Cognitive and Opportunistic Relay for QoS Guarantees in Machine-to-Machine Communications

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Abstract—Deploying spectrum sharing machine-to-machine (M2M) communications with the existing wireless networks achieves ubiquitous data transportation among objects and the surrounding environment to benefit our daily life. However, the lack of schemes to completely characterize M2M network topology, to efficiently share radio resource, and to provide quality-of-service (QoS) guarantee regarding end-to-end delay creates challenges to practically facilitate M2M communications. Via mathematical derivations, the network connectivity, degree distribution, and average distance are provided for large M2M networks. To achieve reliable communications upon such M2M networks, inspired by cognitive radio technology and cooperative communications, a *cognitive and opportunistic relay* (COR) scheme is proposed. Specifically, machines with the proposed COR autonomously sense the primary systems' spectrum usage so as to mitigate detractive interference and adopt opportunistic forwarder selection for lower link delay of packet transmissions. Furthermore, by analytical deriving the effective capacity of the COR over connected M2M networks, the throughput under statistical QoS guarantee and the corresponding delay violation probability are proposed to specify the QoS guarantee capability of the networks and thus suggest the conditions of dependable end-to-end transmissions. Simulation results confirm that the proposed COR effectively achieves the delay guarantee performance, to yield a novel framework for facilitating reliable M2M communications in large machine networks.

Index Terms—Machine-to-machine (M2M) communications, quality-of-service (QoS), effective capacity, cognitive radio, cooperative relay, opportunistic forwarding, ad hoc networks

1 Introduction

Recently machine-to-machine (M2M) communications have received considerable attention [1], [2], [3] as to achieve autonomous operation known as the Internet of Things or cyber-physical systems (such as smart grid), facilitating services via linkage between cyber and physical worlds. Cloud-based network architecture makes tremendous amount of machines in the swarm to form a large M2M communication network [1]. Wireless infrastructure to support such large M2M communications had been considered in the next generation wireless systems such as 3GPP long-term evolution advanced (LTE-A) [4], [5]. For efficient use of spectrum, the M2M network and the existing wireless networks might share the identical spectrum, which potentially results in terrible interference between both networks. However, lacking complete understanding for geometric properties of such large-scale network makes even more difficult to deal with the inter-system interference. In practice, to employ the multi-hop M2M network into machine swarm, achieving the merits of cooperative diversity from numerous machines and providing QoS guarantees for reliable data transportation are two essential capabilities. As a result, a networking algorithm that can take advantage of large-scale network properties along with effective spectrum sharing and achieve cooperative diversity as well as QoS guarantee for reliable transmissions becomes an urgent need to realize M2M communications.

Some research efforts explored QoS provisioning over 3GPP LTE-A based cellular systems, particularly for M2M communications. Different from others, M2M traffic includes video (e.g., monitoring application) as well as latency-sensitive control data, and brings the strong need of QoS guarantees. In [6], a reallocation-based assignment is proposed to maximizes the spectral efficiency with QoS guarantees in multi-service wireless machine systems, achieving a good tradeoff between performance and computational complexity. Furthermore, three radio resource management techniques are presented in [7] in order to maintain a load- or QoS-balanced system across a composite wireless network. In [8], a stochastic model is proposed to investigate the feasible QoS qualities, such as average throughput, sensing overheads, etc., for dynamic spectrum access networks under the TDMA-based primary networks. In [9], such a QoS consideration is further extended to multiuser multi-channel access and the effect of collision for the optimal stopping rules of dynamic channel switching. A comprehensive traffic measurement and characterization is provided in [10] for cellular network-based M2M communications. A tight integration of device-to-device communications into an LTE-A network is further examined in [11] to desirably exploit spectrum of the existing radio networks. In addition, several existing studies [12], [13], [14] deal with different traffic characteristics from

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various M2M applications. In [12], a massive access management on the air interface is proposed to address enormously diverse QoS characteristics from tremendous machines, enabling the first and the last mile connections in M2M communications. In [13], an accelerated slotted-ALOHA scheme is proposed for event-driven M2M communications to greatly reduce the access delay under highly bursty traffic. In [14], a M2M system architecture based on LTE system is presented and the corresponding latency for three kinds of real-time M2M applications is studied. However, there lacks a comprehensive and practical study of possible collaboration among a large number of machines to improve the QoS guarantees in these machine type communications.

In this paper, rather than having separate explorations for routing algorithms and QoS provisioning schemes like existing researches, we propose a cognitive and opportunistic relay (COR) algorithm with QoS guarantees for large M2M communications. Specifically, through mathematical derivations, we first study some crucial geometric properties of large multi-hop M2M networks and investigate the condition to establish connected M2M networks. Lower and upper bounds of average distance in such networks are examined to characterize the average number of hops that data packets need to traverse for any pair of machines in networks. This attribute dominates the QoS guarantee capability of end-to-end transmissions and thus plays a crucial role for reliable communications. Different from the existing approaches of ad hoc networking [15], [16], [17] that optimize the relay selections regarding relay capabilities, COR employs paradigm shift among relay machines to enable distributed concatenation of multiple single-hop transmissions. Specifically, inspired by the cognitive radio networking [18] and cooperative communications, COR upon such connected M2M networks enables machines to cognize and to adapt to the communication environment for mitigating inter-system interference, and exploits opportunistic selections for cooperative relay machines regarding link transmission qualities. In particular, inspired by the work in [19], the opportunistic relay selection of COR algorithm is built upon on opportunistic randomized network coding with respect to delay-aware routing metrics. By analytical deriving the effective capacity of the COR over connected multi-hop M2M networks, we propose a systematic approach to achieve the system throughput with QoS guarantee and the corresponding delay violation probability. We summarize our proposed framework as follows:

- A complete study is first presented to explore essential geometric properties for reliable communications over large multi-hop M2M networks.
- COR algorithm is then proposed to employ paradigm shift for the distributed concatenation of multiple single-hop transmissions.
- With the aid of effective capacity, the QoS guaranteed throughput via COR algorithm is obtained by the proposed systematic approach.

Simulation results show that the proposed COR completely characterizes the delay guarantee performance for two-state activity model of video surveillance traffic. Note that, different from [20] which only derives the delay upper bound in M2M communication networks, this paper deals with the actual packet delay that is experienced through the exploitation of the proposed novel COR algorithm. Furthermore, to provide statistical delay guarantees, the work in [20] accommodates upper bound performance of delay violation probability via Markov inequality, which is relatively loose statistical bound. This paper, on the other hand, employs more sophisticated effective bandwidth theory to facilitate the performance analysis, accurately capturing the arrival process of incoming traffic. What is more important, the original concept of effective capacity [21] for single-hop transmission in link level is extended to end-to-end communications in network session level. Such consideration resorts to achievable capacity under QoS constraint, gives more detailed investigation of realistic performance, and thus is important for practical applications. With the joint consideration of effective bandwidth and effective capacity, the actual achievable delay guaranteed throughput is further yielded and several performance evaluations are conducted to reveal the impacts of delay and throughput from different types and degrees of cognitive and opportunistic nature. Therefore, we develop the framework to facilitate multi-hop M2M communications for latency-sensitive applications, practically realizing such promising technology to meet the need of serving great number of machines.

The rest of this paper is organized as follows. Section 2 gives the related work and Section 3 presents the system model and spectrum sharing for machine swarm. Geometric properties of large M2M networks are examined in Section 4. The COR for the connected M2M networks is proposed in Section 5. In Section 6, we derive the effective capacity for QoS guarantees of the COR and further propose the QoS guaranteed throughput acquirement. Performance evaluation is provided in Section 7 and the paper concludes in Section 8.

2 Related Work

Cognitive radio technology is generally recognized as a well-suitable approach to solve the spectrum scarcity for the dramatically increasing need of wireless connection capabilities. In the literature, many solid contributions have been reported to alleviate interference, due to concurrent spectrum access, with QoS provisioning for different next-generation wireless systems. In [22], an optimal channel-hopping sequence is proposed to provide the maximum aggregate throughput for cognitive radio users under the primary users' QoS requirements. A *two channel sensing and access* scheme within a single time slot is provided in [23] to largely improve the throughput of cognitive users. In [24], a distributed scheduling and spectrum allocation is further considered to maximize network throughput subject to delay constraint under the assumption of single-path forwarding. A cognitive radio resource management is provided for QoS guarantees in autonomous femtocell networks [25] and with the extension in cyber-physical systems [26]. In [27], an integration between cognitive radio technology and stochastic geometry is presented to estimate network topology for possible QoS provision in M2M communications for the fifth generation cellular networks. In [28], a cooperative relaying technique is further exploited to more effectively and efficiently utilize available transmission resources for QoS requirements. Furthermore, in [29], a

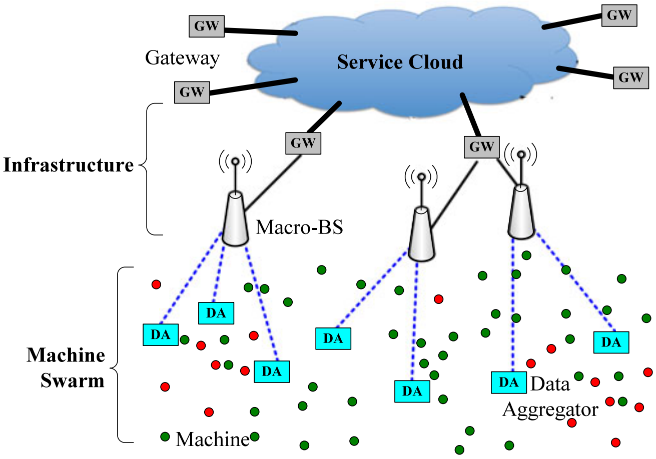

Fig. 1. Cloud-based network architecture for M2M communications.

delay optimal scheduling with cooperative beamforming is proposed to access busy time slots or spatial spectrum holes without causing interference and providing significant QoS gains. In [30], a new architecture for home M2M networks is provided and its QoS management under cognitive gateway is considered. Moreover, in [31], cognitive M2M communications are applied in the smart grid and the QoS study for the integration of reliability and timeliness is presented. However, above remarkable efforts do not thoroughly explore traffic flow together with proposed schemes, while disregarding realistic routing protocol at network layer. Thus, they can only deal with the simplified network topologies, such as single-hop flows, three-node relay networks, or multi-hop flows with fixed routes, on top of simple statistical assumptions, e.g., breaking a multi-hop flow into multiple single-hop flows with the same traffic arrival to ease the analysis. Furthermore, how to provide a realistic and reliable data transmissions with delay guaranteed throughput, especially for video surveillance application, upon a large-scale cognitive M2M networks is urgently needed but still open in the literature.

3 System Model

3.1 Network Model

Cloud-based M2M communications are generally realized by the two-tier heterogeneous network architecture as [1], [2], [3]: a pool of machines with short-range communication capability and another tier involving wireless infrastructure and service cloud as Fig. 1. Service cloud provides the accesses to M2M services and peer-to-peer social networks, linking physical world to cyber world. Furthermore, cloud's gateways (or data aggregators) smartly collect and process data from machines. Here, data aggregators denote some powerful devices that functionally serve as the local access points, collect the data from neighboring machines, and transmit to Macro-BSs. Instead of having a central controller for conventional cellular networks, machines distributed communicate with each other. Moreover, due to wireless fading, each machine can only communicate with others around certain distance. Assume that there are n machines and each pair of machines within r distance can communicate. Thus, the geometric random graph (GRG) [32] with parameters n and r is suited for our network model. $GRG(n, r)$ defines a graph with n vertex following homogeneous poisson point process (PPP) and edges are established when vertexes are closer than radius r. PPP characterizes randomly distributed machines on a unit flat (i.e., $[0, 1] \times [0, 1]$ square) in our consideration. For transmitting data across machine pool, constructing a connected network for M2M communications is demanded and thus the connectivity for large multi-hop M2M networks via social network analysis is presented later in Section 4.1. In the following derivations for properties of such networks, we assert a network has certain properties with high probability (i.e., almost surely or a.s.), when $n \to \infty$ and $r(n) \to 0$.

Wile each machine equips with short-range communication capability, multi-hop relay networking is requisite for end-to-end data transportation. Considering a single source-destination pair, there exist a source machine (denoted as S), a destination machine (denoted as D), and several relay machines that help forward traffic from S to D. Without loss of generality, series of packets with Poisson arrival and variable service time are adopted, and each transmission link is modeled as a $M/M/1/\infty/FCFS$ queueing model [33]. In particular, Poisson packet arrival is chosen as it suits for modeling the aggregate traffic of a large number of similar and independent packet transmissions. Also, to serve packets of variable size, exponential distribution is chosen due to packet length distribution. We assume that the source's traffic has Poisson arrival with rate λ, and the service rate of link $L_{x,y}$ is exponential distributed with rate $\mu_{x,y}$. Note that while we use the continuous time traffic model for cognitive machines, the channel sensing capability of machines should belong to time slotted systems regarding the practical implementation. That is, instead of continuous sensing the channels, machines follow the slotted scheme to decide the channel availability. The detailed modeling and explanation are provided in Section 3.2. Also note that for the delay-aware designs in the rest of this paper, we focus on the packet delay involving transmission and queueing latencies than propagation and processing latencies, to provide the least packet delay and to benchmark the performance of any further sophisticated designs.

3.2 Spectrum Sharing for Machine Swarm

Exploiting spectrum sharing in M2M communications, the cognitive radio technology is applied to enabling dynamic spectrum access of machines. Spectrum occupancy of the existing users (or primary systems) is modeled as a continuous-time Markov chain (CTMC) with channel available (communication link is idle) and unavailable (the link is busy) states for cognitive usages [34]. It is assumed the transmissions of primary systems are not slotted. The channel holding time for primary systems are independent and exponentially distributed with aggregated parameter $\gamma_{x,y}^{-1}$ for available state and $\chi_{x,y}^{-1}$ for unavailable state on link $L_{x,y}$. To capture the interaction between the unslotted primary systems and the proposed slotted sensing of cognitive machine system, the stationary distributions of the channel available and unavailable states are provided under previous CTMC model as

$$\nu^0_{x,y} = \frac{\chi_{x,y}}{\gamma_{x,y} + \chi_{x,y}} \tag{1}$$

$$\nu^1_{x,y} = \frac{\gamma_{x,y}}{\gamma_{x,y} + \chi_{x,y}}. \tag{2}$$

Thus, for the proposed cognitive machine system, it adopts slotted scheme with the probabilities of channel availability and unavailability on each slot as $\nu^0_{x,y}$ and $\nu^1_{x,y}$, respectively. These channel distributions are then utilized in our designated algorithm later, which aims to employs opportunistic machine relay through randomized network coding technique to fulfill reliable data transportation upon machine swarm.

4 Geometric Property of M2M Communication Networks

To facilitate our design of relay algorithm for M2M networks in Section 5, we first examine essential geometric properties (i.e., network connectivity, degree distribution, and average distance) of such large networks as follows, so that multihop in machine swarm can be reasonably realizable.

4.1 Connected M2M Networks and Their Degree Distribution

Constructing a connected network is the prerequisite for successfully transmit messages across machine swarm. In the following, we first derive the lemma that characterizes the relationship between graph partition and the corresponding machine distribution. We then exploit the result in lemma to provide the sufficient condition for connected M2M networks in Corollary 1.

Lemma 1. *As n machines follow PPP on a unit flat (i.e., $[0,1] \times [0,1]$ square) and the partition of flat into blocks (i.e., smaller squares with area $\log n/n$) is applied, there is at least one machine in each block a.s., while $n \to \infty$.*

Proof. Please refer to Section 3.1 in [20]. □

Note that, *Lemma 1* holds for any partition with area of blocks larger than $\log n/n$ (e.g., the one gives blocks with area $(r/\sqrt{5})^2$ and $r \geq \sqrt{5 \log n/n}$). Thus we come to the connectivity for connected M2M networks in the following.

Corollary 1. *For a M2M network modeled by $GRG(n,r)$, if $r \geq \sqrt{5 \log n/n}$, the M2M network is a.s. connected.*

Proof. Please refer to Section 3.1 in [20]. □

For connected M2M networks modeled by $GRG(n,r)$ (i.e., $r \geq \sqrt{5 \log n/n}$), it assumes that n machines locate with PPP and each pair of machines are connected by an edge when they are closer than distance r. Considering a specific machine in $GRG(n,r)$, an edge connecting to its neighbor exists with probability πr^2 for total $n-1$ possible neighbors and the degree distribution is a binomial r.v. While we are interested in large M2M networks for $n \to \infty$, the distribution becomes a Poisson r.v. with

$$\mathbf{Pr}\{K = k\} = \frac{(n\pi r^2)^k \exp\{-n\pi r^2\}}{k!}. \tag{3}$$

Degree distribution of a network exhibits the number of machines that connect to a specific machine in a network, showing the possible incoming traffic to a single machine in connected M2M networks. It dominates reliable communications, while heavy loads invoke deadlocks in link traffic and thus produce a standstill for end-to-end data transportation.

4.2 Average Distance of Connected M2M Networks

For average distance (in hop-count) among pairs of machines in connected M2M networks, we examine the euclidean distance over all pairs of vertexes in $GRG(n,r)$. In particular, Lemma 2 first provides the geometric relationship between any euclidian distance and its projection lengths in connected M2M networks with GRG model. Proposition 1 further provides the distance properties for any uniform distribution nodes. Finally, Theorem 1 utilizes the above derived results and provides the average distance for connected M2M networks where machines are uniformly distributed in two dimension plane.

Lemma 2. *For euclidian distance d, let d_x and d_y denote for the projective length of d in unit flat for x and y axes, respectively. Then, in connected $GRG(n,r)$, d (in hop-count) has the upper bound $\sqrt{5}(d_x + d_y)/r$ and the lower bound d/r, given $r \geq \sqrt{5 \log n/n}$.*

Proof. Parting the unit flat into blocks with area $(r/\sqrt{5})^2$ as usual and substituting each block with a single machine, these machines are connected and form a lattice by *Corollary 1*. For an arbitrary path with length d in the lattice, there must be a corresponding path, satisfying the upper bound $\sqrt{5}(d_x + d_y)/r$, in $GRG(n,r)$. On the other hand, while the maximum step length is r for each hop, d follows the lower bound and completes the proof. □

Note that, we assume $\sqrt{5}(d_x + d_y)/r$ and d/r are integers in *Lemma 2* as the real values are $\lceil \sqrt{5} d_x/r \rceil + \lceil \sqrt{5} d_y/r \rceil$ and $\lfloor d/r \rfloor$. However, when $r \to 0$, the difference can be neglected. Before further calculating the average distance, we first have the following proposition for uniform r.v..

Proposition 1. *Let $U(S)$ denote the uniform distribution on S, where S is a connected subinterval of $\mathcal{R}^k$, and $|\cdot|$ and $\|\cdot\|$ denote absolute value for one dimension and euclidean distance. If two r.v. $X, Y \sim U([0,1])$, $\mathbf{E}[|X-Y|] = 1/3$. And if r.v. $X, Y \sim U([0,1] \times [0,1])$, $\mathbf{E}[\|X-Y\|] \geq \sqrt{2}/3$.*

The equality of *Proposition 1* comes from the derivation in calculus and the inequality comes from $\sqrt{a^2+b^2} \geq (|a|+|b|)/\sqrt{2}$. Thus, we are ready for the distance as follows.

Theorem 1. *While $r \geq \sqrt{5 \log n/n}$ for a connected M2M network with $GRG(n,r)$, the average distance $d(n)$ (in hop-count) is bounded almost surely as*

$$\frac{\sqrt{2}}{3r} < d(n) < \frac{2\sqrt{5}}{3r}. \tag{4}$$

Proof. For $GRG(n,r)$, let y be a random chosen vertex with position X_n and $x_1, x_2, \ldots, x_{n-1}$ be the rest of vertexes with positions $X_1, X_2, \ldots, X_{n-1}$, we have $X_1, X_2, \ldots,$

$X_n \sim U([0,1] \times [0,1])$. We further let the projections of these n vertexes on x axis be $Y_1, Y_2, \ldots, Y_n \sim U([0,1])$. For $d(n)$ of M2M network, we have the lower bound

$$\frac{\|X_n - X_1\| + \|X_n - X_2\| + \cdots + \|X_n - X_{n-1}\|}{r(n-1)} \quad (5)$$

and the upper bound

$$\frac{2\sqrt{5}(|Y_n - Y_1| + |Y_n - Y_2| + \cdots + |Y_n - Y_{n-1}|)}{r(n-1)} \quad (6)$$

from *Lemma 2*. By law of large number,

$$\frac{\|X_n - X_1\| + \cdots + \|X_n - X_{n-1}\|}{n-1} \to \mathbf{E}[\|X_n - X_1\|] \quad (7)$$

and

$$\frac{|Y_n - Y_1| + \cdots + |Y_n - Y_{n-1}|}{n-1} \to \mathbf{E}[|Y_n - Y_1|]. \quad (8)$$

By *Proposition 1*, two bounds are therefore obtained. □

For connected M2M networks (e.g., $r \sim \sqrt{\log n/n}$), *Theorem 1* suggests that $d(n)$ follows the order $1/r$, given significant number of machines. That is, $d(n)$ is $\Theta(1/r) = \Theta(\sqrt{n/\log n})$. Furthermore, while $d(n)$ provides average number of hops that will be traversed by packets, it highly relates to average delay for end-to-end transmissions as we will see in following section and thus plays the crucial role for message delivery in M2M networks. Note that, the results obtained here is similar to [35]. However, there are some major differences between two works. First, when we consider the M2M network connectivity, we provide a practical lower bound of transmission distances instead of giving a "big-O" performance bound, which is more from information theory perspective. Furthermore, we employ GRG for the M2M topology due to its suitableness of modeling large-scaled ad-hoc networks. Upon such a model, we are able to obtain the results for average distance in a much easier and simpler approach. What is more important, rather than satisfying and stopping with the theoretical results in literature work, we extend our analysis into a realistic routing algorithm that exploits the merits from the theoretical perspective. Such an approach enhances the algorithm performance in a solid and effective manner.

5 The COR Algorithm for M2M Networks

Avoiding interference, M2M network needs to be aware of the spectrum usage of existing systems. Furthermore, inspiring from cooperative diversity of numerous autonomous machines, it is beneficial for the network to exploit cooperative communications in its multi-hop transportation. In the following, the COR is proposed to incorporate spectrum sharing in Section 3.2 and opportunistic routing [19], [36] into routing protocol design for M2M network. Existing approaches of ad hoc networking [15], [16], [17] need entire information for possible forwarders' relay capabilities and make great difficulty when applying in M2M networks due to their scales. Instead of investigating the optimal forwarder (s), the concept of paradigm shift is exploited in COR algorithm. That is, we assume *Source* only roughly knows the location of *Destination*, specifically the direction to *Destination*. Each relay machine contributes its single-hop transmissions and shifts the dominant role in multi-hop relay networking. Such relay machines distributively guide the traffic flow along *Source-Destination* direction via random network coding [37], providing a significant networking methodology for large M2M networks.

Algorithm 1 (COR scheme:)

1) The *Source* first partitions its traffic into batches of packets for transmissions.
2) At each *Source*'s available time slot, *Source* makes its forwarder set (i.e., $i \in R(S)$) by the *Destination*'s direction, requests spectrum availabilities from its forwarders (i.e., $\nu^0_{S,i}$, $i \in R(S)$), and prioritizes forwarders in the relay candidate list by link metric $m_{S,i}$. *Source* then randomly mixes packets in a batch via random network coding and broadcasts coded packet with the list and the availability information (i.e., $\nu^0_{S,i}$, $i \in R(S)$).
3) While the ACK message is not heard from *Destination*,
   a) *Source* repeats Step 2 until it hears ACK.
   b) For each relay machine z, if z receives a packet from others, it decodes the packet and recodes packet's incoming direction in θ_z, saves new information in its buffer, and checks the list.
      i) If z is in the list, z calculates its triggering ratio Φ_z according to the list and advances its counter by the ratio.
   c) At each z's available time slot, z examines whether its counter is positive.
      i) If so, z makes its forwarder set (i.e., $i \in R(z)$) from θ_z, requests $\nu^0_{z,i}$, and prioritizes forwarders in the new list according to $m_{z,i}$. z then randomly mixes its buffered packets, broadcasts coded packet with the new list and $\nu^0_{z,i}$ ($i \in R(z)$), and decrements its counter by one.
4) *Destination* continuously decodes the collection of coded packets to verify whether it gets all packets of the batch. If so, *Destination* broadcasts ACK back to *Source*, eliminating the packets buffered in relay machines and enabling the next transmission batch.

The scheme exploits opportunistic relay selection regarding spectrum availability of cooperative links into packet delay. Specifically, it establishes forwarder sets, designs triggering ratios with counters, and proposes link metrics and candidate lists in delay perspective. Moreover, COR algorithm further broadcasts ACK packets to enable next batch transmission in the source machine. Such transmission functionalities of opportunistic routing and broadcasting enable the entire system to function well even under certain amounts of packet loss due to wireless fading or dynamic spectrum access. Note that while it is very challenging to make a coherent cooperation among a large number of machines, this paper aims to enable a reliable routing algorithm in the current stage, which is more urgent and important than to design a complicated algorithm with great accuracy. In particular, the delay-aware designs of routing algorithms and QoS guarantees are focused on the transmission and queueing delays, instead of propagation and processing delays such as decoding latency. As we provide the least packet delay that any other network coding design tries to approach, the results obtained here serve as the benchmark for performance comparison with further sophisticated designs. A more refined network coding design with the consideration of effective coding indexes, decoding delay, optimal patch size as well as the corresponding ACK mechanism, will be research focus in the future. In the following, to guide link transmissions along the direction from *Source* to *Destination*, forwarder selections for *Source* in Step 2 and for relay machines in Step 3c (i) are first given in Proposition 2. Furthermore, Lemma 3 and Lemma 4 provides a delay-aware routing metrics for source and relay nodes respectively. With this direction setup and routing metrics, Proposition 3 provides the forwarder candidate list to enable better forwarder selection along the end-to-end routes. Finally, Proposition 4 gives an adaptive policy for triggering ratio in terms of the received candidate lists to facilitate the opportunistic routing algorithm.

Proposition 2. *Given* Destination *D's direction, the forwarder set of* Source *S, denoted by $R(S)$, is given as*

$$R(S) = \{j | j \in N(S) \text{ and } |\angle\overrightarrow{SD} - \angle\overrightarrow{Sj}| \leq 90^\circ\}, \tag{9}$$

where $N(i)$ is i's neighbors and $\angle\vec{x}$ is the angle of vector $\vec{x}$; for relay z, when it receives a packet from i, θ_z is updated as

$$\theta_z \cap \left[\angle\overrightarrow{iz} - 90^\circ, \angle\overrightarrow{iz} + 90^\circ\right]; \tag{10}$$

if the intersection gives ϕ, θ_z is set to $[0, 360\,\text{degree}]$. Furthermore, z's forwarder set, denoted by $R(z)$, is given as

$$R(z) = \{j | j \in N(z) \quad \text{and} \quad \angle\overrightarrow{Sj} \in \theta_z\}. \tag{11}$$

With the aid of *Proposition 2*, all packets are transmitted along $\overrightarrow{SD}$ direction in multi-hop transmissions. In addition, to establish the candidate list for *Source* and relay machines, the link metric on the direct transmission of *Source* and relay node z (i.e., $m_{S,i}$ and $m_{z,i}$) are provided in *Lemmas 3* and *4*.

Lemma 3 (Link metric $m_{S,i}$ for Source's forwarder i). *For node $i \in R(S)$, given* Source*'s traffic arrival rate λ no more than link service rate $\mu_{S,i}$, the link metric of* Source*'s direct link $L_{S,i}$ is given by*

$$m_{S,i} = \frac{1}{\nu^0_{S,i}\mu_{S,i} - \lambda}, \tag{12}$$

where $\nu^0_{S,i}$ is the spectrum availability of such link.

Proof. With $M/M/1/FCFS$ queue model and the availability $\nu^0_{S,i}$, link service rate becomes $\nu^0_{S,i}\mu_{S,i}$ as each attempt of transmissions is modeled as a Bernoulli trial with $\nu^0_{S,i}$. In particular, the exponential service time with the Bernouli trial provides the exponential distributed variable for the total service time until successful packet transmission, i.e., the geometric sum of exponential random variables is still exponential distributed with the changed mean. Moreover, from [33], the waiting time distribution of link is $w(t) = (\nu^0_{S,i}\mu_{S,i} - \lambda)\text{exp}^{-(\nu^0_{S,i}\mu_{S,i} - \lambda)t}$ for $t > 0$. Therefore, $m_{S,i}$ modeled as average link delay is obtained by $\mathbf{E}[w(t)]$. □

Lemma 4 (Link metric $m_{z,i}$ for relay z's forwarder i). *For node $i \in R(z)$, given* Source*'s traffic arrival rate λ, link metric of relay z's direct link $L_{z,i}$ is given by*

$$m_{z,i} = \frac{1}{\nu^0_{z,i}\mu_{z,i} - |N(i)|\lambda}, \tag{13}$$

where $|X|$ equals to the number of elements of set X.

Proof. While each relay randomly mixes its buffered packets (from a single *Source*'s batch) for transmissions, we assume each node's output traffic rate is same with *Source* (i.e., λ). For $M/M/1/FCFS$ queue of link, the output process follows Poisson process. Furthermore, there are possibly $|N(i)|$ incident links to machine i with maximum incoming traffic rate as $|N(i)|\lambda$ and thus ends the proof via *Lemma 3*. □

Note that, for a connected M2M network, $\mathbf{E}[|N(i)|] = n\pi r^2$ by Section 4.1. Considering link metric given in *Lemmas 3* and *4*, the relay candidate lists are consequently proposed as follows.

Proposition 3 (For Step 2 and Step 3c (i)). *For* Source *S, the jth machine in S's relay candidate list is machine i if $j = |V^S_i|$ where the set*

$$V^S_x = \{k | k \in R(S) \quad \text{and} \quad m_{S,k} \leq m_{S,x}\}. \tag{14}$$

For relay z receiving a packet from machine y, the jth machine in z's candidate list is i if $j = |V^z_i|$ where the set

$$V^z_x = \{k | k \in R(z)/y \quad \text{and} \quad m_{z,k} \leq m_{z,x}\}. \tag{15}$$

Proof. The candidate list prioritizes machine's forwarders regarding link metric (i.e., $m_{S,i}$ and $m_{z,i}$). For relay z, z's list should not include the one that transmits packet to z for avoiding invalid transmissions and thus we end the proof. □

Triggering ratio and counter of relay enable opportunistic forwarding for COR. Specifically, relay uses packet reception as a signal that it should transmit by advancing its counter with triggering ratio. We propose the ratio Φ_z for relay z as follows.

Proposition 4. *For relay machine z receiving a packet with the candidate list from machine y, if z is the jth candidate of list, z's triggering ratio is set as*

$$\Phi_z = \prod_{k \lessdot z}\left(1 - \nu^0_{y,k}\right), \tag{16}$$

where $i \lessdot j$ denotes machine i is preferred as y's forwarder than machine j (i.e., $m_{y,i} < m_{y,j}$.)

Proof. As a packet receiving from y, relay z should forward only when other relay(s), who have better relay capabilities regarding link metric, fail the reception from y. Φ_z gives the probability for that event and thus triggers z's relay. □

Our goal is to maximize the permissible throughput while fulfilling QoS requirement. A powerful concept of effective capacity that maximizes the supported data rates subject to given QoS constraint exactly meets the need. Thus, rather than examining point-to-point transmission, we adopt effective capacity as a bridge to propose a systematic approach for statistical QoS guarantees via COR in the following.

6 The System Throughput Achieved by COR with QoS Guarantees

6.1 Statistical QoS Guarantees

Real-time services contend with end-to-end delay and require bounded delay. However, as for time-varying fading, it has been proven that to provide *deterministic* QoS guarantees (i.e., the probability that the packet violates delay requirement is zero) over Rayleigh fading channels is impossible [21]. A practical and reasonable solution is to provide *statistical* QoS guarantees (i.e., the violation probability is bounded by a required value). For this purpose, *effective bandwidth theory* [38], [39] provides the delay violation probability as

$$\Pr\{Delay \geq D_{max}\} \approx \exp(-\theta\delta D_{max}), \tag{17}$$

where D_{max} is the delay requirement, θ is a positive constant referred to QoS exponent, and δ is a constant jointly determined by the arrival process and the service process. As shown in (17), a large θ implies a *stringent* QoS requirement guaranteed by the system while a small θ implies a *loose* QoS requirement guaranteed. Therefore, θ describes the degree of statistical QoS guarantee that can be provided by the system.

6.2 Effective Capacity of M2M Networks Adopting COR

Effective capacity [21], which is the duality of effective bandwidth, specifies the maximum constant arrival rate that can be supported by the system subject to a required θ. It is analytically defined as

$$E_C(\theta) \triangleq -\frac{\Lambda_C(-\theta)}{\theta} = -\lim_{t\to\infty}\frac{1}{\theta t}\log\{E[e^{-\theta S[t]}]\}, \tag{18}$$

where $S[t] \triangleq \Sigma_{i=1}^{t} R[i]$ is the partial sum of the discrete-time stationary and ergodic service process $\{R[i], i = 1, 2, \ldots\}$.

$$\Lambda_C(\theta) = \lim_{t\to\infty}\frac{1}{t}\log\{E[e^{\theta S[t]}]\} \tag{19}$$

is the Gärtner-Ellis limit of $S[t]$ and is a convex function differentiable for all real θ. When the sequence $\{R[i], i = 1, 2, \ldots\}$ is uncorrelated, it is clear that $E_C(\theta)$ reduces to $-\log\{L_{R[1]}(\theta)\}/\theta$, where $L_{R[1]}(\cdot)$ stands for the Lapalce-Stelijes Transform (L.S.T.) of service process $R[1]$. Since the fading channel model generates an independent identically distributed service process, it can greatly simplify the effective capacity derivations. In the following, we first examine the waiting time processes of the first hop and yth hop in Lemma 5 and Lemma 6 respectively. With the aids of above two lemmas, the effective capacity regarding COR in end-to-end transmissions are obtained in Theorem 2.

Lemma 5 (Waiting time process for the first hop). *Considering that* Source *probabilistically employs* $|R(S)|$ *forwarders for its traffic, the waiting time process of the first hop in end-to-end transmissions has exponential distribution with mean* $1/\omega^{(1)} = 1/[(\sum_{1\leq i\leq|R(S)|}\nu^0_{S,i}\mu_{S,i}) - |R(S)|\lambda]$.

Proof. From *Lemma 3*, the waiting time process of link L_{Si}, $i \in R(S)$ has exponential distribution with mean $\nu^0_{S,i}\mu_{S,i} - \lambda$. As COR employs $|R(S)|$ cooperative links, the waiting time process for the first hop becomes the minimum of the all (i.e., these $|R(S)|$ processes) and ends the proof. □

Lemma 6 (Waiting time process for the yth hop). *Assume that there are* η_y *cooperative links account for the yth hop's relay in end-to-end transmissions, the waiting time process of the yth hop has exponential distribution with mean* $1/\omega^{(y)} = 1/(\sum_{1\leq i\leq\eta_y}\nu^0_{Ti,Ri}\mu_{Ti,Ri} - |N(Ri)|\lambda)$, *where Ti and Ri are the transmitter and receiver for link i, respectively.*

Proof. The proof is similar to *Lemma 5* as the number of cooperative links are given by η_y for the yth hop. □

In light of proposed COR, the end-to-end latency is well characterized with the aid of waiting time analysis in *Lemma 5* and *Lemma 6*. The achievable capacity under such delay constraint can then be obtained. We finally provide the effective capacity and the corresponding upper bound for connected M2M networks in the following.

Theorem 2. *Considering that the COR is applied to connected M2M network, the effective capacity with upper bound for end-to-end transmissions is respectively given by*

$$E_C(\theta) \approx \begin{cases} \frac{\sqrt{\pi}}{2}\sqrt[4]{\frac{\omega^*}{\theta}}\exp\left(-\sqrt{\frac{\theta}{\omega^*}}\right) & 2\sqrt{\frac{\theta}{\omega^*}} \gg \frac{3}{4} \\ \frac{1}{2}\sqrt{\frac{\omega^*}{\theta}} & 0 < 2\sqrt{\frac{\theta}{\omega^*}} \ll \sqrt{2} \end{cases} \tag{20}$$

$$E_C^U(\theta) = -\frac{1}{\theta}\log\left\{\exp\left(-\frac{\theta}{\omega^*}\right)\right\}, \tag{21}$$

where $\omega^* = \min\{\omega^{(1)}, \omega^{(2)}, \ldots, \omega^{(d(n))}\}$.

Proof. While COR is applied in connected M2M network, for the ith hop of end-to-end transmissions as $i \in [1, d(n)]$, the waiting time process has exponential distribution with mean $1/\omega^{(i)}$ from *Lemma 5* and *Lemma 6*. The reciprocal service process, denoted by $X_i(t)$, becomes inverse gamma distributed with parameter $(1,1/\omega^{(i)})$. That is, $f_{X_i}(x_i) = 1/\left(\omega^{(i)}x_i^2\right)\exp\{-1/\left(\omega^{(i)}x_i\right)\}$. Via moment-generating function, $X_i(t)$'s L.S.T. is

$$\begin{aligned} L_{X_i}(\theta) &= \int_0^\infty \exp\{-\theta x_i\}\frac{1}{\omega^{(i)}x_i^2}\exp\left\{-\frac{1}{\omega^{(i)}x_i}\right\}dx_i \\ &= 2\sqrt{\frac{\theta}{\omega^{(i)}}}K_1\left(2\sqrt{\frac{\theta}{\omega^{(i)}}}\right), \end{aligned} \tag{22}$$

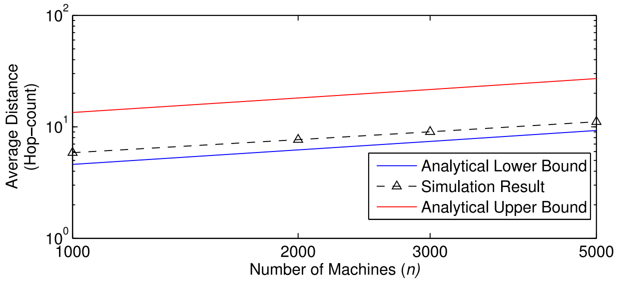

Fig. 2. Average distance of connective M2M networks for $r = \sqrt{5\log n/n}$ with respect to number of machines.

where $K_1(\cdot)$ is the modified Bessel function. And the effective capacity for the ith hop is obtained from the approximation of $K_1(\cdot)$ in [40] as

$$E_C^i(\theta) \approx \begin{cases} \frac{\sqrt{\pi}}{2}\sqrt[4]{\frac{\omega^{(i)}}{\theta}}\exp\{-\sqrt{\frac{\theta}{\omega^{(i)}}}\} & 2\sqrt{\frac{\theta}{\omega^{(i)}}} \gg \frac{3}{4} \\ \frac{1}{2}\sqrt{\frac{\omega^{(i)}}{\theta}} & 0 < 2\sqrt{\frac{\theta}{\omega^{(i)}}} \ll \sqrt{2}. \end{cases} \quad (23)$$

Thus, the effective capacity $E_C(\theta)$ of end-to-end transmissions as the minimum supportable arrival rate of $d(n)$ concatenated hops is given by (20). Furthermore, from Jensen's inequality, the upper bound $E_C^U(\theta)$ for achievable effective capacity is obtained as (21). That is, $E[e^{-\theta R[1]}] \leq \exp\{-\theta E[R[1]]\}$ for service process $R[1]$. □

Theorem 2 identifies the "jammed" hop (i.e., the one has minimum supportable arrival rate) in end-to-end transmissions and provides the effective capacity of COR over connected M2M networks. Thus, it successfully extends original concept of effective capacity from single-hop transmission in link level to end-to-end communications in network session level.

6.3 The QoS Guaranteed Throughput Acquirement

As D_{max} denotes the required delay bound of end-to-end traffic, the acquirement of throughput under QoS (i.e., delay) guarantee is proposed in the following.

Algorithm 2 (QoS guaranteed throughput acquirement:)

1) With the method proposed in [41], calculate the effective bandwidth $E_B(\theta)$ of the real-time traffic for the source-destination pair.
2) Effective capacity $E_C(\theta)$ via COR can be obtained from *Theorem 2*.
3) Find the solution of θ such that

$$E_B(\theta) = E_C(\theta) = \delta. \quad (24)$$

4) Derive the delay violation probability by

$$\mathbf{Pr}\{Delay \geq D_{max}\} = \exp(-\theta\delta D_{max}). \quad (25)$$

5) Obtain the achievable effective capacity with the corresponding violation probability.

As effective capacity identifies the maximum arrival rate under required QoS, the achievable effective capacity and the delay violation probability in Step 5 provide the attainable throughput and delay bound, thus accommodating the conditions of dependable M2M communications.

7 Performance Evaluation

In this section, for the connected M2M network, we let r equal to $\sqrt{5\log n/n}$ in $GRG(n, r)$. First, the analytical bounds of average distance and the verified simulation are presented by averaging over 100 samples for $n = 1{,}000$, 2,000, 3,000 and 50 samples for $n = 5{,}000$. Furthermore, we evaluate the proposed COR algorithm with video surveillance traffic [42] transmitting in M2M networks. In particular, two-state traffic activity model of such an application is adopted, and the behaviors of primary systems are simulated from the corresponding CTMC models in Section 3.2. Cognitive machines are then able to utilize the available channel for their video data transmissions.

7.1 Average Distance of Large M2M Networks

Fig. 2 shows the average distance of connected M2M networks with respect to size of machine swarm in scaling perspective. The average distance is measured as follows: we calculate the hop-count for every end-to-end path in network, and average the calculated results to obtain the average value. While analytical results perfectly bound the simulation, the average distance increases with size of machines and tighter lower bound is provided as compared to upper bound. Moreover, the average distance scales with $1/r$ (i.e., $\Theta(\sqrt{n/\log n})$) as mentioned in *Theorem 1*. All these results confirm that we accurately predict the geometric properties of M2M networks via sophisticated mathematical derivations.

7.2 Simulation Results on the Video Surveillance Traffic

To evaluate the spectrum sharing capability of COR in connected M2M networks, we study the effective capacity of the COR and the upper bound with respect to primary transmitters' (PTs') activities and primary receivers' (PRs') forbidden areas. In particular, PTs' activities are characterized by the probability set $\{\nu^1_{x,y}\}$ in Section 3.2 that shows the channel unavailability around links $\{L_{x,y}\}$ seen by cognitive machines in their slotted system. Moreover, PRs' forbidden areas are the disks centered on PRs, where cognitive machines cannot operate in order to protect primary systems' traffic. This area can be characterized by the interference temperature of primary systems [43]. In Fig. 3, given the PTs' activities and the PRs' forbidden areas, the maximum achievable effective capacity of the system is decided that characterizes the upper bound for any designated routing algorithms. Thus, as different QoS constraints θ come from different applications over the system, it does not affect the upper bound performance. On the other hand, the effective capacities of COR under different activities close to each other. Furthermore, Fig. 4 shows that COR's performance approaches upper bound for large radius and smaller θ as more cooperative machines are disable under a tighter QoS requirement. Therefore, the results certify that COR presents the achievable effective capacity under different opportunistic nature for M2M communications.

In addition, to further examine the provision of statistical QoS guarantee from the COR algorithm, we consider the

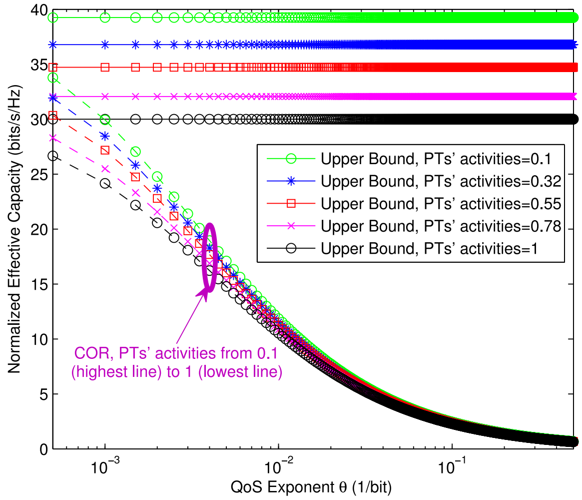

Fig. 3. Effective capacities of COR with upper bounds under different PTs' activities.

video surveillance (or monitoring) traffic [42] and adopt its two-state traffic activity model for the arrival process. The delay bound D_{max} is set to $250\,\mathrm{ms}$, which comes from $200\,\mathrm{ms}$ for end-to-end delay and $50\,\mathrm{ms}$ for radio interface tail latency. The video codec is $12.2\,Kb/s$ and traffic activity factor is 50 percent. Regarding different PTs' activities, Fig. 5 shows the simulation results for the effective capacity from COR and the effective bandwidth of video surveillance traffic. In particular, effective capacity provides the maximum constant arrival rate that is supportable by the COR algorithm with respect to the required QoS exponent θ; effective bandwidth gives the accurate arrival characterization for the incoming video data. The results indicate that the effective capacity from COR decreases when PTs become more active, and the intersection points of two planes further give the corresponding delay violation probability. Moreover, Figs. 6 and 7 provide the delay bond violation probability of COR under various primary systems' behaviors. The violation probability increases when the transmitters' activities increase or the receivers' forbidden areas expand. We can observe that as the probability is perfectly restricted below 0.05 for all kinds of PTs' activities, it becomes intolerable

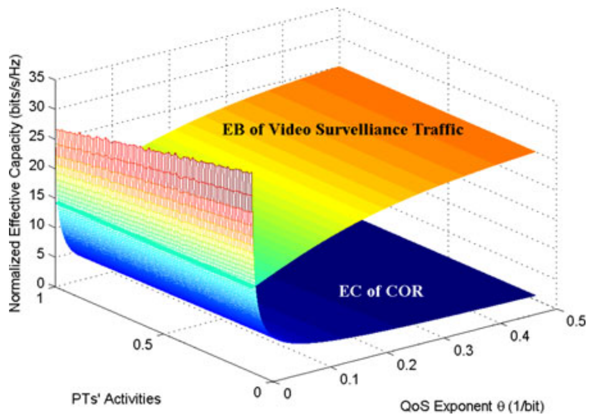

Fig. 5. Effective capacities of COR and effective bandwidth from video surveillance traffic under different PTs' activities.

even when the forbidden areas are small (i.e., with small radiuses). That is, while machines are shut down under such circumstance, COR significantly loses the merit of cooperative relay. In sum, above results confirm that the proposed COR completely characterizes the achievable effective capacity and the corresponding delay violation probability for applications, enabling the QoS guarantees in M2M communications.

Remarks. Proposed COR algorithm realizes the novel concept of paradigm shift in multi-hop networking over large M2M networks. Rather than employing optimal relay selections with regard to relay capabilities in existing solutions, COR enables multiple relay machines to distributively guide the end-to-end traffic along *Source-Destination* direction. By concatenating multiple single-hop transmissions from such machines and applying statistical QoS guarantees, the reliable data transportation is achieved with guaranteed system throughput. A new methodology is thus provided for networking designs in M2M communications.

8 Conclusion

This paper resolves the most critical challenge of providing statistical QoS guarantees for reliable M2M communications via scrupulous connections in the machine swarm. With the

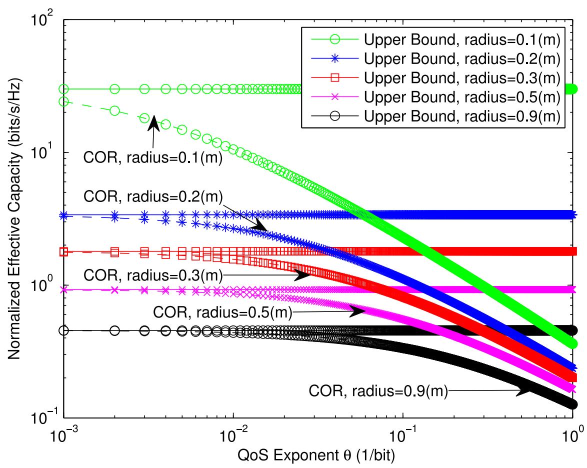

Fig. 4. Effective capacities of COR with upper bounds under different radiuses of PRs' forbidden areas.

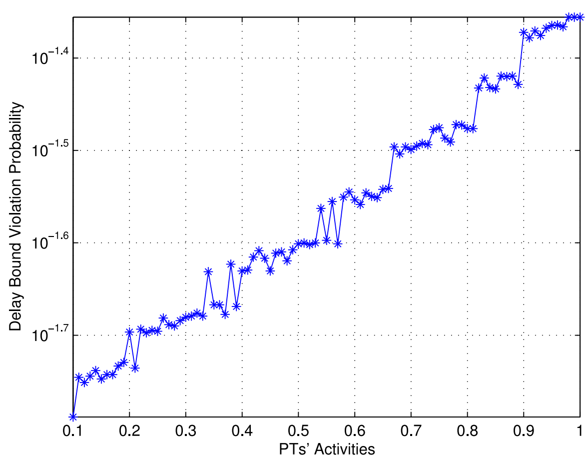

Fig. 6. Simulation result on the delay bound violation probability with respect to PTs' activities.

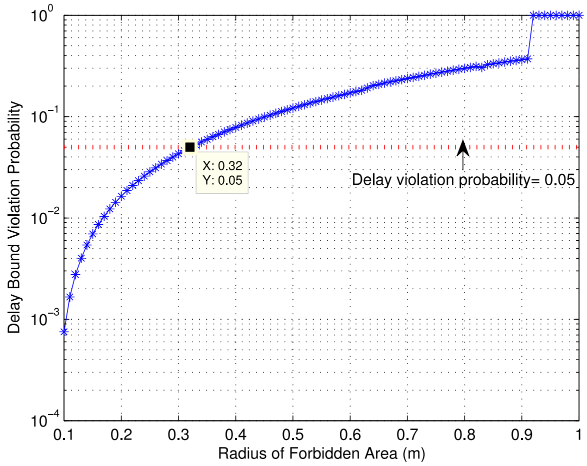

Fig. 7. Simulation result on the delay bound violation probability with respect to radiuses of PRs' forbidden areas.

aid of mathematical derivations, the geometric characteristics of large M2M networks are well studied for sophisticated designs of COR algorithm. The proposed COR for connected M2M networks enables spectrum sharing for tremendous amount machines, achieving ubiquitous communications without any impacts on the legacy of the existing wireless networks. COR provides statistical delay guarantees, facilitating a smooth transmission of the video surveillance traffic and thus meeting the urgent needs for corresponding standardization progress. Simulation results show that the theoretical bounds accurately identify the average distance of connected M2M network and the proposed COR effectively achieves the statistical delay guarantees, thus yielding a practical routing algorithm to adequately cooperate machines for timing-wise M2M applications.

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