traffic, Shafiq *et al.* [66] have investigated statistical properties of MTC data using real data traffic in the United States. The authors compared MTC and HTC traffic with respect to aspects such as temporal patterns, device mobility, application usage and network performance. The results of their investigation corroborate that although MTCDs have different traffic patterns as compared to HTC devices, they are generally competing with HTC for shared network resources. Soltan Mohammadi *et al.* [45] also highlighted the key difference in HTC and MTC traffic and stated that MTC's traffic is uplink dominant and can be generated any time of the day, contrary to HTC which is downlink dominant and is mostly generated during daytime and evening. Moreover, contrary to HTC devices, MTCDs are application specific; tailored according to the requirements of particular applications.

More generally, the transmission from MTCDs possesses unique and challenging characteristics including: scalability and ubiquity of access [62], periodic [45] or event driven traffic [20], time controlled transmission [21], low or no mobility [45], [67], uplink-dominance [158], small packet size [55], and usual requirement of low data rates [24]. A detailed comparison and discussion on MTC's application requirements can be found in [17], [24], [29], [41]. The huge diversity and unique traffic characteristics of MTCDs pose serious challenges to the existing cellular networks that encompass MTC.

B. MASSIVE MTC CHALLENGES

An MTC network aims to construct a well-coordinated and comprehensive communication among all devices [68]. The increased share of MTCDs by 51% along with the 200 times hike of global mobile data traffic by 2020 [15] pose serious challenges to the cellular networks. Although, the bandwidth requirements of MTC is well below the available bandwidth in the cellular networks, the multitude of devices may create significant congestion at the base station (BS). A BS may serve hundreds of thousands of MTC and HTC devices and may not cope with the simultaneous massive requests of these devices, resulting in massive congestion and signalling overhead at access and core network.

Another challenging issue is concerning with the locations of MTCDs. The MTCDs may be deployed at arbitrary locations [24] such as deep indoors or cell edges; making it difficult to be under the coverage of cellular networks. In addition, there are strict design requirements for MTCDs [24], [67] including low complexity and computational capabilities, which may further aggravate the said challenges.

Energy efficiency is also a serious concern for MTC. The MTC devices are mainly battery operated, assumed to be working for few years without battery replacement. In such case, communication over the long distance to the BS may not be feasible and efficient. In case of battery depletion, an MTCD cannot function properly and will not be the part of the network. If it happens to significant number of MTC devices in the network, the overall functionality of network may not be achieved.

The scant available resource is also a challenging factor in cellular network with the provision of HTC and MTC. Contention based protocols are usually advocated for MTC to provide access to the BS [69]. However, due to large number of devices, contention based protocol do not meet the diverse QoS requirements of MTC devices. The massive number of MTCDs also creates an imbalance regarding share of resources between HTC and MTC devices in the cellular networks.

III. MASSIVE MTC: EXISTING SOLUTIONS TO COPE MASSIVE ACCESS

The 3GPP proposes certain enhancements in the cellular networks to effectively cater the challenges concerning energy efficiency and poor coverage. These are briefly explained in the following subsection.

A. 3GPP CELLULAR ENHANCEMENTS FOR mMTC

In 3GPP Releases 12 and 13, several new features have been added to LTE, such as physical layer changes to reduce the device complexity and increase coverage, and higher-layer procedures to reduce the power consumption of devices. In [74], the authors have provided a high-level overview of the new features introduced in 3GPP Release 13 including enhanced MTC, narrow band IoT and enhanced discontinuous reception. These are explained as follows.

1) DISCONTINUOUS RECEPTION

In wireless networks, devices continuously or very frequently listen to the downlink control channel to check whether there are pending downlink data transmissions intended for them or there are uplink resources available for transmission [17]. In this vein, the radio circuitry of devices is always on, thus consuming energy [70]. Although this approach is efficient to reduce latency in highly demanding applications, like those in HTC, however, it is inefficient for busty packet data traffic patterns with long silent periods, the case of massive MTC. Therefore, the concept of duty-cycling, also referred to as Discontinuous Reception (DRX) [71], can be used for such traffic patterns. Time is divided into DRX Cycles, comprising both On and Off Periods. During the Off Period, devices can switch off their receiver circuitries to save energy, and they are said to enter into sleeping state. During the On Period, devices can monitor the downlink control channel. LTE defines two types of DRX cycles: i.e., Short DRX Cycle and Long DRX Cycle [40]. Long DRX Cycle allows devices to stay in the sleep mode longer than Short DRX Cycle.

Such operation can significantly improve the energy efficiency in LTE networks. However, the execution of a DRX scheme inevitably increases latency and communication delay. Devices in sleeping state cannot immediately react to traffic changes. For this reason, and in order to meet diverse Quality of Service (QoS) requirements, LTE defines The extended Discontinuous Reception (eDRX) [72] improves the power efficiency of devices, minimized idle mode procedures and admission control in terms of QoS [17].

2) ENHANCED MTC

The enhanced MTC (eMTC) [73], also called LTE Cat-M1 [19], or Cat-M, is a promising cellular low-powered wide-area (LPWA) technology introduced in the 3GPP Release-13 standardization. It intends to minimize modem complexity, power consumption, and extends coverage over existing legacy handset modems, such as category 0 user equipments (UEs), as compared to Release-12 MTC specification. This technology is an enhancement for LTE networks to support MTC for the IoT [17]. An eMTC UE can be deployed in any LTE evolved Node B (eNB) configured to support eMTC and can be served together with other LTE UEs by the same eNB [74].

The eMTC is standardized to ensure that for Massive IoT deployment and coverage, it supports long battery life of about 10 years with a 5 Watt-Hour battery system for effective utilization. This technology uses power savings management (PSM) [40] and extended discontinuous reception (eDRX) [72] as its power savings mechanisms to achieve long battery life for Cat-M1 devices.

3) NARROW BAND IoT

Narrow band IoT (NB-IoT) is designed to provide better indoor coverage, support of a massive number of low-throughput devices, with relaxed delay requirements and lower energy consumption [75]. It is also termed as LTE Cat-NB1 [17]. The NB-IoT is a massive LPWA technology proposed by 3GPP for data perception and acquisition intended for intelligent low-data-rate applications such as smart metering and intelligent environment monitoring [76]. The objectives of NB-IoT include lower cost than eMTC, lower delay sensibility, extended coverage, and longer battery

TABLE 2. Comparison of solutions for massive MTC access.

Solution Type	References	BS Access	Shortcomings
Push-based schemes	[22], [40], [69], [80]–[90]	Direct	Pushing traffic towards BS is not suitable for simultaneous massive access by mMTC devices
Pull-based schemes	[22]	Direct	May create overload at paging channel; Access priority of individual MTC devices within a group cannot be guaranteed
MTC clustering	[40], [41] [23], [45], [91], [95]–[99], [101]–[103], [178]	Through CH	Induces load at power-constrained CH
Cloud-based MTC	[7], [40], [110]	Through clouds	Suitable only for delay tolerant MTC devices
Cognitive MTC	[47], [78], [104]–[109]	Through CR technology	Sensing of medium requires more resources by resource-constrained MTC devices
Data aggregation	[24], [78], [100], [112] [111], [113]–[115], [118]–[121], [160]	Through GW	Costly solution in terms of hardware and maintenance; wireless gateways compete for resources in resource-constrained networks

life, to support a massive number of MTCDs [76]. NB-IoT is originally designed for MTCDs with low mobilities [40].

NB-IoT decreases the bandwidth requirements to 180 kHz. This narrowband bandwidth allows the device complexity to be further reduced at the expense of decreased peak data rate (around 50 kb/s for uplink and 30 kb/s for downlink). Furthermore, NB-IoT UEs only support limited mobility procedures. Thus, NB-IoT targets use cases with reduced mobility and very low data rate (e.g., metering devices) with the possibility of reusing GSM or LTE spectrum [74].

Concluding Remarks: Beside the above mentioned cellular enhancements, 3GPP has also proposed pull- and push-based [22] schemes. Several other solutions are also proposed by research community to handle the aforementioned challenges. The subsequent subsection briefly reviews these proposals along with their limitations.

B. CATEGORIZATION OF SOLUTIONS FOR MASSIVE MTC ACCESS

In order to handle the massive access challenges in MTC network, multiple candidate solutions are proposed in literature to efficiently utilize wireless resources and reduce congestion at the BS. In this vein, ETSI and 3GPP also defined three different access mechanisms as: the direct access, gateway access and cluster-head access [18], [77]. In direct access, an MTCD can directly access the BS, while in the gateway access, an MTCD may gain access through MTC gateways (MTCGs). In coordinator/cluster-head access, a set of the MTCDs act as coordinators to relay the data of the MTCDs in their vicinity. Each access method has its own pros and cons. However, the main advantages of using gateway or cluster-head access are reduced connections and energy efficiency.

On the basis of these access mechanisms, several solutions are proposed for cellular MTC in the literature. We are categorizing these proposed solutions as: radio access network (RAN) overload control, cognitive radio, MTC clustering, data aggregation and cloud-based MTC solutions. This categorization is based on the working of these proposals in cellular MTC networks. In practice, these proposals can be used in-conjunction to address certain issues. A comparison of these schemes is presented in Table 2.

1) RAN OVERLOAD CONTROL

The RAN provides radio resources to the MTC and HTC devices, therefore, it plays an important role from control plane perspective [62]. This coexistence of HTC and MTC is inducing a great burden on RAN at LTE/LTE-A networks, particularly, due to the huge signaling traffic generated by mMTC. In order to access the BS, MTCDs first choose a preamble and transmit their request. When a massive number of MTCDs access a network simultaneously, a preamble can be selected by more than one MTCD at the same time and collisions may occur. Collided MTCDs are backed off for a random time period before another random access (RA) attempt. Hence, physical random access channel (PRACH) may get blocked and the access requests of normal UEs may also be affected [40]. Mehmood *et al.* have stated that these collisions and congestions at the network causes higher power consumption and packet loss rate, unpredictable delays and unrestrained utilization of radio resources [78]. To solve the severe overload problems in the LTE-A RAN, cellular network operators can minimize the frequency of attempts of MTCDs to implement a particular procedure without having to throttle them from connecting to the network [79].

Within 3GPP LTE-A, several possible schemes have been identified to overcome the congestion on RACH at the RAN; which can be classified into pull- and push-based schemes [22], backoff scheme [80], slotted access scheme [81], access-class barring scheme [82], [83], resource separation scheme [84], [85], dynamic resource allocation scheme [69], [86], group-based random access [87], [88] and prioritized random access [87]. A detailed discussion and comparison of existing PHY and MAC layers solutions for managing RAN overload are surveyed in [12], [34], [37], [40], [89], [90] and reflect the feasibility of different proposals over LTE-A to handle mMTC access.

The RAN overload schemes such as access class barring and the like, alone cannot fully alleviate the overload

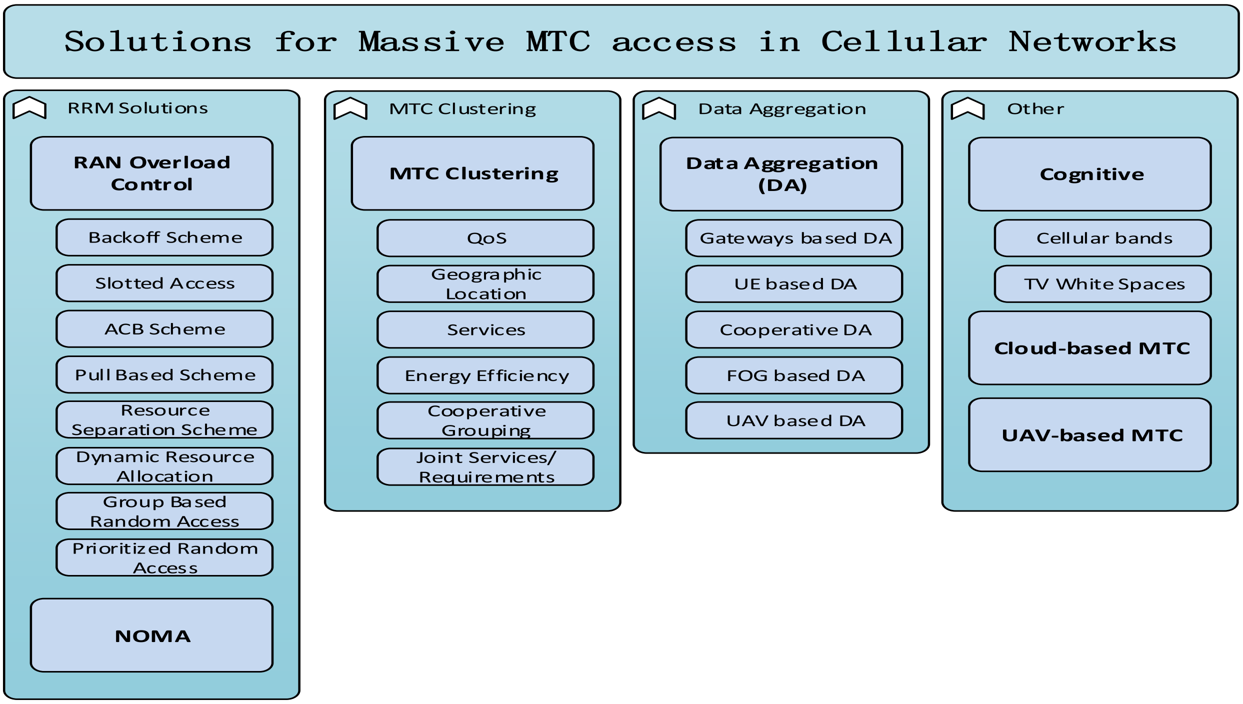


FIGURE 2. Categorization of solutions for massive access of MTC in cellular networks.

problem [91]. Moreover, these methods do not mitigate co-channel interference between cellular UEs and MTCDs and result in increased communication delay for massive MTCDs [92]. Condoluci *et al.* [67] have proposed a 3GPP-compliant architecture for UDNs to solve the issue of simultaneous massive access of MTC along with the arbitary deployment-location issue. Their proposed architecture allows MTCDs to connect to Home evolved NodeBs (femtocells) thus improving access delay, energy efficiency and success probability. Chen *et al.* [41] suggested that D2D communications [5], wireless local and personal area networks (WLANS and WPANs) [67] and LTE-Unlicensed can be employed to complement the existing cellular networks. Thus, it can be inferred that in practice, RAN overload techniques can be used in congestion with other proposals to meet the traffic and device dynamics in 5G networks.

2) MTC CLUSTERING

It is in general difficult for the signal transmitted by the low-powered MTCDs to reach the destination due to long propagation path or shadowing [93]. Clustering is a key technique to increase energy efficiency, scalability and network life-time [23]. In this technique, MTCDs are group together on the basis of some characteristics such as QoS [94], energy efficiency [95], services [96], geographic location [97], cooperative grouping [98], signal to interference ratio (SIR) [45] or joint services / requirements [40], [41], [91] with one MTCD is selected as cluster head (CH). A CH is then responsible to collect data from the surrounding MTCDs and relay it to the BS. In this way, the number of access requests to the BS is limited to the number of CHs [34]. Clustering/grouping of MTCDs decreases the load on random access channel [34], [95], [96], [99] and is termed as proactive approach by [100]. Cooperation among MTCDs and a group-based operation seems to provide a promising approach to offload massive signaling from the BS [31]. A suitable selection of the CHs can also contribute to decrease the energy consumption of the cellular system by exploiting multi-hop transmissions over high-gain links in place of direct transmissions over poor quality links [34].

In literature, several proposals are put forward that consider or term CH as data aggregator such as in [101], [102]. Since MTCDs are already battery constrained [7] with low processing power [54], the additional burden of relaying may put further strains on these devices. In cluster-based schemes, CHs are subject to higher power consumption [40] and may fail because of energy depletion before other MTCDs [34]. Moreover, the MTCDs are not provided with large storage capabilities, therefore, the CHs may not be able to buffer large amount of data and as a result, frequently transmit MTC data to the BS. This paper classifies data aggregation schemes based on aggregating devices other than MTCD itself, therefore, clustering techniques are not included in that classification.

3) COGNITIVE RADIO BASED MTC

Cognitive radio (CR) technology provides a novel approach to address the challenges of spectrum scarcity, which remained a serious issue in wireless networks [104]. Cognitive MTC, i.e. MTC employing cognitive radio technology, is expected to be indispensable in the era of 5G IoT [47]. Cognitive radio based solutions limit MTC massive access to the BS by allowing MTCDs to opportunistically access the unused bands in their vicinity without affecting the spectrum utilized by primary users [78], [105], [106]. Cognitive MTC can be carried out through employing either cellular bands [104], [105] or TV white spaces [107], [108].

In CR based MTC, the MTCDs have to sense the spectrum which is costly in terms of battery consumption and device complexity. Li *et al.* [109] have introduced a technique for MTC access with dynamic cognitive service operators for enabling the efficient RACH resource allocation for spectrum sharing. The authors have proposed an aggregator-based MTC access model in which a cognitive virtual operator can lease RACH resource from a spectrum owner for a certain time duration to set up a service relationship with the aggregator. The data aggregator plays the role of a third party that transmits aggregated M2M data to a cognitive operator, which does not own the radio spectrum but rather leases it from a spectrum owner. Their proposed architecture does not consider the delay intolerant MTCDs and also the privacy remains an open issue because of lack of control in the absence of centralized network operator. Even though cognitive radio based MTC offers several benefits, still there is a limited research work available in this area. The medium sensing requirement in CR based MTC also calls for suitable approaches to tackle this issue. Therefore, techniques are required for making the operation of spectrum sensing suitable for resource-constrained MTCDs and exploiting the potential benefits of CR based MTC.

4) CLOUD-BASED MTC

For MTC service providers, deploying and managing MTC application servers, is expensive in terms of CAPEX and OPEX. Cloud technologies can foster the development process of MTC applications, saving the money for maintaining servers. Moreover, cloud service providers can better protect MTC applications from potential security threats. The power and energy restrained MTCDs can be better served by offloading their processing and storage to the cloud [7]. Thus the integration of clouds and IoT/MTC is suitable for providing new MTC services and applications [110].

For MTCDs and applications in a wide coverage area, long delay of the cloud-based MTC approach can not be ignored, especially for mission-critical or delay intolerant M2M traffic. Furthermore, large amount of data is exchanged between cloud servers and MTCDs, thus consuming bandwidth and other network resources [7]. These limitations can be removed by employing fog/edge computing technology. As a result, the delay can be reduced significantly by deploying edge nodes near to MTCDs. As fog/edge nodes can make local decisions and respond to MTCDs immediately, the delay requirement for delay-sensitive M2M applications can be satisfied. This is discussed in detail later in this paper.

5) DATA AGGREGATION

Data aggregation is an effective way to reduce unnecessary message transmissions and relieve traffic congestion in RANs. Data aggregation is a technique developed for collecting, processing and transmitting data from resource-constrained MTCDs [110] in order to achieve: improved energy consumption and network life time, reduced traffic load and eliminating data redundancy [53]. According to Liao and Song [111], the aggregated MTC transmissions exhibit similarity to HTC transmissions when proper RRM schemes, access strategies and data aggregation schemes are employed.

Since the scope of this paper is on data aggregation due to its significant benefits both for the network and for the MTC devices. Therefore, the next section explains its effect and also the role of aggregators as defined by ETSI.

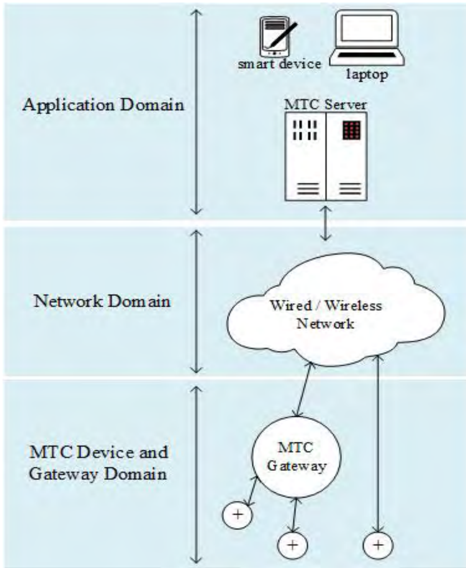


FIGURE 3. High level MTC architecture by ETSI [56].

IV. DATA AGGREGATION AS SOLUTION FOR MASSIVE ACCESS

The solutions based on data aggregation have been advocated in literature [24], [78], [100], [112], [113] because of its potential benefits both for the network operators and the MTCDs. Data aggregation in MTC networks results in reduced power consumption [24], [114], enhanced resource allocation efficiency [99], reduced excess signaling load [115] and enhanced quality of cell-edge MTCDs' links [23], [100], [106]. In data aggregation schemes, a data aggregator is designated to collect, process and relay the data to a BS. The ETSI further explained its role in the MTC network as following.

A. ETSI ARCHITECTURE AND ROLE OF DATA AGGREGATORS

In [56], ETSI has specified a high level architecture for MTC, in which the role of gateway is defined. The main components and their functionalities of this architecture are explained in Table 3 and shown in Figure 3. The gateway is responsible to aggregate and forward collected MTC data to a central

TABLE 3. High level architecture for M2M communication specified by ETSI [56].

Component	Domain	Functionality
MTCD	Device domain	A device that runs MTC applications by using MTC service capabilities. It sense its environment at the specified interval/events.
MTC gateway	Device domain	A device that acts as proxy to collect and process data from MTCDs in its coverage area and transmit the collected data to the network domain.
MTC area network	Device domain	A network that provides connectivity between MTCDs and MTC gateways. Any WLAN/WPAN technology like Bluetooth, Wi-Fi can be used.
Access network	Network domain	It provides connectivity between MTCD domain and the core network. Access network can be wired or wireless like xDSL, satellite, UTRAN and WiMAX.
Core network	Network domain	It provides services like IP connectivity, service and network control functions, roaming, interconnections with other networks and the like.
MTC service capabilities	Application domain	It consists of servers that store, process, manage and control the MTC data send by the MTCD or MTCG. The legitimate users can remotely control their MTCDs by using MTC applications on their smart devices like smartphones or laptops.

application or to MTC application server that processes the information and triggers actions when needed.

As it is described in ETSI architecture for MTC that the MTC devices may connect to the network through gateway using capillary or cellular connections. Thus, on the basis of radio access technologies (RATs), MTC networks can be classified as cellular MTC networks and capillary MTC networks [40], [47], [100] as shown in Figure 4. In cellular MTC networks, MTCDs are equipped with embedded subscriber identity module (SIM) and communicate with MTC gateways/BS using licensed bands such as LTE-A [37], [47]. Machine type communication through LTE-A cellular networks is expected to constitute a significant part of the IoT [116]. On the other hand, in capillary MTC networks, MTCDs communicate using any of unlicensed short-range radio access technologies such as HaLow, ZigBee, smart utility networks (SUN), Bluetooth Low energy (BLE) and the like [40]. The MTC capillary network provides local connectivity to MTCDs using short-range radio access technologies while it connects to the backhaul cellular network through a gateways also termed as capillary gateways [117].

B. THE EFFECTS OF USING DATA AGGREGATION

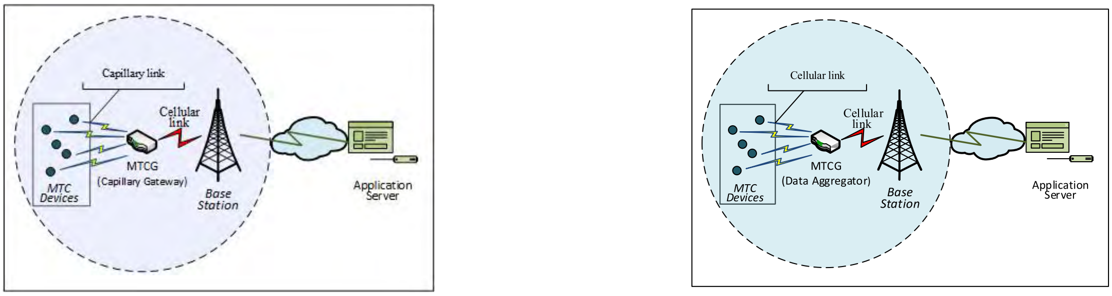
The use of data aggregation brings candid solution to resolve challenges induced by massive access in MTC network. The usefulness of data aggregation is analyzed by several authors in cellular and capillary networks. Matamoros and Anton-Haro [118] have presented the effect of using data aggregation in capillary MTC networks, while Lo *et al.* [114], Tsai *et al.* [119], Xie *et al.* [120] and Noor *et al.* in [100] have presented its effects in cellular networks. Figure 5 shows that how the use of data aggregators reduces network traffic.

Lo *et al.* [114] have put forward a four-tier based cellular MTC network architecture, introducing relay nodes as data connectors/aggregators. These relay nodes are responsible for aggregating data from multiple MTCDs into single large packet and then transmitting it to the MTC servers. Thus, reducing the transmission power of energy-constrained MTCDs. Both Tsai *et al.* [119] and Xie *et al.* [120] analyzed the effect of data aggregation on the throughput and access delay in M2M network along with the discussion on the analytical models. However, no particular mechanism for data aggregation realization has been proposed. Another experimental study has been carried out by Noor *et al.* in [100] to quantify the effect of data aggregation on cellular radio access signalling overhead. They have conducted a detailed experimental study in order to measure, quantify, and analyze the signaling overhead of two classes of M2M services: smart metering and vehicular applications. Two practical signaling reduction techniques are proposed and analyzed, with focus on aggregation as an efficient approach to overcome the resulting surge in signaling load. Their study has revealed that high aggregation levels, which offer minimum signaling, come at the cost of high delays.

As mentioned earlier, this paper is presenting a review of state-of-the art data aggregation proposals. It is worth mentioning here that the data aggregation solutions surveyed in this paper are based on MTC uplink transmission. However, data aggregation for downlink MTC are not considered here. Interested readers may refer to [121], for MTC downlink data aggregation.

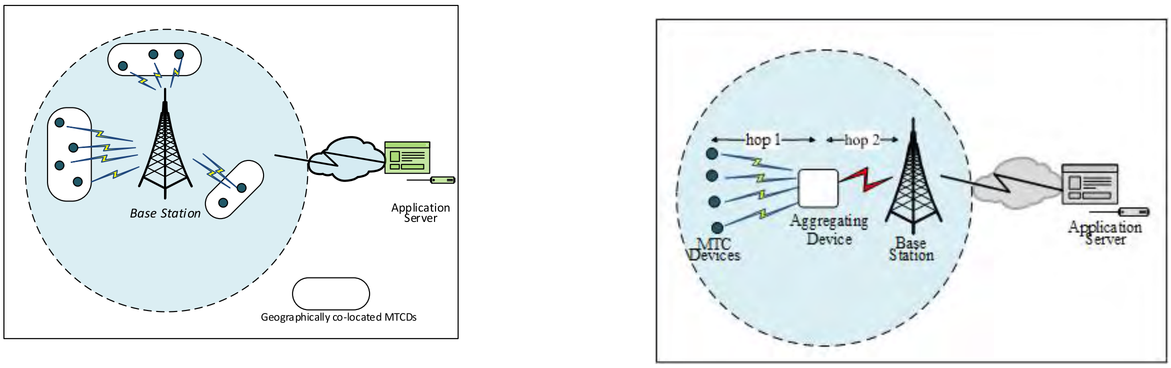
C. CATEGORIZATION OF DATA AGGREGATION TECHNIQUES

Data aggregation (DA) remained a powerful and advantageous technique for collecting sensors' data in WSNs. Due to its potential benefits, it is also widely adopted in mMTC networks. Data aggregation involves an MTCG to collect and process data from MTCDs in its coverage area. An MTCG is a powerful node than MTCDs and may be equipped with resources such as protocol translation [54], storage, multiple communication technologies (like cellular and low power communication technologies) [115] and processing capabilities [55]. An MTCG is connected to the BS through cellular networks such as LTE-A while the communication between MTCD and MTCG can either be through cellular



(a) (b)

FIGURE 4. **General architecture of capillary and cellular MTC networks. (a) Capillary MTC networks. (b) Cellular MTC networks.**



(a) (b)

FIGURE 5. **Illustration of effect of data aggregation on the BS. (a) No aggregation. (b) With aggregation.**

networks or through other wireless communication standards such as IEEE 802.11x [116].

Several data aggregation based proposals exists in literature. Therefore, in this section, we are reviewing these proposals and also categorizing them according to the aggregation technique and type of aggregator. Data aggregation techniques/proposals for MTCDs can be categorized on the basis of aggregating device as : DA using dedicated gateway, UE based DA, DA based on UAV, Fog based DA and Cooperative DA.

1) DA BASED ON DEDICATED GATEWAYS

The DA techniques with gateways require a standalone, dedicated MTCG or relay node that is responsible for aggregating MTCDs' data in its vicinity. The network-controlled MTCG facilitates communication among MTCDs [4] and provides cellular backhaul connectivity. Depending upon the gateway density with which an MTCD can simultaneously connect, DA schemes can be divided into two classes: single dedicated gateway and multiple dedicated gateways. A comparison of single vs multiple dedicated gateways is shown in Figure 7.

a: SINGLE DEDICATED GATEWAY

The use of a dedicated, standalone MTCG effectively reduces the number of connections to the BS at the cost of extended communication delay. The gateway acts as a proxy [65], collects and examine the MTC data in its vicinity. Depending upon the delay tolerance of the MTC data, the gateway transmits it to the BS [151]. Malak *et al.* [23] have suggested that hierarchical networks can provide efficient data aggregation for battery-constrained MTCDs. They have developed a coverage probability-based optimal and energy-efficient data aggregation scheme for hierarchical MTC networks to minimize the average total energy expenditure. An energy-efficient MTCD to MTCG communication has been investigated through physical layer optimization. The algorithm is performed sequentially in several phases. In every phase, some nodes are selected as gateways in a probabilistic fashion, and the nodes with uplink data transmit their payloads to the closest gateway. After transmission of the payloads, the transmitters switch off, and the aggregators perform a new phase of the algorithm. Hence, in every phase there is a new hierarchy of gateways that receive the payloads from the gateways of the previous phase. The authors have provided a model based on stochastic geometry to select the gateway's density that optimizes energy efficiency.

khan *et al.* [122] have presented a data aggregation and multiplexing scheme for cellular M2M traffic in order to improve LTE-A radio resource utilization. The 3GPP standardized layer 3 in-band relay nodes have been used to aggregate uplink MTC traffic. However, the authors have not

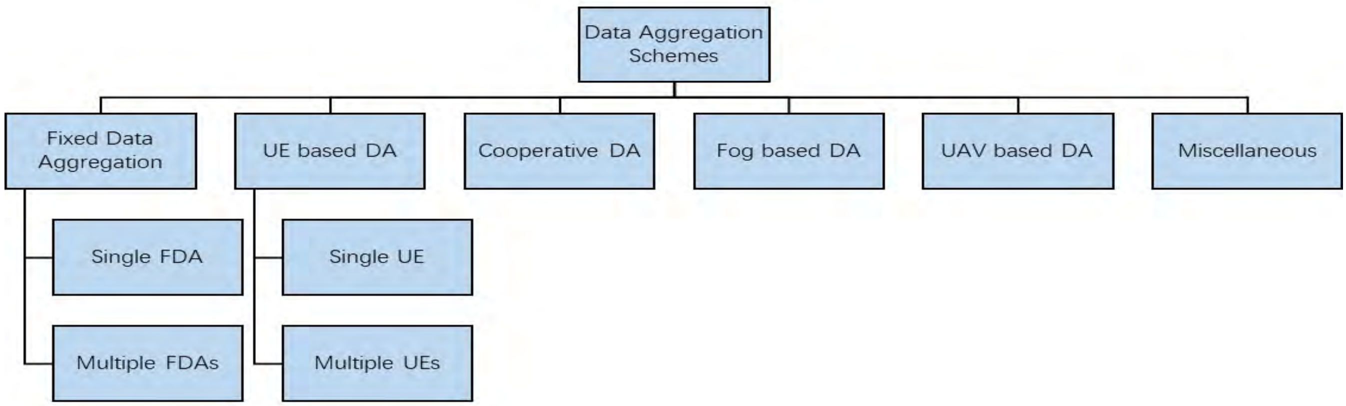
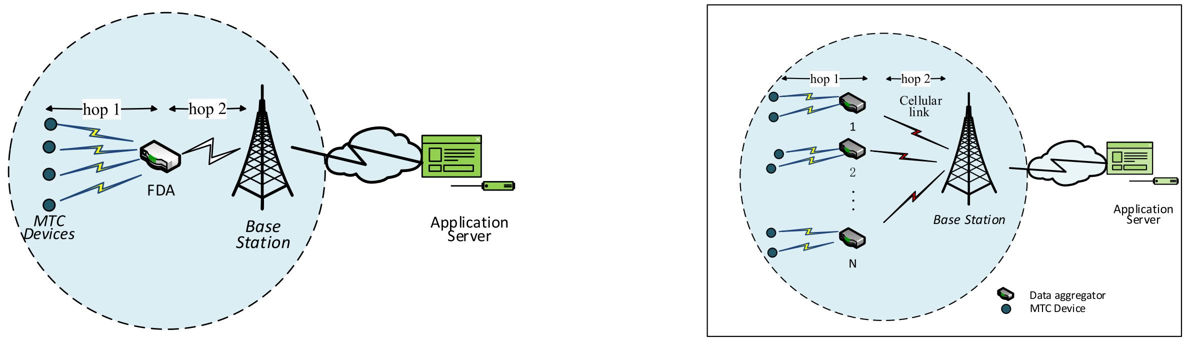


FIGURE 6. Classification of data aggregation techniques.



(a) (b)

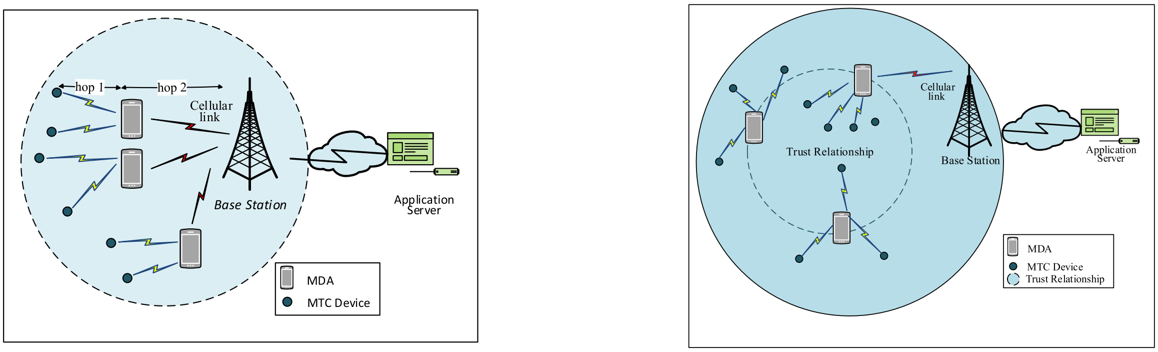
FIGURE 7. Comparison of single and multiple fixed data aggregation techniques. (a) Single FDA. (b) Multiple FDAs.

consider MTCDs' QoS requirements and the results are evaluated only on the basis of simulation with no mathematical analysis.

Ali and Rajatheva [123] have presented the concept of opportunistic spatial orthogonalization of MTC interference at the BS; for HTC and MTC coexistence in cellular networks. In their proposed scheme, the cellular users share uplink resources with MTCDs; the cellular users that lie at large distance from MTCG are chosen for resource sharing. The proposed method has exploited received interference diversity at the BS for each resource block (RB) and has allocated radio resources to the MTCDs with minimum interference on the BS. OFDMA based system has been employed with focus on interference minimization at the BS while the interference at MTCG has been taken as background noise. It is assumed that one RB is shared between uplink cellular user and one MTCD to MTCG link. The authors have considered delay tolerant MTCDs having minimum or no mobility. The BS needs to keep information of all the MTCDs that require to transmit their data along with their CSI information; making this proposals suitable for MTCDs with periodic traffic type. The results have been obtained through simulations only.

Some papers have examined MTC with data aggregation over large scale networks [124]–[126]. Kwon and Cioffi have derived the distribution of signal-to-interference ratio (SIR) for wireless network in [124]. The authors have derived outage-optimized geometric densities of randomly deployed aggregators. The effect of random deployment of both the aggregators and MTCDs on SIR performance has been analyzed. *Nearest neighbor rule* is employed by the aggregators to serve the MTCDs in their vicinity. Mass deployment of aggregating nodes was considered in order to reduce the control-overhead problems in MTC networks. The paper does not address the MTC QoS requirements which vary for different MTC applications and services. Moreover, the collisions on the random access channel have not been considered in addition to the traffic load at an aggregator.

Guo *et al.* [125] and Lopez *et al.* [126] have also presented a data aggregation solution for mMTC for a large scale network. Using stochastic geometry, the authors have analyzed the benefits of using data aggregation in large scale network in terms of energy efficiency and reduced congestion. Their data aggregation schemes also involve resource allocation at the aggregator in addition to aggregation. The provision



(a) (b)

FIGURE 8. Comparison of single and multiple UEs based data aggregation techniques. (a) Single UE based data aggregation. (b) Multiple UEs based data aggregation.

of resource allocation at the aggregator further abates the signaling nuisance at the BS.

b: MULTIPLE DEDICATED GATEWAYS

In [56], it is specified that an MTCD can be connected to the network domain, through multiple gateways. In this vein, Tefek and Lim [94], considered the allocation of MTCDs to more than one aggregators at the same time. In their proposed SIR based relaying, more than one MTCGs may decode data packets of an MTCD. Since this consideration may result in duplicate data transmission to the aggregators due to lack of cooperation between the MTCGs. Therefore, to overcome this problem, they proposed location based relaying. MTCDs exchange location information with MTCGs and only the MTCDs that are in close proximity of an MTCG are allowed to connect with it.

c: CHALLENGES AND LIMITATIONS OF DATA AGGREGATION WITH DEDICATED GATEWAYS

The use of gateways effectively reduces the number of connections to the core network at the cost of extended communication delay. The gateway-based schemes use a dedicated aggregator device that is fixed at a certain location. The optimal positioning of gateway is very critical in order to achieve the promised energy efficient results concerning data aggregation. However, this cannot be achieved for all the MTCDs due to their variable distances from the gateway. Furthermore, all the existing proposals about using single gateways suffer from the single point of failure, which may occur due to the unavailability of a gateway due to any device or network malfunction. In short, schemes based on gateways suffer from two main problems namely gateway's sub-optimal positioning and single point of failure.

2) UE BASED DATA AGGREGATION

In the current era, smartphones/UEs share the same geographical space as MTCDs. Since MTCGs are deployed at particular locations and thus have variable distances from the MTCDs; Smartphone, due to their intrinsic mobility can come close to the MTCDs, thus shortening the communication distance between them. In this way, power can be saved due to reduced transmission distance between MTCDs and UEs [112]. According to Pereira and Aguiar, in such a scenario UEs can play an important role of MTCG acting as proxy gateway for neighboring resource-constrained MTCDs [48].

The use of UEs as gateways provides reliability and improves energy consumption [115]. Hossain and Hasan [4] have argued that network-assisted communication among UEs and MTCDs can significantly increase the overall spectrum and energy efficiency of the cellular networks. However, some authors such as [41], [96] do not favor the use of UEs as MTC gateways due to their limited battery power and mobility. Nevertheless, the role of UEs is changing due to the advent of D2D communication in current era. The intelligence at UEs [5] is being utilized for peer assisted content delivery networks [127], crowdsensing [128], data offloading [112], load balancing [129], [130], cooperative relaying [131]–[133], caching and resource allocation [5], [134]–[138] and for information dissemination in disaster stricken areas [139]. Several authors favors the use of a UE as gateways for MTCDs [115], [140], [141] particularly for health-care applications [48], [128], [142]. Furthermore, the issue of battery depletion of UEs can be eliminated by employing either energy harvesting techniques [143] or packet transmission scheduling through linear programming [144].

On the basis of number of UEs used for aggregating/relaying MTC data, UE based data aggregation solutions can be classified as: single UE and multiple UEs. Figure 8 illustrates the single and multiple UEs based data aggregation techniques.

a: SINGLE UE AS GATEWAY

In mobile M2M communications, smartphones are also envisioned to play the important role of M2M gateways for nearby MTCDs with constrained resources and limited connectivity [128]. The problem of sub-optimal positioning of

TABLE 4. Comparison of aggregation schemes based on fixed data aggregation.

Related Work	Year	Contribution	Analytical Tool	Shortcomings
Kwon and Cioffi [124]	2013	Stochastic analysis of wireless channel, transmit power and random deployment of MTCGs effecting the SIR distribution with randomly deployed MTCDs in an area	Stochastic Geometry	No consideration of collisions at RACH and load at MTCGs
khan *et al.* [122]	2016	Novel data aggregation and multiplexing scheme for cellular networks to improve radio resource utlization	Simulations	Lack of mathematical analysis
Malak *et al.* [23]	2016	A coverage probability-based optimal data aggregation scheme for MTC networks to obtain energy efficiency	Stochastic geometry	QoS requirements of MTCDs are not considered
Ali and Rajatheva [123]	2017	Opportunistic spatial orthogonalization of MTC interference at BS	Simulations	BS keep track of CSI and MTCDs which need to transmit data
Guo *et al.* [125]	2017	Stochastic analysis of interference at large scale networks with resource allocation at the aggregators	OP through stochastic geometry	Fixed resource allocation by the aggregator
Tefek and Lim [94]	2017	Dynamic resource allocation by the aggregator and SIR based relaying in large scale networks	OP through stochastic geometry	Homogeneous MTC traffic considered focusing delay tolerant MTCDs
Salam *et al.* [132]	2018	Priority based resource allocation by the aggregator	Outage probability (OP)	Random access by MTCDs to send requests to the aggregator
Lopez *et al.* [126]	2018	Hybrid OMA-NOMA based data aggregation scheme for large scale networks	Success probability through stochastic geometry	Fixed number of resource availability considered at the aggregator
Salam *et al.* [113]	2018	Prioritized access for delay intolerant MTCDs	Outage probability	-
Zhao *et al.* [63]	2018	Joint mode selection, radio resource allocation and power control to improve overall system data rate and reduce average traffic delay.	Coalition formation game	Varying QoS requirements of MTC are not considered

a dedicated gateway can also be addressed with the use of mobile data aggregators (MDAs). The authors in [140], [141], [143] have proposed to employ user equipment (UE) as data aggregator to gather data from its surrounding MTCDs. The proposed schemes show that the sub-optimal positioning of a dedicated gateway can be compensated by the mobility of a UE at the cost of more communication delay.

The authors in [141] have employed D2D communication for aggregating and trunking MTC traffic. They are the pioneers to propose UE as gateway for MTCDs. They proposed a time division multiple access (TDMA) based medium access control (MAC) scheme for relaying MTC data to the BS through UEs. They employed trunked radio system to determine the basic trade-off between latency and transmit power for delivering the aggregated data of MTCDs.

The authors in [140] employed joint user decoding to relay MTC traffic through network assisted D2D communication underlying downlink transmission of regular cellular users. They developed a closed form expression of maximum zero-outage downlink for multiple MTCDs connected to the UE.

When smartphones/ UEs are used as MTC gateways, one of the concern is that their energy may get depleted quite often. Therefore, energy harvesting can be employed to solve this issue. One of the possible way to harvest energy can be from ambient radio signals [4]. Atat *et al.* have proposed to use radio frequency (RF) energy harvesting to cater for the battery depletion issue of UEs and have proposed an RF energy harvesting model based on stochastic geometry [143]. The authors have favored to offload MTC traffic onto underlay D2D links for efficient management of radio resources and prolongation of MTC's devices battery life. Underlay D2D communication has been utilized and a tradeoff between spectrum partition factor and time that UEs spent in harvesting energy for MTC relaying has been analyzed. They have also analyzed the spectral efficiency and coverage probability of underlay D2D assisted MTC traffic. Their simulation results have revealed that by employing a small partition factor along with sufficient channel resources, a balance between cellular users and D2D users and a higher MTC and D2D spectral efficiency can be achieved in dense cellular networks.

Similar to the work by [141], the authors in [145] have proposed trunking and aggregation of MTC data in a large scale network. They have considered homogeneous deployment of MTCDs in an area and have proposed the association of at most one MTCD with the UE. Poisson hard sphere model for UE coverage has been considered for a large scale network.

Resource allocation for MTCDs by UE was first considered by [147]. The authors have considered a hybrid HTC and MTC model in cellular networks where a UE is configured as an MDA for MTCDs. They have proposed a novel resource allocation scheme based on residual energy of MTCDs. They have highlighted the fact that in IoT, usually a group of MTCDs operate collaboratively for monitoring of a certain area, therefore, energy efficiency and lifetime prolongation are important design aspects for MTC over cellular networks. They have proposed an algorithm for radio resource allocation for MTCDs, in which MTCDs with less residual energy is preferred over MTCDs with more energy. They have also proposed to grant more transmission time to MTCDs with less residual energy.

Pereira *et al.* [128] have mapped two applications that rely on the role of a smartphone as a gateway, which acts as a proxy to connect legacy devices to the IoT using a standard middleware. They have illustrated the advantages of using M2M, and have measured the energy savings obtained, showing improvements of smartphones' battery life by avoiding transmitting duplicated data. It is shown that the choice between using random access memory (RAM) and hard drive to store sensor data can have impact on battery consumption. They have also highlighted some of the challenges when UE are used as gateways. These include: UE mobility, IP addressing, resource aware application development, data collection from UE and storage.

Yang *et al.* [146] have studied an uplink energy minimization problem with NOMA and energy harvesting for MTC networks. The optimization problem is formulated to minimize the total energy consumption by optimizing the power control and time scheduling, where the throughput constraints for both MTCDs and UEs as well as the minimal required harvested energy constraints for MTCDs are all considered. In their proposed scheme, they have considered UEs as gateways for MTC traffic and orthogonal TDMA is employed by multiple MTCDs to transmit their data to the UE. They have considered orthogonal time resources for UEs, therefore no inter-UEs interference is possible. To cater the battery needs of MTCDs, they have proposed that each MTCD may harvest energy when the UEs transmit data to the BS.

b: MULTIPLE UES AS GATEWAYS

The solutions proposed in [140], [141], [143], [145], [147] are based on single UE. Except [147], all of these works are focusing on the uniform QoS requirements for all the MTCDs. Only delay tolerant MTC data was considered by these works. The authors in [147] performed resource allocation for MTCDs with less residual energy. These works also did not take into account the non-availability issue of MDAs. An MDA may become unavailable due to load, battery depletion, mobility or any other malfunctioning. In that case an outage for MTCDs will occur.

To improve the coverage, throughput and energy efficiency of the cellular network, collaboration among UEs and MTCDs is mandatory [148]. Muti-hop D2D communication is employed by [148], [149] for relaying MTC data through set of UEs. A multi-hop network-assisted D2D communication scheme for relaying MTC data along with a resource allocation strategy to meet the QoS requirements of MTC traffic was proposed by Rigazzi *et al.* in [149]. In their proposed scheme, the collector node transmits MTC data to UE through opportunistic D2D communication. The BS is responsible for D2D cluster discovery, obtaining CSI of all the cluster members and thus construction and maintenance of directed acyclic graph among nodes (MTCDs (sensor and collector nodes) and UEs). No simulation or mathematical analysis was provided to validate the effectiveness of their proposed scheme.

Swain *et al.* in [148] presented a stochastic geometry based framework to analyze the coverage probability and average data rate of a three-hop MTC network deployed along with UEs and conducted extensive simulations to study the system performance. Coverage and average rate analysis of both MTC uplink and downlink communication is considered. The simulation results show that the three-hop M2M network formed from out-of-range MTCDs and UEs can significantly improve the coverage and average rate of the entire network. In their proposed model, the problem of UE mobility is addressed by using space-time graph by the BS. The BS has to keep track of UEs' futuristic positions by developing and maintaining space-time graph of the set of UEs relaying MTCDs' data. It should be noted that in their proposed multihop D2D communication, the set of UEs are not aggregating MTCDs' data, rather each UE is responsible for relaying the data of an MTCD to next hop (UE/BS). In addition, the load on a UE is also not considered. Although the proposed scheme is favoring out of coverage MTCDs through multihop relaying by UEs, however, their proposed scheme is not considering the delay intolerance of MTCDs, moreover, instead of aggregating MTCDs' data, the UEs are only relaying the data of each MTCD.

The set of UEs in both [148], [149], perform relaying of MTCDs' data. In other words, to relay MTC data to the BS, multi-hop D2D communication is employed by routing MTC data through UEs. These schemes are beneficial for out of range MTCDs, however, they do not curtail the amount of MTC traffic at the BS. Moreover, the load on UE is also not taken into account.

In our proposed scheme [115], we have analyzed the performance of single and multiple FDAs and UEs in MTC network. We proposed to employ multiple UEs for MTC data aggregation and developed a trust framework for the selection of trusted MDAs. Social graph is a convenient tool to illustrate the relationship between two nodes [131]. The proposed technique eliminates the dependency on a single device to aggregate data in addition to the improved communication delay as compared to single UE. The proposed multiple UEs selection scheme significantly improved the communication delay and outage probability as compared to schemes based on single FDA, UE and multiple FDAs. The improved performance is credited by leveraging the delay tolerance and abridged transmission distance.

TABLE 5. Comparison of schemes employing UE based data aggregation.

Related Work	No. of UEs	No. of hops to BS	Contribution	Shortcomings
Pratas and Popovski [140]	Single	One	MTC traffic relaying through network assisted D2D links underlying downlink transmission of primary cellular users	UE's mobility and load not considered
Rigazzi *et al.* [141]	Single	One	TDMA based MAC scheme for MTC data trunking and aggregation through UE by employing D2D communication	UE's mobility and load not considered
Atat *et al.* [143]	Single	One	RF energy harvesting to cater the issue of battery depletion by UEs	UE's mobility and load not considered
Afzal *et al.* [145]	Single	One	Trunking and aggregation of MTC data in a large scale network	UE's mobility and load not considered
Zhang *et al.* [147]	Single	One	Novel resource allocation scheme by UE for MTC data aggregation based on residual energy of MTCDs	UE's mobility and load not considered
Pereira *et al.* [128]	Single	One	Use of UE as gateway for smart health monitoring and crowdsensing	UE's unavailability not considered
Rigazzi *et al.* [149]	Multiple	Multiple	Multi-hop D2D communication scheme for MTC along with a QoS aware resource allocation strategy for MTC traffic.	Set of UEs performing relaying instead of data aggregation
Swain *et al.* [148]	Multiple	Multiple	Coverage and rate analysis MTC network through UE routing.	Set of UEs performing relaying instead of data aggregation
Salam *et al.* [115]	Multiple	Two	Aggregation of MTCDs data through trust-based grouped UEs	Favors delay tolerant MTCDs
Yang *et al.* [146]	Multiple	Two	Data aggregation and time scheduling with NOMA using UEs as aggregators	Favors delay tolerant MTCDs

c: CHALLENGES AND LIMITATIONS OF USING UES AS DATA AGGREGATORS

Despite the usefulness of the UE based data aggregation schemes, particularly the one proposed in [115], the proposed scheme is well suited for delay tolerant services. Most of the existing work is also focusing on the same QoS requirements for all the MTCDs, which is highly unlikely as an mMTC network may comprise of both delay tolerant and intolerant services. Cooperative relaying techniques can reduce the attenuation and extend the communication range for low-powered MTCDs [131]. In next subsection we are presenting a review of cooperative aggregation in MTC networks.

3) COOPERATIVE DATA AGGREGATION

Cooperative communication [150], [151] was introduced to solve the problems faced by single user channel. Since its advent, cooperative relaying has been extensively used for enhancing network capacity [115].

The problem of mobile aggregator's overwhelming and single point of failure can be solved by using multiple mobile aggregators, as proposed in [115]. However, an MTC network is a combination of both delay tolerant and intolerant MTC services. This implicates the urge to propose a solution that caters the requirements of both of these MTC services. Therefore, a cooperative data aggregation algorithm is proposed by Salam *et al.* [132] that employs a fixed data aggregator (relay node or MTC gateway) to aggregate delay intolerant MTC data while trust-based group of user equipments is employed to relay delay tolerant MTC data. Figure 9 illustrates the cooperative data aggregation scheme proposed in [132]. The outage probability for three hop communication scenario is analyzed. The numerical and simulation results reveal that the proposed cooperative algorithm performs better as compared to existing single and multiple aggregators schemes.

Huang *et al.* [131] have proposed an architecture based on energy harvesting and social-aware relays in large scale networks. The authors proposed two different relay selection strategies, namely, social-aware random relay selection and social-aware best relay selection. They argued that deployment cost of relays can be reduced through energy harvesting techniques. Through stochastic geometry model, the outage probability and network throughput of the proposed cooperative relaying strategies are derived and multiple MTC transmitter-receiver pairs and relays form independent homogeneous Poisson point processes, respectively. The simulations and mathematical analysis reveal that social awareness can contribute towards the stability of communication and perform better as compared to techniques that do not consider social networking characteristics.

4) UAV BASED DATA AGGREGATION

The mMTCDs are typically unable to transmit over a long distance due to their energy constraints. Therefore, in such scenarios, UAVs can dynamically move towards them, collect their data, and transmit it to ground BS [68].

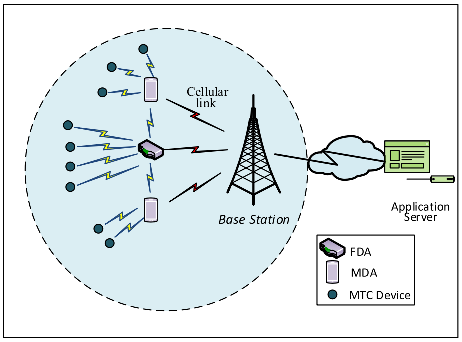


FIGURE 9. Illustration of cooperative data aggregation [132].

The drones or UAVs play the role of mobile aggregators or BSs for mMTC networks [152].

Hattab and Cabric [92] highlighted the issues raised with the coexistence of cellular UEs and MTCDs and discussed the problems of resource-sharing-based and orthogonal-based solutions. To tackle these issues, they have proposed an architecture which employs UAVs or drones as mobile aggregators. Each UAV is equipped with single-antenna cellular radios and can serve a cluster of MTCDs by hovering at low altitudes. In their proposed architecture, they have employed time-division duplexing protocol for enabling spectrum sharing between HTC and MTCDs and load-aware power control protocol limits the interference from HTC devices. To increase the number of simultaneously served MTCDs; resource-splitting is also employed. The results were obtained through simulations only.

Challenges and Limitations:

The research on UAVs as data aggregators for MTCDs is still in its infancy and not much research is done in this area. The work in [92] opens new ways of data aggregation by UAVs. However, the proposed architecture requires the location information of HTC and MTCDs along with the number of HTC devices connected to the BS. Therefore, new proposals and techniques are required to employ drones as aggregators for reducing transmit power of MTCDs deployed in scenarios such as bridge, warehouse monitoring, pest control, water management and the like.

5) FOG BASED DATA AGGREGATION

The on-demand and scalable nature of cloud makes it well-suited for resource constrained MTCDs. However, the distant cloud servers results in long communication delays and increased networked traffic [7]. Fog or edge computing may be employed to tackle these issues [7], [9], [153] especially in IoT use cases [110]. The central idea of fog/edge computing us to place computing resources close to the MTCDs generating the data in order to reduce communication latency and bandwidth demands [7]. Fog nodes can be small base stations, access points, vehicles or even UEs [110].

In [9], Fitzgerald *et al.* have formulated mixed-integer programming problems to optimize routing for both data aggregation and multicast dissemination in IoT egde networks. Throughput optimization for cases with only unicast aggregation was also presented. The fog nodes provided multiple data collection gateways at the network edge, and actuators directly utilized sensor measurements. Numerical results demonstrated that the performance is affected by the network size. Their proposed schemes have the potential to provide energy efficient solutions for future IoT edge networks.

The exponential growth of IoT applications/MTCDs is becoming challenging for cloud-based systems. Contrary to conventional sensor-gateway-cloud model, Lyu *et al.* in [153] presented sensor-fog-cloud architecture for collecting data from smart meters in an area. In their proposed model, Fog nodes can act both as data aggregators as well as Fog servers. The proposed energy-efficient data aggregation model focuses on the security of the aggregated data. For this purpose, encryption techniques are applied both at Fog and Cloud levels. It is ensured that the Fog nodes can not extract meaningful information from the data aggregated from the smart meters other than the desired statistics. Their proposed model saves significant energy consumption, mitigates bandwidth bottleneck and reduces time delay in the network, thus helping to prolong the network lifetime.

6) MISCELLANEOUS DATA AGGREGATION TECHNIQUES

The aggregation techniques mentioned above, are based on the type of data aggregator used. However, data aggregation can be possible through other techniques too. Huang *et al.* in [154], proposed a new admission control model for MTC, which classifies all MTC requests into delay-intolerant and delay-tolerant first, and then aggregates all delay-tolerant requests, aiming to reduce the number of requests from devices to base stations. An admission control algorithm based on this model is devised to prevent congestion and to improve the quality of services, and a network calculus based performance-analyzing technique is developed for this model. Both theoretical analyses and simulation results revealed the effectiveness of the proposed model.

For exploiting network slicing, data aggregation (DA) can be adopted to effectively address the massive connectivity and latency requirement. In [155], Xu *et al.* proposed a network slicing based data aggregation technique. Different from conventional DA scheme where data aggregation is performed based on device locations, the authors performed DA according to latency requirement for MTCDs, with aim to exploit the benefits of network slicing and thus improve network access capacity and decrease access latency. The DA problem is formulated as a 0-1 Linear Programming and an efficient two-step algorithm to aggregate the MTC data for accessing a specific network slice is presented. The performance of proposed network slicing based data aggregation for typical MTC scenarios is analyzed through simulations. Simulation results show that their proposed scheme significantly outperformed traditional MTC access schemes (without network slicing) in terms of network capacity, access congestion degree, and latency. No mathematical tool is utilized for supporting the proposed scheme.

Liao and Song [111] considered the coexistence of HTC and MTC traffic in cloud-RAN (C-RAN) networks and studied the effect of computing-resource constraint of C-RAN networks on the achievable sum-rate of MTC gateways/aggregators. The authors analyzed the computing resource consumption of each transmission from HTC and MTCDs and found that the maximization of the sum-rate of MTC gateways is a binary integer non-linear programming problem with a non-convex inequality constraint i.e. NP-hard and highly intractable for a large scale network. The authors proposed to relax the combinational problem into a general continuous non-linear programming (NLP) problem, and developed suboptimal iterative algorithm. It is shown that the availability of computing resources at the C-RAN network has significant influence on the HTC users' satisfaction and also the number of MTCDs supported by the gateways. The results revealed that the more the resources available at the C-RAN, the more MTCDs are supported by the MTC gateways. However, it was not studied that how the proposed architecture will satisfy the requirements of MTCDs with strict delay constraints as may be the case emergency alarm messages.

D. DATA AGGREGATION IN CAPILLARY NETWORKS

The use of capillary network and gateway was studied by many researchers to reduce the network congestions [156]. To alleviate the issues caused by trillions of MTCDs in 5G networks, Chih-Lin *et al.* [157] put forward an MTC architecture consisting of multiple aggregators; each aggregator responsible for specific MTC traffic. The authors considered MTCDs' connection with the aggregators through cellular/capillary networks, however, the effect of simultaneous massive access of these devices at aggregators is not taken into account. Each aggregators requests for resources depending upon the type of aggregated MTC data.

Following the same footsteps, [158] proposed to use multiple data aggregators to overcome the link congestion at single aggregator and also the suboptimal positioning of the aggregator. The authors proposed to use *Nearest neighbor rule* for the allocation of MTCDs to the aggregators. However, the authors did not consider the interference caused by massive MTC access at the aggregator, rather they considered *idealized* capillary network between MTCDs and the multiple aggregators with no interference.

Matamoros and Anton-Haro [118] presented a DA scheme in capillary networks for environmental monitoring systems. They propose to compress data at the aggregator to overcome the network overload problem but also to enable the network to support massive number of MTCDs. Shariatmadari *et al.* in [159] put forward an aggregation scheme for capillary networks within cellular networks. In their proposed aggregation scheme, MTCDs connect to the fixed (static) aggregator using capillary connections. The aggregator sends the aggregated data to the BS upon the expiry of aggregation period. The authors have considered only static MTCDs. Moreover, The LTE model used in [159] considers a simplified connection establishment, not taking into account that recently active aggregators do not need connection establishment Furthermore, the use of a fixed aggregation period introduces fixed, potentially large, latency for the MTC transmissions.

Tsai *et al.* [160] evaluated the performance of data aggregation in terms of energy efficiency, thus to increase the lifetime of capillary M2M networks. The system group the M2M devices into clusters and each CH is an M2M gateway. This gateway collects data from cluster M2M devices and send to M2M application server periodically.

AlQahtani pioneered to propose priority based scheduling for MTC data aggregation in [161]. The author proposed a priority-based data aggregation scheme at the M2M gateway that effectively maintains a good trade-off between the power consumption and delay requirement. The MTCDs are classified into three different classes depending upon their delay requirements. The authors developed an analytical model for the MTCG that performs aggregation for different priorities using the M/G/1 queuing model. The system performance is analyzed with respect to the average waiting time, system delay and power consumption. There proposed scheme considered only one MTCG which may be overwhelmed by massive access of MTCDs at peak hours or emergency.

V. DISCUSSIONS ON DATA AGGREGATION TECHNIQUES

In this article, the massive connectivity issue of MTCDs is thoroughly discussed and an overview of various approaches to solve this nuisance has also been presented focusing on data aggregation techniques. In Table 6, the advantages and limitations of various data aggregation techniques has been presented along with their challenges in 5G networks.

Contrary to WSNs, MTC networks are infra-structured networks in which MTCDs communicate with the MTC servers through capillary or cellular networks; this communication mostly takes place through gateways. The MTC architecture provided by ETSI [56] and the effect of relay/proxy nodes specified by [65], [114], paved the way for several proposals based on MTC gateways for MTC networks. The MTC gateways ensure the always-availability for MTCDs, as they are being provided by constant power supplies. These are usually owned by third party providers and can be deployed at indoor and outdoor scenarios. Besides data aggregation, they can provide resource allocation for the MTCDs, thus, alleviating burden at the BS. A major challenge for these legacy gateways is to provide resource allocation to MTCDs based on their stringent QoS requirements.

The proposed advantages of MTC legacy gateways can be achieved when they are deployed at optimal locations. However, in actual MTCDs can be deployed at deep indoors and the like, thus making it difficult for MTCDs to be under the coverage of these gateways. A promising approach for such a scenario is to use UE as gateways for these devices. Since a UE can come close to MTCDs during its mobility, therefore, MTCDs can send their data with much reduced transmit power. UE based gateways are much natural choice

TABLE 6. Comparison of various data aggregation techniques/types.

Data aggregation type	Advantages	Limitations	Challenges
MTC gateway	Always availability	Costly in terms of hardware cost, maintenance, power consumption, and resource utlization	QoS aware resource allocation for massive MTC access
UE based	Less costly, easily rechargeable batteries	Unsuitable for delay intolerant MTCDs	Mobility/un-availability, malicious UEs
Cooperative	Reduced deployment/maintenance costs	Suitable for urban deployments due to shortage of UEs in rural areas	Cooperation among heterogeneous aggregating devices like drones, UEs and MTCGs
Fog based	Reduced communication latency and bandwidth demands	–	Geo-dependence and servers' physical locality
UAV based	Improve availability in difficult terrain on top of reduced architecture cost	Undefined operational mechanism and norms	Sky pollution, regulations, battery, physical collisions

for several MTCDs like wearables or on-body sensors. Since the simultaneous massive access of MTCDs can overwhelm these UEs, therefore, two optimal solutions for this issue are: using multiple-trusted UEs as gateways and cooperative communication. Since the deployment of legacy MTC gateways is costly in terms of hardware and software maintenance, power consumption and the like, therefore both of these proposals can alleviate these additional costs of MTC gateways.

In case of multiple-trusted UEs, the social-aware D2D relationships among the UEs can be exploited and in the absence or overwhelming of one UE, its trusted UEs can be used as gateways for MTCDs in an area. This type of aggregation technique is useful not only at homes or offices but in case of flash-crowds like at stadiums, shopping malls and the like. A major challenge of this approach is malicious UEs or non-trusted nodes in the absence of trusted nodes.

The advantages of cooperative communications can be employed in MTC networks by employing both the legacy/fixed gateways and UEs in a cooperative manner. Since an MTC network is comprised of both delay tolerant and intolerant MTCDs, therefore, the legacy gateways can satisfy the QoS needs of delay intolerant MTCDs, while delay tolerant data can be relayed through UEs. This technique reduces the overall cost of MTC networks in terms of hardware and software maintenance and the like. This technique is suitable mostly for urban scenarios due to the availability of several UEs. However, in rural areas, this technique will not be feasible, due to lack of sufficient trusted UEs.

To collect data of MTCDs from arbitrary or hostile locations, drones or UAVs can be used as an aggregating device. In several places, deployment of legacy gateways is usually not feasible, for example on mountains or near water bodies, therefore, to reduce the transmission costs of MTCDs, drones can be employed. The maneuverability of these drones can be controlled to make them come close to the transmitting devices, thus further reducing the transmit power of MTCDs; elongating their battery lives. A major challenge faced by these drones based aggregation techniques is defining their trajectories to reduced power or fuel consumptions and avoiding physical collisions.

VI. JOINT APPROACH OF DATA AGGREGATION AND RESOURCE ALLOCATION

In addition to the challenges concerning the mechanism of data aggregation, limited available resources for aggregation causes exacerbation. The spectrum resource available for data aggregation is limited, which entails the implementation of efficient resource scheduling [162]. Conventionally contention based schemes are used to provide channel access. Radio resource allocation and scheduling between the MTCG and MTCDs can be carried out at the aggregator through BS's assistance [116]. Recently, Dawy *et al.* also proposed to extend the role of data aggregators to include more intelligent functionalities such as resource scheduling and spectrum sharing [24]. The network-assisted gateways may control the communication among MTCDs thus resulting in improved performance in cellular networks [4].

In this vein, the most recent work includes [94], [125], [126] and [132]. The authors in [94], [125] and [126] considered interference in a large scale cellular network and the resource allocation is performed by the aggregator. In both [125] and [126], it is assumed that fixed number of resources has been assigned to the aggregator by the BS. The proposed scheme in [125] performed well as long as the number of MTC requests are less than or equal to the resources available at the aggregator. The issue of unavailability of resources due to fixed resource allocation has been solved by [94] with dynamic resource allocation scheme and through hybrid OMA-NOMA based aggregation scheme proposed by [126]. In the proposed scheme in [94], the number of resources were requested from the BS by an aggregator, depending upon the MTC transmission requests. Lopez *et al* [126] have extended the work in [125] and proposed a hybrid OMA-NOMA based data aggregation scheme. Their work focused mainly on the aggregating phase and proposed that the limited available resources at the aggregator can be assigned to more MTCDs through NOMA. However, all these proposed schemes favor the MTCDs with better signal to noise ratio (SNR) with total disregard to distant devices. Moreover, the heterogeneity of MTCDs with variable QoS is also not considered in any of these works.

A dynamic resource allocation scheme is proposed in our previous work [132] to allocate channel resources to MTCDs. Since the QoS of different MTC services vary [116], therefore, the proposed scheme in [132] considered prioritized resource allocation. Unlike existing resource allocation schemes based on RSS and CRS [94], [125], [126], the proposed scheme in [132] additionally considers the queuing delay, QoS requirements, and pending number of devices in a class. It is observed from simulation results that this ruminated consideration of utilizing diverse parameters for resource allocation and aggregation has brought significant improvement in terms of outage probability, energy efficiency and system capacity.

In [163], Zhang *et al.* proposed a non-orthogonal RRA scheme for an MTC-group, in which the MTCG is configured as a relay to assist the uplink transmissions of the served MTCDs. Through coordinating the transmit powers at the MTCG and MTCDs, the aggregate energy consumption of the MTCDs can be minimized while their delay constraints being also satisfied. The simulation results verified that the proposed RRA scheme can well coordinate the transmit powers at the MTCG and the MTCDs.

Yang *et al*. [164] proposed an energy efficient resource allocation for cellular MTC networks taking into account two different multiple access strategies namely: NOMA and TDMA. Their main aim was to minimize the total energy consumption of the cellular MTC network through joint power control and time allocation while considering circuit power consumption. They compared energy consumption between NOMA and TDMA schemes for uplink MTC, taking into account non-linear energy harvesting. Their numerical and simulation results revealed that TDMA is suitable for high power MTCDs while NOMA is a preferred approach for low power MTCDs since energy consumption of NOMA is less than TDMA.

A. ACCESS MANAGEMENT AND DATA AGGREGATION

Random access mechanisms and data aggregation are studied separately in literature. However, in [165], Guo *et al.* have presented joint random access and data aggregation for MTCDs. For preamble collision reduction, ACB is used as random access method for MTC to aggregator link. Stochastic geometry is employed to determined joint ACB-enhanced random access and data aggregation for mMTCDs. The results corroborate that provision of more preambles in the random access usually not efficient for MTC, therefore, these parameters should be chosen carefully for benefiting MTC over cellular networks.

To further enhance the access management in MTC networks, in [113], we have proposed prioritized contention based MTCD access with dynamic resource allocation by the aggregator. In our proposed scheme, the MTCG or fixed aggregator is responsible for handling delay intolerant MTCDs and resource allocation is performed dynamically depending upon the requests from the MTCDs. The proposed scheme consisted of two phases: contention phase and allocation phase. In the contention phase, the MTCDs contend for resources at FDA according to their priority. The devices having higher priorities or which have waited for a long time are given priority. When these MTCDs are attached to the aggregator, it also assigns resources according to their priorities. The simulation and analytical results revealed that the proposed two-staged dynamic resource allocation scheme performed well as compared to the existing proposals.

B. D2D COMMUNICATION AND MTC

When D2D communication is employed by MTCDs to transmit their data to the aggregating device, it results in offloading massive MTC traffic from the BS [112] and also reduces the power consumption of MTCDs due to the reduced communication distance [63]. In this vein, Zhao et al. [63] proposed a joint mode selection and resource allocation method for MTC-type D2D links to enhance the system sum-rate based on the coalition formation game. The coalition formation game was adopted enabling the UEs to choose their transmission modes and radio resources autonomously. They formulated the problem to maximize the throughput with SINR and power constraints for both D2D links and cellular UEs. In the proposed model, MTCDs can transmit data to the gateway through D2D communication; they can also transmit data directly to the BS through cellular links. Even though the authors considered HTC and MTC's traffic differences in terms of power consumption, data rate and packet size; however, they have not taken into account the variable QoS requirements of MTCDs. Moreover, the adaptive power allocation problem was also not taken into account.

In order to improve the availability and battery life of MTCDs, context-aware device-to-device (D2D) communication is exploited in [166]. By applying D2D communication, some MTC users served as relays for other MTC users who experience bad channel conditions. Moreover, signaling schemes are also designed to enable the collection of context information and support the proposed D2D communication scheme.

Li *et al.* [167] proposed a downlink transmission scheme leveraging cooperative D2D communications and the network coding in order to reduce both the cellular resources consumption and the transmit power consumption for MTCDs. A feasible protocol stack based on the modifications on current LTE system was proposed and an analytical framework to quantify the system performance has been developed.

VII. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

The challenges induced by massive MTC have been extensively studied in the scientific community (both academia and industry), there are many research areas still to be solved. The research challenges faced by MTC networks and open

TABLE 7. Open research issues and challenges in massive MTC networks.

Open issue/ research challenge	Brief description
MTC data security	The gigantic deployment of un-monitored MTCDs and the lack of centralized control over networked-devices raise security risks like data integrity, physical attacks on MTCDs and the like.
User privacy	The deep pervasiveness of MTCDs and the extent of collection of users' personal data and monitoring their activities is a threat to users' privacy, confidentiality and the like.
MTC data caching	Caching data from several kind of monitoring and measurement MTCDs is challenging and requires caching techniques different from the legacy caching techniques used for popular content downloading.
Cooperative aggregation	Several kinds of aggregating devices including UEs, MTCGs and drones will share the same geographical space; cooperative aggregation by these devices would provide several benefits to the MTC networks.
Energy harvesting	Energy harvesting techniques are required not only for resource-constrained MTCDs but also for BSs and aggregating devices like drones, UEs and gateways.
Cognitive MTC	The realization of cognitive MTC requires new models and architectures to integrate advanced machine learning tools, natural user interfaces and semantics into the MTC network.
Social MTC	The interactions among 'social objects' calls for new techniques and security concerns to enable secure and trust-worthy communication among these objects without jeopardizing the privacy of consumers.

research issues are summarized in Table 7. In the following subsections, we are explaining these issues to pave the way for future research in these areas.

A. MTC DATA PRIVACY AND SECURITY

Billions of MTCDs and applications are installed to collect/sense/monitor several kinds of users data. This gigantic increase in mMTC devices connected to the Internet is a threat to data privacy, security, integrity, and confidentiality [78]. Moreover, due to the pervasive presence of IoT, physical objects become security risks far more than the Internet itself [11]. This is due to the fact that the data collected by MTCDs includes (but not limited to) personal information, critical health information, user activities and behaviors, life styles and the like. Even though the aim of this data collection is to improve individual's living standards, however, it increases private users' visibility in both domestic and work domains [11] and is prone to individual's privacy, theft and fraud. Furthermore, MTCDs' deployment is itself a major security concern because the devices are unattended in most cases and for most of the time [171] and thus are vulnerable to various attacks.

Atzori *et al.* [11] showed their concern over the security and privacy risks involved in IoT/ MTC networks. They argued that since the deployed MTCDs are usually not monitored by human beings, therefore, these devices are prone to physical attacks. Secondly, since the MTC networks involved communication over cellular and capillary networks; the lack of centralized control and transmission over wireless medium also prone to attacks like *man-in-the-middle* attack. Another major security and privacy concern in these networks is that most MTCDs are resource-constrained. The complex cryptographic algorithms can not be used in these MTCDS as these algorithms require resources like computation and communication.

In [42], Barki *et al.* presented three categories of attacks to MTC networks namely: physical, data and logical attacks, depending upon the targeted entity i.e. MTCD, MTC data and proper functioning of the system, respectively. They also highlighted the challenges in developing security mechanisms for MTCDs. These included: device scalability and heterogeneity, resource constraints, traffic type, limited bandwidth, multiple operators and the like. To handle these challenges and overcome the security risks, the authors have reviewed the existing solutions with respect to key management, entity authentication, and privacy. The authors argued that due to the factors like unattended device deployment, data mining tools, resource and energy constraint devices; design of robust and effective security mechanisms remained an open issue and is of major concern to protect users' privacy and data integrity.

Chen and Lien [104] highlighted two main security and privacy threats/attacks in MTC networks: distributed denial-of-service (DDoS) attack and inference attacks. In DDoS, MTC can be jammed to restrict their operation. In *inference attacks*, meaningful information about individual's lifestyle can be extracted logically or statistically e.g. by monitoring smart meter readings in smart grid communications.

Mehmmod *et al.* suggested that the legacy authentication, accounting and authorization schemes should be optimized according to the new requirements of MTC networks and proper procedures should be defined for accessing user's data [78]. Yang *et al.* [168] highlighted the various possible attacks on MTCDs and reviewed several mechanisms to overcome these security threats to IoT devices and applications.

Since huge number of MTCDs may get connected to Internet due to lack of implementation of proper security mechanisms, therefore, security and privacy of users/consumers and their properties remain an open issue. To what extent users' data can be collected and for how long it should be stored [11]; also requires serious research attention both from academia and industry.

B. MTC CACHING

The low-rate monitoring, measurement, and automation data generated by MTC applications running on massive MTCDs can be cached to reduce total traffic load [110]. However, IoT data are different from multimedia data in that the IoT data have short lifetimes. Thus, different caching policies are required. Vural *et al.* [169] proposed a model that takes into consideration both the communication costs and freshness of a transient IoT data item. The network load can be reduced significantly especially for highly requested data. However, caching of MTC data is challenging and require further research in this area.

C. COOPERATIVE AGGREGATION

Cooperative communication provides benefits like improved channel throughput and enhanced energy efficiency in wireless networks [70], [151]. The cooperative aggregation techniques discussed in this article, mainly considered cooperation among UEs and gateways. As 5G would encompass heterogeneous devices, techniques and technologies, therefore, within a macro-cell, multiple gateways, drones and the like can be deployed to cater the needs of MTCDs and services. In future, cooperation among these aggregators in terms of resource sharing or load balancing can be considered.

D. ENERGY HARVESTING

By the end of this decade, there would be 235 million tons of carbon emission annually and electric energy consumption is expected to be 414TWh [170]. A significant portion of global carbon emission is from the information and communication technology [171]. For environmental protection, green communication [70], [171] is necessary to achieve energy efficiency in wireless networks. It is one of the challenges of 5G networks to improve the energy efficiency of battery-constrained devices [4] and should adopt techniques for environmental protection. Energy harvesting is a technique to enable the devices to power their services through energy harvested from renewable energy sources like wind and sun [170].

Energy harvesting and green communication are essential not only for the MTCDs but also for BSs [171] and aggregating devices like smartphones, drones and the like. There are several natural sources for energy harvesting, however, it is required to efficiently harvest the energy from these sources. Electromagnetic radiation [104], vibration [108], temperature, sunlight, wind [47], motion differences [27], RF [143] and the like can be used as energy sources to harvest energy into UAVs and wireless devices (smartphones and MTCDs).

In [170], Wang *et al.* developed a low power, low-complexity strategy for adaptive traffic offloading and bandwidth allocation for energy harvested MTC networks. Their main focus was on grid-MTC networks. Since, there would be billions of MTCDs, and plenitude of UEs, drones and the like in next decade, therefore, more energy harvesting based proposals are required to tackle the energy-constraint issues and to enable a green MTC [57] network in particular and to save the environment of the earth in general.

E. COGNITIVE MTC

The current era is witnessing the realization of smart cities/homes/buildings equipped with diverse and massive number of MTCDs that enable real-time monitoring and sensing. These MTCDs transmit the sensed data to their respective MTC application servers and then respond to the control messages from these servers. All these transmissions between servers and MTCDs takes places through various networks; consuming resources and require energy for operation. This resource- and energy-consuming communication can be reduced by employing Cognitive MTC/IoT i.e. equipping MTCDs with cognitive capabilities to operate intelligently and autonomously [172].

Ploennigs *et al.* [173] takes the concept of smart buildings to the next generation i.e. cognitive buildings and proposed an architecture that integrates IoT and cognitive capabilities to enable the MTCDs installed in the buildings to learn the building behavior; assisting human beings to tackle the undesirable incidents. Their proposed architecture combines data integration, semantic meta-data modeling and automated analytics. Their work corroborated the efficiency of cognitive IoT to enable easily deployable, scalable and self-learning MTC network.

The concept of cognitive MTC is still in initial stages of its development and realization. The diversity of MTCDs and application requirements calls for new models and architectures for integrating advanced machine learning tools, natural user interfaces and semantics for the realization of cognitive MTC for better management of buildings and conserving energy and other resources. Moreover, according to Genc *et al.* [172], the high computational complexities of cognitive algorithms make them inapplicable for MTCDs/ IoT devices with low-power processors.

F. SOCIAL MACHINE TYPE COMMUNICATION

The smart objects around us are being revolutionized from 'smart objects' to 'social objects' [174]. In social IoT (SIoT) [175], objects /devices collaborate with other objects / devices to satisfy certain objectives driven from human beings [176]. This collaboration /communication among MTC objects can be termed as social MTC. The technological advancements in this field are turning the *smart* [177] objects to *cognitive* [173] and *social* [174] objects; paving the way for social MTC in which the networked objects will establish communications with other objects based on their social relationships to achieve certain goals. This new paradigm shift not only calls for new proposals to enable social MTC in SIoT, but also opens new threats and security risks for humans' privacy. The social-aware D2D communication takes place

TABLE 8. List of abbreviations and acronyms.

Acronym/Abbreviation	Definition	Acronym/Abbreviation	Definition
3GPP	Third Generation Partnership Project		
ACB	Access Class Barring	NB-IoT	Narrow Band Internet of Things
BS	Base Station	OP	Outage probability
CDA	Cooperative data aggregation	OMA	Orthogonal Multiple Access
CH	Cluster head	PHY	Physical Layer
cMTC	Critical MTC	QoS	Quality of service
CR	Cognitive radio	RACH	Random Access Channel
CSI	Channel State Information	RAN	Random access network
		RAT	Radio access technology
D2D	Device to device communication	RF	Radio Frequency
ETSI	European Telecommunications Standards Institute	RRA	Radio resource allocation
FDA	Fixed data aggregator	RRM	Radio Resource Management
HetNet	Heterogeneous Network	RRS	Random resource Scheduling
HTC	Human type communication	RSS	Received Signal Strength
IoT	Internet of Things	SIR	Signal to Interference Ratio
LPWA	Low Power Wide Area	SNR	Signal to Noise Ration
LTE	Long Term Evolution	TDMA	Time Division Multiple Access
LTE-A	Long Term Evolution Advanced	UDN	Ultra dense network
MAC	Medium Access Control	uMTC	Ultra-reliable MTC
MDA	Mobile Data Aggregator	UE	User equipment
MTC	Machine type communication	WLAN	Wireless Local Area Network
mMTC	Massive Machine Type communication	WPAN	Wireless Personal Area Network
M2M	Machine to machine communication		
MTCG	Machine type communication gateway		

between HTC devices, which are quite less in number as compared to MTCDs. Furthermore, this type of D2D communication is usually network-assisted [5], thus BS is aware of all of these communications. However, the massive number of MTCDs along with lack of centralized control in MTC, requires serious attention for social MTC both from academia and industry.

VIII. CONCLUSION

Future 5G networks will be based on heterogeneity of devices, technologies and architectures including IoT, UAVs, cloud and edge computing, and the like. There would be a massive roll out of IoT/MTCDs; the simultaneous and unpredictable access of these device will cause congestion and overload in 5G and beyond networks. In this paper, we investigated various solutions to cope the challenges induced by such devices with a main focus on data aggregation. Data aggregation is seen as a promising technique to reduce the number of simultaneous access at a single point by distributing it across multiple locations, geographically. However, privacy and security are deemed as one the main challenges faced by data aggregation. This paper provides significant insights about the current and future directions of various solutions to cater massive access in mMTC network.

APPENDIX

The acronyms and abbreviations used in this article are enlisted in Table 8.

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