Statistical QoS Control of Network Coded Multipath Routing in Large Cognitive Machine-to-Machine Networks

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***Abstract*—Machine-to-machine (M2M) communication enables many applications such as smart grid, vehicular safety, and health care among many others. To achieve ubiquitous data transportation among objects and the surrounding environment, deploying spectrum sharing M2M communications with existing wireless networks is a must. A general large-scale cognitive M2M network (CM2MN), adopting cognitive radio technology, consists of multiradio systems, the primary system (PS), and secondary system(s) with tremendous cooperative cognitive machines, under heterogeneous wireless architecture. For these CM2MNs, due to dynamic spectrum access (DSA) nature, there exists possibly unidirectional opportunistic wireless fading links and thus traditional flow control mechanisms at link level do not fit anymore. Furthermore, effective end-to-end quality-of-service (QoS) control is still required to provide a reliable transportation for such multihop CM2M communications. Facing the above challenges, we propose a novel statistical QoS control mechanism through cooperative relaying, realizing virtual multiple-input and multiple-output (MIMO) communications *at session level*. In particular, a probabilistic network coded routing algorithm and the statistical QoS guarantee are first proposed to coordinate and cooperate tremendous machines. Next, based on the proposed guarantee and routing algorithm, the statistical QoS control mechanism is designed to enable MIMO communications for the session traffic. Specifically, *the diversity mode* is used to deal with PS's opportunistic nature and wireless fading, and *the spatial multiplexing mode* is employed to obtain the maximum end-to-end throughput. Simulation results confirm that under our control solution, the great improvements of end-to-end delay violation probability are obtained, thus practically facilitating network coded multipath routing in large CM2MNs.**

***Index Terms*—Cognitive radio, cooperative relay, effective capacity, machine-to-machine (M2M) communications, network coded multipath routing, statistical quality-of-service (QoS) control.**

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I. Introduction

Machine-to-machine (M2M) communication enables many applications such as smart grid, vehicular safety, and health care among many others. To achieve ubiquitous data transportation among objects and the surrounding environment, cognitive radio networking appears as a promising technology to considerably enhance network efficiency given a fixed bandwidth via cooperative relaying of cognitive radios [1]–[3]. By sensing the spectrum and opportunistically accessing the spectrum hole from the usage of primary system(s) (PS), such networking mechanism incorporates dynamic spectrum access (DSA) to fulfill great spectrum utilization [4], [5]. Therefore, without assuming any infrastructure support, the cognitive M2M networks (CM2MNs) enable cognitive machines to reliably communicate in a distributed multihop manner. However, due to opportunistic access, there are potentially good number of unidirectional (before timeout) opportunistic wireless links [3] in such networks. This situation creates a great challenge in providing an effective end-to-end quality-of-service (QoS) control to facilitate reliable traffic transportation in general large multihop CM2MNs.

Furthermore, among many advanced techniques (e.g., forward error correction, link adaptation, incremental redundancy, etc.), multiple-input–multiple-output (MIMO) techniques are well known for bringing numerous benefits to point-to-point wireless channels, such as higher spectral efficiency or more reliable communication. By coherently coordinating the transmission and reception among multiple mobile stations, emerging virtual (or network) MIMO technology [6]–[25] can achieve improvements on system throughput by cooperating among one-hop transmission of cellular systems, resulting in more degrees of freedom and improved spatial diversity gain. Specifically, with cooperative communication (CC) [26], [27], single-antenna devices can share the antennas of others, which leverage the spatial diversity of MIMO techniques. Reference [28] further shows the equivalent of MIMO schemes and CC through theoretical and simulative analysis over three-node network with the help of network coding.

Virtual MIMO techniques enable frequency reuse within each cell and are recently extended to multiuser cellular systems [6]–[8]. With random beamforming (i.e., it consists of activating/deactivating certain beams for transmission) in receiver design, the multiuser diversity is exploited over wireless channels in [7] and for cognitive radio networks in [8]. Reference [7] proposes a simple power allocation technique for random beamforming leading to equal power allocation among the active beams. Addressing a single pair of CR's transmitter and receiver [8] employs multiantennas at CR's transmitter to effectively balance throughput maximization and interference avoidance for PS's traffic. However, above efforts only focus on single-hop transmissions. While collaboration among nodes could be realistic in multihop networks, there lacks a systematic approach to coordinate nodes' operations at the network-level cooperation. Moreover, traditional flow control mechanisms are based on the assumption of bidirectional links and rarely considered implementing new paradigm of links such as opportunistic and unidirectional due to wireless fading, access, operations, in multihop cognitive systems. Consequently, we shift the paradigm of the virtual MIMO into network coded multipath routing algorithms with respect to *session-level* traffic on top of multihop CM2MNs for a wide range of applications. Reference [29] is, therefore, suggesting the error control mechanism for this new scenario. Inspired from cross-layer design and network flow perspective of network coding [30], we exploit statistical QoS controls to facilitate MIMO communication on top of the cooperative relay via various routings.

In this paper, we develop the cooperative relay model for general large multihop CM2MNs. In particular, large-scale CM2MNs have tremendous machines (e.g., trillion nodes) and are characterized by spatial distribution of nodes. Probabilistic forwarding protocol (PFP), serving as a network coding aware routing algorithm, is proposed upon such network to enable network coded multipath forwarding. Moreover, a statistical QoS guarantee, called L-QoS guarantee, is further proposed to deal with the interaction between underlaid routing algorithm and end-to-end QoS requirements. Based on these accomplishments, cooperative QoS control (CQC) is designed to facilitate statistical control and to obtain the optimal cooperating sets that guarantee the given QoS requirements. We summarize our main contributions as follows.

1) With the aid of network coded multipath routing algorithms, we exploit statistical QoS guarantees and controls on top of multihop communication in large CM2MNs.
2) Rather than being limited to diverse path application [31], [32] when examining multipath transmissions, we employ network coding within underlaid routings for QoS controls to generalize the study.
3) For large CM2MNs, CQC mechanism enhances cooperative relaying by expanding the cooperative set for the enjoyed delay violation bound.

Simulation results confirm the effectiveness of statistical QoS control that combines QoS guarantees with routing algorithms in flow perspective to enable MIMO communication in multihop CM2MNs. Specifically, a cross-layer performance evaluation from network layer to application layer is provided, demonstrating the practicality of statistical control of MIMO communication in realistic channels over multihop CM2MNs. Rather than dealing with the NP-hard problem [33] associated with the routing solution, with the aid of flow aspect of network coding [30], we support statistical QoS guarantees for the traffic. The only requirement for underlaid routings is that they are suitable to employ network coding for transmissions, while these routings are common in literatures [34]–[37].

To the best of our knowledge, this work is the first to propose a statistical QoS control that enables virtual MIMO *at session level*, to drive network coded multipath routes for QoS guarantees in large CM2MNs. This paper is organized as follows. Section II presents related work. Section III provides the system model. Statistical QoS guarantees are examined in Section IV. Statistical QoS controls of network coded multipath routing algorithms are proposed and evaluated in Section V. Section VI draws conclusion.

II. Related Work

Virtual (network) MIMO scheme design is widely utilized for both cellular systems [9]–[14] and wireless sensor networks (WSNs) [15]–[19]. Additionally, it concerns the coherent coordination for downlink [9], [10] and uplink [11], [12] transmissions between base stations and user devices. Virtual MIMO increases spectral efficiency, robustness, and data rates [14]. Reference [13] proposes an efficient cell-clustering algorithm, and systematically determines a set of cooperative access points in the network. Reference [11] provides QoS-aware power allocations for both noncollaborative and collaborative virtual MIMO. Reference [12] studies the energy-spectral efficiency for a multiuser virtual MIMO system with decode-and-forward protocols. On the other hand, Ref. [15] analyzes a cooperative MIMO scheme with Alamouti code for the single-hop transmission. Refining the results in [15] by considering the training overhead required in MIMO-based system, Ref. [16] proposes an energy-efficient virtual MIMO-based architecture. In [17], instead of a MIMO transmission, a multiple-input–single-output (MISO) transmission is examined between two virtual MIMO nodes. For cross-layer design in WSN to jointly achieve energy efficiency and delay reduction, both Refs. [18] and [19] propose virtual MIMO scheme with routing protocol, while [18] minimizes the intracommunication and [19] investigates fixed and variable rates in nodes. All the previous research works focus on CC either at the physical layer or for single-hop communication, thus neglecting the merits of MIMO communication in network layer or multihop scenarios.

Employing CC at network session level [20]–[25], [29], [33], [38]–[41] emerges as a solution to exploit user diversity and provides remarkable gains in reliability and capacity. Reference [33] illustrates the benefits of using CC in multihop wireless networks by investigating the joint problem of relay node assignment and multihop flow routing. Reference [38] analyzes the throughput of secondary networks and provides information on how a cognitive radio channel can be utilized at the network level. Reference [39] focuses on three-node chain topology and provides end-to-end throughput analysis for multihop wireless network. Reference [29] exploits a path-time code in *ad hoc* cognitive systems to deal with error control without the need of link feedback. Reference [20] presents a cross-entropy based method to obtain the optimal relay subset in two-way amplify-and-forward MIMO relaying systems for reducing computational complexity and maximize sumrate. For large-scale mobile ad hoc networks, Ref. [40] characterizes the throughput-delay tradeoffs with network coding from the scaling law perspective. Two phase transmissions among primary and secondary systems are assumed in [21] in order to leverage MIMO in cooperative cognitive radio network. Reference [41] further extends cognitive radio resource management over autonomous femtocell networks, statistically guaranteeing the QoS of traffic. To avoid the complex matrix-based MIMO model, Ref. [22] develops an optimal degrees-of-freedom-based model for multihop MIMO networks with same achievable rate region as that of the matrix-based model. Through analyzing the diversity-multiplexing tradeoff, Ref. [23] derives the bounds on the tradeoff for MIMO interference channel with a relay, while [24] provides the diversity and multiplexing gains for multihop MIMO relay network. Reference [25] proposes a tractable and accurate cross-layer model for multihop MIMO networks. However, these excellent explorations do not thoroughly consider realistic routing at network layer, and thus only deal with simplified network topologies and assumptions. Inspired from our previous work [42], in this paper, instead of separately exploiting the actual transmission with control mechanisms, we propose statistical QoS controls of network coded multipath routing algorithms based on cooperative relaying over opportunistic multihop CM2MNs.

III. System Model

A CM2MN inherits DSA nature of cognitive radio, employs cooperative relaying, and thus brings opportunistic nature between PS and CR from link level to network level. The link-level access schemes for cognitive radio are summarized in [43] and the new paradigm (i.e., opportunistic link) for the link nature is studied in [37] by extending network coding concept to opportunistic routing in cognitive radio network. Through statistically guaranteeing the QoS of transmission employed by underlaid routings, network coding inspired control mechanisms are proposed. Such mechanisms facilitate functions of MIMO including diversity and spatial multiplexing with respect to end-to-end transportation, providing a new methodology to realize MIMO communication in *session-level* scenario over multihop CM2MNs.

A. Network Model

As in Fig. 1, a general multihop CM2MN consists of a cognitive machine source (CM$_S$), a cognitive machine destination (CM$_D$), several cognitive machines acting as cooperative relay nodes (CM$_R$s) that can forward packet(s) from CM$_S$ to CM$_D$, and multiple primary mobile stations (PSs) with their infrastructure. We can reconstruct the directed graph model from a good number of cooperative relays to multihop multipath structure and further abstract the graph into an equivalent cooperative relay model. In this conceptual model as [29], the R end-to-end paths for each source–destination pair are similar to R-antennas in MIMO communication for single-hop transmission. We consider large-scale CM2MNs (i.e., there are a great number of nodes such that end-to-end transmission costs more bandwidth and entire network is characterized by spatial distribution of nodes). Furthermore, variable packet size transmitted in slotted systems is utilized for our traffic model.

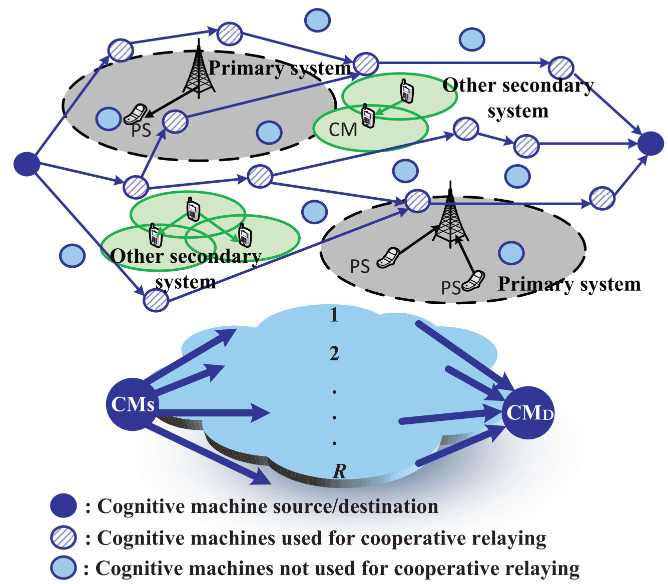

Fig. 1. Network model for network coded multipath routing algorithms in large multihop CM2MN.

B. Statistical QoS Guarantees and Controls

Real-time services are based on end-to-end delay and demand bounded delays. From the impact of time-varying fading, it has been proven that to provide *deterministic* QoS guarantees (i.e., the probability of delay requirement violation is zero) over the Rayleigh fading channels is impossible [44]. As a result, a practical and reasonable solution is to provide *statistical* guarantees (i.e., the probability that the packet violates its delay constraint is bounded) in QoS control. For this purpose, we propose statistical QoS guarantees and controls with regard to local information and dedicated routing algorithms. For large CM2MNs, L-QoS guarantee adopts effective capacity [44] for statistically guaranteeing QoS as it concerns the achievable capacity under the QoS constraint (i.e., the capability for the maximum arrival rate that one can support without violating the required QoS), while original definition of the capacity lacks time delay concept. Instead of examining point-to-point transmission, the guarantee explores effective capacity over CM2MNs, achieved by underlaid routing, and the upper bound performance. By the effective bandwidth theory [45], [46] for voice over IP (VoIP) modeling in 3GPP LTE [47], the end-to-end delay violation probability is provided. CQC mechanism further enhances the cooperative relay technology from expanding the cooperative set and statistically guaranteeing QoS for the desired end-to-end delay violation bound.

IV. L-QoS Guarantee

In this section, we study statistical QoS guarantees by examining the effective capacity with respect to the underlaid routings in large CM2MNs. The network of interest has a large network size (e.g., a large number of nodes such that end-to-end information costs more bandwidth than communication bandwidth) and is characterized by spatial distribution of nodes. With QoS constraint for traffic from the effective bandwidth theory [45], [46], we design and evaluate L-QoS guarantees within Poisson networks (i.e., the locations of nodes follow Poisson point process [48]). These guarantees are suitable for network coding aware algorithms such as Algorithm 1 in Section IV-A.

Algorithm 1. Probabilistic Forwarding Protocol (PFP)

1: *Source* firstly partitions its traffic into batches.
2: At each available time slot of *Source*, *Source* requests the spectrum available probabilities from its neighbors (i.e., $\sigma_{Sj},\ j \in N(S)$) and prioritizes them in the forwarding candidate list regarding link metric $\gamma_{S,j}$. *Source* then randomly mixes packets in a single batch via random network coding [30] and broadcasts coded packet with the list.
3: **if** the ACK message is not heard from *Destination*, **then**
4:     *Source* repeats Step 2 until it hears ACK.
5:     **for** each relay node z received packet from others, **do**
6:         z decodes the packet, saves unheard information in its buffer, and check the list.
7:         **if** z is first in the list, **then**
8:             it requests $\sigma_{z,j}$ from $j \in N(z)$ and prioritizes them in the new list according to $\gamma_{z,j}$.
9:             It then randomly mixes its buffered packets and broadcasts coded packet with the new list.
10:         **else if** z is in the kth of list, **then**
11:             it counts down a random backoff timer for exponential duration with mean k/ξ.
12:             When the timer expires, it transmits the coded packet with new list in Step 8 and Step 9.
13: *Destination* continuously decodes the collection of coded packets to verify whether all packets are received. If all packets of the batch are completely received by *Destination*, *Destination* broadcasts ACK back to *Source*, eliminating the packets buffered in relay nodes and enabling the next transmission batch.

A. Routing Protocol for Large-Scale CRNs

The protocol in Algorithm 1 fulfills opportunistic relay selection regarding packet delay of cooperative links by designing link metric and candidate list in delay perspective by modeling each opportunistic link as $M/M/1/\infty$/FCFS queue. To establish the forwarding candidate list in Step 2) for Source and Step 8) and Step 12) for relay nodes, the link metric on the direct transmission of Source and relay node z (i.e., $\gamma_{S,j}$ and $\gamma_{z,j}$) are provided in *Lemma 1* and *Lemma 2*.

Lemma 1 (The link metric $\gamma_{S,j}$ for Source's neighbor j): For node $j \in N(S)$, given Source's traffic arrival rate λ no more than link service rate $\mu_{S,j}$, the link metric of Source's direct link $L_{S,j}$ is given as

$$\gamma_{S,j} = \frac{1}{\sigma_{S,j}\mu_{S,j} - \lambda} \tag{1}$$

where $\sigma_{S,j}$ is the spectrum available probability of the link.

Proof: With $M/M/1$/FCFS queue and the availability $\sigma_{S,j}$, the link service rate becomes $\sigma_{S,j}\mu_{S,j}$ for modeling each attempt of transmissions as a Bernoulli trial with probability $\sigma_{S,j}$. Furthermore, by [49], waiting time distribution is $w(t) = (\sigma_{S,j}\mu_{S,j} - \lambda)\exp^{-(\sigma_{S,j}\mu_{S,j}-\lambda)t}$ for $t > 0$. $\gamma_{S,j}$ modeled as the average link delay is thus obtained by $\mathbf{E}[w(t)]$. ■

Lemma 2 (The link metric $\gamma_{z,j}$ for relay z's neighbor j): For node $j \in N(z)$, given Source's traffic arrival rate λ, the link metric of relay z's direct link $L_{z,j}$ is given by

$$\gamma_{z,j} = \frac{1}{\sigma_{z,j}\mu_{z,j} - |N(j)|\lambda} \tag{2}$$

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

Proof: As each relay randomly mixes its buffered packets for transmissions from a single Source's batch, we assume that each node's output traffic rate is the same as Source (i.e., λ). For $M/M/1$/FCFS queue, the output process of links follows Poisson process. Besides, there are possibly $|N(j)|$ incident links to node j and the maximum incoming traffic rate is $|N(j)|\lambda$. Thus, we end the proof via *Lemma 1*. ■

Considering the link metric in *Lemma 1* and *Lemma 2*, the forwarding candidate list for each node is consequently obtained in the following proposition.

Proposition 1 (For Step 2, Step 8, and Step 12): For Source node CR_S, the ith node in its forwarding candidate list is node j if $i = |V_j^S|$ where the set

$$V_x^S = \{k | k \in N(S) \text{ and } \gamma_{S,k} \leq \gamma_{S,x}\} \tag{3}$$

for relay node z receiving the packet from node y, the ith node in z's forwarding candidate list is node j if $i = |V_j^z|$ where the set

$$V_x^z = \{k | k \in N(z)/y \text{ and } \gamma_{z,k} \leq \gamma_{z,x}\}. \tag{4}$$

Proof: The candidate list prioritizes node's neighbors according to link metric (i.e., $\gamma_{S,j}$ and $\gamma_{z,j}$). Furthermore, for relay node z, z's list should not include the neighbor that transmits packet to z for avoiding invalid transmissions and thus we end the proof. ■

Briefly, PFP carries out random network coding inspired probabilistic forwarding, exploiting the cooperative diversity in large-scale CM2MNs.

B. Effective Capacity

Effective capacity [44] is the duality of effective bandwidth and it specifies the maximum constant arrival rate that can be supported by the system subject to a given required θ, where θ is a positive constant refereed to QoS exponent as in (14). Analytically, the effective capacity can be formally defined as

$$E_C(\theta) \triangleq -\frac{\Lambda_C(-\theta)}{\theta} = -\lim_{t\to\infty}\frac{1}{\theta t}\log\{E[e^{-\theta S[t]}]\} \tag{5}$$

where $S[t] \triangleq \Sigma_{i=1}^{t} R[i]$ is the partial sum of the discrete-time stationary and ergodic service process $\{R[i], i = 1, 2, \ldots\}$. $\Lambda_C(\theta) = \lim_{t\to\infty}\frac{1}{t}\log\{E[e^{\theta S[t]}]\}$ 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 $-\frac{1}{\theta}\log\{L_{R[1]}(\theta)\}$, 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 (i.i.d.) service process, it can greatly simplify the effective capacity derivations. We further provide an upper bound $E_C^*(\theta)$ for simplified $E_C(\theta)$ since $f(x) = e^{-x}$ is a (strictly) convex function for x. From Jensen's inequality, $E_C(\theta) = -\frac{1}{\theta}\log\{E[e^{-\theta R[1]}]\} \le E_C^*(\theta) = -\frac{1}{\theta}\log\{e^{-\theta E[R[1]]}\}$. Moreover, for the strictly convex function, the equality implies that $R[1] = E[R[1]]$ with probability 1 (i.e., $R[1]$ is a constant).

Definition 1: With fading channel model and service process $\{R[i], i = 1, 2, \ldots\}$ of the network, the effective capacity for end-to-end transmission is

$$E_C(\theta) = -\frac{1}{\theta}\log\{L_{R[1]}(\theta)\} \tag{6}$$

where $L_{R[1]}(\cdot)$ stands for the L.S.T. of $R[1]$, whose upper bound is

$$E_C^*(\theta) = -\frac{1}{\theta}\log\{e^{-\theta E[R[1]]}\}. \tag{7}$$

By *Definition 1*, which virtually regards the whole network as a single link, the original effective capacity concept is extended from single-hop transmission in link level to end-to-end communication in network session level. Therefore, we obtain the achievable capacity under the QoS constraint for practical applications.

1) Relay Network and Poisson Network: For three-node relay topology and Poisson topology (i.e., the spatial distribution of nodes follows Poisson point process [48]) of multihop CM2MN, we first examine the average rate of service time process and then discuss the effective capacity for the whole network with the help from *Definition 1*.

Proposition 2: For three-node relay network, the average rate $\mu_{R[1]}^R$ of service time process for variable packet size of slotted system is

$$\mu_{R[1]}^R = \min\{\mu c_{\mathrm{SR}}, \mu c_{\mathrm{RD}}\}\Pr\{D_{\mathrm{SRD}} < D_{\mathrm{SD}}\} + \mu c_{\mathrm{SD}}\Pr\{D_{\mathrm{SRD}} > D_{\mathrm{SD}}\}. \tag{8}$$

For Poisson network, the average rate $\mu_{R[1]}^P$ of service time process is obtained from PFP, due to the high complexity of analytical derivations in large networks.

Proposition 3: For variable packet size in slotted systems with the average rate $\mu_{R[1]}^N$ of service time process of whole network, the effective capacity is given by

$$E_C^N(\theta) \approx \begin{cases} \frac{\sqrt{\pi}}{2}\sqrt[4]{\frac{\mu_{R[1]}^N}{\theta}}e^{-\sqrt{\frac{\theta}{\mu_{R[1]}^N}}}, & \text{for } 2\sqrt{\frac{\theta}{\mu_{R[1]}^N}} \gg \frac{3}{4} \\ \frac{1}{2}\sqrt{\frac{\mu_{R[1]}^N}{\theta}}, & \text{for } 0 < 2\sqrt{\frac{\theta}{\mu_{R[1]}^N}} \ll \sqrt{2} \end{cases} \tag{9}$$

with the upper bound as

$$E_C^{N*}(\theta) = -\frac{1}{\theta}\log\left\{e^{-\frac{\theta}{\mu_{R[1]}^N}}\right\}. \tag{10}$$

Proof: Under variable packet size in slotted systems, the service time process for whole network is exponentially distributed with rate $\mu_{R[1]}^N$ and its reciprocal service process $X(t)$ is inverse gamma distributed with parameter (1, $1/\mu_{R[1]}^N$), i.e., $f_X(x) = \frac{1}{\mu_{R[1]}^N x^2}e^{-\frac{1}{\mu_{R[1]}^N x}}$. From the moment-generating function, the L.S.T. of $X(t)$ is

$$\begin{aligned} L_X(\theta) &= \int_0^\infty e^{-\theta x}\frac{1}{\mu_{R[1]}^N x^2}e^{-\frac{1}{\mu_{R[1]}^N x}}dx \\ &= 2\sqrt{\frac{\theta}{\mu_{R[1]}^N}}K_1\left(2\sqrt{\frac{\theta}{\mu_{R[1]}^N}}\right) \end{aligned} \tag{11}$$

where $K_1(\cdot)$ is the modified Bessel function. Therefore, the effective capacity of the network is

$$E_C^N(\theta) \approx \begin{cases} \frac{\sqrt{\pi}}{2}\sqrt[4]{\frac{\mu_{R[1]}^N}{\theta}}e^{-\sqrt{\frac{\theta}{\mu_{R[1]}^N}}}, & \text{for } 2\sqrt{\frac{\theta}{\mu_{R[1]}^N}} \gg \frac{3}{4} \\ \frac{1}{2}\sqrt{\frac{\mu_{R[1]}^N}{\theta}}, & \text{for } 0 < 2\sqrt{\frac{\theta}{\mu_{R[1]}^N}} \ll \sqrt{2} \end{cases} \tag{12}$$

with [50] and its upper bound is from *Definition 1* as

$$E_C^{N*}(\theta) = -\frac{1}{\theta}\log\left\{e^{-\frac{\theta}{\mu_{R[1]}^N}}\right\}. \tag{13}$$

■

C. L-QoS Guarantee

To provide soft QoS guarantees for the traffic, it is practical to design statistical QoS guarantees through the effective bandwidth theory [45], [46]. The probability that the packet delay violates the delay requirement is

$$\Pr\{W \ge D_{\max}\} \approx \exp(-\theta\delta D_{\max}) \tag{14}$$

where θ is related to QoS requirement and δ is a constant jointly determined by the arrival process and the service process. As shown in (14), a large θ implies a stringent QoS requirement guaranteed by the system while a small θ implies a loose QoS requirement guaranteed. In other words, θ describes the degree of statistical QoS guarantee that can be provided by the system.

In order to verify the practicality of L-QoS guarantee, we adopt the VoIP traffic in 3GPP LTE [47] and the effective bandwidth theory [45], [46]. A simple two-state voice activity model is used as follows. The probability of transition from state 0 (i.e., silence or inactive state) to state 1 (i.e., talking or active state) is r_{01} while the probability of staying in state 0 is r_{00}. On the other hand, the probability of transition from state 1 to state 0 is r_{10} while the probability of staying in state 1 is r_{11}. From the uplink VoIP supported by 3GPP LTE, the full source rate from voice codec v is 12.2 Kb/s and voice activity factor (VAF)

TABLE I

SIMULATION PARAMETERS AND VALUES FOR PERFORMANCE EVALUATIONS IN SECTIONS IV-D AND V-B

Parameters	Values
Large CM2MN: Poisson topology	
Area for PPP [48]	36 (m^2)
Cognitive machines' density	1
PS's density	0.3
PS-Rx's required power level	0.01 (dB)
cognitive machines' transmitted and noise power	0.42 (dB)
Total concerned spectrum band	5 (MHz)
Pass-loss exponent	3.5
Characteristics of 3GPP LTE VoIP traffic [47] *transmitted in Section V-B*:	
Maximum permissible delay bound (D_{max})	20 (ms)
Delay bound violation probability (ε)	0.02
Voice codec (v)	12.2 (Kb/s)
Voice activity factor	50%
CM_S's Poisson packet arrival rate (λ)	5 (pkt/sec)

(i.e., the probability in the talking state) is 50% which means $r_{01} = r_{10} = 0.5$. The effective bandwidth is

$$E_B(\theta) = \frac{1}{\theta}\log \cdot \left\{\frac{1}{2}\left(r_{00} + r_{11}e^{v\theta} + \sqrt{(r_{00} + r_{11}e^{v\theta})^2 - 4(r_{00} + r_{11} - 1)e^{v\theta}}\right)\right\}. \quad (15)$$

With $E_B(\theta)$, effective capacity $E_c(\theta)$, and (14), the delay violation probability is $\Pr\{W \geq D_{\max}\} \approx \exp(-\theta^*\delta^* D_{\max})$, where (θ^*, δ^*) is the intersection point of $E_C(\theta)$ and $E_B(\theta)$.

Therefore, we statistically guarantee QoS for traffic transmitted by underlaid PFP in networks with different network structures as follows:

1) obtain the average rate of end-to-end service time process from *Proposition 2*;
2) get the effective capacity of the network through PFP by *Proposition 3*;
3) adopt L-QoS guarantee discussed in Section IV-C.

D. Performance of L-QoS Guarantee

We implement L-QoS guarantees over Poisson network topology in large multihop CM2MN with parameter settings in Table I. We evaluate the network with different opportunistic nature which is characterized by primary transmitters' (PS-Txs') activities and primary receivers' (PS-Rxs') avoidance regions. From the concept of effective capacity, we characterize the maximum arrival rate supported by the algorithm or system given the QoS constraint. In Fig. 2, we provide the effective capacity with PFP and the upper bound performance with different activities of PS-Txs and varied QoS constraint θ. It shows that the upper bound does not vary with θ and while under different activities, the performance with PFP is close to each other. In Fig. 3, the effective capacity with PFP and the upper bound performance with different radiuses of PS-Rxs'

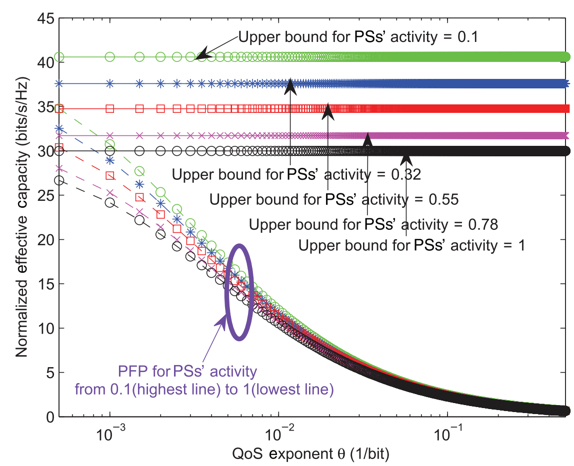

Fig. 2. Effective capacity with PFP and the upper bound with different activities of PS-Txs in large multihop CM2MN.

such region for protecting PSs' traffic) are presented. Since the effective capacity with PFP is upper bounded and increases when θ decreases, PFP approaches the upper bound for large PS-Rx's avoidance region for small θ (i.e., the more cooperative relays are disable under a tighter QoS requirement guaranteed by the system). The results certify that the proposed L-QoS guarantee precisely displays the achievable effective capacity with PFP in large Poisson CM2MN under QoS constraint; therefore, this guarantee generalizes the statistical QoS guarantees with network scalability.

V. STATISTICAL QoS CONTROLS

Instead of studying MIMO on one-hop communication links, network coded multipath routing algorithms examine multiple links concurrently to fulfill MIMO communication on network level. Statistical QoS control, called CQC, utilizes L-QoS guarantee in Section IV. The control mechanism has the diversity and spatial multiplexing modes as conventional MIMO in single link physical layer transmission. Diversity mode is accounted for the reliability of end-to-end transmission in delay aspect and spatial multiplexing mode is designed for the max-

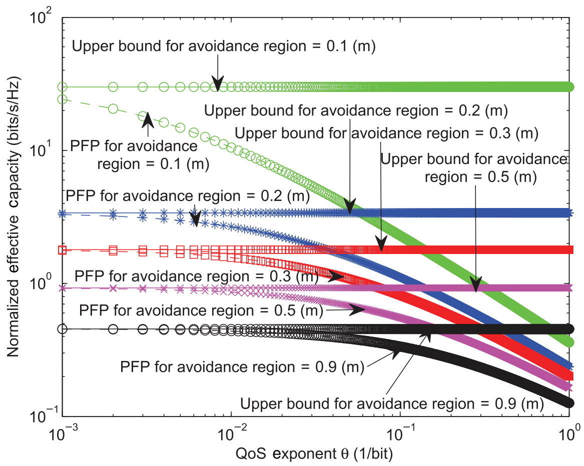

Fig. 3. Effective capacity with PFP and the upper bound with different radiuses of PS-Rxs' avoidance region in large multihop CM2MN.

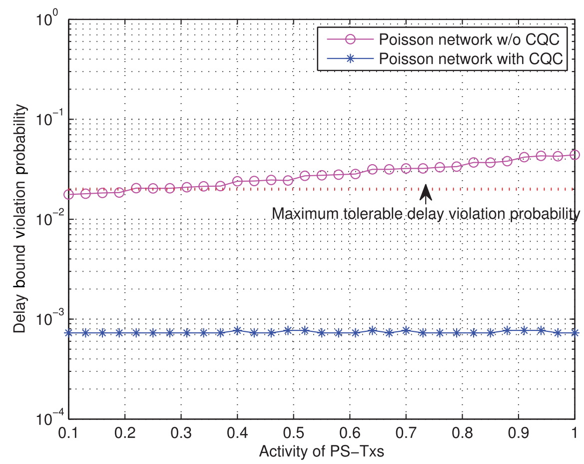

Fig. 4. Diversity mode for CQC with different activities of PS-Txs in large multihop CM2MN.

initiate explorations of networking control (i.e., exploiting MIMO communication upon networks) guiding the transmissions for the reliable communication in multihop CM2MNs.

A. Cooperative QoS Control

Inspired from cooperative relaying [3], CQC increases the number of cooperative nodes for requested performance. By employing multipath transmissions constituted from node combining and considering maximum permissible delay bound $D_{\max}$ and delay bound violation probability ε, CQC obtains the size of cooperating set Ω^*, and impels the whole network to support the end-to-end delay that guarantees L-QoS of traffic. Note that as the cooperating set size is a one-dimensional (1-D) parameter, several 1-D searching algorithms can be easily applied to find the optimal Ω^*. Moreover, when dealing with large system of CM2MNs, existing distributed heuristic can be further applied to give a satisfactory solution.

Algorithm 2. Cooperative QoS Control (CQC)

1: Set Ω^* to the size of currently cooperating set (i.e., the number of nodes in the network excluding source and destination).
2: Calculate the average service rate for the network from *Proposition 2* and obtain the effective capacity of the network $E_C^N(\theta)$ from *Proposition 3*.
3: Find the solution of θ, which satisfies

$$E_B(\theta) = E_C^N(\theta) = \delta. \tag{16}$$

4: Derive the delay violation probability by

$$\Pr\{W \geq D_{max}\} = e^{-\theta\delta D_{max}}. \tag{17}$$

a) If $e^{-\theta\delta D_{max}} > \varepsilon$, Ω^* is determined by

$$\min \Omega^*, \ s.t. \ e^{-\theta_{\Omega^*}\delta_{\Omega^*} D_{max}} \leq \varepsilon \ and \ 0 \leq \Omega^*. \tag{18}$$

b) If (18) is not satisfied, increase Ω^* by one and repeat Step 2 to Step 4 to find the appropriate Ω^* such that (18) is satisfied.

For large CM2MNs (i.e., networks with large network size, which might be statistically characterized by spatial distribution of nodes), L-QoS guarantee provides the guaranteed throughput while employing PFP. In order to fulfill the transmission rate of real applications, CQC further exploits the cooperative relaying in QoS guarantee. It first utilizes L-QoS guarantee to obtain the effective capacity of the network in Step 2) and then expands the size of cooperative set to met the need in (18). Consequently, CQC manages the networking control and is adopted for MIMO communication in large multihop CM2MNs as for Section V-B.

B. MIMO Communication for Session-Level Traffic

Facing various characteristics of traffic in different environments (or networks), statistical QoS control meets the requirement and therefore enables MIMO communication by employing diversity and spatial multiplexing modes alternatively. While CQC mechanism is in charge for large CM2MNs, we consider Poisson topology and adopt the VoIP traffic in 3GPP LTE [47] as the real-time traffic. A two-state voice activity model is discussed previously in Section IV-C. By setting simulation parameters as in Table I, we obtain diversity and spatial multiplexing characteristics of CQC and certify the practicality of our designs for MIMO communication of session-level traffic in multihop CM2MNs.

1) Diversity Mode: We aim at deploying cooperative diversity to enhance the transmission availability for cognitive machines' traffic. That is, even under PSs' high usage circumstance, cognitive machines can still have a reliable transmission with required QoS guarantees. In particular, CQC inherits from L-QoS guarantee and characterizes the opportunistic nature with the activities of PS-Txs and the radiuses of PS-Rxs' avoidance regions. Fig. 4 shows the impact of varied PS-Txs' activities with and without CQC, while Fig. 5 shows the impact of PS-Rxs' avoidance regions. Since the avoidance region decides cognitive machines' unworkable status, it influences machines' transmission more than PS-Txs' effect. Through expanding the cooperative set (i.e., increasing the number of cooperative

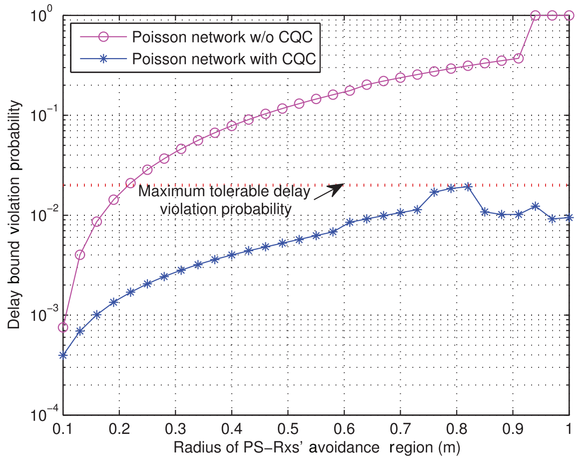

Fig. 5. Diversity mode for CQC with different radiuses of PS-Rxs' avoidance region in large multihop CM2MN.

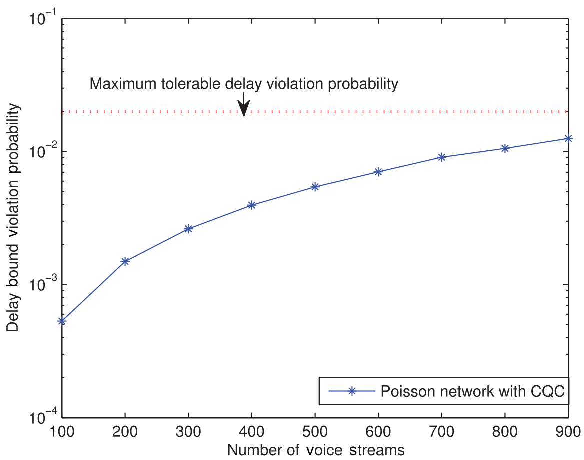

Fig. 6. Spatial multiplexing mode for CQC in large multihop CM2MN.

nodes), CQC perfectly protects the traffic under the maximum tolerable delay violation probability in large CM2MN.

2) Spatial Multiplexing Mode: Instead of using cooperative relays to compete opportunistic nature for cognitive machines' transmissions, we seek a spatial multiplexing mode for MIMO communication (i.e., the ability to support multiple traffic streams concurrently). To meet the requirement through equivalent network partition, CQC extends node combing scheme to multiple streams, rather than single traffic. By defining suitable cooperative sets for each stream, Fig. 6 shows the desired performance obtained by CQC without violating the delay bound even under heavy traffic load in Poisson network.

Remarks: Above evaluations verify the feasibility of statistical QoS control that enables MIMO communication of session-level traffic in multihop CM2MNs. For large Poisson topology, diversity mode conquers the opportunistic nature from the interaction between PSs and cognitive machines to provide a reliable transmission; spatial multiplexing mode aims to achieve the maximum end-to-end throughput for uses' application. Similar to MIMO in physical layer communication links, there also exists the tradeoff between two modes with the optimal decision strategy. The strategy shall be relevant to the channel conditions and topologies of networks, i.e., it might employ interference models with stochastic geometry and random graphs to characterize the transmission quality for end-to-end traffic. It thus provides best switching point between two modes for optimal decision, as an open problem due to its complexity.

VI. Conclusion

In this paper, we have proposed statistical QoS control to enable MIMO communication of session-level traffic in large multihop CM2MNs. In particular, the proposed CQC mechanism combines statistical QoS guarantee with routing algorithm from traffic flow perspective, rather than directly solving the NP-hard problem. QoS guaranteed throughput and tractable end-to-end delay violation bound are provided by our designs for reliable transportation with network coded multipath routing algorithms. This mechanism at end-to-end session level is actually applicable to any kind of wireless networks with the aid of cooperative relaying from its compact resolution and is suitable for the implementation due to its great practicality. With error control in [29] and statistical QoS control in this area, we achieve reliable communication via packet transportation; therefore, we presented an original and important paradigm for network coded multipath routing algorithms over multihop CM2MNs which is also suitable for general wireless networks.

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