A 3D Topology Optimization Scheme for M2M Communications

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***Abstract*—Communication networking leverages emerging network technologies such as topology management schemes to satisfy the demand of exponentially increasing devices and associated network traffic. Particularly, without efficient topology management, Machine-to-Machine (M2M) communications will likely asymmetrically congest gateways and eNodeBs in 3rd Generation Partnership Project (3GPP) Long-Term Evolution (LTE) and Long-Term Evolution Advanced (LTE-A) networks, especially when M2M devices are massively deployed to support diverse applications. To address this issue, in this paper, we propose a 3D Topology Optimization (3D-TO) scheme to obtain the optimal placement of gateways and eNodeBs for M2M communications. By taking advantage of the fact that most M2M devices rarely move, 3D-TO can specify optimal gateway positions for each M2M application, which consists of multiple M2M devices. This is achieved through global optimization, based on the distances between gateways and M2M devices. Utilizing the optimization process, 3D-TO likewise determines optimal eNodeB positions for each M2M application, based on the distances between eNodeBs and optimal M2M gateways. Our experimental results demonstrate the effectiveness of our proposed 3D-TO scheme towards M2M communications, with regard to throughput, delay, path loss, and packet loss ratio.**

***Keywords*—M2M communications, 3GPP LTE/LTE-A, Topology optimization, M2M applications**

I. Introduction

Unlike Human-to-Human (H2H) communication that highly relies on human intervention, Machine-to-Machine (M2M) communication, also known as Machine Type Communication (MTC), enforces connectivity between massive devices independently [1], [15]. M2M communication has become the skeleton of Internet-of-Things (IoT) communication and enables a myriad of smart applications in the realms of public safety, smart grid, smart transportation, smart health, smart city, etc. [3], [10], [16]–[18], [20].

Nonetheless, 3rd Generation Partnership Project (3GPP) Long-Term Evolution (LTE) and Long-Term Evolution Advanced (LTE-A) network infrastructures are unprecedentedly challenged with the explosion of M2M devices. Then, the development of intelligent networking techniques to satisfy the demand of exponentially increasing M2M devices and their traffic becomes critical. This calls for developing effective topology optimization to support M2M communications.

In this paper, we propose a 3D topology optimization (3D-TO) scheme for M2M communications in 3GPP LTE/LTE-A networks, which can efficiently improve M2M communication performance with respect to throughput, delay, path loss, and packet loss ratio. 3D topology optimization focuses on the repositioning of M2M gateways and eNodeBs, such that load-balanced network topology can be achieved. In this scheme, within a particular M2M application, 3D-TO first identifies an optimal position for each M2M gateway in the feasible deployment space. The optimization procedure is performed on the basis of minimizing the summation of the distances between each M2M gateway and its associated M2M devices. Utilizing the same optimization process, 3D-TO also specifies optimal eNodeB positions, but instead considers the distances between eNodeBs and their connected M2M devices' associated optimal M2M gateways. Under the minimization of distance between devices, 3D-TO can largely reduce relay times and path loss in data transmission. Through experimental simulation, we validate the effectiveness of our proposed 3D-TO scheme in terms of throughput, delay, path loss, and packet loss ratio.

The remainder of this paper is organized as follows: In Section II, we introduce the system model. In Section III, we introduce our approach in detail. In Section IV, we present experimental results to validate the effectiveness of our approach. In Section V, we review related works. Finally, in Section VI, we conclude the paper.

II. System Model

In 3GPP LTE/LTE-A networks [13], M2M devices are deployed with a MTC server and *Evolved Packet Core* (EPC), which consists of *Mobility Management Entity* (MME), *Serving Gateway* (S-GW), and *Packet Data Network Gateway* (P-GW). Particularly, MME is engaged in the control plane, performing activities such as roaming, handover and security management, and also selects S-GW and P-GW for M2M devices and user equipment (UEs). S-GW operates in the user plane to enable data transmission towards eNodeBs (eNBs) and P-GW, while P-GW establishes secure connections between M2M devices (UEs). All three EPC components are connected to eNodeBs via interface, and eNodeBs

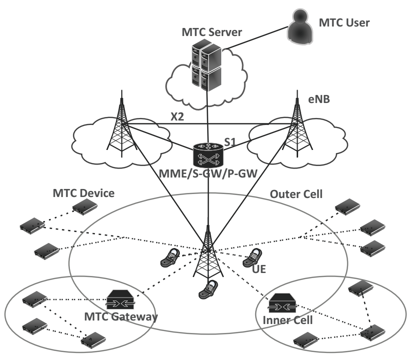

Fig. 1. System Model of M2M Communications in LTE/LTE-A Networks

communicate with each other through interface. The MTC gateway enables a mixture of diverse access methods (wireless LAN, WiMAX, ZigBee, etc.) to EPC, while the MTC server is accessed by the MTC users (smart home, logistic service, remote surveillance, etc.) to exploit diverse Internet of Things applications supported by massive M2M devices through some *Application Programming Interface* (API) provided by the network operator [19].

Within each M2M application, as shown in Fig. 1, we consider large networks organized by eNodeBs as outer cells, and small networks managed by MTC gateways as inner cells. To be specific, massively deployed M2M devices in outer cells can be bonded to eNodeBs either directly via LTE/LTE-A link, or indirectly via MTC gateways, under which the device-to-device communications between M2M devices might be enabled by distinct wireless network protocols other than LTE/LTE-A. MTC gateways in inner cells are able to not only optimally select transmission paths between M2M devices, effectively balancing their energy consumption, but also facilitate a connection to back-hauling. For the simplicity of our topology optimization analysis in 3D-TO, we assume that M2M devices do not move over time, but instead have fixed positions. Notice, however, that our proposed topology optimization mechanism can be extended to mobile device scenarios, as well as mixed mobile/stationary devices scenarios. All notations used in this paper are shown in Table I.

TABLE I
NOTATION

	Feasible and infeasible deployment space.
	Number of M2M applications.
	M2M application.
	Number of eNodeBs in application .
	eNodeB in application .
	Number of devices associated with indirectly.
	Number of gateways connected to .
	gateway connected to .
	Number of devices associated with .
	device associated with .
	-axis of .
	-axis of .
	-axis of .
	Coordinate of stationary point regarding .
	Hessian matrix regarding .
	Coordinate of position closest to .
	-axis of optimal .
	-axis of optimal .
	-axis of optimal .
	-axis of optimal .
	-axis of optimal .
	-axis of optimal .
	device associated with .
	-axis of .
	-axis of .
	-axis of .
	Coordinate of stationary point regarding .
	Hessian matrix regarding .
	Coordinate of position closest to .

III. Our Approach

In 3D-TO, M2M device positions are considered, such that a more efficient network topology can be obtained. Within a particular M2M application, optimal gateway positions can be identified in the feasible deployment space via a minimization of the distances between gateways and their connected M2M devices. Consequently, optimal feasible eNodeB positions for the same M2M application are specified by applying the same minimization mechanism to the distances between eNodeBs and their connected M2M devices optimal gateways.

3D topology optimization is used to specify optimal gateway and eNodeB positions within the feasible deployment space, denoted as , for each M2M application. Then, the infeasible deployment space (lakes, swamps, volcanoes, etc.) can be avoided. With a given space ( ), assume that the number of M2M applications is . In application , where , denote the number of eNodeBs as . As to each eNodeB in , where , refer to the number of M2M devices connected to it not via gateway as , the number of gateways associated to it as , and the number of M2M devices correlated to gateway , where , as .

Based on those deployed devices, our *topology optimization* mechanism comprises the following two steps: (i) *Step 1. Optimal gateway position*, and (ii) *Step 2. Optimal eNodeB position*.

Step 1. Optimal Gateway Position: In this stage, 3D-TO identifies optimal gateway positions in for each M2M application, such that the distance between each gateway and its associated M2M devices is minimized, resulting in reduced relay times and path loss. Intuitively, if the connectivity of devices can be guaranteed over long distances between devices, it can more likely be assured over short distances resulting from our optimal gateway positioning. Assume that the coordinate of M2M device , which is connected to gateway towards eNodeB in M2M application through one or multiple hops, as . If the summation of the squares of distances between devices is minimized, the summation of distances between devices will likely be minimized as well. For the simplicity of our analysis, we use the square functions of the distances between gateway and its associated M2M devices:

(1)

In order to identify the optimal position that minimizes the distance between devices, the stationary points of Equation (1) must be assessed, because extreme values can only occur at stationary points. In this regard, we obtain the first derivatives of the distance function from Equation (1) as follows:

(2)

By leveraging Equation (2), there exists only one stationary point. As the stationary points of the device distance function cause its first derivatives to be zeros, if we assume that the coordinates of the only stationary point of Equation (1) are , then we can have the coordinate of -axis as , it is similar for the coordinate of -axis to be derived as , along with the coordinate of -axis as .

Notice that is also the center-of-gravity of all M2M devices associated with gateway . As the only stationary point makes its corresponding extreme value either smallest or largest, the next step is to further identify whether it is the one that makes the distance between a gateway and its associated M2M devices smallest. To this end, we derive the second derivatives of Equation (1), which form a *Hessian Matrix* [14] :

It is observed that H is a positive definite matrix, meaning that is the minimum point of the square distance function, represented by Equation (1), which then is a strictly convex function [2]. Thus, if falls into the feasible deployment space, it will be the optimal gateway position. Otherwise, the optimal gateway position has to be the one, denoted as , which is closest to , in the feasible deployment space, according to the concavity of Equation (1). Recall that is the center-of-gravity of M2M devices, which means gateways are placed in or closest to the center. This implies that our optimal gateway position also considers the density of M2M devices by orientating gateways near to the area with high M2M device density, and father from the area with low M2M density. Assume that the coordinate of the optimal gateway position that we are looking for as , then it will be , if . If , the coordinate will be .

Regarding the specification of , the procedure is exactly the same as that demonstrated for identifying , with the exception that the stationary point in becomes the point of interest. We need simply to move in over to its closest spot in , and the concavity of Equation ensures that is the minimum point of Equation (1) in . After finalizing the optimal gateway position for , 3D-TO then determines the optimal eNodeB position for based on their associated M2M devices and the generated optimal gateway positions.

Step 2. Optimal eNodeB Position: In this stage, the optimal eNodeB position, denoted as , for each is confirmed, and the device connectivity is also guaranteed. As to each M2M application , 3D-TO determines the optimal eNodeB positions via a minimization of the distances between eNodeBs and their associated M2M devices optimal gateways generated in *Step 1*.

Assume that the number of M2M devices, which are connected to eNodeB in application through one or multiple hops as . If we represent the coordinate of M2M device , as . Then, we can also have the square function of distance between and , as:

(3)

With the illustration of *Step 1*, we also enumerate below the first derivatives of Equation (3) to identify the stationary points. There is one which can minimize the distance between and , .

(4)

Assume that the coordinates of the only stationary point of Equation (3) are . By setting each derivative in Equation (4) to be zero, we can have the coordinate of x-axis as , and the coordinate of y-axis as , along with the coordinate of z-axis as .

Notice that is the center-of-gravity of all the M2M devices and optimal gateways, which are associated with . Next, we find the second derivatives of Equation (3) to be the following *Hessian Matrix* .

is also a positive definite matrix, which implies to be a point minimizing strictly convex distance function, represented by Equation (3), similar to that illustrated in *Step 1*. Thus, the optimal eNodeB position will be either , or the closest point to it that lies in the feasible deployment space, denoted as , if is determined to lie in the infeasible deployment space. As the center-of-gravity (or nearest point to the center-of-gravity) of M2M devices and optimal gateways, or also takes the density of M2M devices and optimal gateways into account. The coordinate of the optimal eNodeB position that we are looking for will be , if . If , the coordinates will be .

If relocating the optimal eNodeB is needed, the affirmation of will follow the same process in *Step 1*. Thus, the optimized topology for M2M communications in 3GPP LTE/LTE-A networks is accomplished.

Recall that 3D-TO finds optimal gateway and eNodeB positions, based on a procedure of minimization over distances between gateways, eNodeBs and their associated M2M devices, with the consideration of restriction from the infeasible deployment space. This also leads the optimal positions of gateways and eNodeBs to be the centers of gravity of their associated M2M devices, which validates the device density attention property of 3D-TO.

IV. Performance Evaluation

In our performance evaluation, we first implement 3D-TO in MATLAB to numerically demonstrate its effectiveness, and then deploy certain numeric results from MATLAB into NS-3 to further assess the performance of 3D-TO in a real network simulation environment[1]. In our evaluation, the comparison baseline against 3D-TO is the normal case without any topology optimization towards M2M gateways and eNodeBs.

First, we conduct our numeric demonstration over the average and variance of distances between devices of each M2M application in MATLAB, with the consideration of a number of coexisting M2M applications enabled by massive M2M devices. Thus, we set the number of M2M applications to 2000. Within each M2M application, there are 2 eNodeBs, 6 M2M gateways, and 1000 M2M devices. The initialized three-dimensional positions of all devices are generated randomly,

[1]Certain commercial equipment, instruments, or materials are identified in this chapter in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

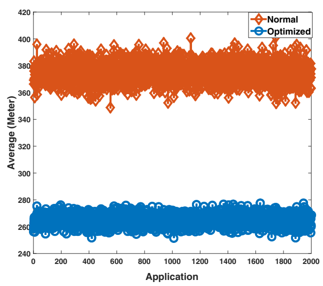

Fig. 2. Distance Average

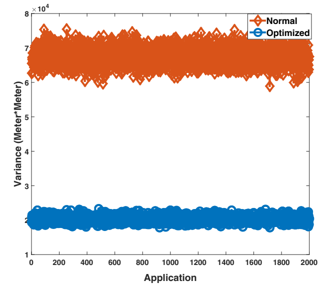

Fig. 3. Distance Variance

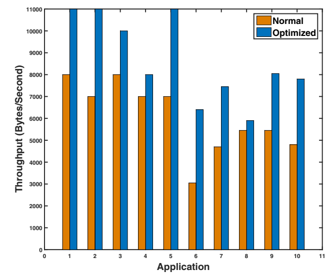

Fig. 4. Throughput

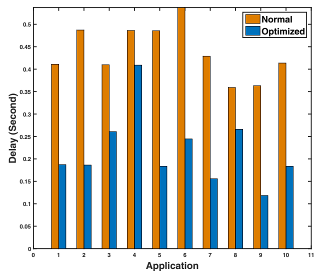

Fig. 5. Delay

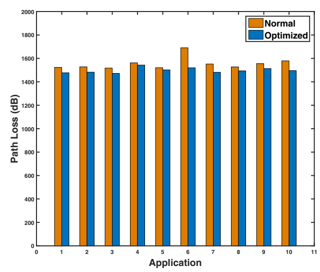

Fig. 6. Path Loss

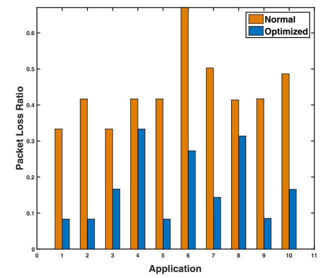

Fig. 7. Packet Loss Ratio

and one single eNodeB is directly connected to 250 M2M devices and 3 M2M gateways, which are directly or indirectly associated with another 250 M2M devices via one or multiple hops. In addition, we assume that M2M devices separated by distance less than the transmission range are also paired up via either LTE/LTE-A link or other kinds of wireless links (WLAN, WiMAX, ZigBee, etc.). The network connectivity is guaranteed by the cooperation among the transmission ranges of eNodeB, M2M gateway, and M2M device, which are 1000 m, 500 m, and 50 m, respectively.

Second, for simulations in NS-3, we shrink the network size due to the capacity limitation of our computing hardware. Thus in NS-3, we implement 10 M2M applications, consisting of 1 macro eNB, 2 home eNBs (working as M2M gateways), and 12 UEs (serving as M2M devices with fixed positions) in each application. The macro eNB is directly connected to 6 UEs and 2 home eNBs, and each home eNB is associated with 3 UEs. All device positions in NS-3 are determined according to the results generated from MATLAB by applying 3D-TO. For simplicity, communications between devices are all enabled under LTE standard, with UDP as the transmission protocol.

3GPP has standardized the arrival traffic of M2M communications as a *Beta* distribution with a small data transmission feature [3], [4]. Thus, we set up a *Beta* distribution for each M2M application and randomly generate integers from 1 to 4 as , , and the function range (in seconds). The effectiveness of 3D-TO is assessed based on the following metrics: (i) *Throughput* is computed based on the entire data transmissions of all M2M devices in each M2M application, (ii) *Delay* is computed based on the average time of M2M devices to finish transmitting data in each M2M application, (iii) *Path Loss* is examined based on the overall power attenuation of all M2M devices in each M2M application, and (iv) *Packet Loss Ratio* is defined as the ratio of lost data packets over the total transmission data packets associated with all M2M devices in each M2M application. For generality, we repeat the experiment 10 times, taking the average of all 10 iterations as the data in the figures.

Fig. 2 and Fig. 3 show the performance comparison of 3D-TO and the baseline normal case (i.e., without topology optimization), with respect to distance average and variance. As we can see from the figures, the average and variance of distances between devices of each M2M application running 3D-TO is much lower than those of M2M applications without 3D-TO. For instance, 3D-TO reduces the average distances between devices of all M2M applications to below 280 m, seen in Fig. 2, while the average distances between devices of almost all M2M applications in the normal case are above 400 m. In Fig. 3, the variances of distances between devices of all M2M applications with 3D-TO are lower than 24 000 , but reach around 70 000 for most baseline M2M applications without 3D-TO.

Fig. 4 illustrates the average throughput of each M2M application in the normal and optimized cases, respectively. As we can see from the figure, our proposed 3D-TO scheme performs better than the normal case without topology optimization in all 10 M2M applications. This implies that 3D-TO can significantly improve LTE network performance in terms of throughput. For example, certain M2M applications, running 3D-TO in Fig. 4, achieve a throughput as high as 11,000 bytes/second, and even the application with the worst performance has a throughput above 5,700 bytes/second. In contrast, only 2 M2M applications without topology optimization reach a throughput at 8,000 bytes/second, while most maintain a throughput under 5,600 bytes/second.

Fig. 5 highlights the comparison of 3D-TO and the normal case with respect to delay. As we can see from the figure, the average delay performance for each M2M application with 3D-

TO is much better than that of the M2M applications without 3D-TO. For example, 3D-TO maintains a delay under 0.27 s for almost all M2M applications in Fig. 5, and some even reach as low as 0.12 s. Nonetheless, in the normal case, without topology optimization, the delay of all M2M applications is above 0.35 s.

Fig. 6 shows an evident decrease for each M2M application with respect to path loss by applying 3D-TO. Fig. 7 illustrates the packet loss ratio of M2M applications in both the normal case without topology optimization and optimized case with 3D-TO. As we can see from the figure, our proposed 3D-TO scheme outperforms the normal case in each M2M application. For example, all M2M applications running the normal case in Fig. 4, have a packet loss ratio above 0.3, even reaching as high as 0.68. In comparison, the packet loss ratio of almost all applications in the optimized case with 3D-TO is below 0.3, with some M2M applications with packet loss ratios below 0.1.

V. Related Works

In order to improve M2M communications in 3GPP LTE/LTE-A networks, a number of research efforts have been devoted to M2M topology optimization [5]–[9], [11], [12].

Topology optimization has been generally adopted in M2M communication networks to obtain interference reduction, energy economy, and the extension of operating lifetimes. Primarily, topology optimization consists of topology construction and topology maintenance, which are responsible for initialization optimization and connectivity preservation, respectively [5], [7]–[9], [11]. For instance, Lee *et al.* in [7] proposed a distributed energy-efficient topology control algorithm to establish a best-parent based new topology in the construction phase, and a signal topology reconstruction by monitoring energy status of neighbors in the maintenance phase. The algorithm delivered significant energy efficiency and prolonged lifetime. Li *et al.* in [8] designed a network flow theory-based topology adaption algorithm with low time complexity. The authors analyzed the heterogeneity property of M2M networks and identified an optimal solution for energy efficient topology control.

Unlike the existing schemes highlighted, our proposed 3D-TO (3D Topology Optimization) scheme considers not only the identification of optimal device positions, but also the avoidance of obstruction areas. Our work consists of a thorough theoretical modeling of topology construction and maintenance based on distance minimization. We have also conducted experiments in both Matlab and NS-3 to demonstrate the performance of our proposed approach.

VI. Conclusion

In this paper, we proposed a 3D topology optimization (3D-TO) scheme that can optimally construct network topology for M2M applications in 3GPP LTE/LTE-A networks. Particularly, 3D-TO applies the first derivative to extract the stationary point of the distance between devices, and then utilizes the second derivative to identify it as the one that minimizes the distance. Our proposed scheme is capable of leveraging M2M device positions to obtain optimal M2M gateway and eNodeB placement. The results of our extensive experimentation validate that 3D-TO obtains better network performance in throughput, delay, path loss, and packet loss ratio than the baseline configuration.

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