Cognitive Machine-to-Machine Communications for Internet-of-Things: A Protocol Stack Perspective

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***Abstract*—Machine-to-machine (M2M) communications enables networked devices to exchange information among each other as well as with business application servers and therefore creates what is known as the Internet-of-Things (IoT). The research community has a consensus for the need of a standardized protocol stack for M2M communications. On the other hand, cognitive radio technology is very promising for M2M communications due to a number of factors. It is expected that cognitive M2M communications will be indispensable in order to realize the vision of IoT. However cognitive M2M communications requires a cognitive radio-enabled protocol stack in addition to the fundamental requirements of energy efficiency, reliability, and Internet connectivity. The main objective of this paper is to provide the state of the art in cognitive M2M communications from a protocol stack perspective. This paper covers the emerging standardization efforts and the latest developments on protocols for cognitive M2M networks. In addition, this paper also presents the authors' recent work in this area, which includes a *centralized* cognitive medium access control (MAC) protocol, a *distributed* cognitive MAC protocol, and a specially designed routing protocol for cognitive M2M networks. These protocols explicitly account for the peculiarities of cognitive radio environments. Performance evaluation demonstrates that the proposed protocols not only ensure protection to the primary users (PUs) but also fulfil the utility requirements of the secondary M2M networks.**

***Index Terms*—Cognitive radio, Internet-of-Things (IoT), low power and lossy network (LLN), machine-to-machine (M2M), medium access control (MAC), protocol stack, routing, routing for low power and lossy networks (RPL).**

I. Introduction

THE communication industry has seen a tremendous growth over the last two decades. A plethora of technologies exist nowadays with a single objective of providing ubiquitous connectivity between people on the planet. The next big thing in communications would be a truly cworld of not only the people but also the everyday objects. Therefore, this decade is widely predicted to see the rise of connected devices that are not mobile phones and do not require human control.

Machine-to-machine (M2M) communications is an emerging communication paradigm that provides ubiquitous connectivity between devices along with an ability to communicate autonomously requiring no human intervention. M2M communications acts as an enabling technology for the practical realization of Internet-of-Things (IoT). The IoT is envisioned as "*a global network of connected devices having identities and virtual personalities operating in smart spaces and using intelligent interfaces to communicate within social, environmental, and user contexts*" [1]. This vision of IoT represents a future where billions of everyday objects and surrounding environments will be connected and managed through a range of communication networks and cloud-based servers [2].

Market size projections show a large potential for M2M market that is expected to grow rapidly in the next few years. This is due to a number of factors including the widespread availability of wireless technologies, declining prices of M2M modules, and economic incentives. Some of the most prominent M2M application areas include security and public safety (surveillance systems, object/human tracking, alarms, etc.), smart grids (grid control, industrial metering, demand response), vehicular telematics (fleet management, enhanced navigation, etc.), healthcare (telemedicine, remote diagnosis, etc.), manufacturing (production chain monitoring), and remote maintenance (industrial automation, vending machine control, etc.) [3].

M2M communications will be realized through a range of technologies and networks. Generally, M2M networks can be divided into two broad domains: 1) *capillary* M2M and 2) *cellular* M2M networks. In capillary M2M networks, M2M devices form a device area network wherein connectivity is provided through short-range communication technologies (such as ZigBee and Wi-Fi). Wide area connectivity is provided through a gateway. Capillary M2M networks are generally characterized by a huge number of low-cost and low-complexity devices, requirements of high energy efficiency and reliability, unplanned deployments, high packet loss ratios, use of low-power link layer technologies, etc. In literature, this type of networks is also referred to as low power and lossy networks (LLNs). In cellular M2M networks, M2M devices are equipped with embedded SIM cards and have the ability of communicating autonomously with the cellular network like a normal user equipment. Cellular M2M has unique characteristics [4] of small data transmissions, mostly mobile-originated (uplink) traffic, little or no mobility of devices, service requirements of high energy efficiency, etc.

On the other hand, *cognitive* M2M communications (M2M communications employing cognitive radio [5] technology) [6] is expected to be indispensable in the era of IoT. A large

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number of connected devices, as envisioned for the IoT, will create a major challenge in terms of spectrum scarcity. Through dynamic spectrum access capabilities, cognitive M2M not only improves spectrum utilization but also exploits alternate spectrum opportunities. In addition, cognitive M2M is inherently equipped to address the challenges of interference management, energy efficiency, and device heterogeneity. Moreover, cognitive M2M opens new application areas for M2M communications.

Despite active research on M2M communication, especially over the last couple of years, cognitive M2M communications is still a vastly unexplored field with only a handful of studies. The main objective of this paper is to provide the state of the art in cognitive M2M communications from a protocol stack perspective. To the best of our knowledge, this is the first study on protocol aspects of cognitive M2M communications. We begin our discussion with the motivation for cognitive M2M in Section II. In Section III, we identify the key requirements of a protocol stack for M2M communications and provide a brief overview of different protocols. In Sections IV–VII, we introduce the protocol stack for cognitive M2M communications and cover the latest developments at different layers including the authors' recent work in this respect. This is followed by a discussion and some directions for future work in Section VIII. Finally, Section IX concludes this paper.

II. Cognitive M2M Communications

Cognitive radio technology [5] provides as a novel approach to address the spectrum scarcity and spectrum inefficiency issue in wireless networks. In cognitive radio networks, unlicensed users (secondary users) dynamically access the frequency band/channel whenever the licensed user [primary user (PU)] is absent and need to vacate the band/channel whenever the latter is detected.

There are several motivations for using cognitive radio technology in M2M communications (and hence the term cognitive M2M) [6]. Some of the main challenges of M2M networks can be successfully addressed through cognitive M2M as described below.

- *Spectrum scarcity:* A fundamental challenge in M2M is the ever increasing number of M2M devices. It is expected that a multitude of connected devices (e.g., according to Ericsson, 50 billion connected devices will exist by 2020) will exist in the near future. This creates a major challenge for existing communication networks in terms of spectrum congestion. With dynamic spectrum access capabilities of cognitive radio, existing spectrum can be utilized more efficiently in order to avoid the potential shortage of spectrum and to support large-scale data transmission.
- *Interference:* With a multitude of connected devices operating in unlicensed bands, significant interference issues will arise between self-existing and co-existing M2M networks. This will not only deteriorate the performance of M2M network, but also adversely affect the conventional human-to-human (H2H) services operating in the unlicensed bands. Hence, there is a need of exploring alternate spectrum opportunities such as TV white spaces (TVWSs) [7], which refer to large portions of UHF/VHF spectrum that is becoming available on geographical basis as a result of switchover from analog to digital TV. TVWS are attractive because of significant bandwidth availability (location-dependent, e.g., on average 50–150 MHz [8] in the U.K.) and superior propagation characteristics.
- *Coverage issues*: A critical issue in some M2M applications such as smart grid is the huge variability in device locations. Some devices might be deployed in areas where wireless propagation is not always guaranteed, especially if operating in the industrial, scientific and medical (ISM) band (worldwide unlicensed band of 2.4–2.485 GHz). Cognitive radio-equipped M2M networks can effectively overcome this issue through dynamic spectrum access of better propagation bands such as TVWS.
- *Green requirement:* A fundamental requirement in M2M communication is energy efficiency. Hence, energy savings become particularly important to enhance the network lifetime. The use of cognitive radio technology has been demonstrated to be green (or energy efficient), as devices can adaptively adjust their transmission power levels based on operating environments [9].
- *Device heterogeneity:* M2M networks are diverse in terms of applications and services, which may cause diversity in network protocols and data formats. The cognitive ability is particularly suitable for M2M communication in order to deal with device and protocol heterogeneity, as M2M networks will be more efficient and flexible if devices are smart enough to communicate with others freely.

Apart from addressing the technical challenges, cognitive M2M also introduces a variety of new applications such as home multimedia distribution systems, intelligent roads for future intelligent transportation systems (ITSs), and urban broadband services [6].

III. Protocol Stack for (Capillary) M2M

A technically viable communication architecture is crucial for the realization of IoT. The community has a consensus for the need of a standardized architecture which replaces proprietary approaches by means of a transparent end-to-end architecture. This section presents a standardized protocol stack for capillary M2M[1] communications.

The core requirements of the protocol stack for capillary M2M communications include the following [10].

- *Energy-efficient protocol stack:* Majority of M2M devices are battery-operated and do not have the ability to draw power from the mains. Moreover, they are often deployed in areas where frequent human access, and hence battery replacement is not always feasible. Therefore, the protocol stack must exhibit low energy consumption.
- *Internet-enabled protocol stack:* It is of paramount importance that M2M networks are Internet protocol (IP)-enabled, so that M2M devices have a universal language for communication.

[1]Note that the protocol stack for cellular M2M depends on the underlying cellular network.

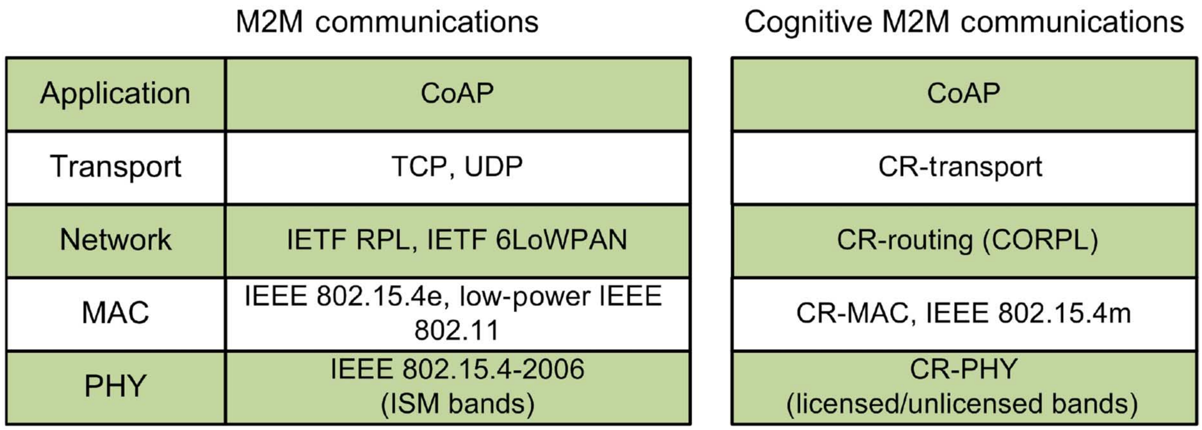


Fig. 1. Protocol stack for (capillary) M2M communications and cognitive M2M communications.

- *Highly reliable protocol stack:* Most M2M networks are inherently lossy in nature owing to operation in challenging wireless environments with frequent link failures. Hence, reliability must be ensured at different layers of the protocol stack.

Fig. 1 shows the standardized protocol stack for capillary M2M communications. Efforts from different standardization bodies have led to the development of different protocols in order to meet the requirements of M2M networks. While a detailed discussion on different protocols is beyond the scope of this paper, it is important to explain how these protocols meet the requirements of M2M networks.

At the physical (PHY) layer, the most prominent standard in low-power radio technology is the IEEE 802.15.4-2006 [11], which is expected to be sufficient for meeting the energy efficiency requirements of M2M devices. IEEE 802.15.4-2006 protocol is designed to operate on worldwide unlicensed frequency band of 2.4–2.485 GHz (ISM band). Current hardware implementations are optimized for short- to medium-range communication. Efforts are already underway in the CMOS community to increase the range of low-power sensor radios [12]; a technological advancement that will bring new horizons for the IoT.

At the medium access control (MAC) layer, newly developed IEEE 802.15.4e [13] protocol will be adopted. The protocol uses *time-synchronized channel hopping* to combat fading and interference. It also uses a rigid slot structure with centralized or distributed scheduling to achieve high energy efficiency. Another strong candidate at the MAC layer is the low-power Wi-Fi (IEEE 802.11) [14], which promises high energy efficiency (through a power saving mode) while providing easy integration to existing infrastructure with built-in IP compatibility.

From networking perspective, Internet Engineering Task Force (IETF) 6LoWPAN [15] protocol will be instrumental in connecting M2M devices to the Internet. 6LoWPAN bridges the gap between Internet and low-power M2M devices by providing IPv6 networking capabilities through special encapsulation and header compression techniques that allow IPv6 packets to be sent over low-power link layer technologies. Given the low power and lossy nature of M2M networks, routing issues can be very challenging. IETF has recently standardized an effective routing protocol known as routing for low power and lossy networks (RPLs) [16], which is capable of quickly building routes, distributing routing knowledge among nodes with little overhead, and adapting topology in an efficient way. RPL is expected to be the standard routing protocol for majority of M2M applications including smart grid.

At the transport layer, conventional transmission control protocol (TCP) [17] and user datagram protocol (UDP) [18] are expected to be adopted. Last but not the least, IETF-constrained application protocol (CoAP) [19] will be adopted at the application layer. CoAP is based on RESTful architecture [20], making it interoperable with HTTP for simplified integration while meeting the specialized requirements of multicast support, low overhead, and simplicity for resource-constrained M2M networks.

As mentioned earlier, cognitive M2M communications will be for the IoT. Hence, a new requirement for protocol stack arises, i.e., *cognitive radio-enabled protocol stack*. The adoption of cognitive radio at the PHY layer of M2M communications creates new challenges for upper layers. Hence, a completely new protocol stack is required with cognitive radio-aware MAC, routing, and transport protocols as shown in Fig. 1.

Despite active research on M2M communications over the last couple of years, cognitive M2M communications is still a vastly unexplored field with only a handful of studies. With reference to the standardization of cognitive M2M, efforts are still in infancy. Recently, IEEE has established the 802.15.4m task group (TG) [21] in order to specify cognitive radio-aware PHY and MAC layers for cognitive M2M networks.

In the following, we provide the state of the art in cognitive M2M communications and cover the latest developments at different layers of the protocol stack. Since research on cognitive M2M is in nascent stages, we also highlight the key challenges at different layers.

IV. PHY Layer for Cognitive M2M

The resource-constrained nature of M2M devices creates various challenges for the PHY layer design of cognitive M2M networks. Some of the main challenges include low

TABLE I
IEEE 802.15.4 PHY LAYER DESIGNS FOR COGNITIVE M2M NETWORKS

PHY layer description	Frequency bands
Direct sequence spread spectrum (DSSS) PHY with O-QPSK modulation	779–787 MHz, 868–868.6 MHz, 902–928 MHz, 2.4–2.483 GHz
Parallel sequence spread spectrum (PSSS) PHY with ASK modulation	868–868.6 MHz, 902–928 MHz
DSSS PHY with BPSK modulation	868–868.6 MHz, 902–928 MHz, 950–956 MHz
Chirp spread spectrum (CSS) PHY with DQPSK modulation	2.4–2.483 GHz
Ultra wideband (UWB) PHY with BPSK modulation	3–10 GHz
M-ary PSK (MPSK) modulation	779–787 MHz
Guassian frequency shift keying (GFSK) with DQPSK modulation	950–956 MHz

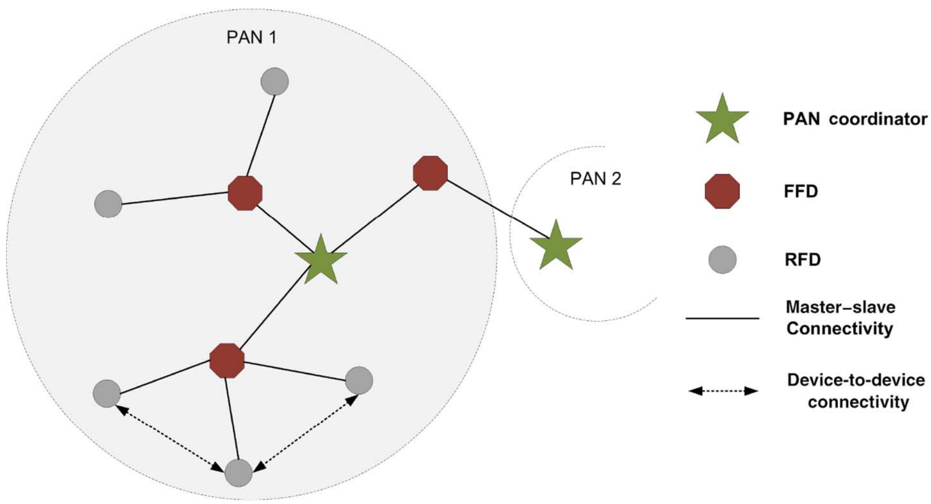


Fig. 2. Network topology in IEEE 802.15.4m.

complexity software-defined radio (SDR) based transceivers for energy-efficient reconfigurability operations, lightweight spectrum sensing algorithms with high detection probability, and low cost dynamic spectrum access solutions that require minimum overhead.

While a lot of research exists on conventional cognitive radio architectures, spectrum sensing algorithms, and spectrum access solutions, the aforementioned challenges have been rarely addressed in literature. The IEEE 802.15.4m TG provides the PHY layer specifications for cognitive M2M networks working in TVWS. Till date, seven different PHY layer designs in seven different regulatory domain-specific frequency bands. A summary of these designs is given in Table I. However, these designs are mainly from modulation and coding perspectives only. Moreover, there is little investigation on the complexity of these designs for cognitive M2M networks.

V. MAC LAYER FOR COGNITIVE M2M

A. IEEE 802.15.4m

The network topology in an IEEE 802.15.4m-based cognitive M2M network consists of two types of devices: 1) the full function device (FFD), with a complete set of MAC functionalities, and 2) the reduced function device (RFD) with a limited set of functionalities. Multiple devices form a device area network or a personal area network (PAN). Each PAN has a PAN coordinator, which acts like a centralized controller. Devices inside a PAN are connected through a master–slave connectivity as shown in Fig. 2. The FFDs having the capabilities of becoming coordinators can be further connected to other devices to establish extended hierarchies. In addition to the cluster-tree topology, device-to-device connectivity is also possible, i.e., devices within the same hierarchy are able to directly connect to one another.

The master device is responsible for enabling the operation of associated slave devices. The master device obtains the channel availability information and sends an enabling signal. Devices in a PAN periodically scan for the enabling signal and register with the master device upon reception.

In addition, the IEEE 802.15.4m TG specifies a *dynamic band switching* (DBS) mechanism for flexible operation across a range of bands. The main benefit of DBS mechanism is the co-existence with the primary network. The master device announces its DBS intention while operating in the current band along with relevant operation and execution timing parameters. This completes the DBS setup. If there is no DBS disabling from the initiating master device, the operation in new band will take place at the execution time.

B. PRMA-Based Cogntive MAC

A packet reservation multiple access (PRMA)-based MAC protocol for cognitive M2M networks has been proposed in [22] and [23]. PRMA can be considered as a combination of slotted ALOHA, time division multiple access (TDMA), and a reservation scheme. It is particularly attractive for M2M communications considering the scalability and energy efficiency requirements, periodic traffic patterns, and large-scale deployments.

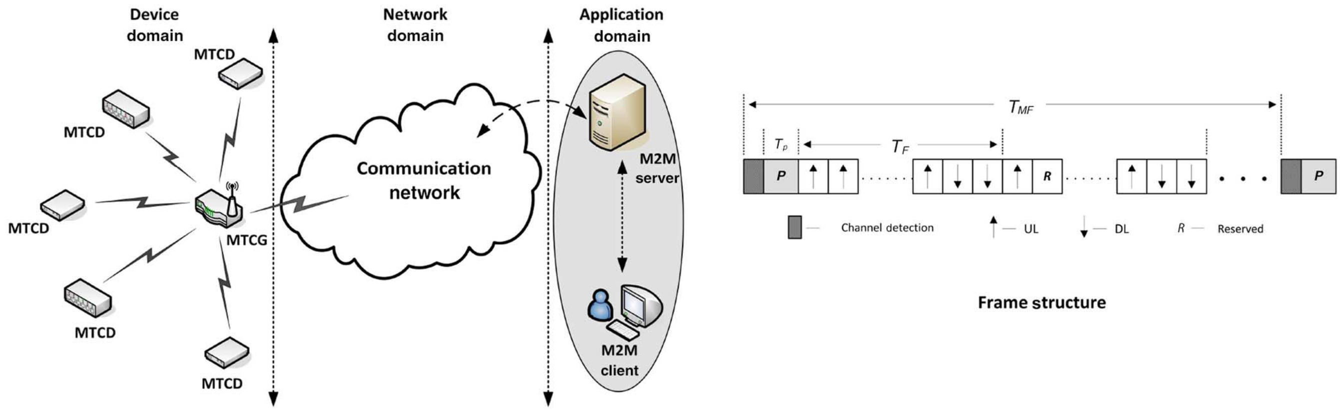


Fig. 3. Network topology and frame structure for PRMA-based cognitive MAC protocol. Since M2M communications is also referred to as machine-type communication (MTC), M2M devices are referred to as MTCDs and M2M gateway is referred to as MTCG.

The authors consider a generic M2M architecture comprising of M2M devices (MTCDs) and M2M gateway (MTCG) as shown in Fig. 3. The connectivity between the MTCDs and the MTCG exists in a master–slave manner. Hence, the MTCG acts like a centralized controller and is responsible for channel detection (using spectrum sensing techniques) as well as maintaining the operation of associated MTCDs.

The frame structure for MAC layer operation is also shown in Fig. 3. The underlying available channel (cognitive channel) is divided into a number of fixed length time slots, each able to carry a single packet. A fixed number of time slots are grouped into a frame. In order to efficiently utilize the cognitive channel, time division duplex (TDD) mode of operation is used. Since the traffic is mainly in the uplink (UL) (MTCD to MTCG), the ratio of downlink (DL) to UL time slots is kept small and only few time slot are assigned for any possible DL (MTCG to MTCD) communication and acknowledgements (ACKs). The DL timeslots are also used to broadcast the status (reserved or available) of UL time slots. A fixed number of frames are grouped together into a multiframe. Each multiframe starts with a channel detection period followed by a preamble or a multiframe control header that is used by the MTCG to broadcast an enabling signal carrying channel availability of a vacant channel after performing spectrum sensing operation. The MTCDs scan for an enabling signal. If an enabling signal is received, the MTCDs associate with the master device, i.e., the MTCG.

Initially, all the UL slots of a frame are available for contention. The contention procedure follows a slotted ALOHA scheme. Each MTCD that has data to send will contend in an available slot by transmitting a packet with some *permission probability*. If the packet is received correctly by the MTCG, it will send a positive ACK in the DL time slot, which also implies a reservation of the same slot in subsequent frames. In case of a collision with another contending MTCD, the contention procedure is repeated again in another time slot as determined by a random backoff value.

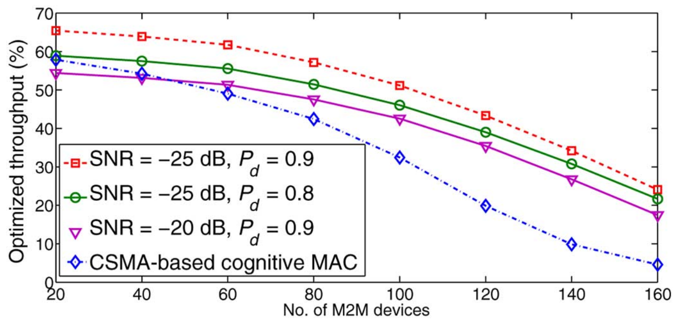
The length of the reservation cycle is kept limited to a multiframe, i.e., at the start of a multiframe, all MTCDs will contend again for reservation. This is to ensure fairness among the MTCDs. In addition, regulatory constraints require the channel availability information to be updated periodically. Hence, there is an associated probability of change in the status of underlying available cognitive channel during the next round of spectrum sensing.

In order to account for the quality-of-service (QoS) requirements of MTCDs in resource assignment, the protocol is equipped with a specialized backoff procedure that incorporates QoS requirements in the backoff taken after a collision (during the contention phase), such that devices with critical QoS requirements take a smaller backoff and hence given priority in channel access.

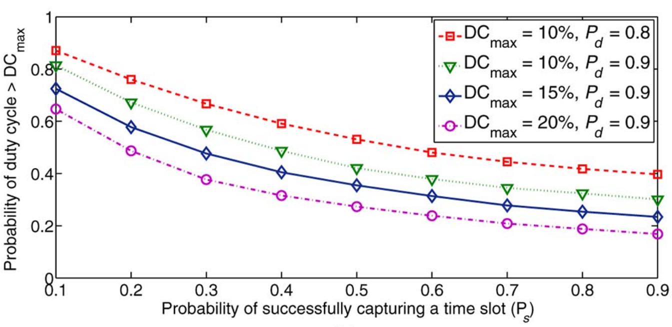
The MAC frame structure is further optimized in terms of the optimal channel detection time and the optimal reservation cycle, considering different tradeoffs pertaining to primary network protection (in terms of interference) and the utility (in terms of the duty cycle which directly affects the energy efficiency) of the secondary M2M network [24]. A detailed performance evaluation has been carried out in [22]–[24] through analytical modeling and simulation studies. The results in Fig. 4 show that the protocol exhibits good scalability characteristics. Under moderate device density of 80–100 MTCDs, throughput of up to 60% or more can be achieved depending upon the signal-to-noise ratio (SNR) level of the sensed primary signal and threshold probability of detection, while keeping the interference to PUs to a minimum as well as satisfying the energy efficiency requirements to an appreciable extent, and thus provides a viable solution for practical cognitive M2M environments such as smart grid. Moreover, the PRMA-based cognitive MAC protocol outperforms the CSMA-based cognitive MAC [25] (which is also centralized) owing to its scheduling nature. The pure contention nature of CSMA-based cognitive results in poor scalability.

C. CRB-MAC

A receiver-based cognitive MAC protocol, termed as cognitive receiver-based (CRB)-MAC, has been proposed in [26]. CRB-MAC is designed with special emphasis on energy efficiency and reliability requirements of M2M devices operating in challenging wireless environments such as smart grid. In order to achieve high energy efficiency, CRB-MAC employs *preamble sampling* [27] approach to tackle *idle listening* and



(a)



(b)

Fig. 4. Performance evaluation of PRMA-based cognitive MAC. (a) Optimized throughput subject to detection and interference constraints (P_d refers to threshold detection probability for primary signal detection). (b) Probability of violating the duty cycle constraint ($\mathrm{DC}_{\max}$ denotes the maximum allowed duty cycle).

support sleep/wakeup modes without synchronization overheads. CRB-MAC exploits the broadcast nature of wireless medium and adopts an opportunistic forwarding approach with multiple receivers as discussed later in detail. This approach improves the reliability of the network along with reducing the number of retransmissions.

Fig. 5 illustrates the CRB-MAC protocol operation along with the timeline for different nodes. As shown in the figure, a node S wants to send data to the sink/gateway node by forwarding toward its first hop neighbors (within the transmission range). First, it performs spectrum sensing (with duration given by T_s) to detect any PU activity. If the channel is detected as busy with PU transmission, the sender node goes to sleep mode. The sensing operation is repeated after a duration of checking interval (T_{CI}). If the PU is detected to be absent, the node starts transmitting the preamble followed by the data. The preamble consists of multiple micro-frames (each of duration T_m) and contains identification information for neighboring nodes to distinguish between PU transmission or sensor node transmission. All the nodes within the transmission range of S detect and sample few micro-frames of the preamble to extract necessary information (e.g., sequence number of the data). As shown in Fig. 5, only three neighboring nodes of S (i.e., nodes A, B, and C) are eligible to forward the data toward the sink node. They all wake up and receive the data transmitted by node S. If the received data packet is detected to be erroneous, it is simply discarded. The nodes receiving the data packet do not send any ACK message. However, they set a timer (Δt) before forwarding the data to the next hop. The timer is set relative to a node's distance[2] from the sink. The node with the shortest timer (closest to the sink) is most likely to forward the data toward the sink. Right after the expiry of the timer, each neighboring node performs the sensing operation. If the channel is occupied by the PU, the node goes back to sleep mode for a duration of T_{CI}. However, if a sensor node transmission is detected, each node compares the sequence number of the transmitted data with its own. If the sequence numbers match, it means that the same data is being transmitted by another node. Therefore, it discards the data packet. Otherwise, a free channel indicates that this node is the winner and can start transmitting the preamble (e.g., in Fig. 5, node A is the winner). The sender node S retransmits the data if none of the participating nodes in the contention window is successful to forward the data packet. The sender node can realize this by performing the sensing operation just before ending the contention window (passive ACK). The duration of contention window T_{CW} is set according to the transmission radius of sender nodes. In case of multiple hops, the same operation continues until the data is received by the sink.

A detailed performance evaluation of CRB-MAC has been carried out in [26] through analytical modeling and simulation studies. The results in Fig. 6 demonstrate that in lossy wireless environments, CRB-MAC is more resilient to channel quality variations and generates less retransmissions, which enhances the overall energy and delay performance. Moreover, high reliability can be provided by increasing the number of receivers.

VI. Network Layer for Cognitive M2M

A. CORPL

Routing in cognitive radio environments becomes challenging due to a number of reasons. First, the routing protocol must explicitly account for the spectrum sensing state of different nodes, as the multihop network becomes virtually disconnected at the node engaged in spectrum sensing. Second, the routing protocol must provide *temporal* as well as *spatial* protection to PUs. The former refers to the protection provided to PU transmitters, whereas the latter refers to the protection for PU receivers, which is particularly important for those applications where the transmission is unidirectional (e.g., TV broadcast). The protection to the PU transmitter is subject to accurate detection of the PU activity. On the other hand, PU receivers are difficult to detect and can be easily affected by the transmission from neighboring CR users. Therefore, the network layer should provide explicit protection to PU receivers by avoiding regions where such users might be present [28]. Third, the protection provided to PUs results in a performance tradeoff for the secondary network. Hence the routing protocol must optimize the operation for both primary and secondary networks depending upon the level of protection for the former and the QoS requirements of the latter.

RPL is expected to the standard routing protocol for majority of M2M applications as mentioned earlier. In this regard, an enhanced RPL-based routing protocol for cognitive radio-enabled M2M networks has been proposed in [29].

[2]The distance is determined by the network layer. For example, in case of RPL [16] protocol, each node is assigned a *rank*, based on an *objective function* that determines a node's virtual position with respect to the sink node.

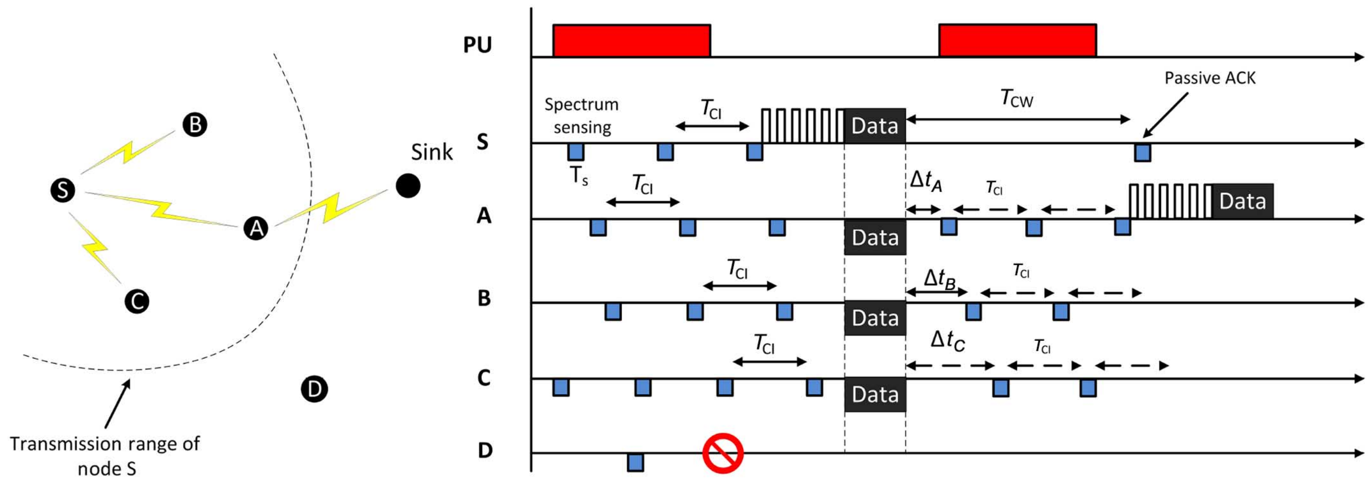


Fig. 5. Timeline of CRB-MAC protocol with an illustrated scenario of sender and receiver nodes.

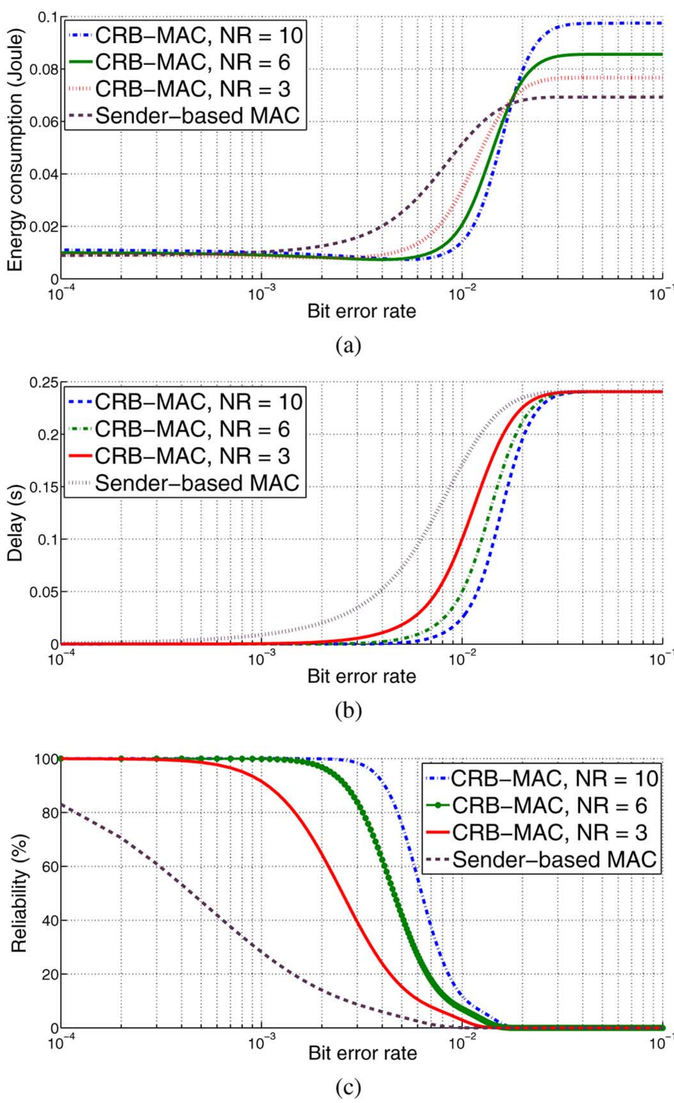


Fig. 6. Performance evaluation of CRB-MAC over a single hop. (a) Energy consumption. (b) Delay. (c) Reliability; NR denotes the number of receiver nodes.

The main objective of the proposed protocol, termed as cognitive and opportunistic (CO)RPL, is to retain the *directed acyclic graph* (DAG)-based approach of RPL and at the same time introduce novel modifications to allow its application in CR environments. To address the aforementioned challenges, CORPL uses an opportunistic forwarding approach [30] that consists of two key steps: 1) selection of a forwarder set, i.e., each node in the network selects multiple next hop neighbors and 2) a coordination scheme to ensure that only the best receiver of each packet forwards it (unique forwarder selection). In CORPL, each node maintains a forwarder set such that the forwarding node (next hop) is opportunistically selected.

The DAG construction process in CORPL follows a similar procedure as in RPL. After detecting a vacant channel, the gateway node transmits a *destination information object* (DIO) message. CORPL uses *expected transmission count* (ETX) [31] as the default metric for rank computation. The ETX of a link will be measured and updated continuously, once the link starts to carry data traffic. The rank computation method for a node joining the DAG is illustrated in Fig. 7.

The forwarder set is constructed in such a way that the forwarding nodes are within the transmission range of each other. During the DIO transmission, each node also reports some additional information using the option field of the DIO message. Each node updates the neighborhood information through the DIO message transmission. Based upon the neighborhood information, each node dynamically prioritizes its neighbors in order to construct the forwarder list.[3] The priorities are assigned according to a cost function.

The cost function to prioritize the nodes in the forwarder set depends on the routing class. CORPL considers two different routing classes. The first class (*class A*) assigns a greater importance to PU receiver protection; whereas, in second class (*class B*), the end-to-end latency is the key consideration for supporting the high priority delay sensitive alarms. These two classes of protocols are explained as follows.

[3]The forwarder list refers to the arrangement of nodes in the forwarder set according to their respective priorities.

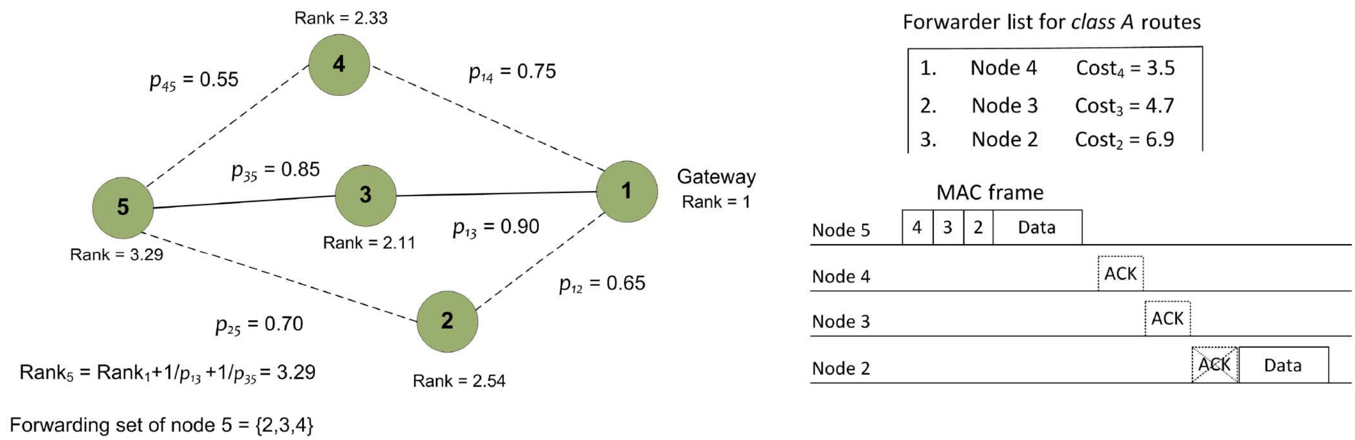


Fig. 7. Rank computation in CORPL based on ETX. The default parent for node 5 is node 3 owing to a smaller rank compared to nodes 2 and 4. An example forwarder list for *class A* routes is also shown along with the timeline of coordination scheme. Note that a node who fails to receive the ACK will forward the frame as well.

In order to reduce interference to PU receivers (which can be present anywhere in the coverage area of PU transmitters), the routes for the secondary network should be selected such that they pass through regions of minimum coverage overlap with the PU transmission coverage.

For delay-sensitive alarms, the node must find the next hop that guarantees the deadline. If the deadline has elapsed, the packet will be dropped. The node assumes that the time before the deadline can be uniformly shared among the nodes in the route. The delay before the packet is correctly transmitted to the next hop that depends on: 1) delay until a vacant channel is found (t_1) and 2) the average delay until the next hop correctly receives the packet (t_2). While t_1 depends on PU activity and spectrum sensing outcome, t_2 is characterized by the MAC layer and can be estimated by the packet delivery ratio. The node that provides the highest margin for delay budget (DB), i.e., (DB $\geq t_1 + t_2$), will be given the highest priority in the forwarder list.

In order to ensure unique forwarder selection, CORPL employs a simple overhearing-based coordination scheme based on the ACK frames as shown in Fig. 7. A forwarding node forwards the data to the next hop and generates an ACK. This ACK is captured by the nodes in the forwarder set. If the highest priority node fails to forward the frame within a time-out period (no ACK is received), the node with the next highest priority forwards it.

CORPL employs two different techniques for mitigating the performance degradation due to spectrum sensing. The first technique improves the performance through gathering sensing schedule information of the neighboring nodes. The second technique improves performance by decreasing the spectrum sensing time. Reduction of sensing time is possible when a node is situated in region of low PU activity, and hence the number of channel changes that occur over time is small.

A system-level performance evaluation of CORPL has been conducted in [29] by assuming a square region of specific area, which is occupied by nine PU transmitters. The secondary users are Poisson-distributed with a certain density. The results in Fig. 8 demonstrate that CORPL improves the reliability of the network using the diversity of routes. The performance gain in terms of packet delivery ratio is significant under poor channel conditions. Moreover, by opportunistically selecting the suitable next hop, CORPL reduces the deadline violation probability (DVP) for delay sensitive traffic by up to 38% and harmful interference to PU receivers by up to 50%.

VII. Transport Layer and Above

In literature, the problem of adapting conventional transport layer protocols (TCP and UDP) for cognitive M2M networks has been rarely investigated. For general cognitive radio *ad hoc* networks (CRAHNs), a transport protocol has been proposed in [32]. The proposed protocol, termed as TP-CRAHN (transport protocol for CRAHNs), adapts TCP for cognitive radio environments. TP-CRAHN is specially designed considering the peculiarities of cognitive radio environments and explicitly accounts for the periodic spectrum sensing, PU activity, channel availability, and bandwidth variations. The protocol integrates as an end-to-end metric, the spectrum sensing, and switching functionalities in a cognitive radio network, apart from the classical concerns of congestion, flow control, and connection losses due to node mobility. By relying on updates from the intermediate nodes and the destination feedback, the source maintains information about the network state and responds appropriately by adjusting its transmission rate. TP-CRAHN provides valuable insights for adapting TCP and other transport layer protocols for cognitive M2M networks.

The cognitive radio-based PHY layer does not require any changes at the application layer. Although cognitive M2M introduces a variety of new applications, CoAP is expected to be the standard application layer protocol.

VIII. Discussion and Future Work

In order to implement this protocol stack in cognitive M2M networks, M2M devices must be equipped with cognitive functionalities. From feasibility perspective, an important concern is that such functionalities are considered to be complex and expensive for low-cost M2M devices. However, with recent advances in microelectronics and signal processing

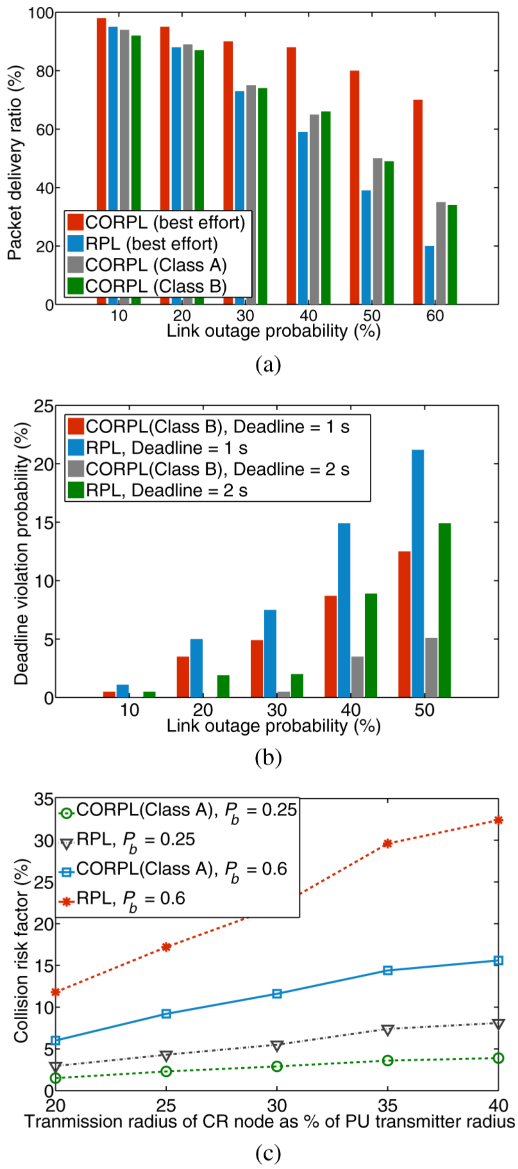


Fig. 8. Performance evaluation of CORPL. (a) Packet delivery ratio. (b) Deadline violation probability. (c) Collision risk factor.

communities, M2M devices are becoming increasingly sophisticated to perform spectrum-oriented operations. A model for a cognitive machine capable of performing different functionalities such as network interconnection, spectrum cognition, and network management is proposed in [6]. From practical perspective, not all M2M devices in a network need to be fully equipped with cognitive functionalities. For example, in a *centralized* architecture, as proposed in the PRMA-based cognitive MAC (Section V-B), a master–slave operation can be provided such that another node provides cognitive functionalities for M2M devices. Such centralized architecture keeps the device end simple. However, it may result in reliability and scalability issues for large-scale cognitive M2M networks. An alternate approach is the *distributed* architecture, as proposed in the CRB-MAC (Section V-C), where each node in the network is equipped with cognitive functionalities. The distributed architecture scales well with the size of the network and also increases the overall reliability. However, all nodes in the network must be equipped with cognitive functionalities. In order to achieve the best tradeoff of both architectures, the most suitable approach is to deploy a hybrid architecture comprising of multiple device domains co-existing in a distributed manner, wherein each domain has a centralized controller.

It can be easily inferred that research on cognitive M2M communications is far from complete. A number of challenges remain that need to be addressed. In the following, we highlight some research directions for future work.

- It would be interesting to investigate the PRMA-based cognitive MAC protocol with multiple device domains (multiple M2M networks). In this case, each device domain has a centralized controller, which is the MTCG. The primary challenge is the coexistence of multiple secondary M2M networks as each network may have different service requirements. A simple MAC layer coexistence solution is the frame scheduling for each M2M network based on its priority. However, this requires a common control channel for communication among MTCGs belonging to different M2M networks. Apart from this, certain aspects of protocol operation require further investigation such as the design of reservation cycle. Moreover, cooperative spectrum sensing techniques [33] can be employed to improve the channel detection performance by exploiting the correlation in the sensed information of multiple MTCGs.
- Joint design of different layers (cross-layer design) can improve the performance of cognitive M2M networks through joint optimization of parameters at different layers. Therefore, it would be interesting to investigate joint design of CORPL with PRMA-based scheduling in multihop cognitive M2M networks. Similarly, joint design of CORPL and CRB-MAC protocol can be explored.
- It is particularly important to investigate the performance of the proposed MAC and routing protocols under the dynamics of transport layer. This may provide useful insights on designing low overhead transport protocols for cognitive M2M networks.
- QoS requirements in M2M communications are mostly application-specific. The resource-constrained nature of M2M devices makes QoS provisioning a challenging task for varying data delivery models such as periodic, event-driven, and query-initiated. Therefore, cognitive radio-aware protocols for M2M networks must also be context aware in order to meet the diverse QoS requirements as well as to provide differentiated QoS.

IX. Concluding Remarks

M2M communications is an enabling technology for the practical realization of the IoT. M2M communications will revolutionize every aspect of present day life by creating smart homes, smart grids, smart transportation, smart buildings, and smart cities. Cognitive radio technology will play a crucial role in realizing the vision of IoT. In this paper, for the first time, the use of cognitive radio technology in capillary M2M networks has been investigated from a protocol stack perspective. Successful operation of cognitive M2M requires an energy-efficient, reliable, and Internet-enabled protocol stack with cognitive radio-aware protocols from PHY to transport layer. Apart from highlighting the key challenges at different layers and the emerging standardization efforts, this paper covers the latest developments on protocols for cognitive M2M networks.

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