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Machine-to-machine communications: Technologies and challenges

Kwang-Cheng Chen ^{a,b,c,*}, Shao-Yu Lien ^{a,d}

^a Graduate Institute of Communication Engineering, National Taiwan University, Taiwan

^b INTEL-NTU Connected Context Computer Center, National Taiwan University, Taiwan

^c Research Laboratory of Electronics, Massachusetts Institute of Technology, United States

^d National Formosa University, Taiwan

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ABSTRACT

Machine-to-machine (M2M) communications emerge to autonomously operate to link interactions between Internet cyber world and physical systems. We present the technological scenario of M2M communications consisting of wireless infrastructure to cloud, and machine swarm of tremendous devices. Related technologies toward practical realization are explored to complete fundamental understanding and engineering knowledge of this new communication and networking technology front.

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1. Introduction

Following tremendous deployment of Internet and mobile communications, Internet of Things (IoTs) and cyber–physical systems (CPS) emerge as technologies to combine information communication technology (ICT) with our daily life [1–3]. By deploying great amount of machines that are typically wireless devices, such as sensors, we expect to advance human being's life in a significant way. In particular, autonomous communications among machines of wireless communication capability creates a new frontier of wireless communications and networks [4,5]. In this paper, we will survey some technological milestones and research opportunities toward

achieving machine-to-machine (M2M) wireless communication ultimately serving human beings.

Fig. 1 delineates the fundamental network architecture of cloud-based M2M communications, consisting of cloud, infrastructure, and machine swarm (or machine oceans, to stand for a great amount of machines). Networking in the cloud, typically done by high-speed wired/optical networking mechanism, connects data centers, servers for applications and services, and gateways to/from the cloud. The infrastructure interconnects cloud and machine swarm/ocean, which can be wired or wireless. In this paper, we focus on wireless infrastructure, which allows flexibility and mobility to enable M2M applications and services. For potentially wide geographical range and diversity of deployment, cellular systems play the key role in (wireless) infrastructure. We therefore introduce 3GPP type of systems supporting M2M [5–7] in details. The data aggregators (DAs) are transmitting/receiving, collecting, or fusing information between infrastructure and machine swarm, which can be considered as the access points to

* Corresponding author at: Graduate Institute of Communication Engineering, National Taiwan University, Taiwan. Tel.: +886 2 3366 3568; fax: +886 2 2368 3824.

E-mail addresses: chenkc@cc.ee.ntu.edu.tw (K.-C. Chen), shaoyu-lien@gmail.com (S.-Y. Lien).

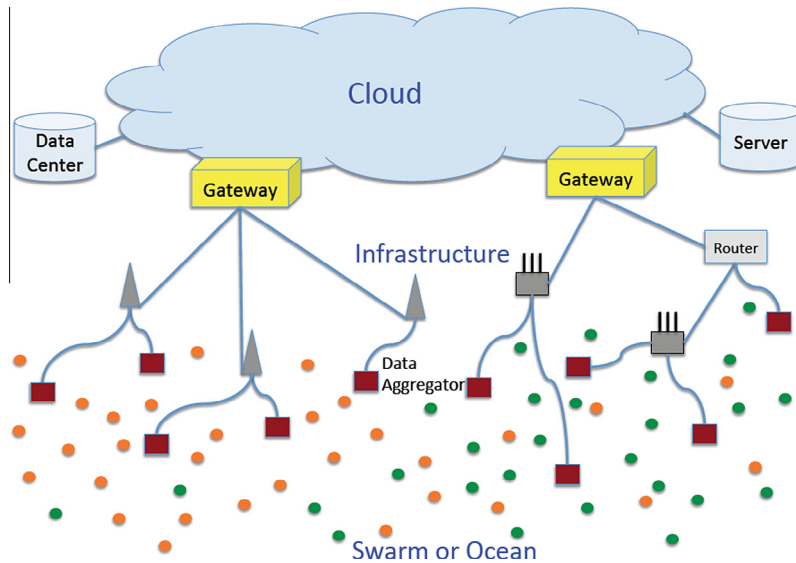


Fig. 1. Cloud-based M2M communications.

infrastructure networks. Finally, the number of machines can go up to trillions according to various reports. Such a huge number of wireless devices form machine swarm or machine ocean, and create a new dimensional technology challenge in wireless communications and networks, after the triumphs of wireless personal communications for billions of handsets in past two decades. It also suggests potential challenges in deployment, operation, and security and privacy.

Consequently, the organization of this paper surveys and highlights technology for M2M wireless communications as follows. Section 2 is dedicated to wireless infrastructure. Section 3 summarizes technology to achieve efficient communications in machine swarm/ocean. Various issues in deployment, operation, and security and privacy, are explored in Section 4.

2. Wireless infrastructure

To practice M2M communications, few realizations of M2M communications have been proposed, such as leveraging Bluetooth (IEEE 802.15.1), Zigbee (IEEE 802.15.4), or WiFi (IEEE 802.11b) technologies. However, there is still no consensus on the network architecture for M2M communications over these wireless technologies. Considering that the ultimate goal of M2M communications is to construct comprehensive connections among all machines distributed over an extensive coverage area, the network architecture of M2M communications leveraging these wireless technologies can generally be considered as the heterogeneous mobile ad hoc network (HetMANET), and faces similar challenges that can be encountered in the HetMANET. Although a considerable amount of research has provided solutions for the HetMANET (connections, routing, congestion control, energy-efficient transmission, etc.), it is still not clear whether these sophisticated solutions can be applied to M2M communications due to constraints on the hardware complexity of a MTC device.

Because of these potential concerns, scenarios defined by 3GPP thus emerge as the most promising solution to enable wireless infrastructure of M2M communications [5,8,9].

2.1. Ubiquitous connections via 3GPP heterogeneous network (HetNet) architecture

To provide ubiquitous wireless connections for user equipments (UEs) of human-to-human (H2H) communications in indoor and outdoor environments, a special network architecture known as heterogeneous network (HetNet) is introduced by 3GPP LTE-Advanced [10–12]. In the HetNet, in addition to conventional macrocells formed by evolved universal terrestrial radio access (E-UTRA) NodeBs (eNBs), there are picocells formed by small transmission power eNBs deployed underlay macrocells to share traffic loads of macrocells, femtocells formed by HeNBs deployed underlay macrocells to enhance signal strength and coverage in the indoor environment, and relay nodes (RNs) deployed in coverage edges of macrocells. The 3GPP infrastructure provides higher layers connections among all stations of eNBs, HeNBs, and RNs. Although, in the HetNet, there is potential interference between small cells in the air interface (of picocells, femtocells, and RNs) and macrocells, such interference can be effectively mitigated by applying recent solutions ([14] for picocells, [13–17] for femtocells, and [18,19] for RNs). As a consequence, by attaching to these stations, ubiquitous connections among all machines can be provided. In 3GPP, a machine is referred to a machine-type communication (MTC) device. An illustration of the M2M communications in 3GPP is shown in Fig. X. By the 3GPP infrastructure, a secure, energy efficient, reliable and mobility-empowered connection at the same level of common UEs can be provided for M2M communications.

Although 3GPP provides all these technical merits, it does not suggest a successful practice of M2M communica-

tions. The most challenging issues lie in a severe signaling congestion on the air interface and a complicated management in the network, as it is estimated that the number of MTC devices will be 1000 times larger than the number of UEs [20]. Although considerable solutions have been proposed for solving these critical issues by cooperative among stations [21–24], a group based operation of MTC devices has been regarded as a promising direction [8,25–27], and device-to-device communications later.

2.2. D2D empowered group based operations of MTC devices

The primary idea of grouping a number of MTC devices into a swarm is to reduce the number of communications between a MTC device and 3GPP E-UTRA and evolved packet core (EPC). That is, a group header gathers requests, uplink data packets and status information from MTC devices in the group, and then forwards such traffic to a station of 3GPP. The group header also relays management messages and downlink data packets from a station of 3GPP to MTC devices in the group. By avoiding direction communications between a MTC device and 3GPP E-UTRA, signaling congestion on the air interface and a complicated management in the network can be alleviated. This is the spirit of the group-based management defined by 3GPP [8]. For M2M communications, MTC devices can be grouped (i) *logically based on service demand patterns of MTC devices*, or (ii) *physically based on locations of MTC devices*.

For (i), considering one of major applications of MTC communications is to collect measurement data from MTC devices (e.g., data reports from meters in smart grid networks or navigation signals from positioning sensors in navigation networks), traffic of such application typically has characteristics of periodical packets arrival, small data (each MTC device only sends or receives a small amount of data), and with certain hard or soft jitter constraints. The schedule of a large amount of packets with small data to meet corresponding jitter constraints is a huge computational burden and challenge. To tackle this challenge, MTC devices of similar characteristics can be merged into a group *logically*, then resources for these MTC devices can be scheduled and managed in the basis of groups. Consider M groups of MTC devices indexed by $i = 1, \dots, M$. The packet arrival period of MTC devices in the i th group is $1/\lambda_i$, and a granted time interval with length τ is allocated to each group periodically (based on the packet arrival period of the group) for packet transmissions of MTC devices in the group. When granted time intervals are allocated according to present priority among groups and a group with a larger λ_i has a higher priority, the jitter of packets in the i th group is bounded above by [25]

$$\delta_i^* = \tau + \sum_{k=1}^i \frac{\gamma_k}{\gamma_i} \tau, \quad \text{for } i = 2, \dots, M \quad (1)$$

if $\delta_i^* + \tau < 1/\gamma_i$, and $\delta_i^* = \tau$ for $i = 1$. This result significantly facilitates to reduce the complexity on scheduling. Denote δ_i as the jitter constraint of packets in the i th group. The scheduler only needs to check $\delta_i \leq \delta_i^*$ for all i , then it is guaranteed that jitter constraints of all packets in all groups can be satisfied.

For (ii) to *physically* group MTC devices, a new communications paradigm is essential: a direct communication between a group header and an MTC devices. To enable such a direction communications among MTC devices, we shall note a communications paradigm that will be defined in 3GPP Rel. 12 referred to device-to-device (D2D) communications [28–30]. To significantly reduce the transmission energy at the UE side, always transmitting packets to E-UTRA then E-UTRA relaying these packets to the destination UE may not be an optimum scheme, especially when the source UE is located nearby the destination UE. To orientate this situation, 3GPP plans to provide the interface and protocols for direct packets exchanges among UEs as D2D communications. By facilitations of the interface and protocols of D2D communications, MTC devices in a group can communicate with the group header without the intermediate of 3GPP E-UTRA to enable the group-based operation of MTC devices. Precise system design and performance evaluations are still subject to further study.

2.3. Cognitive operations of MTC devices

Even though the group based operation of MTC devices can potentially alleviate signaling congestion and management burden in M2M communications, these issues may not be resolved when the number of MTC devices grows enormously in the future. Under this circumstance, the operator may need to deploy more stations of E-UTRA and separate traffic as well as the management of UEs and MTC devices. That is, there can be E-UTRA stations for UEs and E-UTRA stations for MTC devices coexisting with each other, as shown in Fig. 2, to relax signaling congestion and management burden. However, under such a coexisting deployment, interference between conventional human-to-human (H2H) communications (that is, conventional links between UEs and E-UTRA) and M2M communications turns to be a challenging issue. Although interface of E-UTRA (i.e., X2 interface) can leverage a centralized coordination for interference mitigations, this scheme is not suggested, due to a centralized coordination creating significant management burden. An appropriate solution for interference mitigation between H2H and M2M communications lies in a distributive resource management, and a powerful technology known as *cognitive radio* (CR) is particularly noted.

Since E-UTRA stations for UEs and E-UTRA stations for MTC devices belong to identical technology, there is no priority among these stations. This operation is exactly a particular mode of the CR operation referred as the “interweave” coexistence [31]. The operation of the interweave coexistence between H2H and M2M communications can be outlined in Fig. 3 [32].

- MTC devices only utilize unoccupied radio resources from that of H2H communications. For this purpose, MTC devices perform interference measurement and report measurement result (indicating occupied resources by H2H communications) to the group header by D2D communications technology. As a result, the group header shall acquire interference situations of all MTC devices in the group. However, if all MTC

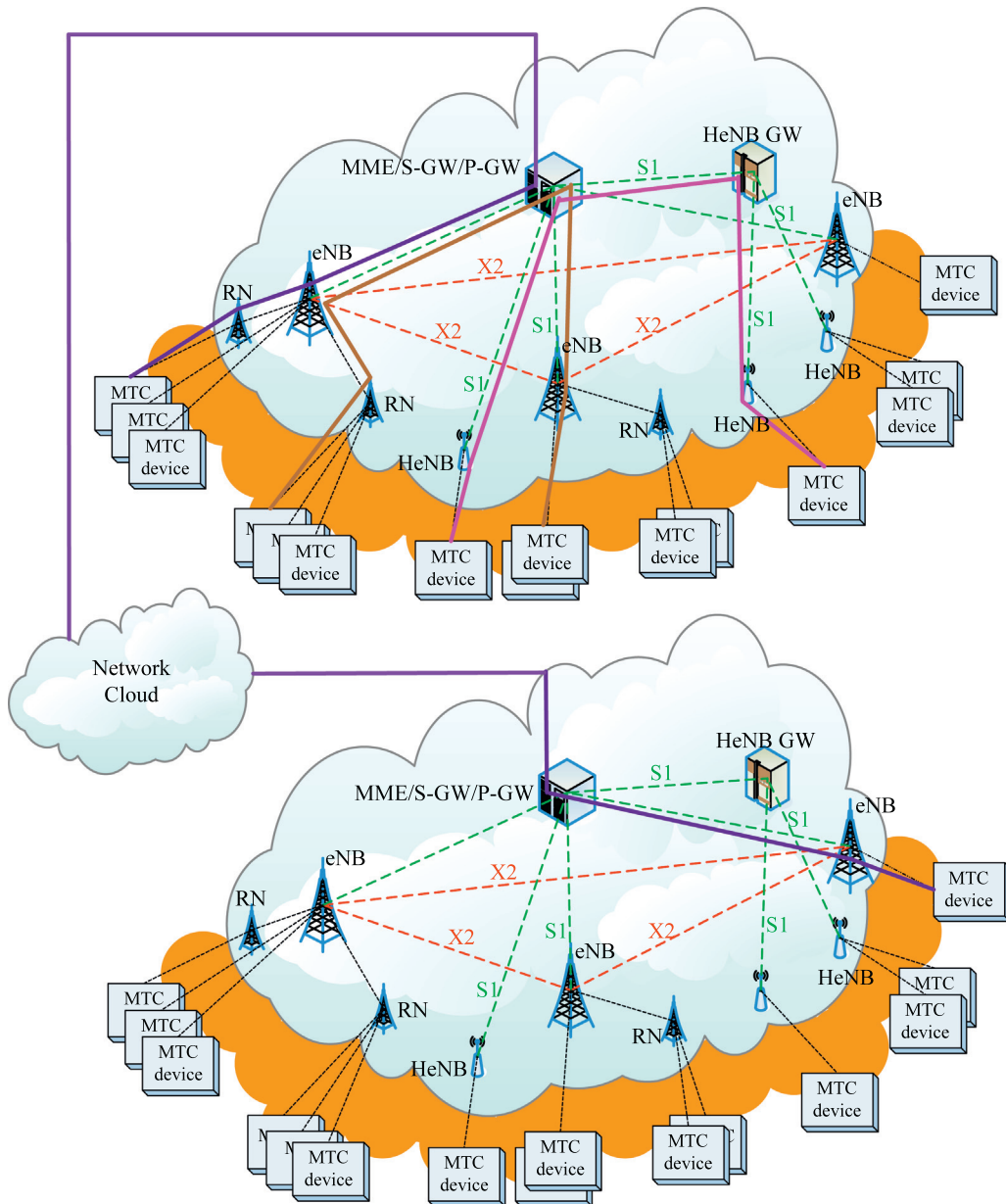


Fig. 2. Connection scenario of 3GPP MTC devices (a similar illustration is shown in [11]).

devices shall report the measurement result to the group header, the channel to the group header suffers severe congestions. To tackle this issue, a powerful technology known as *compressed sensing* is particularly noted. Compressed sensing originates as a signal processing technology, which is able to sample a (audio/image) signal with a sampling rate far lower than that of the Nyquist rate and the sampled signal can be recovered with an acceptable error rate if certain constraints can be satisfied. Specifically, denote the number of MTC devices in a group as V . At each measurement, if each MTC device only perform interference measurement with a probability q , then the expected number of MTC devices involved in interference measurement

and reporting result is $Vq \ll V$. For this purpose, the coverage of a group is divided into N isotropic grids. Denote the true interference from H2H communications as $\Psi = [\varphi_1, \varphi_2, \dots, \varphi_N]^T$, the compressed sensing is obtained by multiplying a sample matrix on Ψ as

$$y = \Phi\Psi + \varepsilon \tag{2}$$

where Φ is a $R \times N$ matrix with each element taking "1" with probability qV_n/V , and taking "0" with probability of $1 - qV_n/V$, where V_n is the number of MTC devices within the n th grid in a group. After obtaining Vq measurement reports, interference from H2H communications can be reconstructed by searching the minimum l_1 norm of Ψ ,

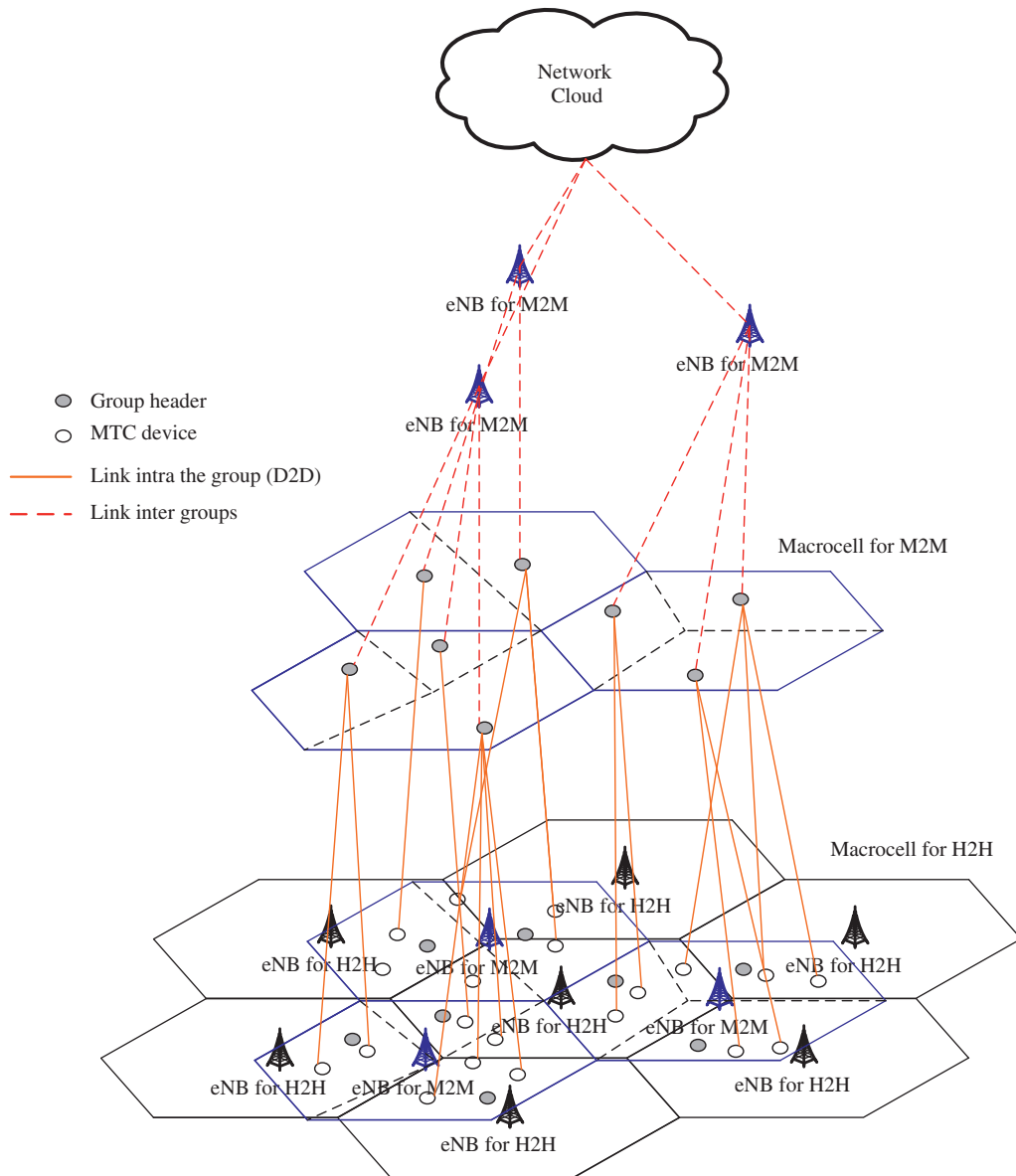


Fig. 3. Coexistence of E-UTRA for M2M communications and H2H communications (a similar illustration is shown in [32]).

$$\Psi^* = \arg \min \|\Psi\|_1 \text{ s.t. } \|\Phi\Psi - y\|_2 \leq \epsilon \quad (3)$$

through applying the second order conic programming if $R = O(K \log \frac{NM}{K})$, where l_p norm of Ψ is

$$\|\Psi\|_p \equiv \left(\sum_{n=1}^N |\varphi_n|^p \right)^{1/p} \quad (4)$$

K is the sparsity of Φ , $\epsilon = \|\Omega\epsilon\|_2$ and Ω is a random basis.

- The group header delivers measurement results to E-UTRA stations for M2M communications. E-UTRA stations then perform compressed sensing calculation for the interference (from H2H communications) reconstruction and allocate unoccupied radio resources to the group. MTC devices then can communicate with each other in the D2D fashion in the group, or communicate with MTC devices in other groups by relays of the group header and E-UTRA stations.

- Once a radio resource is occupied by M2M communications, this radio resource is regarded as suffering server interference and will not be utilized by H2H communications, as UEs perform channel estimation before transmissions.

By this particular mode of CR operations and the group based operation, challenging issues of signaling congestion and heavy management burden can be effectively resolved.

2.4. The QoS guaranteed optimal control for cognitive operations of MTC device

The major concern in CR operations stated above is potential efficiency of radio resources. To avoid interference

to/from H2H communications, E-UTRA stations shall allocate radio resources for MTC devices to perform interference measurement (although the number of MTC devices involved in interference measurement can be significantly reduced by the compressed sensing technology mentioned above). These radio resources for interference measurement are overheads, as all MTC devices cannot perform data transmissions nor receptions by these radio resources for interference measurement. If radio resources for interference are allocated very frequently, although time-varying interference from H2H communications can be accurately estimated, there is a severe resources waste. On the other hand, if radio resources for interference are allocated very frequently rarely, although overhead is reduced, interference from H2H communications may not be alleviated. As a result, the measurement period can be an very critical factor impacting the performance of MTC devices, especially the most critical QoS guarantees.

To solve this challenge, we particular note an equilibrium of statistical delay guarantees that

$$\Pr\{\text{delay} > d_{\max}\} \approx e^{-\theta \delta d_{\max}} \quad (5)$$

as providing a deterministic delay guarantee of $\Pr\{\text{delay} > d_{\max}\} = 0$ over wireless channel has been shown impossible [33], where d_{\max} is the delay bound and δ is jointly determined by the arrival process of traffic and the service process of the system. From (5), it can be observed that a small θ implies that the system can only support a loose QoS requirement, while a large θ means that a strength QoS requirement can be supported by the system. To reach the equilibrium of (5), the effective bandwidth and the effective capacity serve significant foundations.

The effective bandwidth [34,35], denoted by $E_B(\theta)$, specifies the *minimum service rate needed to serve the given arrival process subject to a given θ* . On the other hand, the effective capacity, denoted by $E_C(\theta)$, is the duality of the effective bandwidth, which specifies the *maximum arrival rate that can be supported by the system subject to a given θ* . If θ^* can be found as the solution of $E_B(\theta^*) = E_C(\theta^*)$, δ can be obtained by

$$\delta = E_B(\theta^*) = E_C(\theta^*) \quad (6)$$

Consequently, the system can achieve the equilibrium of the statistical delay guarantee

$$\Pr\{\text{delay} > d_{\max}\} \approx e^{-\theta^* \delta d_{\max}} \quad (7)$$

With the facilitation of above foundations, the optimal control of the measurement period and radio resources allocation for a group of MTC devices can be summarized in the following.

- (1) Calculates the effective bandwidth $E_B(\theta)$ of the real-time traffic for a group of MTC devices.
- (2) Set the measurement period to an initial value.
- (3) Allocate $s = 1$ radio resource to a group of MTC devices.
- (4) Find the solution of θ such that $E_B(\theta) = E_C(\theta) = \delta$.
- (5) Derive the delay violation probability by $\Pr\{\text{delay} > d_{\max}\} \approx e^{-\theta^* \delta d_{\max}}$.

- (a) If $e^{-\theta^* \delta d_{\max}} > \nu$, where ν is the upper bound of the acceptable QoS violation probability, determine s by

$$\min_{1 \leq s \leq S} \{s\}, \text{ s.t. } e^{-\theta^* \delta d_{\max}} \leq \nu \quad (8)$$

- (b) If (8) is not satisfied, decrease the measurement period by one if the current measurement period value is larger than two and repeat Step (4) and (5) until (8) is satisfied.

The above optimal control for QoS guarantees enables reliable transmissions of a massive number of MTC devices via the facilitation of the cognitive radio technology and the group base operations of M2M communications. Consequently, the most critical challenges of signaling congestion, spectrum congestion, and heavy management burden on the air interface of M2M communications can be effectively resolved.

More research opportunities exist in the areas of MTC and D2D communications in 3GPP [35], potential networking protocols to facilitate direct communications among devices if appropriate, and complete realization under cognitive cellular networks [36].

3. Statistical networking in machine swarm/ocean

Technology to connect wireless devices under M2M scenarios has been proposed and developed for years, such as RFID, Bluetooth, Zigbee, and WiFi, corresponding to various on-going or announced IEEE 802 standards. The scope of this survey does not focus on such short-range wireless communication technology. Instead, we assume availability for such physical layer wireless connectivity and communication technology, but focus more on new challenges beyond physical transmission, particularly networking in this section.

In machine (or sensor) swarm/ocean, potentially except data aggregators (DAs), energy-efficiency and therefore low-power transmission becomes a must and no way to compromise, no matter for battery life or energy harvesting operation from nature. From current energy harvesting technologies [37], the subsequent wireless communication techniques must be short-range, or mid-range with extremely low data rates. Under a large number of machines, multi-hop ad hoc networking is evitable in realistic deployment and operation. Furthermore, the operating communication protocols in each machine must be simple and energy-efficient in implementation, as further challenges.

Spectrum is always a critical issue in wireless communications. Under the shortage of wireless spectrum, the spectrum utilization for communications in the machine swarm may most likely fall into two categories of spectrum sharing: (i) Machines as secondary users to dynamically access the temporarily inactive spectrum of primary users, to form networking, which is known as cognitive radio networks (CRNs) [38–42]. (ii) Multiple networks in the machine swarm to share a dedicated spectrum, which can be treated as (spectrum sharing) heterogeneous wireless networks. In this section, we focus on state-of-the-art tech-

nology to implement multi-hop cognitive radio networks and multi-hop spectrum sharing heterogeneous¹ wireless networks, and associated research opportunities for this wide-open knowledge.

Prior to more technologies in-depth, please consider the fundamental technological challenges in front of spectrum sharing multi-hop networking in the machine swarm:

- Facilitation of spectrum sharing ad hoc networks: The ad hoc networking is already difficult [43], and even much more challenging under spectrum sharing [44], particularly no control channel available in the spectrum sharing machine swarm. Spectrum sharing generally invokes *opportunistic networking* to complicate stochastic analysis and operation of networking.
- Cooperation in sensing, relays, and networks: Cooperative sensing [45–47], cooperative relay [48,49], and cooperative networks [50,51], are easy to assume and to show excellent performance in a localized view. However, cooperation suggests some critical assumptions behind the scene. For cooperative sensing, the bandwidth to collect information from cooperative sensors may be much greater than the required bandwidth to transmit signal. Cooperative relay is good to enhance performance at link level, but it generates more interference, time to occupy radio spectrum though maybe in smaller geographical range, and further trust and security concerns [52]. Similarly, cooperation among networks implies signaling overhead and cost on network management and is neither obvious nor straightforward from many aspects.
- Large but resource efficient multi-hop networks: With almost all machines (or sensors) are relatively simple in hardware and software, to maintain efficient operation for a large ad hoc network of machines is open to human's engineering knowledge. As a matter of fact, the fundamental performance of wireless ad hoc networks has been a research challenge in very recent years, which hopefully suggests the efficient and saleable design of large multi-hop ad hoc networks [53–55] but still remains open.

We will explore various subjects to provide part of the answer for above fundamental technological and intellectual challenges. From Section 2 and similarly in this section, keen readers might already note that we approach the cross-layer system and network design from radio resource directly by diminishing the role of medium access control [56] for the ease of presenting system architecture. Such a concept via interdisciplinary technology is somewhat similar to so-called *layerless dynamic networks* in [55] and shall be explored further in later of this section. In addition, although there lacks widely accepted models for wireless channels and aggregated activities of high-density machine swarm (i.e. large network), the results of ad hoc cognitive radio networks generally apply in the fol-

¹ Heterogeneous wireless networks here mean multiple independent (but may cooperate) wireless networks, and slightly different from heterogeneous networks for multi-tier cellular systems in Section 2, though still consistent in general definition.

lowing. We therefore suggest a revolution paradigm to *statistically* network the machines in the swarm, to avoid the difficulty of tremendous control overhead in end-to-end ad hoc networking.

3.1. Sensing spectrum opportunities for dynamic spectrum access

In spectrum sharing communication in machine swarm, prior to each transmission, each machine shall sense the channel availability first to avoid potential collision destroying spectrum efficiency [38] by facilitating dynamic spectrum access toward ultimate spectrum efficiency. Conventional spectrum sensing to detect or to sense spectrum hole(s) or white space(s) at link level (i.e. for an opportunistic transmission between a CR-Transmitter and CR-Receiver pair) targets at a single primary system and is used to decide between the two hypotheses in discrete-time statistical signal processing, namely

$$y[n] = \begin{cases} w[n] & n = 1, \dots, N \quad H_0 \\ hs[n] + w[n] & \quad \quad \quad H_1 \end{cases} \quad (9)$$

where $y[n]$ represent observation samples, $s[n]$ and $w[n]$ are contributed from PS signal and noise respectively, and h is the corresponding channel gain observed at the CR transmitter. Numerous techniques to achieve the goal of spectrum sensing have been proposed with more details in [57,58], while the detection and estimation techniques include

- Energy detection.
- Matched filtering.
- Cyclostationary detection.
- Wavelet detection.
- Covariance-based detection.
- Multiple-antenna.
- Sequential hypothesis testing and thus universal source coding.

Cooperative sensing [45–47] has been introduced to alleviate the hidden terminal problem in sensing. However, most spectrum sensing techniques deal with a single link-level transmission of targeting successful transmission signal based on CR-transmitter's observation on spectrum availability, instead of successful transmission for networking purpose. As networking consisting of a number of time-dynamic links, state-of-the-art sensing techniques designed for networking purpose are summarized as follows:

- Spectrum availability of CR-Receiver: As recalled and indicated in [59], the successful transmission over a CR link relies on spectrum availability not only at CR-Transmitter's location but also at CR-Receiver's location. For networking purpose, we shall understand the availability of multiple links in CRN, and likely associated with location information.
- Statistical inference: One major issue in spectrum sensing is the time-lagged information of spectrum availability at earlier time slot of measurement, rather than the time slot in transmission. That is, we execute

spectrum sensing at time $t_{n-L}, \dots, t_{n-1}, t_n$, however, the CR-transmitter transmits at time t_{n+1} and spectrum availability information up to t_n is not immediately useful, as a major blind side in tremendous spectrum sensing research. Fortunately, this can be easily resolved by applying statistical inference [59,60].

- Radio network tomography: Ideally, to achieve perfect sensing for entire wireless network, we have to know the channel statistics of each link in the network, that is, h_{ij} between node i and node j , $\forall i, j$. For wired networks, a technology known as Internet tomography [61] is developed based on statistics. However, for radio networks, it is much more challenging until cognitive radio network tomography [60] that leverages the concept like medical tomography to transmit a test radio signal into the network and to statistically infer the radio source in the entire wireless network. Subsequently, spectrum sensing can be generalized into.
- Spectrum map: A major difference of spectrum sensing between a cognitive radio link and a cognitive radio network lies in the preference of spectrum opportunity (or available radio resource) assessment on the tendency of future hops for cognitive radio network. In other words, *spectrum map* indicating spectrum availability associated with location would be precisely wanted in CRN and any spectrum sharing networks. The challenge here, beyond cooperative sensing, is to collect such spectral-spatial information with minimal overhead and thus bandwidth, preferred without such overhead. Two methods are suggested to accomplish such a goal: *synthetic aperture radar* (SAR) [62] and *compressive sensing* [63]. As a matter of fact, compressive sensing to take advantage of the sparsity nature of spectrum availability for networking (i.e. no need to know the complete spectrum information) could play an interesting role for spectrum sensing [63,64].
- Information fusion: Since spectrum sensing requires *information fusion* from spectrum sensors, it suggests another highly potential alternative to design a spectrum-efficient spectrum sensing for CRN. We can use a single sensor, that is, the transmitter itself, to sense multiple kinds of heterogeneous information from CRN. With a newly developed theory of *heterogeneous information fusion and inference* (HIFI), we can infer the status of CRN spectrum availability as good as cooperative sensing but without any extra transmission of detection/estimation signal [65].
- Source coding: From the concept of spectrum map, spectrum sensing in a CRN is equivalent to a kind of source encoding of spectrum map. As we described later, source coding without prior knowledge of statistics means universal source coding. Concurrently, spectrum sensing via universal source coding is introduced in [66] with more open in front.

In the most challenging high-density machine swarm, spectrum sensing immediately affects the effectiveness of dynamic spectrum access. Though still in early stage to investigate, efforts start to integrate spectrum sensing with dynamic/opportunistic spectrum access, particularly introducing intelligent methodologies like Markov decision pro-

cess [67,68], multi-armed bandit [69] and machine learning into the scenario [70–72] to iteratively optimize the networking performance.

3.2. Connectivity of spectrum sharing wireless networks under interference

Interference is always a key concern in spectrum sharing networks that is obviously an interference-limited, and even in large ad hoc networks allowing concurrent transmissions for spectral efficiency. Even if the spectrum availability information can be obtained smoothly, we still have an open issue, whether connectivity of spectrum sharing wireless networks is appropriate for networking under interference. We will reveal the answer in the following.

3.2.1. Stochastic geometry analysis of inference in a wireless network

One of the major challenges for communication in machine swarm or any large wireless network, particularly under the scenario of spectrum sharing, is the characterization of interference. Based on interference analysis, we can ensure concurrent transmissions to maximize the utilization of the given spectrum, under the scenarios of cognitive radio networks or spectrum sharing heterogeneous wireless ad hoc networks. Recent introduction of stochastic geometry analysis supplies a great tool to fulfill this analytical need [73–75]. The mathematical model of network interference can therefore be well organized and demonstrated to model cognitive radio networks (CRNs) [73]. Furthermore, the interference in large wireless networks has remarkably explored in [74], to understand some fundamental behaviors in interference-limited wireless networks. As each link in such wireless link may be suffer severe fading and potential outage, random graph model of wireless networks becomes an important analytical tool, while [75] presents an excellent review, based on stochastic geometry, to enable a lot of subsequently useful analysis. There are generally three critical factors in such modeling:

- Spatial distribution of the nodes.
- Wireless propagation characterization.
- Overall impact of interferers including mobility and session lifetime.

We can always describe network topology via a graph $\mathcal{G} = (V, E)$, defined by the collection of vertices, V , and the collection of edges, E . A vertex represents a node in a wireless network and an edge represents a link between two nodes. Erdős and Rényi pioneer the random graph theory. Among a number of random graph methodologies, we usually model the spatial distribution of the nodes according to a homogeneous *Poisson* point process in the two-dimensional infinite plane. The probability of n nodes being inside a region \mathcal{R} (not necessarily connected) depends only on the total area $A_{\mathcal{R}}$ of the region and is given by

$$\mathbb{P}\{\mathfrak{n}|\mathcal{R}\} = \frac{(\lambda A_{\mathcal{R}})^{\mathfrak{n}}}{\mathfrak{n}!} e^{-\lambda A_{\mathcal{R}}}, \quad \mathfrak{n} \geq 0 \quad (10)$$

where λ is the spatial density of (interfering) nodes.

Regarding propagation and fading effect, the received power, P_{Rx} , at a distance r from a transmitter with power P_{Tx} is

$$P_{Rx} = \frac{P_{Tx} \prod_k Z_k}{r^{2d}} \quad (11)$$

where d is the amplitude loss exponent depending on the environment with typical range from 0.8 (hallways) to 4 (dense urban), and 1 for free-space propagation from point source. $\{Z_k\}$ are independent random variables to account for propagation effects such as fading and shadowing. Earlier model of link availability can also serve the purpose of modeling session lifetime.

The opportunistic nature of spectrum sharing wireless networks (including CRN) and fading statistics of each link in wireless networks suggest random networks for modeling. Details of random network analysis or more precisely random graphical analysis are well documented in recent publications such as [76–78]. It is generally believed that Poisson Point Process (PPP) node distribution or Random Geometric Graph (RGG) represents the bottleneck performance of wireless networks.

3.2.2. To hop or not to hop

Trials to understand the fundamental limits in wireless (ad hoc) networks have been explored over a decade, e.g. [79]. A breaking through to delineate the capacity of wireless ad hoc networks implicitly suggests the challenge of facilitating large multi-hop networks [80,81]. Following similar approach, the strategy to hop or not to hop in machine swarm has been studied under the scenario of data from machines and sensors to a data aggregator that is typically an access point to wireless infrastructure as Fig. 1 [82]. In addition to conventional throughput capacity and delay, energy consumption is taken as another consideration. The conclusions consistent of key results in [83] are summarized as follows:

- For a small number of machines (or of high priority traffic), single-hop transmission scheme is suggested as currently 3GPP approach [25]. Machines outside the immediate range of the DAs in the 3GPP LTE-A systems, cooperative access [21] can be adopted, exactly as Section 2.
- For a large machine swarm, multi-hop transmission scheme to minimize delay suggests an optimal transmission range $\sqrt{\frac{\log n}{\pi n}}$, where n is the number of machines in the unit circle area.
- For machines requiring low energy consumption and long live time in the machine swarm, the optimal transmission range, $\sqrt{\frac{E_{standby} + E_R}{E_{Tmin}} \left(\frac{\log n}{\pi n} \right)}$, is suggested to minimize the energy consumption, where $E_{standby}$ and E_R denote the standby and receiving power consumption, and E_{Tmin} is the transmission power to reach above optimal transmission range.

Under the scenario of cognitive radio networks or spectrum sharing heterogeneous wireless networks, the precise

analysis to provide the answer of “to hop or not to hop” is still unavailable due to complicated interference. However, one recent result investigated the cooperative replay in opportunistic networks [84], to verify the conditions for successful cooperative relay.

3.2.3. Transmission capacity and connectivity of CRNs

Since Gupta and Kumar’s pioneer analysis [85], the practical limit of wireless ad hoc networks has attracted significant interests. While studying code division multiple access, *outage* well known in wireless communications has been noted as a practical criterion to define the capacity of wireless networks [86]. The consequent *transmission capacity* of wireless networks has been widely accepted as the maximum spatial density of *local* unicast transmissions given an outage constraint multiplying information rate [87], and as a measure of limiting performance of a wireless ad hoc network. In other words, for a maximal outage ϵ and information rate R , the maximum spatial density of transmissions is obtained as λ , and then the transmission capacity is $\lambda(1 - \epsilon)R$. With general fading, transmission capacity of wireless ad hoc networks is difficult to obtain. However, upper bound was developed in [88] and later upper bound of mean node degree and lower bound on node isolation probability were also analytically derived under general fading [89]. Although the transmission capacity for CRN or spectrum sharing heterogeneous wireless ad hoc networks is still in need so that we can ensure the meaning of communications in machine swarm, we still can somewhat realize such feasibility. The more critical issue to facilitate spectrum sharing ad hoc networks might be analytical understanding of connectivity, the degree for each node in the network connecting to neighboring nodes. Obviously, the connectivity is so critical to design routing algorithms and many other networking functions, and is so difficulty to analytically tackle this challenge. Further intellectual breaking through is surely required.

In addition to stochastic geometry, the relationship of random graphs and statistical mechanics has been amazingly noted [83,91], which plays a key role in subsequent study using the concept of *percolation* in statistical mechanics [92]. The intuitive meaning of percolation in statistical mechanics explains quick phase transition, say from liquid water to solid ice in a quick, large-scale and homogeneous way once temperature dropping to 0 °C. In wireless networks, we can use Fig. 4 to intuitively explain percolation in wireless networks. Once reaching the percolation threshold, the entire wireless network can quickly get connected away from original rather isolated configuration. Please note the change of transmission range to result in almost full connection in the figure that is similar to what we see in condense matters as a branch of physics. The efforts trying to analyze connectivity in multi-hop wireless networks are actually not new [93,94], however, it is still distant for spectrum sharing cooperative ad hoc networks (or at least CRN), which is important in facilitation of communications in machine swarm.

Based on stochastic geometry, a pair of nodes gets connected if the channel capacity of the link between them is greater or equal to target information rate. Through the interference analysis to get percolation threshold, we can

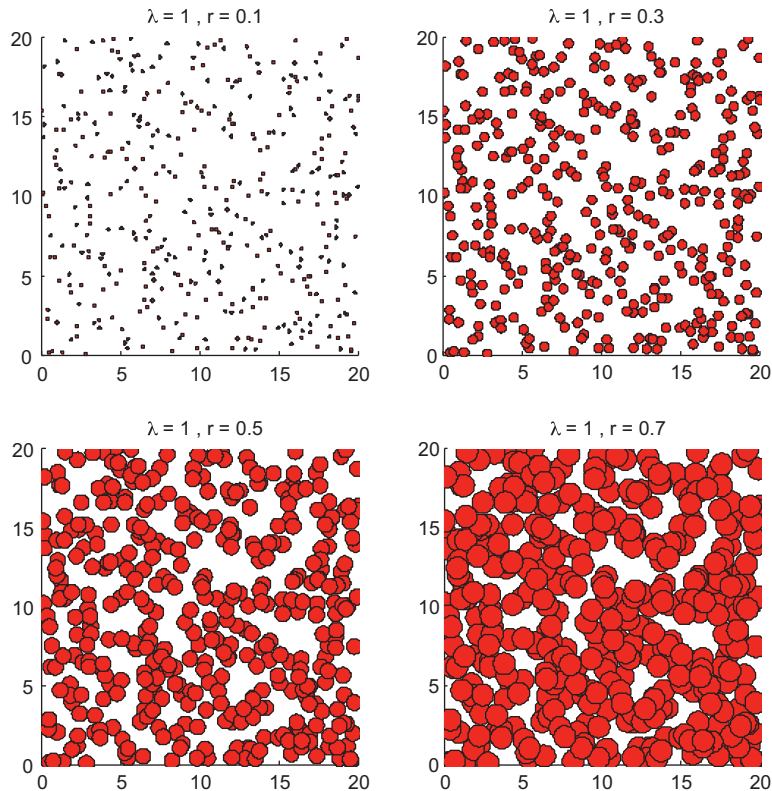


Fig. 4. When λ denotes node density and r denotes transmission range, percolation (from rather isolated connections to pretty full connections) happens (taken from [90]).

obtain the degree of node in semi-closed form for CRN and thus optimal power allocation to maximize the effective mean degree of a secondary user node in CRN [95]. In the same paper, it is also extended to obtain the results for multiple cooperative spectrum sharing heterogeneous ad hoc networks as the most general case. By looking some typical parameter settings, we may conclude the positive feasibility of spectrum sharing multi-hop networking for machine swarm. Based on such connectivity analysis, we can further show that a node can realize cooperation from hybrid and interconnected wireless networks and wireless infrastructure [96]. It suggests that spectrum sharing multi-hop networking in machine swarm, as Fig. 1, is definitely possible as a firmed answer for major challenges at beginning of this section. In front of us, there are a great number of new challenges of exact ways to design such networking in machine swarm.

3.3. Routing in cooperative cognitive ad hoc networking

To implement cooperative multi-hop (ad hoc) networking for machine swarm, routing might be the first challenge into system design. Routing for ad hoc networks has been widely studied for a long time [43], but generally requires end-to-end routing information to establish the routes, which is not feasible in spectrum sharing machine swarm at all, due to spectral efficiency and likely unidirectional opportunistic availability [38]. We use Fig. 5 to illus-

trate multi-hop cognitive radio networking in machine swarm or sensor networks. In this scenario, a source CR (denoted as node n_s), a destination CR (denoted as n_D), and several relay CRs (denoted as n_{rS}) that can cooperatively relay packet flowing from n_s to n_D . We assume there are n relay CRs. In order to avoid the interference to PSs, CSN links are available under idle duration of PSs that DSA can effectively fetch such opportunities, after successful spectrum sensing. Link available period in CSN results in random network topology even all nodes being static. We assume that the n_s , the n_D , and the n_{rS} can be mobile. Suppose that there are K possible opportunistic paths between n_s and n_D . The set of total K opportunistic paths is denoted as $\mathcal{P} = \{p_1, p_2, \dots, p_K\}$, where the i th opportunistic path p_i consists of J_i links, for $i = 1, 2, \dots, K$. n_s transmits a set of data X_1, X_2, \dots, X_K over these K paths. The values of the data are observed from some joint distribution and can be either continuous or discrete.

Cooperative routing has been introduced into sensor or energy-sensitive ad hoc networks, though based on Gaussian–Markov field [97] or static grid networks [98]. With the help of spectrum map (no need to be perfectly known), the spectrum aware routing is first proposed consisting of two parts: leveraging opportunistic routing based on spectrum map as local routing (among neighborhood), and global routing following the trend of spectrum map via greedy routing [99]. Spectrum map can actually indicate strong interference area with the help of tomography even an

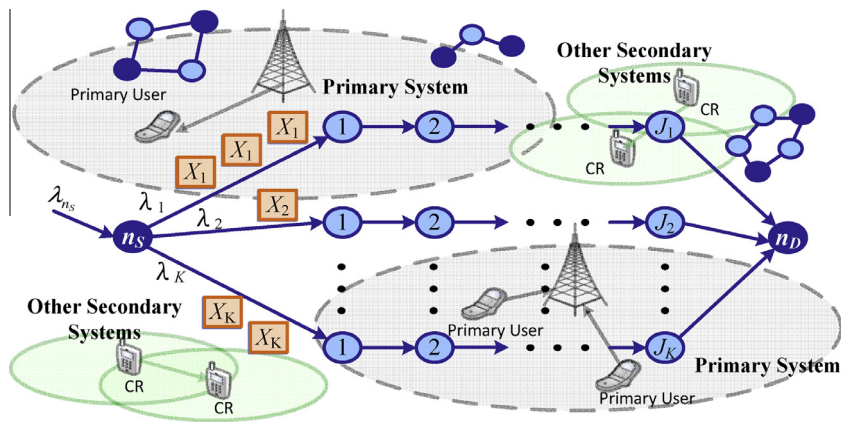


Fig. 5. Multi-hop cognitive radio multi-path networking in machine swarm.

incomplete spectrum map [100]. If such spectrum map is constructed by compressive sensing, it is shown to achieve successful routing by considering the information needed to route [63]. Routing under insufficient spectrum map information is critical to routing in machine swarm as impossible to obtain complete spectrum information for each machine under spectrum efficiency. The value of [63] lies in demonstration a simple routing algorithm proceeding on incomplete information, but reach the goal *statistically* speaking. Such a statistical concept could be extremely useful to implement machine swarm communications, as we cannot execute precise control but we can achieve our goal in a statistical manner in a large network. In parallel, applying interference information to form a routing game is studied in [101], and local routing in dense RGG sensor networks is investigated in [102].

Similar to diversity in wireless communications, *route diversity* can greatly improve reliability of ad hoc networks [103] and surely spectrum sharing multi-hop networks, which is also known as *multi-path routing* that is precisely depicted in Fig. 5. *Network coding* is a branch of information theory to optimize information flow in a network [104]. We can therefore apply simple network coding to greatly improve the rate-delay operation in ad hoc networks [105], and further reliability with rate-delay performance [106]. Such multi-path networking will be our foundation of statistical control and error control over cognitive radio ad hoc networks in next sub-section. As optimization can be conducted for delay or for energy, it is reasonable to conjecture that energy aware routing shall equivalently proceed [98,107].

Under the thinking of network operating under incomplete information, *statistical control* of networks has been developed as the way that must go and will be described in detail. However, *statistical routing* is still a missing part in spite of above theoretical ground. Under a slightly different motivation to consider the randomness of channels and interference, statistical routing is developed in [108]. Assuming perfect spectrum sensing to know the SINR of each transmitter–receiver pair, we again consider data *percolation* through a wireless network by the packet delivery *probabilities* to optimize routes, transmission probabilities,

and corresponding transmission power. For totally N nodes to transmit, the optimization becomes

$$\max \sum_{n=1}^N U_n(r_n) - \sum_{n=1}^N C_n(\rho_n) \quad (12)$$

subject to various physical constraints, where the utility function $U_n(r_n)$ is a function of rate r_n and cost function $C_n(\rho_n)$ is a function of physical layer transmission parameters. A successive convex approximation is beautifully developed to find a Karush–Kuhn–Tucker (KKT) solution for the optimization to complete statistical routing. How to combine above together would be a great technical challenge to facilitate statistical routing in machine swarm, which have to proceed based on local information (i.e. no end-to-end information) only but achieve the purpose of communications in terms of statistical performance.

3.4. Statistical control of QoS and error control

After introducing statistical networking in previous sub-section, *statistical control* of networking would immediately follow as next technology challenge. When each link in the network is opportunistically available under fading and interference, the assumptions of control channel, feedback, end-to-end information, are not realistic. To avoid tremendous control overhead, the rationale is to statistically control the target performance in a large network without micro-management to reach satisfactory performance in statistics, similar to the law of large number or large deviation [109]. In such a way of statistical control, we may consume more resource to create diversity at the beginning but may actually save resource finally and more reliable [103] due to the saving of control overhead.

We first consider the methodology to retain quality of service (QoS) in CRN. Please recall Fig. 5, if we allow source node to proceed multi-path forwarding to against random link availability due to (i) opportunistic spectrum access (ii) outage by fading and interference (iii) packet violation of time-to-live, we may apply the effective bandwidth discussed in Section 2 [32–35] to statistically retain delay control as [110], and further statistical QoS provisioning

in interference-limited underlay CRN [111]. It is also possible for heterogeneous services in CRN [112]. We may imagine an end-to-end “session” on top of these multi-paths. This achievement is particularly useful to applications like video surveillance and wireless robotics.

Although end-to-end feedback sounds impossible in machine swarm of cognitive radio capability, the end-to-end error control is still desirable. Again leveraging multi-path forwarding, we may implement hybrid ARQ (HARQ) into packets to different paths. Although there might not be able to successfully receive desirable packets from all paths, this is exactly as the operation of HARQ and thus achieves end-to-end error control in CRN [113]. Similarly, we may apply error control for local communication in heterogeneous ad hoc networks, to improve the connectivity and thus networking performance in the ad hoc network [114].

A more exciting scenario can be viewed by just looking at n_S and n_D , while the multi-path multi-hop networking is treated as an aggregated “multi-input-multi-output channel” 3×3 (in Fig. 5). n_S and n_D equivalently have multiple antenna to/from this aggregated “channel”, to form a *virtual MIMO* on top of this imaginary “session”, different from traditional definition of virtual MIMO controlled by network. Via such abstract mapping, we can modify the well-known space-time codes into *path-time codes* (PTC) [115]. By creating appropriate encoding matrix (permutation coding matrix or maximum-distance coding matrix), we modify sphere decoding to achieve significant error correcting gain. PTC can be generally applied to CRN or any ad hoc networks, which shall enable a new design paradigm in ad hoc networks, reliable end-to-end performance without control overhead and feedback in each link, a significant advantage for spectrum and energy efficiency.

More control issues in CRN can be found in literature such as queue control for service interruption [116], topology control [117], congestion control [118], and call admission control [119]. To practically implement spectrum-sharing communication in machine swarm, tremendous technical opportunities are required for various control mechanisms.

3.5. Heterogeneous network architecture

Although we demonstrate the feasibility of spectrum sharing multi-hop networking in Section 3.2, we still have to make sure whether such an approach is effective, particularly a packet of reasonable delay from source to destination. In large networks, this is not easy as we can abstractly consider from the social network analysis or random graph analysis. The *network diameter* is a good indicator of the required number of hops between two nodes in a network [SN]. Although network diameter has been widely studied [76], PPP network arrangement of high interests in wireless networks was not known. Unfortunately, in machine swarm, network diameter analytically derived from PPP network topology suggests intolerable number of hops for communications in machine swarm [120].

To resolve this challenge of autonomous M2M communications, we may ironically recall a result from social net-

work research, to reflect a novel truth of interplay between technological networks and social networks [121]. A famous theory in social networks is the 6-degree separation for any two persons in the world, a large human “network”. Obviously, the network diameter of this large human network cannot be 6. By digging into this *small world phenomenon*, a *short cut* always exists to link two far separated persons within the neighborhood [122]. Suggested in [120], we shall establish a man-made short cut among data aggregators (DAs) in Fig. 1. Luckily, such a short cut or like an information expressway is actually available as part of wireless infrastructure and cloud networking given in the heterogeneous network architecture of Fig. 1 and discussed in Section 2. The study of message delivery time is explored in [120] to show significant performance improvement, and general study in [123]. The rest of challenge is placement of DAs studied in [120] to show satisfactory performance adopting uniform distribution. Extending earlier QoS control techniques, we enjoy statistical QoS guarantees in machine swarm without detailed micro and end-to-end control [124].

Heterogeneous network architecture involves a lot of system design issues under active research at this time for both 3GPP cellular networks and IP-based wireless networks such as wireless LANs.

3.6. (Information Dynamics and) Traffic Reduction and In-Network Computation

Data gathering/collection [125], distributed detection and data fusion [126], data analysis [127], and data aggregation [128], have been extensively studied for wireless sensor networks of different purposes but primarily for the efficiency of processing data. In light of large wireless networks, a novel technology known as *in-network computation* was proposed to process data before reaching final destination in large wireless sensor networks [129]. It suggests a useful concept to combine computation and communication in a sensor network, to form a new design paradigm as computing compromising computation and communication (i.e. moving data). Further applications of in-network computation in wireless sensor networks can be found in [130], as a sort of practical realization of *context computing*. However, to deal with the fundamental spectrum efficiency in large networking for machine swarm is still missing in technology development.

Along the development of network coding and peer-to-peer networking, an interesting idea was developed by considering a special and ideal case to identify the optimal way to send n packets among n transmitter-receiver pairs using the nature of broadcasting in wireless networks [131]. The goal is to minimize the total traffic load or total energy, however, please note that minimizing traffic suggests another way to enhance spectral efficiency if we consider a practical definition of spectral efficiency as *network throughput per bandwidth*, which serves a side benefit from original research. The facilitation of this special case is via source coding into networking scenario, *network-aware source coding* or more precisely Hoffman coding. This nice idea is subject to further generalization, as the unrealistic assumption in Hoffman coding is *prior* knowledge of prob-

ability distributions that means each node knowing the entire network information. Universal source coding [132] serves the purpose without the need of priori statistics. Focusing on data gathering in wireless sensor networks, joint opportunistic source coding and opportunistic routing has been remarkably developed [133]. Pointed in Sections 3.3 and 3.4, network coding enhances performance by mixing information contents prior to forwarding packets. This research further explores joint source coding and (opportunistic) routing in a successful way via leveraging correlation of data in data gathering. Intuitively, the performance gain comes from (i) multiple independent receiving equivalent to diversity gain (ii) compression by Lempel–Ziv universal source coding when two correlated packets are received by one node. Unfortunately, this scheme assumes a node knowing the average number of hops for all forwarding candidates. In a large ad hoc network, efforts are still required for practical applications. Another experimental study is reported by considering finite alphabets for the data to be collected and transmitted in multi-hop networking [134]. By leveraging the broadcasting nature and information fusion like compression, it is shown that certain portion of relays are not needed anymore to significantly reduce the traffic in a network to equivalently increase the effective spectral efficiency (i.e. allowing more packets to transmit for other purposes). For large machine swarm, this provides an alternative to significantly enhance spectral efficiency (i.e. network throughput per bandwidth), though control information is still required.

The control information in a large network can consume tremendous bandwidth and opposite to spectral efficiency. Fig. 6 depicts the possibility of traffic reduction in information collection multi-hop sensor networks. Before machine R_m to transmit, it receives messages from two other ma-

chines and then compresses into a new message together with its own information collection. For machine R_n collecting information from the field, because R_n is within the transmission range of R_m indicated by red circle, it can compute the extra information to transmit and possibly realizes no extra information to transmit based on what R_n heard from R_m , which can this possibly save transmission bandwidth. Instead of further information theoretical study, traffic reduction (or equivalent transmission energy reduction) in the data collection wireless networks can be formulated as straightforward fusion together with quantization (i.e. compression) [135]. Then, we can show that a node can overhear from other nodes due to the nature of broadcasting to execute compression and thus to effectively save (or eliminate) portion of relay transmissions in a network while keeping the same precision of estimation. However, instead of the assumption on control information of entire network in this approach, this approach assumes that the multi-hop tree network topology that still requires efforts to establish in advance though each node does not require *prior* knowledge of network topology. Consequently, traffic reduction in general multi-hop networks remains an open problem.

However, in network computation and source coding are not only useful in traffic reduction for better spectral efficiency (or, equivalently energy efficiency for less relays). A practical and therefore desirable design in large machine swarm is to reduce end-to-end delay and/or energy efficient networking, without the required knowledge of end-to-end routing information at each node nor any prior knowledge of network topology. As shown in Fig. 5, n_S transmits a set of data X_1, X_2, \dots, X_K over these K paths. The values of the data can be observed from some joint distribution. Such observations may not consume bandwidth as a part of spectrum sensing or CRN tomography [59]. In-

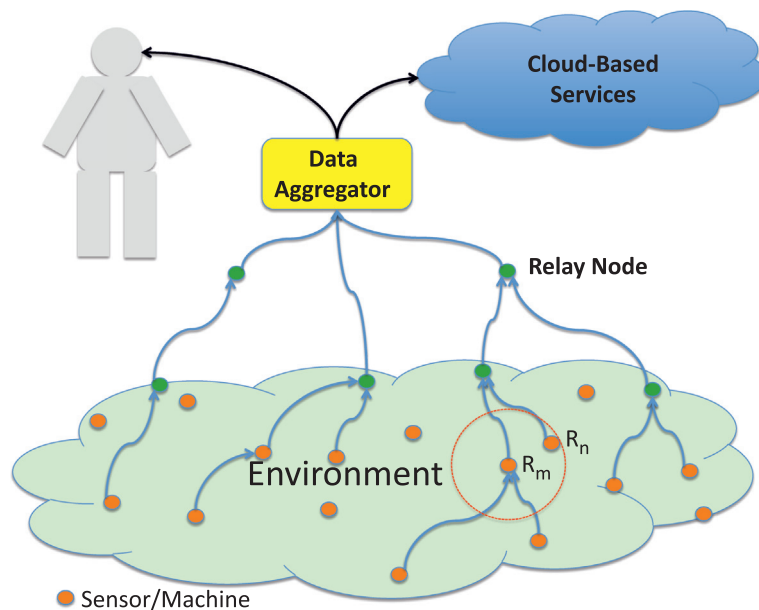


Fig. 6. Traffic reduction leveraging the nature of broadcasting.

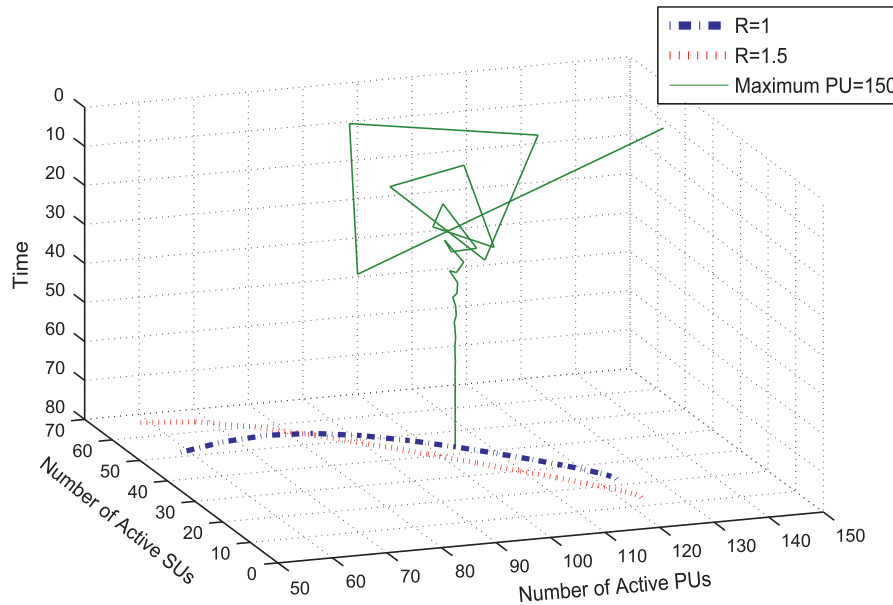


Fig. 7. Phase diagram for time dynamics of CRs sharing spectrum [138].

network computation for distributed source encoding and linear block coding, together with greedy routing can actually greatly enhance spectrum utilization or minimize end-to-end delay in machine swarm of cognitive radio capability [136], to indirectly enhance spectral efficiency. In new trend of applying source coding into routing, we therefore introduce a new way to execute in-network computation for the benefit of communication resource by leveraging the broadcasting nature of wireless communications without the need of global networking information.

3.7. Nature-inspired approaches toward time dynamics of networks

For decades since the birth of computer networks, network functions are designed typically based on a snapshot at certain timing and then to develop algorithms to optimize performance. The benchmark methodology via optimization is summarized in [137] as the state-of-the-art network design. However, we are more interested in time dynamics of networks, particularly multi-hop networks, as networks are not expected to operate in steady state. Before exploring time dynamics of spectrum sharing networks, please recall another new design paradigm from several places in Section 2 of this paper: to treat *radio resource* as the core of cross-layer design, such as the heterogeneous network design for cyber–physical system based on allocation of radio resource blocks for either access or interference mitigation.

Following the cross-layer design philosophy centered by radio resource allocation, the spectrum sharing wireless networks, no matter CRN or heterogeneous ad hoc networks, can be view as nodes/users to share radio resource, which is pretty much similar to predator–prey relationship. Radio resource units correspond to preys and net-

work users/nodes are just like predators to consume radio resource (i.e. preys). Prey–predator population dynamics are well studied by mathematicians in past centuries. Appropriate modifications can perfectly represent CR systems [138]. Most importantly, the time dynamics of CRs can perfectly described such as Fig. 7 showing system evolution with time and steady state performance (also suggested spectrum utilization). This amazing approach is just a starting point. Further development by including access protocols and graphical analysis is expected to reveal more fundamental behaviors of spectrum sharing machine swarm networking and common wireless networks.

4. Energy-efficient implementation, security and privacy, network economy, deployment and operation

Following above explorations on the fundamental technology of M2M communications, more practical aspects have to be considered toward realistic implementation, deployment, and operation.

4.1. Application scenarios of M2M system

M2M along with Internet of Things extends human life in a diverse way. Facilitation of autonomous M2M communications to handle the interaction of cyber and physical systems, in addition to fundamental technologies, relies on corresponding application scenarios [139–144]. Namely but not an exhaustive list,

- Smart home/office.
- Smart community and smart city.
- Environmental and ecology monitoring for safety, disasters, agriculture, etc.

- Surveillance.
- Energy-efficient control such as smart grid.
- Healthcare.
- Factory automation.
- Intelligent vehicles.
- Wireless robotics.

Such applications suggest further technology opportunities in M2M communications.

- Energy efficient wireless communications and networks.
- Spectrum efficient communications and networks.
- Scalable communication networks.
- Information-centric networks (with capability of information fusion, in-network computation, and data analysis/mining).
- Addressing and index, mobility management, service discovery, and middleware.
- Security and privacy.
- Green devices for communication and computing.

We use the following block diagram as Fig. 8 to illustrate potential M2M system function, while the role related to M2M communication and interaction with entire M2M system has been also delineated. In addition to those technologies that we described in earlier sections as the framework of M2M communications, there are some more of our particular interests in later of this section.

4.2. Energy harvesting communication networks

An emerging technology is the design of new communication systems and networks due to machines and sensors operating on harvested energy. For tremendous amount of machine devices in M2M systems, battery operating hard-

ware can create a great challenge for device management and environmental hazard. As a matter of fact, a device can realistically harvest energy from natural environment through sunlight, vibration, electromagnetic radiation, wind, etc. to operate [37]. Such energy source usually does not support streamline and stable power-supply and usually implies limited storage time and amount of energy. Any communication link relying on energy harvest is therefore opportunistic somewhat like cognitive radio, while the opportunistic nature of cognitive radio comes from spectrum availability and that of energy harvest communications comes from energy availability. Currently, such opportunistic nature is commonly modeled as a random process to give a general stochastic modeling for an energy harvesting communication systems as Fig. 9, and consequently queuing model for energy harvesting networking.

Since the energy harvesting can be viewed as a random process along the time axis, just like a fading channel, the immediate optimization of transmission targets on transmission power [145], and such optimization is equivalent to famous water filling in information theory [146]. A special feature in energy harvesting communication is the constraint on time resulted from energy storage on a machine. Transmission completion time shall be minimized, from the point of view not only from physical-layer communication link but also data networking. Given a deadline T , the maximum departure $D(T)$ is defined given energy arrivals and fading channel. Subsequent optimization methods are obtained for link [146] and scheduling [147]. Further development on broadcasting for multiple transmitter and multiple receivers [148] and optimal transmission for re-chargeable energy harvesting battery [149] are achieved.

In the early stage of technological exploration, some immediate open issues of energy harvesting M2M communications may include:

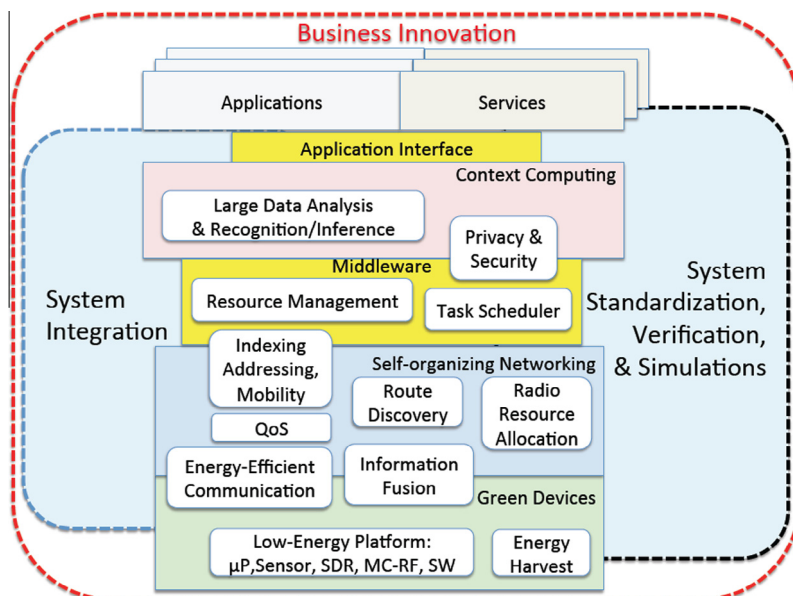


Fig. 8. Functional block structure of M2M systems.

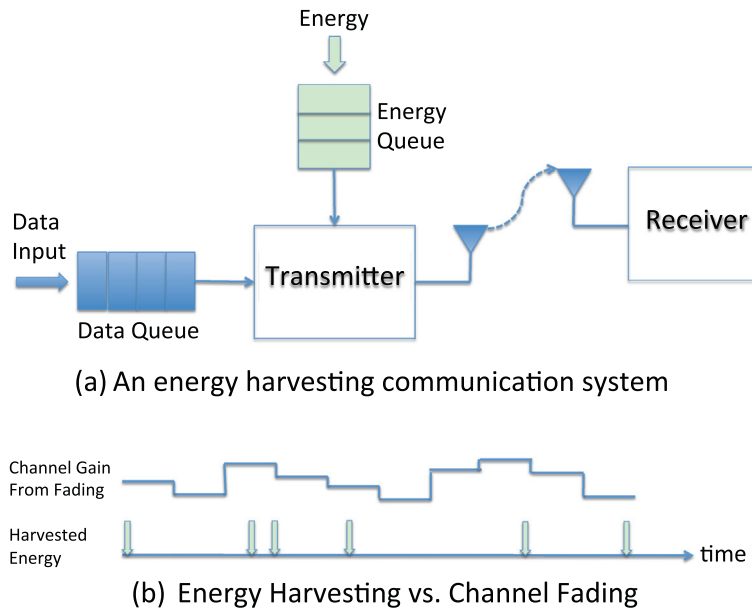


Fig. 9. Stochastic model for an energy-harvesting communication system (a) communication system (b) energy harvesting vs. fading.

- Statistical model(s) of energy harvesting.
- Cross-layer communication system design.
- Optimization of communication and computation energy in a machine.
- Networking protocols and algorithms optimizing energy and spectrum utilization.

In addition to short-term optimization in energy harvesting communications, further machine learning to enhance long-term operation is also considered [150].

4.3. Security and privacy

Cyber security and privacy has been attracting great amount of technical interests in recent years, which we do not want to repeat here. However, machine-to-machine communications involve interactions between cyber and physical worlds, which indeed introduces a lot of new issues in security and privacy [151]. In this paper, among this wide subject area, we orient two newly merging challenges in security and privacy related to M2M systems and communications.

Due to the co-existence of two kinds of networks, cyber and physical, *inference attacks* can play a much more powerful role in privacy and security. Location privacy in mobile communications was initially noted [152]. Later, further inference attacks are suggested. For example, by investigating household electricity consumption along the time through listening a smart meter in smart grid M2M communications, a lot of private life patterns can be inferred logically or statistically. Such a privacy attack and thus privacy preservation methodology can be understood and modeled by utility function and source coding [153] in a novel way.

Another sort of attacks is the distributed denial-of-service (DDoS) attack, which has been first introduced to cellular communications in [154] and can be harmful by easy jamming autonomous M2M communications to disable the operation of physical systems. Such security treat can be magnified by more factors when spectrum sharing M2M communications are conducted, primarily: (i) the existence of phase transition in heterogeneous CRN suggests sensible operating point change in network operation [90] (ii) a spectrum sharing network can be viewed as an eco-system and each node/machine tends to be selfish to evolve its own operating strategy [155]. Therefore, in addition to known attacks, more powerful and hard-to-detect DDoS attacks can be implemented [156]. The defense strategy can leverage information fusion in the network and form a game to retain network resilience [156,157].

4.4. Spectrum sharing network economy

As pointed in Section 3 regarding *layerless* “cross-layer” system design for M2M communications in the machine swarm, radio resource allocation (i.e. spectrum management) becomes the key, which is nice in technology but we have to examine practical feasibility in business operation to fulfill the economic need of M2M system operator. In other words, whether practical operation of spectrum sharing (or cognitive) machine swarm communication is realizable depends on network economy. This concern starts from technological network design by investigating resource allocation [158] by confining the problem as the convex optimization of radio resource in wireless cognitive networks [159]. Most recently, such efforts extend to network coding assisted channel allocation for routing [160]. With more practical economy study into scenario later, the spectrum sharing network economy actually must sat-

isfy four parties: primary system users, secondary cognitive radio users, operator of the primary system and secondary system, and regulator who cares overall spectrum utilization and users' QoS. An auction mechanism is established to ensure such satisfaction of network economy [161]. Such research can be extended to heterogeneous spectrum sharing wireless networks [162] and even cellular systems [163], which suggests economic feasibility of multiple M2M communication operators sharing certain spectrum.

4.5. Implementation, deployment, and sustainable operation

In spite of a lot of explorations on realization of efficient M2M communications, particular challenges in machine swarm. However, we have to look at some practical issues to install, to deploy, and to operate in a sustainable way. For wireless infrastructure, it is an extension of existing well operating cellular-type systems, and there shall not be any major fundamental technological obstacle in spite of tremendous technical efforts in need. Backward compatibility and scalability for potential expansion to accommodate DAs to support large number of machines might be something easy to overlook. Using smart coding, such an access mechanism to DA can be retained as [164].

There are further implementation concerns regarding spectrum sharing cooperative multi-hop networking in machine swarm:

- **Time synchronization:** It is too spectrum-costly to maintain a control channel in machine swarm communication. Typical thinking is to assume time synchronization in CRN to avoid performance loss. Ways to establish network synchronization can adopt algorithms from consensus and cooperation [165] like gossip algorithm, etc. In large network, the synchronization overhead can be significant and further stabilization is not fully understood. However, a different thinking to dynamic access the radio resource in asynchronous way is suggested [166]. Based on game theoretical formulation for each machine, even better performance than synchronous access can be surprisingly achieved. Asynchronous spectrum access can open a brand new door for advances in spectrum sharing network technology.
- **Complexity to implement cognitive radio and spectrum sharing networks:** The complexity of CR implementation is widely considered high. However, a good example is the adaptive frequency hopping (AFH) [167] in IEEE 802.15.2 and Bluetooth 2.0 and later versions. AFH requires to sense the spectrum and then to decide the change of hopping sequence to avoid collisions, such that synchronous (SCO) stream-traffic link can be well maintained among different networks to share the same spectrum. This is pretty much aligned with the principle of cognitive radio or spectrum sharing scenario in machine swarm. However, as long as we can select parameters in an appropriate manner and design accordingly, the incremental complexity in implementation is actually very minimal that can be ignored. With this energy-efficient technology has been widely

used for nearly a decade with billions of users, CRN is really just a technology challenge in effective system design.

- **Processor architecture for devices:** A real fundamental technology challenge lies in energy-efficient processor to effectively support data handling and M2M communication/networking while fitting simple machine or sensor. Among many literatures looking into this subject, we would like to remind a different design paradigm. By looking into communication algorithms, we may note only a few fundamental computation modes governing successful executions, and a scalable processor can be design to reach balance of performance and power consumption [168]. With the need of no more than 20 instructions to execute software, such programmable processor for machines/devices in the swarm implies a coming design paradigm shift for both hardware and software.

For successful operation of machine swarm, we have to note the device management caused by unreliable operation lifespan [142,169] and massive amount of data under cloud-based systems [170]. Finally, a remaining technological challenge in this paper is that reported technical achievements related to communication in machine swarm are most based on cognitive radio networks, and have not been generalized to heterogeneous spectrum sharing ad hoc networks yet. It is still an open research territory of human's engineering knowledge.

4.6. Toward the reference model of M2M communication architecture

The purpose of reference model is to enable easy collaboration during practical implementation and operation among sub-systems, and between hardware and software. M2M communications supports autonomous information (including data and control) transportation within the entire cloud-based IoT systems or cyber-physical systems. Therefore, M2M communication reference model shall allow transparency to application software and scalable to hardware expansion. In spite of tremendous application scenarios in Section 4.1, [171] suggests that the fundamental communication/networking styles are rather limited and we may summarize as follows:

- Streamline traffic of variable rate or fixed rate.
- Periodic traffic.
- Bursty traffic.
- Arbitrary traffic.

Communication patterns implies different functions of M2M communication reference model, while keeping in mind that we wish to minimize the amount of control signal due to tremendous number of machines. Such reference model transparent to applications shall play the central role in hardware and software system integration, linking cyber world and physical systems [172] by referencing Fig. 8. In particular, ad hoc networking in machine swarm based on local information (i.e. no global information) to achieve performance in a statistical manner is still

subject to further research on precise system design. We are expecting to international standardization on top of an appropriate as M2M communication reference model as the final open technological challenge in this paper.

5. Concluding remarks

This paper presents state-of-the-art technologies for the entire M2M communications and remaining intellectual and engineering challenges. As a young technology, we do foresee tremendous potential for M2M systems and M2M communication plays a central role to benefit modern and future human life.

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Kwang-Cheng Chen received B.S. from the National Taiwan University in 1983, M.S. and Ph.D from the University of Maryland, College Park, United States, in 1987 and 1989, all in electrical engineering. From 1987 to 1998, Dr. Chen worked with SSE, COMSAT, IBM Thomas J. Watson Research Center, and National Tsing Hua University, in mobile communications and networks. Since 1998, Dr. Chen has been with National Taiwan University, Taipei, Taiwan, ROC, and is the Distinguished Professor and Deputy Dean in academic affairs for the College of Electrical Engineering and Computer Science, National Taiwan University. Dr. Chen actively involves organization of various IEEE conferences as General/TPC chair/co-chair. He has served editorship with a few IEEE journals and many international journals and served various positions in IEEE. Dr. Chen also actively participates and has contributed essential technology to various IEEE 802, Bluetooth, and 3GPP wireless standards. He has authored and co-authored over 250 technical papers and more than 20 granted US patents. He co-edits (with R. DeMarca) the book *Mobile WiMAX* published by Wiley 2008, and authors a book *Principles of Communications* published by River 2009, and co-author (with R.Prasad) another book *Cognitive Radio Networks* published by Wiley 2009. Dr. Chen is an IEEE Fellow and has received a number of awards including 2011 IEEE COMSOC WTC Recognition Award and co-authored a few award-winning papers published in the IEEE ComSoc journals and conferences. Dr. Chen's research interests include wireless communications and network science.



Shao-Yu Lien received the B.S. degree from the Department of Electrical Engineering, National Taiwan Ocean University, Taiwan, in 2004, the M.S. degree from the Institute of Computer and Communication Engineering, National Cheng Kung University, Taiwan, in 2006, and the Ph.D. degree from the Graduate Institute of Communication Engineering, National Taiwan University, Taiwan, in 2011. After the military service, he joined the Graduate Institute of Communication Engineering, National Taiwan University, as a post-doctoral research fellow in 2012. Since 2013, he has been with the Department of Electronic Engineering, National Formosa University, Taiwan, as an assistant professor. He received IEEE ICC 2010 Best Paper Award and his research interests include the controls of networks and communication systems.