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Research Article

Distributed Energy-Efficient Topology Control Algorithm in Home M2M Networks

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Because machine-to-machine (M2M) technology enables machines to communicate with each other without human intervention, it could play a big role in sensor network systems. Through wireless sensor network (WSN) gateways, various information can be collected by sensors for M2M systems. For home M2M networks, this study proposes a distributed energy-efficient topology control algorithm for both topology construction and topology maintenance. Topology control is an effective method of enhancing energy efficiency and prolonging network lifetime. During the topology construction phase, each node builds a new topology based on the best parent node. Nodes can extend the network lifetime by adjusting transmission power to control the topology. In the topology maintenance phase, each node monitors the energy status of neighbors and triggers topology construction as needed. By balancing energy consumption, topology maintenance also avoids the hot spot problem. Simulation results confirm the superior performance of the proposed algorithm for distributed energy-efficient topology control (DETC) in terms of energy efficiency and network lifetime in home M2M networks.

1. Introduction

Home networks are rapidly developing to include diverse embedded devices, including mobile phones, laptops, digital TV, electronic appliances, and so forth. Recently, home networks have begun to shift from machine-to-human communications to machine-to-machine communications in home environments. The M2M network is now the dominant communication technology in home networks [1]. The M2M environments can be conceptualized as networks that provide data communications between embedded devices without human intervention. Wireless sensors are now the main drivers of M2M communication and are being deployed in various systems, including smart grid, healthcare monitoring, smart lighting control, home automation, and surveillance systems [2]. A typical application of an M2M network is the WSN, which enables the direct exchange of information between machines [3]. By interfacing with WSNs, various kinds of information can be collected by M2M network sensors. M2M networks inherit resource-limited, unguarded and mass-deployed sensor networks but are also characterized by embedded intelligence and self-organization capabilities [4]. Different applications may require different sensor capabilities. Thus, the home M2M network may need different sensors for different application requirements. Due to different sensor capabilities in M2M networks, frequent and abrupt topology change is a common problem. Moreover, the natural limitations of WSNs [5], such as their resource constraints, are unsolved issues in M2M communication. Given the above considerations, M2M network protocols and algorithms require energy-efficient and self-organizing capabilities. A potential solution for addressing these challenges is a topology control algorithm that prolongs the M2M lifetime and transforms the network topology in real time.

Effective topology control is essential for prolonged network lifetime and can optimize the tradeoff between power consumption and real-time performance [6]. In this study, we proposed a DETC algorithm in M2M networks. The DETC algorithm for M2M networks proposed in this study

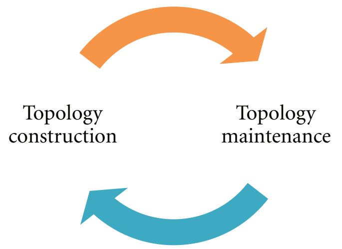

Figure 1: The topology control cycle.

is designed to control the graph representing communication links between nodes in order maximize network lifetime and minimize energy consumption. According to [7], Figure 1 shows the iterative process used for topology control. It consists of two phases: topology construction and topology maintenance. The main motivation behind the topology construction phase is building an energy-efficient topology. Transmission power is known to be the main factor in the energy consumption of each node. By adjusting its own transmission power, each node changes the topology to save energy by choosing the parent node with which it directly communicates. As soon as the topology construction phase establishes the network, the topology maintenance phase is initiated in each node. The M2M network nodes may unexpectedly move or turn power on/off. Moreover, energy consumption should be evenly distributed. The parent of each node must change at the appropriate time. Thus, a topology-maintenance algorithm monitors the topology status and triggers a topology construction phase as needed. This cycle is repeated many times over the network lifetime until all network energy is depleted.

The rest of this paper is organized as follows. Section 2 introduces relevant works. Next, Section 3 elucidates the proposed topology control algorithm. Section 4 summarizes the simulation results. Section 5 draws conclusions.

2. Related Work

Machine-to-machine technology supports wireless communications from machine to machine. This emerging technology for next-generation communications has many potential applications for improving efficiency and reducing network operating costs. Tekbiyik and Uysal-Biyikolglu [8] comprehensively studied shortest path-based energy-efficient routing alternatives for M2M networks. They also developed a classification scheme for current and future applications and the design issues of M2M networks. The evolution of M2M has recently included development of a smart grid framework. Fadlullah et al. [9] surveyed several existing communication technologies with potential smart grid applications for M2M communication. They also presented a reliable technology for improving the performance of conventional ZigBee-based M2M communications in smart grids by incorporating intelligence in a smart meter and M2M devices. Niyato et al. [10] investigated the network design issue of M2M communications for a home-energy management system (HEMS) in the smart grid. A dynamic programming algorithm is applied for optimizing the HEMS traffic concentration while minimizing cost. Based on the findings of the above studies, several researchers have designed schemes for M2M communication technologies in several applications. Energy efficiency is still a major design objective in the machine-to-machine network scenario. However, few studies have discussed the important issue of improving power efficiency in M2M networks.

Topology control is a key technique for improving energy efficiency and is applicable in M2M communication. Ding et al. [11] investigated an adaptive partitioning scheme called connectivity-based partition approach (CPA) for node scheduling and topology control in WSNs. The CPA classifies nodes according to their measured connectivity instead of estimating connectivity based on their positions. It maintains K-vertex connectivity of the backbone, which balances the trade-off between energy efficiency and communication quality. Sethu and Gerety [12] developed step topology control for reducing energy consumption while preserving connectivity in heterogeneous sensor networks without location-based assumptions. Their proposed control is also applicable for nonuniform path loss propagation. Rizvi et al. [13] presented a connected dominating set-based topology control algorithm, A1, which constructs an energy-efficient virtual backbone. By using an efficient algorithm, the topology construction phase of A1 substantially reduces the messages required for an efficient algorithm. Connectivity during topology maintenance and sensing coverage are also enhanced. Chiwewe and Hancke [14] developed the Smart Boundary Yao Gabriel Graph (SBYaoGG) topology control algorithm for increasing energy efficiency and decreasing interference in wireless sensor networks. Use of the SBYaoGG algorithm for optimization ensures symmetric and energy efficient links throughout the network. Üster and Lin [15] devised a hierarchical topology and routing structure with multiple sinks and proposed a general data aggregation approach. An integrated topology control and routing problem was used to improve energy efficiency and prolong lifetimes in data-gathering WSNs. For reduced power consumption, Ma et al. [16] constructed network topologies that minimize the number of coordinators without affecting] network connectivity. Reducing the number of coordinators reduces the average duty cycle and prolongs battery life.

Based on the above observations, most topology control algorithms focus only on topology construction. Numerous researchers have attempted to optimize topology based on a specific property such as reliability, energy efficiency, or connectivity. However, topology maintenance should also be considered when designing topology control algorithms. Because home M2M network are deployed in numerous applications, many different sensor types are needed to satisfy application requirements. To overcome this problem, this study proposes a novel topology control algorithm that prolongs system lifetime by considering both topology construction and topology management. The topology construction phase builds a topology by identifying the OR builds a topology based on the parent node with which it directly communicates. By adjusting the transmission power level and choosing the parent node based on a fair

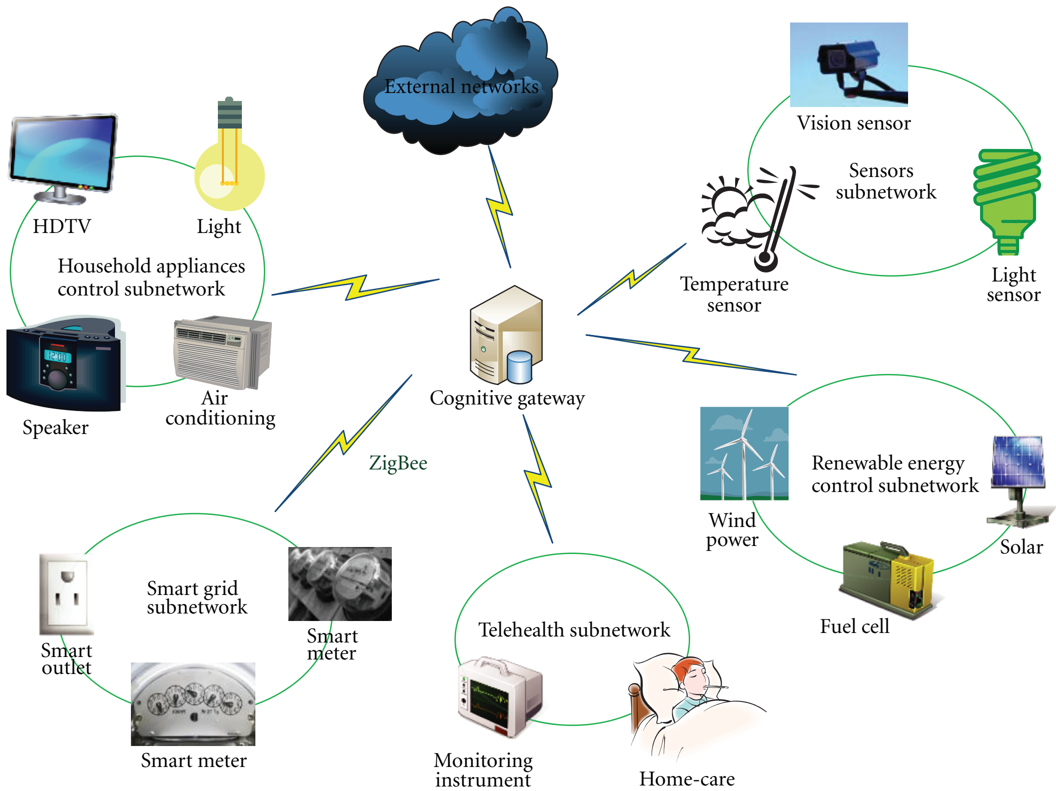

Figure 2: Home M2M sensor network architecture.

energy consumption rule, each node can change the topology to increase energy savings. Each node performs the topology maintenance algorithm to monitor the status of the neighbor and to trigger a topology construction phase that enables a rapid response when needed. By enabling nodes to create and maintain energy-efficient links autonomously, the proposed distributed algorithm scheme achieves the objective of prolonged lifetime.

3. Distributed Energy-Efficient Topology Control Algorithm

This section first defines some assumptions before giving details of the topology control algorithm and its energy efficiency.

3.1. Network Model. The M2M promises diverse services for home environments. Some exemplary applications include smart grid, mobile healthcare, home automation, security, appliance monitoring, lighting, and sensors. The home M2M network includes an external network and multiple subnetworks. The external network includes a central machine home gateway for managing the overall network, collecting data from the overall network, and connecting the home network to the outside world (e.g., the Internet). Each subnetwork is self-organized and is designed for a specific application. However, each network communicates by ZigBee [17] or 802.15.4 [18] standard. Since the IEEE 802.15.4 protocol is designed to minimize energy-efficiency and communication overheads, it is a promising standard for WSN applications. Based on the physical and medium-access control layers of IEEE 802.15.4, the upper layers are defined by the ZigBee protocol stack.

Notably, the sensors in several subnetworks have varying capabilities, as shown in Figure 2. For instance, sensors in the smart grid subnetwork have powerful computing capability and an unlimited power supply. In contrast, some sensors in the household appliances control subnetwork have unlimited energy but may suddenly turn off when the user turns off the household appliance. Sensors in the subnetwork are resource constrained in terms of power supply, computation capacity, and bandwidth. Thus, energy-efficient algorithms could help prolong lifetime in home M2M sensor networks.

This study assumes N identical sensor nodes are distributed randomly in the monitor area. The graph of the network is denoted as $G(V, E)$. Let V be the set of vertices representing the nodes and let E be the set of edges representing the communication links. The distance between node u and v is denoted as $d(u, v)$. Each sensor node can adjust the transmission power to communicate with any other nodes. Here, the widely used transmission power model is applied as follows:

$$\varepsilon(u,v) = \xi \times d(u,v)^{\alpha}, \tag{1}$$

where $\varepsilon(u, v)$ is the required transmission power from u to v, α is the path loss factor between 2 and 4, and a power threshold ξ is considered a constant.

Each sensor can send and receive hello messages with maximum power to find their neighbor nodes $N(v)$. Here, $\varepsilon_{\min}(u, v)$ denotes minimum power needed to deliver a packet from the node u to v. According to the $N(v)$ and $\varepsilon_{\min}(u, v)$, node v can construct a local subgraphic. The $\varepsilon_{\text{rm}}(v)$ is the remaining energy of node v.

3.2. Energy-Efficient Topology Construction Scheme. Topology control adapts to network changes in order to enhance power savings and to prolong network lifetime. In the topology construction phase, an energy-efficient topological property that constructs topology dynamically is established in the network while maintaining connectivity. The monitor area has several sensors with different capabilities. An energy-efficient topology that corresponds with the sensor state must be built. A backbone is formed to enable node pairs in the topology to communicate. A distributed energy-efficient algorithm is proposed for building the topology. Each sensor constructs a local subgraphic $G_v \leftarrow (N(v), L(v))$ and determinates the best parent node $P(v)$. The $P(v)$ is the parent node of node v. The $L(v)$ is a set of links in the subgraphic. Thus, a tree-based backbone for data transmission can be built. Next, the topology control for home M2M networks is described.

According to the above discussion, the sensors in the home M2M network can be classified into four types: (1) The sensors have limited battery power and are always active. (2) The sensors have limited battery power and appear/disappear suddenly. (3) The sensors have unlimited power supply and always alive. (4) The sensors have unlimited power supply and appear/disappear suddenly. Some nodes may that have mobile capability are classified as type 2 or 4. Based on the different sensor characteristics, a new energy-efficient topology must be built to prolong the system lifetime and to satisfy the application requirements in H2M network. Algorithm 1 shows the proposed energy-efficient topology construction algorithm. Each node first constructs a local subgraphic (line 1). The initialization then sets the parent node of node v to NULL (line 2). Candidate set $C(v)$ must then be identified so that the child node can be removed from the neighbor node to avoid the routing loop (line 3). The sink(x) denotes the sink state, that is, whether or not the sink is connected. The objective of the process is to build an energy-efficient topology. Thus, if node u near node $v$has unlimited energy, node v can immediately apply node u at parent node $P(v)$. In lines 4 to 7, node v must find the neighbor with unlimited energy to set the parent node $P(v)$. Transmission power $\varepsilon_{\text{tx}}(v)$ of node v is assumed to adjustable. If so, transmission power $\varepsilon_{\text{tx}}(v)$ is set to the minimum power cost $\varepsilon_{\min}(P(v), v)$ between $P(v)$ and v. If not, the node v must try to find $P(v)$ according to transmission energy cost. The transmission power level $\varepsilon_{\text{pl}}(v)$ for each node in the overall network could be the maximum or between the minimum and maximum. A connected tree topology of the overall network is formed among different nodes using an effective transmission power level $\varepsilon_{\text{tx}}(v)$ such as $0 \le \varepsilon_{\text{pl}}(v) \le n$. Based on analysis of sensor characteristics above, two classifications are possible based on energy considerations. First, if sensor v has unlimited energy supply, the transmission power level in a decrease order (lines 9-10). If possible, a sensor with unlimited energy can deliver packets with maximum power consumption. Second, sensor v has limited battery power, transmission power level in an increase order (lines 14-15). The shorter distance decreases transmission power cost and prolongs lifetime. For a given transmission power level, node v finds the node u with the maximum remaining energy and the shortest path (lines 11–16). The shorter path refers to the hop count HC(u), which is larger than or equal to HC(v). The HC(v) refers to the hop count from sink to v. Transmission power $\varepsilon_{\text{tx}}(v)$ is then set to the minimum power cost $\varepsilon_{\min}(P(v), v)$ (lines 12–17). If no parent nodes have a shorter path from candidate set $C(v)$, node u, which has the maximum remaining energy, is set as the parent node $P(v)$ (lines 21-22). Finally, the *topology maintenance* algorithm is performed (line 24).

3.3. Energy-Efficient Topology Maintenance Scheme. Given a certain number of nodes distributed in a monitor area, the goal of topology construction is building a topology that enhances energy efficiency. Once the topology has been created, the network starts performing the topology maintenance task. Depending on its duration, maintenance can change the topology. According to [7], topology maintenance is defined as the process that periodically restores, rotates, or recreates the network topology when the current reduced topology is no longer optimal. Thus, the topology maintenance mechanism in this study is triggered to build a new topology, to increase the energy efficiency of the nodes, and to increase network lifetime. Because, many applications require a many-to-one traffic pattern in the M2M network, packet delivery may cause an energy imbalance in the nodes in the hot spot near the sink [19]. All packets must be routed through the hot spots around the sink. Because nodes in this hot spot must forward a disproportionately large amount of traffic, they often die at a very early stage. The hot-spot problem is the major limitation on lifetime. Further, numerous unlimited energy supplies and sets of sensors may appear/disappear unexpectedly in the M2M. Therefore, balanced and efficient energy consumption in each node is an important issue.

The dynamic topology maintenance techniques applied in this study create a new topology "on the fly" by triggering the topology construction mechanism as needed [7]. Dynamic topology maintenance mechanisms are advantageous because they use more network information to optimize the energy efficiency of the topology. The topology maintenance process has been described, as shown in Algorithm 2.

During the topology maintenance phase, node v periodically broadcasts a beacon message to its neighbor set $N(v)$. Similarly, each node can receive beacon messages from neighbors (lines 1-2). The beacon packet carries the following information in its header: <*Src*, *EnergyState*, *Parent_Node*, *Sink_State*, *Hop_Count*>. The *Src* is used to identify each packet; *EnergyState* refers to the remaining energy of node; *Parent_Node* records the parent node; *Sink_State* is the index

Function **Topology Construction Algorithm** at node (v) in G:
(1) $G_v \leftarrow (N(v), L(v))$; where $L(v) \in E$
(2) $P(v) \leftarrow \varnothing$
(3) $C(v) = \{xx \in N(v), P(x) \neq v, \text{sink}(x) = \text{true}\}$
(4) If $\{\varepsilon_{\text{rm}}(u) | u \in C(v)\} == \infty$
(5) $P(v) \leftarrow u$
(6) $\varepsilon_{\text{tx}}(v) = \varepsilon_{\min}(P(v), v)$
(7) Break;
(8) else
(9) If $\varepsilon_{\text{rm}}(v) == \infty$
(10) For $\varepsilon_{\text{pl}}(v)$ in decrease order
(11) $P(v) = \text{Max}_u\{\varepsilon_{\text{rm}}(u) | u \in C(v), \text{HC}(u) \leq \text{HC}(v)\}$
(12) $\varepsilon_{\text{tx}}(v) = \varepsilon_{\min}(P(v), v)$
(13) End for
(14) else
(15) For $\varepsilon_{\text{tx}}(v)$ in increase order
(16) $P(v) = \arg\max\{\varepsilon_{\text{rm}}(u) | u \in C(v), \text{HC}(u) \leq \text{HC}(v)\}$
(17) $\varepsilon_{\text{tx}}(v) = \varepsilon_{\min}(P(v), v)$
(18) End For
(19) End If
(20) End if
(21) If $P(v) == \varnothing$
(22) $P(v) = \text{Max}_u\{\varepsilon_{\text{rm}}(u) | u \in C(v)\}$
(23) End If
(24) Trigger *topology maintenance Algorithm*

Algorithm 1: Topology contraction algorithm running on a node v in G.

Function **Topology Maintenance Algorithm** at node (v):
(1) Broadcast beacon message to neighbor $N(v)$
(2) Receive beacon message from each neighbor $N(v)$
(3) $C(v) = \{xx \in N(v), P(x) \neq v, \text{sink}(x) = \text{true}\}$
(4) If $P(v)$ is miss
(5) Trigger *Topology Construction Algorithm*
(6) End If
(7) If $\varepsilon_{\text{rm}}(C(v)) == \infty$
(8) Trigger *Topology Construction Algorithm*
(9) End If
(10) If $\varepsilon_{\text{rm}}(P(v)) < \varepsilon_{\text{rm}}(C(v))$
(11) Trigger *Topology Construction Algorithm*
(12) End If

Algorithm 2: Topology maintenance algorithm running on a node v in G.

which indicating whether or not the node is connected to the sink; *Hop_Count* is the number of wireless links in a path from the sink to the node. Each can collect information about neighbors via beacon packets. The objective is to obtain the candidate set $C(v)$ to avoid the routing loop (line 3). The sensor characteristics observed in the home M2M sensor network indicate that some sensors may appear/disappear suddenly. Thus, three decision rules are used to execute the topology construction algorithm needed to build a new topology in each node. The first decision rule shows that $P(v)$ is miss (line 4). A missing parent node $P(v)$ indicates that v cannot connect to the sink, so a new topology must be built. Next, if an unlimited energy node is activated and joins the network, it should be utilized efficiently (line 7). Node v should try to find a new parent node. Finally, the parent node of v should change when v finds a better node that has more remaining energy. Each node must consume energy equally. When the remaining energy of the parent node is lower than that of the node in the candidate set, the parent node must change. In summary, the topology can vary depending on the time via topology maintenance. During the topology maintenance process, each node uses these three decision rules to trigger the topology construction algorithm. By equally distributing energy consumption, it can prolong the system lifetime.

4. Performance Evaluation

This section presents some simulation results that demonstrate the effectiveness of the proposed DETC algorithm. We evaluate the performance of DETC and compare it with EELTC [16] algorithm and A1 algorithm [13]. A random-node deployment in a 100 m × 100 m area is simulated. The sink is set at the lower left corner. The measurement unit is the time required to send 250 k bits of information to the sink over a multihop link. The communication radius R_c and initial energy level of each node are set to 10 m and 10 K J, respectively. For a mica mote with RF frequency 866 MHz [20], Table 1 [21] specifies the four transmission power levels in the interval [−13 dBm, 5 dBm] where 0 is the minimum and 3 is the maximum transmission power level for communicating among nodes. The energy consumption

Table 1: Energy consumption for different power levels.

Transmission power level ε_{tx}	Emitted power [dBm]
0	−13
1	−7
2	−1
3	5

model was based on the Berkeley mote, that is, energy costs of 0.075 W transmitting at maximum power, 0.03 W when receiving, 0.025 W when listening, and 0.001 W when sleeping. To obtain the most probable result, the average values for 50 rounds were recorded.

The first experiment measured network lifetime during topology control. Network lifetime was defined as the period from the start of network operation to the moment when the first sensor in the network runs out of energy [22]. As expected, the proposed DETC algorithm achieved a longer system lifetime (rising curve in Figure 3) compared to EELTC and A1. Notably, the curve for the EELTC algorithm was actually a declining curve. In terms of network size, the network lifetime for DETC obtained by the proposed approach is longer than that of EELTC and A1, especially for extremely large networks. Due to the hot-spot problem, packet forwarding may cause energy imbalance. Traffic routed through the nodes near the data sink can create a hot spot around the data sink. Thus, the nodes in this hot spot must forward a disproportionately high number of packets and die at a very early stage. However, the topology maintenance phase in this approach can monitor the energy state of sensors and dynamic changes in topology as needed.

In the M2M network, packet transmission is the main energy consumer. A high packet delivery rate increases the energy consumption of nodes. Figure 4 shows that the proposed algorithm performs well in terms of network lifetime under various packet delivery rates. The DETC algorithm can reconstruct a new topology to increase energy efficiency as needed. Additionally, since the node status may appear or disappear suddenly, the DETC can rapidly build a new topology in part of network. The parent node has selected via various power level control. Thus, this approach can provide the good performance of system lifetime. Figure 5 shows the performance of the network lifetime under various power levels. The total number of power levels can affect the network. A large number of power level increases network lifetime. The simulation results suggest that the selected number of power levels is appropriate since $0 \leq \varepsilon_{pl}(v) \leq 3$.

The topology control approach has two phases, topology construction and topology maintenance. The topology construction phase establishes an energy-efficient topological property in the network while ensuring connectivity. When the new topology is built, nodes trigger the topology maintenance phase. Thus, the DETC is more energy efficient compared to EELTC and A1. Figure 6 displays the results of the simulation of the average remaining energy of nodes after the end of the system. The proposed control balances the energy consumption of each node by updating the parent during the topology maintenance. Thus, for network load,

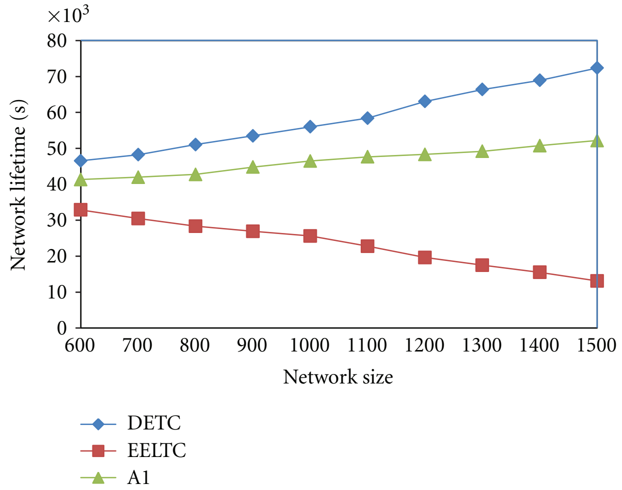

Figure 3: Network lifetime comparison in different network size.

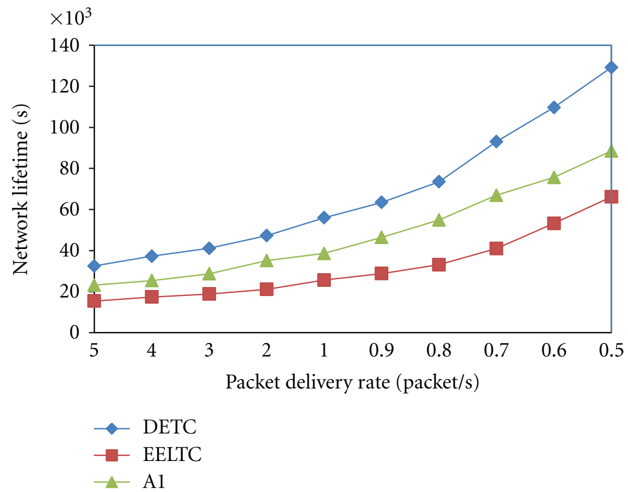

Figure 4: Network lifetime comparison for different packet delivery rate.

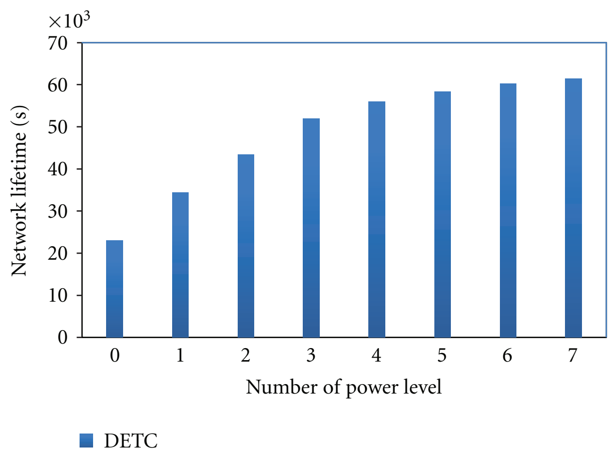

Figure 5: Network lifetime under various number of power level.

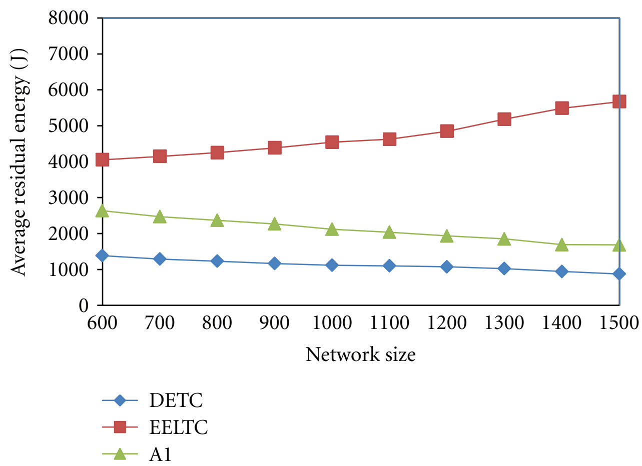

Figure 6: Average remaining energy comparison.

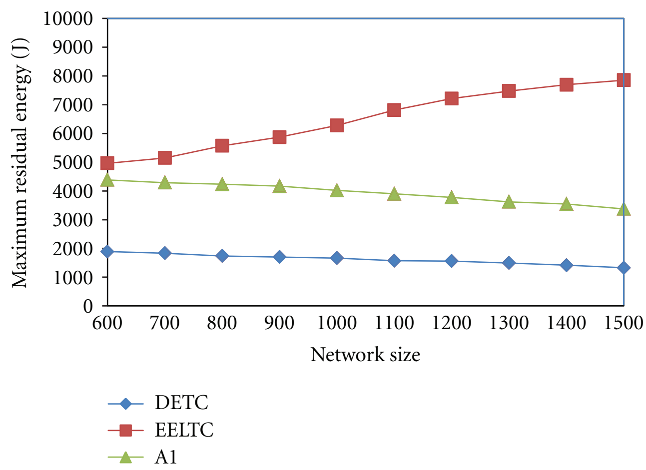

Figure 7: Maximum remaining energy comparison.

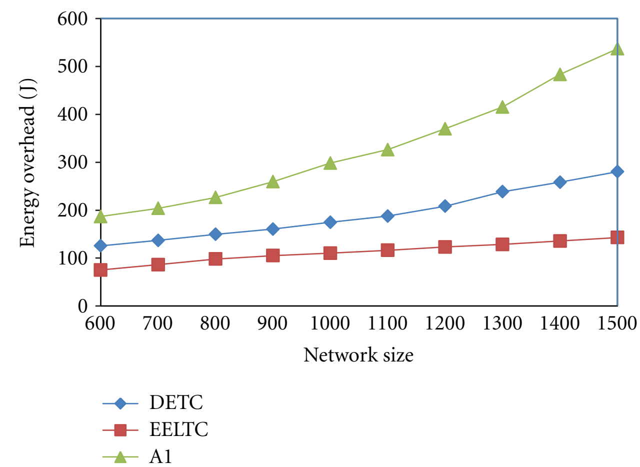

Figure 8: Energy overhead comparison.

the improvement in the average remaining energy of DETC is larger than that of EELTC and A1. This proves that the scheme effectively improves network lifetime. Because the scheme balances the energy consumption of each node in the M2M network, its maximum remaining energy after the end of the system lifetime is low (Figure 7). Balanced power consumption in each node and increased network lifetime are two main benefits of DETC when applying topology maintenance to a topology control. Therefore, topology maintenance is the most important phase in topology control design. However, the topology maintenance phase may require repeated topology reconstruction, which increases energy overhead. Energy overhead is defined as the fraction of the network energy expended on topology construction [23]. In the case of topology maintenance, this metric calculates the overhead during topology reconstruction under appropriate conditions. Figure 8 shows the changes in energy overhead observed in different network sizes. The proposed algorithm obtains a higher energy overhead compared to EELTC because the EELTC is a centralized algorithm and only one topology is constructed. The DETC includes the topology maintenance algorithm, which repeatedly performs topology reconstruction until the end of the system lifetime. The energy overhead of A1 is higher than that of DETC since the topology maintenance process of A1 is triggered when the network energy falls by 10%. Energy overhead increases when the sensors reconstruct a new topology. The proposed distributed algorithm executes the topology construction phase in only one part of the overall network. Therefore, it significantly reduces energy overhead.

5. Conclusions

The M2M network is expected to be among the fastest growing networks in the next several years, and numerous applications are rapidly accumulating. Generally, the wireless sensors are the primary drivers of M2M networks. Therefore, the M2M network needs various sensors to meet the application requirements. This study presented a distributed energy-efficient topology control algorithm for an M2M network. The topology control contains two phases, topology control, and topology maintenance. Unlike conventional algorithms, the control does not focus on topology construction. Once the topology constructed, each node executes a topology maintenance algorithm in place to monitor the status of the neighbor and to trigger a topology construction phase that can rapidly respond as needed. The nodes near the sink node forward traffic between the sink, which causes an energy imbalance. The topology maintenance also avoids the hot spot problem by controlling energy consumption and by rapidly responding when nodes appear/disappear. The topology construction phase builds a topology by identifying the parent node with which it directly communicates. Each node can adjust the transmission power level and choose the parent node based on a fair energy consumption rule, which ensures an energy-efficient topology. The proposed scheme uses a distributed algorithm that enables nodes to create and maintain energy-efficient links autonomously and to achieve the objective of prolonged lifetime with reduced energy overhead. Simulation results confirm that the proposed DETC algorithm extends network lifetime, efficiently allocates energy consumption and reduces energy overhead.

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