Performance Analysis of WSN Clustering Algorithms using Discrete Power Control

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Abstract—*Research efforts in the area of Wireless Sensor Networks (WSNs) are heavily dependent on the development and evaluations of protocols through simulations. Therefore, realistic simulations are vital for the development of viable protocols. However, most of the research efforts that depend on simulations tend to use non-realistic parameters and assumptions. Such examples include use of infinite transmit power levels and no consideration of radio propagation loss and irregularities. These assumptions are common among many clustering protocols, which lead to incorrect estimation of performance metrics such as network lifetime, energy consumed per bit, and connectivity. In this paper we modify clustering protocols by incorporating a model compliant with Crossbow MICAz motes. The energy consumption model takes into account the discrete transmit power levels of the CC2420 radio ship used by MICAz sensor nodes. The radio propagation path loss is modeled by using the Lognormal Shadowing Model. We evaluate a number of clustering protocols including LEACH, HEED, EECS and MOECS. We also present results that demonstrate how realistic assumptions can effect the system behavior in comparison with the results obtained by assuming ideal conditions.*

Index Terms—*Wireless Sensor Networks, Clustering, Discrete power, Energy conservation*

1. Introduction

WIRELESS sensor network (WSNs) have emerged as the-state-of-the-art technology in data gathering from remote locations by interacting with physical phenomena and relying on collaborative efforts by a large number of low cost resource constrained devices [1]. Each sensor node has an embedded processor, a wireless transceiver for communication, a non replenish-able source of energy, and one or more onboard sensors such as temperature, humidity, motion, speed, photo, and piezoelectric detectors [2]. Once deployed, sensor nodes collect the information of interest from their on board sensors, perform local processing of these data including quantization and compression, and forward the data to a base station (BS) either directly or through a neighboring node.

Manuscript received July 10, 2008, accepted January 2009.
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In recent years, clustering has emerged as a popular approach for organizing the network into a connected hierarchy [3]. By using clustering, nodes are organized into small disjoint groups called clusters. Each cluster has a coordinator, referred to as a Cluster Head (CH), and a number of member nodes. Clustering results in a hierarchical network in which the CHs form the upper level and member nodes form the lower level. In contrast to flat architectures, clustering provides distinct advantages with respect to energy conservation by facilitating localized control and reducing the volume of inter-node communication. Moreover, the coordination provided by the CH allows sensor nodes to sleep for an extended period thus allowing significant energy savings. By adapting to a clustered topology, WSNs can share many advantages that result in a direct or indirect impact on the energy efficiency. Some of the advantages as the result of using clustering include network scalability, local route set up, bandwidth management, minimizing communication overheads and data aggregation. As a result of the advantages offered by clustered topology, a number of clustering protocols [4-12] were developed for WSNs. However, most of these protocols contained simplistic assumptions that are far from reality. For example, the energy model originally proposed by LEACH or its slight variation is used. Moreover, assumption like infinite transmit power levels and no consideration of path loss further biases the performance results in an optimistic manner.

This paper makes three contributions which are summarized as follows. Firstly, we take into account the fact that sensor nodes are limited to a few discrete power levels. As an example, Crossbow MICAz [13] motes that use Chipcon CC2240 radio chip. CC2240 chip is limited to only seven transmit power levels. Secondly, a Lognormal Shadowing model is used for calculating radio propagation path loss. Earlier studies [14] have shown that this model to be more accurate for cellular system, making it a favorable and realistic option as compared to the free space model. Thirdly, we propose a simple scheme that allows sensor nodes to adapt to correct output power level based on distance from the transmitter and path loss.

The remainder of this paper is organized as follows. In Section 2, we describe the network model and assumptions. Section 3 summarizes the radio propagation path loss model and Section 4 presents the discrete power control algorithm. In Section 5, we present simulation results that apply both conventional and discrete power model to clustering protocols including MOECS [11] EECS [8] LEACH [4] and HEED. [7]. Section 6 presents a summary of related work. Finally, conclusions and future work is discussed in Section 7.

2. NETWORK MODEL AND ASSUMPTIONS

The following assumptions are made for the sensor network under consideration:

1. Nodes are dispersed randomly following a Uniform distribution in a 2-dimensional space.
2. The location of the BS is known to all sensors. The BS is considered a powerful node having enhanced communication and computation capabilities with no energy constraints.
3. All nodes remain stationary after deployment. All nodes are homogeneous in terms of energy, communication and processing capabilities.
4. Nodes are location unaware i.e. they are not equipped with any global positioning system (GPS) device.
5. The nodes are capable of transmitting at variable power levels depending on the distance to the receiver as in [15]. For instance, MICAz Motes use the MSP430 [16] [17] series micro controller which can be programmed to 7 different power levels.
6. The nodes can estimate the approximate distance by the received signal strength, given that the transmit power level is known, and the communication between nodes is not subject to multi-path fading.
7. A network operation model similar to that of [4, 7, 8] is adopted here, which consists of rounds. Each round consists of a clustering phase followed by a data collection phase.

3. RADIO MODEL

This section presents the radio propagation model adopted in simulations. Equation (1) provides a generalized expression for the strength of a signal at the receiver considering the path loss and fading effects.

$$P_{Rx} = P_{Tx} - PL - Fading \quad (1)$$

Where P_{Rx} is received power in dBm, P_{Tx} is the power at the transmitter in dBm and PL is the path loss. For path loss calculations we use a Log-Normal Shadowing model to provide the value of signal loss $L(d)$ between a transmitting node and the receiving node located at a distance 'd' from each other. The value of $L(d)$ is given by;

$$L(d) = L(d_o) + 10\beta \log\left(\frac{d}{d_o}\right) \quad (2)$$

Where β is the path loss exponent and $L(d_o)$ is the path loss measured at distance d_o. These parameters can experimentally determined or taken from sources such as [14]. The fading effect, as mentioned in equation (1) can be modeled by adding a Gaussian random variable X_σ (with standard deviation σ^2) in equation (2). Hence the received power is given by;

$$P_{Rx} = P_{Tx} - L(d_o) - 10\beta \log\left(\frac{d}{d_o}\right) - X_\sigma \quad (3)$$

Figure 1 presents the typical values of path loss at a receiver plotted against distance from the transmitter.

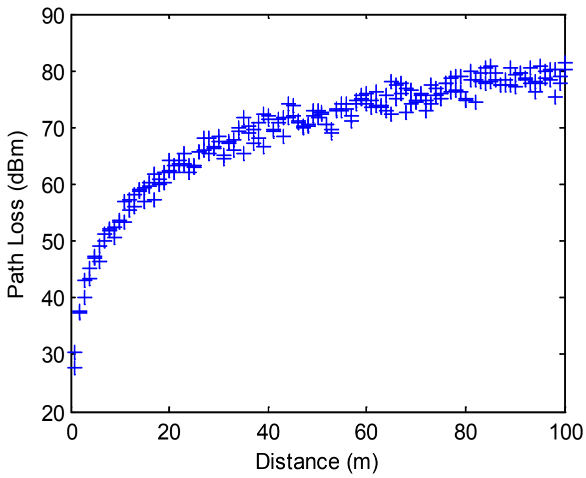

Figure 1: Path Loss Vs. Distance(d_o =87 m , β = 2.5)

4. DISCRETE POWER LEVEL SELECTION ALGORITHM

Most of the clustering protocols described assume that sensor nodes can adjust their power according to the exact distance. Hence the corresponding energy consumption computed in this manner will always be different for two different measurements of '*d*'. In reality, the transmit power level of the sensor node can only be adjusted to discrete values which may result in one power level for multiple values of distance. Therefore the resulting energy consumption for the two different distance would be same. Table 1 provides energy consumed in transmission of a 100 byte packet considering the different power levels used by CC2420. The values of current drawn I_x (3rd column) are taken from the data sheet [16]. It is also worthwhile to note that receiving a packet draws a fixed amount of current, hence the energy consumed remains constant for a given packet size. Table 2 provides the value for energy consumed in receiving a packet of 100 bytes.

Table 1: Energy consumed per packet for different power levels used in CC2420 . (Packet size = 100 bytes, channel rate 250 Kbps, V_{DD}= 1.5 V)

Power Level (k)	P_{Out} [dBm]	I_x [mA]	P_{Tx} [mW]	E_{Tx} /packet [μJ]
1	0.00	17.04	30.67	98.14
2	-1.00	15.78	28.40	90.88
3	-3.00	14.63	26.33	84.26
4	-5.00	12.27	22.08	70.66
5	-10.00	10.91	19.62	62.78
6	-15.00	9.71	17.47	55.90
7	-25.00	8.42	15.15	48.48

Table 2: Energy consumed in reception (Packet size = 100 bytes, channel rate 250 Kbps, V_{DD}= 1.5 V)

I_x [mA]	P_{Rx} [mW]	E_{Rx} /packet [μJ]	E_{Rx} /bit [μJ]
19.60	35.28	112.90	0.1411

In the operational model used for most clustering protocols the advertisement messages from CHs are sent at the fixed (known) power levels. The cluster membership phase involves sensor nodes to adjust their power levels according to their distance from the CH. We propose an algorithm that allows sensor nodes to select the appropriate power level for communicating to the CH. Figure 2 presents the flowchart for power level selection algorithm. It can be noted from Table 1 that power level 7 corresponds to the lowest and power level 0 corresponds to the highest power output.

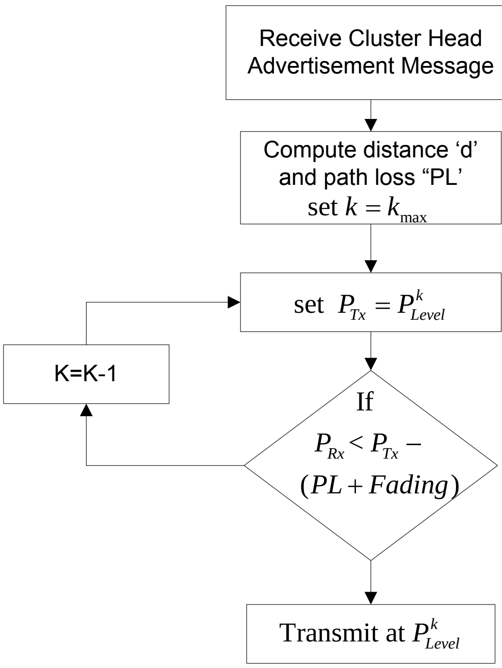

Figure 2: Flow Chart for Discrete Power Level Selection Algorithm

Once sensor nodes have estimated the distance to the CH, it computes path loss and fading. It then sets its transmit power level to the lowest value. Based on the computed path loss and fading it calculates the projected received power at the CH. If the projected received power is greater than the receiver sensitivity, the current power level is used for transmission, otherwise the transmit power level is incremented and same procedure is repeated until the appropriate level is found or highest power level is reached.

Figure 3 presents a comparison of energy consumed in transmission using the discrete power level model and conventional (LEACH) energy model. Measurement for both models is obtained using a packet size of 100 bytes. The discrete power model assumes path loss exponent equal to 2.5 and d_0 equal to 87 m. It can be observed that the discrete power model render more energy consumption at 75 m. It is worth noting the conventional model results in a false optimistic performance. Moreover, a typical round data transmission rounds consists of a large number of transmission from sensor node to the sink and an aggregated packet (single transmission) from the cluster head to the sink. In the conventional LEACH model, the former follows the energy consumption is proportional to the square of distance and in the latter the energy consumption is proportional to forth power of distance [4]. Results presented later in Section 5 demonstrate that the conventional model results are significantly deviated from the discrete power model.

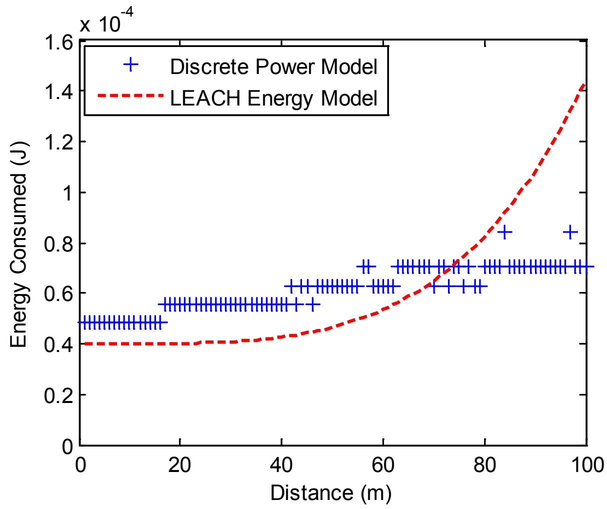

Figure 3: Comparison of Energy Consumed in Transmission with Conventional LEACH Energy Model and Discrete Power Model (Packet Size =100 bytes)

5. SIMULATION RESULTS

This section presents the performance analysis of clustering protocols namely LEACH, HEED, EECS and MOECS. We used MATLAB as the simulation environment. As outlined in Section 2 we used network of 100 nodes placed in an area of 100 x 100 m. The BS location is taken as (50,150) m. All clustering protocols are evaluated with and without (conventional) the discrete power selection scheme presented in Section 3. Each simulation experiment is performed on a unique topology and consists of several rounds of cluster set up phase and data transmission phase. In each round a set of new cluster heads is elected and the non-cluster head nodes send five data packets to their associated cluster head. We also assume that the cluster head is capable of data aggregation and data received from member nodes is therefore sent in aggregated form. In performance analysis of different clustering schemes using both conventional and discrete power model remains on metrics related to network life and energy conservation. The network life time is measured in data collection rounds till the first node runs out of its energy. The network lifetime measured to the death of first node is extensively used in the literature including [4, 7, 8, 11]. Figure 4 presents a performance comparison of network life using both conventional and discrete power model for various clustering protocols mentioned earlier. It is clearly evident that the realistic discrete model results in a significant decrease (in excess of approximately 100% for all protocols) in network life as compared to the conventional model. Based on the discussion in Section 4, a large number of transmissions at higher energy consumption in the discrete model contribute to a quick depletion of sensor nodes' energy.

Figure 5 illustrates results for the random topology where y-axis indicates the mean residual energy of the system normalized to number of nodes and x-axis denotes the number of rounds. It can be observed that the mean residual energy of the system in case of discrete power model is lower than that of the conventional model for all protocols. A sharp slope in case of the discrete power model is indicative of the sensor nodes losing their energy at a much faster rate as compared to the conventional model. These results are also corroborated with the network life results presented in Figure 4.

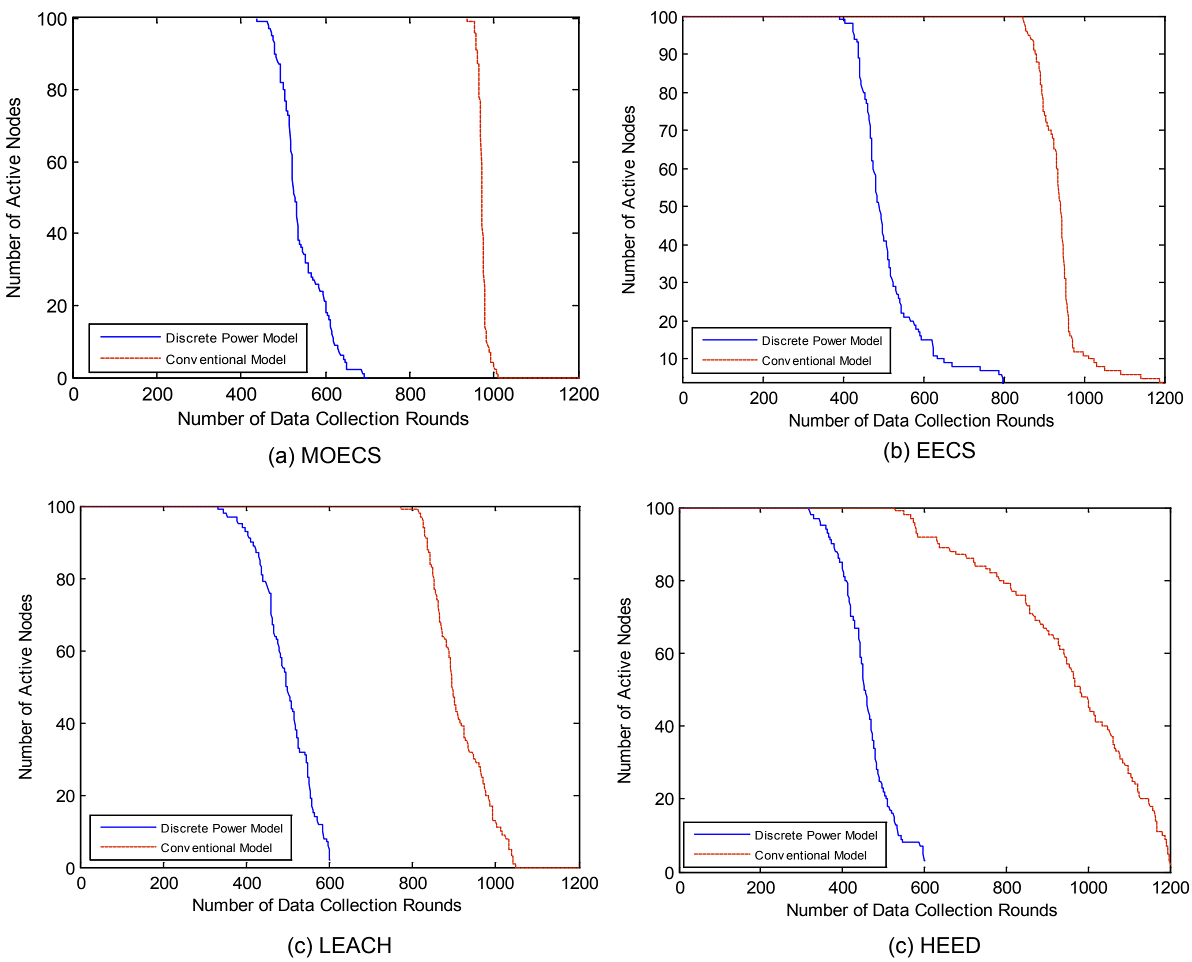

Figure 4: Network Life in Rounds for a) Multi-Objective Energy-efficient Clustering Scheme-MOECS, b) Energy Efficient Clustering Scheme-EECS, c) Low Energy Adaptive Clustering Hierarchy-LEACH, d) Hybrid Energy Efficient Distributed Clustering- HEED

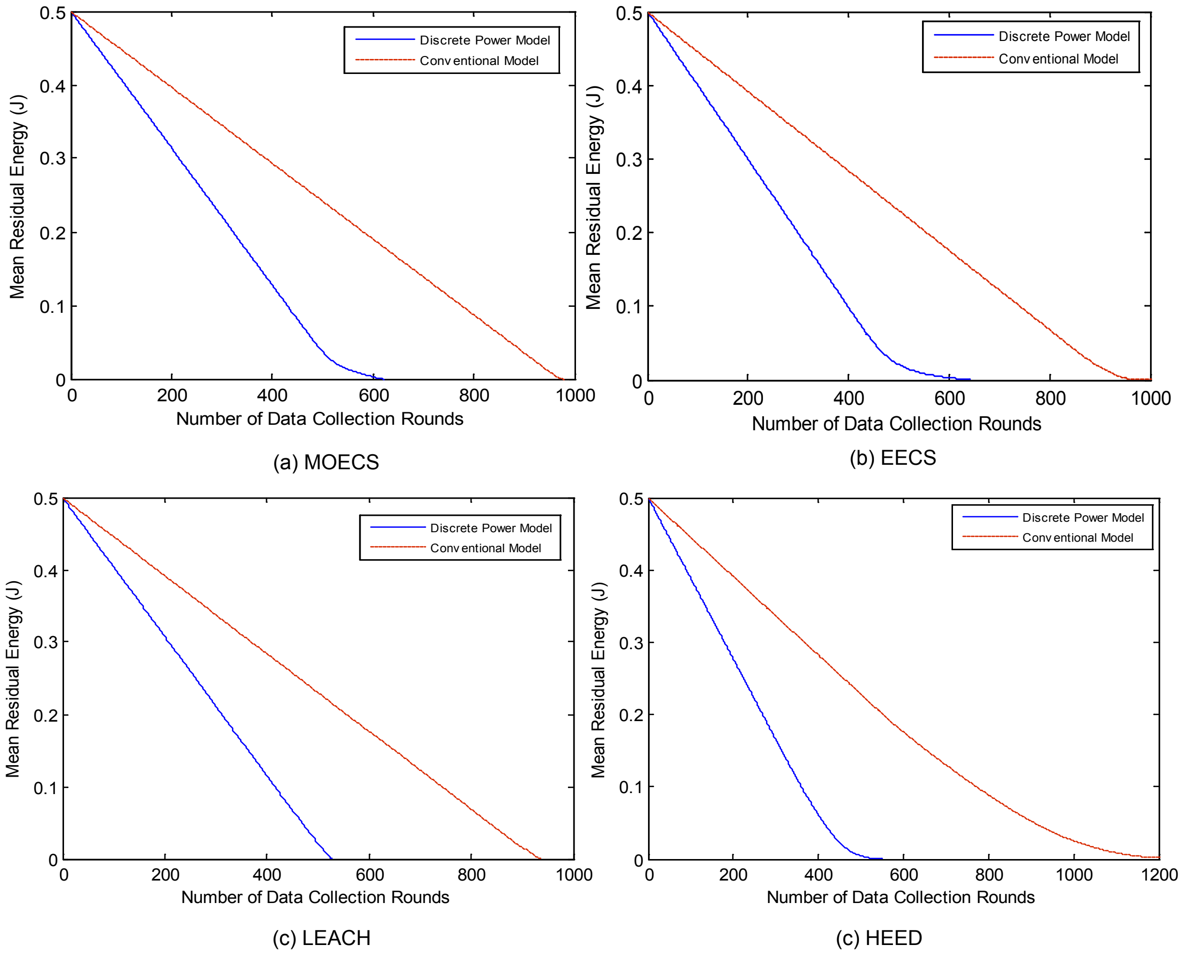

Figure 5: Mean Residual Energy Vs. Number of Rounds for a) Multi-Objective Energy-efficient Clustering Scheme-MOECS, b) Energy Efficient Clustering Scheme-EECS, c) Low Energy Adaptive Clustering Hierarchy-LEACH, d) Hybrid Energy Efficient Distributed Clustering- HEED

We also investigate the energy consumed in transmission (end-to-end, i.e. from sensor node to the BS) on per packet basis. Results in Figure 6 demonstrate the measurements for this statistics for both models. Again it is evident that the discrete power model results in excess of 100% extra energy consumption as compared to the conventional model.

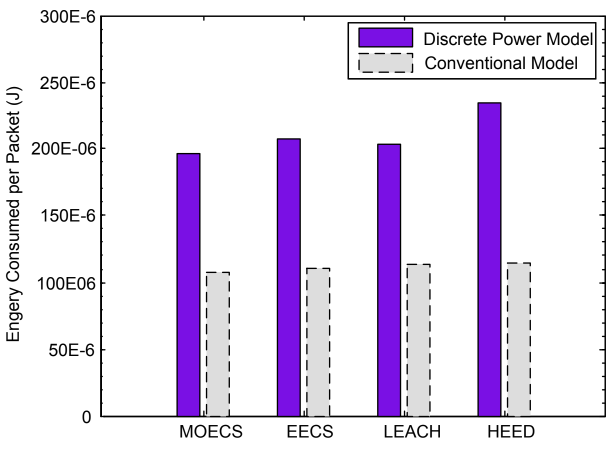

Figure 6: Mean Energy Consumed in Transmission per Packet from Sensor Node to the BS

6. RELATED WORK

Recent relevant studies have [18] [19, 20] have focused on incorporating the realistic radio and energy consumption models in WSNs. The authors in [18] presented an energy model for calculating the transmission and reception cost. This model is based on the first order model presented in [15]. Research results presented in [19] are collected from field experiments involving few sensor motes. These experiments were performed to collect link quality index (LQI) and received signal strength indication (RSSI). The investigations show that transmission power costs do not always increase as the distance increases. Our work in closely related to [19, 20] which are also focused on the CC2420 radio chip. In [20], a similar model as proposed in this paper is implemented in the PROWLER [21] simulator. Our work focuses on the clustering protocols.

7. CONCLUSIONS

In this paper we investigated the effects of incorporating realistic radio models in the simulation of cluster-based WSNs. Most sensor hardware platforms make use of discrete power levels. Therefore incorporating such models into simulations would bridge the gap between simulation and experimentation results. We proposed a simple algorithm that allows sensor nodes to choose appropriate power level based on inducted path loss and distance. We evaluated four clustering protocols using metric relevant to the energy conservation following both discrete power and conventional models. We showed that estimates of network life using discrete power model differ significantly than that of conventional model. Our future work will address effects of controlled mobility, and realistic deployment strategies.

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