Survivability Evaluation of NEMO with Multiple Mobile Routers

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***Abstract*—Mobile networks (NEMO) can be formed with IP-enabled devices in motion. Mobile Router (MR) acts as the gateway for all the nodes inside a mobile network. As the MR is the key entity in NEMO, the load on MR can be very high and can become the performance bottleneck. Increase in number of MRs can improve the reliability, as a single MR can be single point of failure. There have no survivability analysis of NEMO based on multiple MRs. In this paper, we have performed quantitative survivability analysis of NEMO with multiple MRs, taking into consideration possible node and link failures along with denial of service attacks. We have presented numerical results which reveals that increase in number of mobile routers improves the performance of the mobile network by reducing the mean delay and drop probability while withstanding attack packets.**

***Index Terms*—Network mobility, survivability evaluation, CTMC modeling, DDoS attack, Mobile Router.**

I. INTRODUCTION

Mobile networks can be formed with IP-enabled devices including laptops, PDAs, IP-cameras or networks of sensors deployed in vehicles, such as, aircrafts, buses, trains, etc. Internet Engineering Task Force (IETF) proposed NEtwork MObility Basic Support Protocol (NEMO BSP) [1] to facilitate continuous Internet connectivity of hosts moving together.

Network survivability is a crucial aspect for any kind communication. A survivable network has the ability to withstand malicious attacks and to continue to work properly even in the presence of natural or man-made disturbances. It focuses on delivery of essential services and rapid recovery of full services when situation improves [2], [3]. Mobile networks have the challenge of survivability, since the communication channels are accessible to anyone. Hence, it is essential to analyze the survivability of NEMO.

The mobile network can have one or more mobile routers that act as the gateways for all its nodes known as Mobile Network Nodes (MNN). These MRs connect the MNNs to the global Internet, forwarding signaling traffic required for mobility management as well as data traffic to the desired Internet hosts. Thus, the load on MR can be very high In addition, the MR sends signaling messages to the Home Agent whenever the mobile network changes its point of attachment. Therefore, the MR can become the performance bottleneck or single point of failure for the mobile network. Hence, increase of number of MRs can improve the performance and enhance reliability of the network.

Earlier attempts ([3]–[8]) focused on the redundancy and load balancing of the mobility agents (e.g., home agent) to improve the survivability of mobility protocol. These works do not focus on the survivability of mobile router. However, Kuntz et al. [9] propose that the cooperation of multiple mobile routers in NEMO can improve the bandwidth, network coverage, reliability and dynamic load sharing among MRs. Their solution is based on Neighbor Discovery and is validated by a real testbed.

There have been a few works on network survivability evaluation. Chen et al. [2] used a Continuous Time Markov Chain (CTMC) model to evaluate the end-to-end availability of wireless ad hoc networks. Heegaard et al. [10] developed an analytical model to assess the survivability of a network with virtual connections exposed to link or node failures; the model has been validated by simulations. Fu et al. [11] carried out the survivability analysis of SIGMA and Mobile IP which are based on multiple location managers for mobility management. However, the authors are not aware of any survivability evaluation of NEMO that considers various failure types and denial of service attacks which can drastically degrade the performance of mobile network. Our work *differs* from previous work in this respect and we believe this to be *first such work*.

The *objective* of this work is to perform quantitative survivability evaluation of NEMO with multiple MRs, taking into consideration different failure types and malicious attack traffic. We have used CTMC modeling in our analysis.

The *contributions* of the work are: (i) developing a survivability model for NEMO to compute packet drop probability and mean packet delay and (ii) presenting numerical results showing performance and delay metrics while under attacks or failures. Our results reveals interesting relationship among network performance, failure rates and attack strengths that can be used by network engineers to evaluate survivability and robustness of their networks.

The rest of the paper is organized as follows. In Section II, a brief description of NEMO is given. The survivability model is presented in Section III. Section IV presents the numerical results, followed by concluding remarks in Section V.

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II. NEMO ARCHITECTURE

Fig. 1 shows the architecture of a Mobile Network (MN) [1]. There can be different types of MNNs: Local Fixed Nodes (LFN) that do not move with respect to MN, Local Mobile Nodes (LMN) that usually reside in MN and can move to other networks, and Visiting Mobile Nodes (VMN) that get attached to the MN from another network. LMNs and VMNs are MIPv6 capable, and we refer them as *mobile nodes*. The MR attaches to the Internet through Access Routers (ARs). An MN is usually connected to a network called the home network where an MR is registered with a router called the Home Agent (HA). The HA is notified the location of the MR, and re-directs packets, sent by the Correspondent Node (CN) to MNNs.

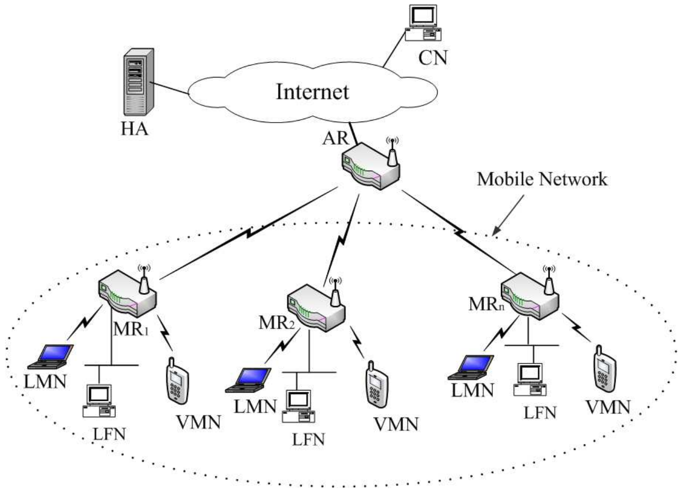

Fig. 1. NEMO with multiple mobile routers.

III. SURVIVABILITY ANALYSIS

The survivability evaluation of NEMO with multiple MRs aims at availability and load-sharing among the routers.

A. Assumptions

For tractability purpose, the following assumptions have been made:

- Total packet arrival to NEMO is assumed to be λ which includes data packets, signaling packets and Distributed Denial of Service (DDoS) attack packets. Arrival of all such packets are Poisson processes.
- Processing time for data, signaling and DDoS packets are exponentially distributed, having same mean value (μ) to control the complexity of the CTMC model.
- The MRs act in such a way that load is shared among them similar to the approach specified in [9].
- Only one MR may fail at a time with highest load.
- The failure of one MR does not halt the whole MN.
- Packets in the buffer of a failed MR are assumed to have been dropped. If there are R routers and B packets in the system, then the failed router will have $L_1 = \lceil \frac{B}{R} \rceil$ packets in its buffer that will be lost.
- Link failure can happen for any router in the MN. If there are R routers and B packets in the system, the link failure will only reduce the number of packets of the system by $L_2 = \lfloor \frac{B}{R} \rfloor$ and those L_2 packets are considered to have remained in the router buffer and will add to the total count when this link is up again at a recovery rate of δ_2.

B. Notations

The notations used in this paper are listed as follows:

N_r	Total number of MRs in the mobile network,
R_i	Number of available MRs in state i,
B_i	Number of packets in state i,
S	Queue size (in number of packets) of each MR,
λ_d	Arrival rate of data packets,
λ_s	Arrival rate of signaling packets,
λ_a	Arrival rate of DDoS attack packets,
λ	Total arrival rate, i.e., $\lambda = \lambda_d + \lambda_s + \lambda_a$,
μ	Processing rate,
γ_1	Node failure rate,
γ_2	Link failure rate,
δ_1	Repair rate from node failure,
δ_2	Repair rate from link failure,
ψ_1	Irreversible node failure rate (i.e., when node failure cannot be repaired),
ψ_2	Irreversible link failure rate (i.e., when a link failure cannot be repaired),
β	Rate of introducing a error-free MR to the system,

C. Survivability Model with multiple MRs

We use a CTMC model for the survivability analysis of NEMO with multiple MRs. There are N_r MRs in the MN each of which has a buffer of size S. Errors can happen in two ways: node failure or link failure. Node failure can happen due to hardware failure of the MR or battery power failure. Link failure can happen when a MR loses connection with the access router of the home / foreign network.

Fig. 2 shows the state transition diagram of the CTMC model. Each state is labeled as (I, J, K) where I represents number of active (or available) routers in the mobile network, J represents total number of packets in the system, and K represents type of failure where $I \in \{0, 1, 2, .., N_r\}$, $J \in \{0, 1, 2, .., SN_r\}$, and $K \in \{0, 1, 2\}$ (0 for no failure, 1 for node failure, 2 for link failure). The states with $K = 1$, and $K = 2$ are intermediate states and these (node and link) failures may or may be resolved, thereby leading to the states with $K = 0$ (i.e., no error states). In the case of recovery (involving transition rates of δ_1 or δ_2), the next state will have the same number of MRs. whereas no recovery scenarios (involving transition rates of ψ_1 or ψ_2) lead to a state having one less MR than the current state.

Fig. 2 shows the transition diagram using a representative state $(R, B, 0)$ which means there are R active MRs with a total of B packets in the system in a ”no failure” state. The possible states that can be reached from this state are:

- Arrival of packets: This event will lead to the state $(R, B + 1, 0)$ with a transition rate of λ/R.

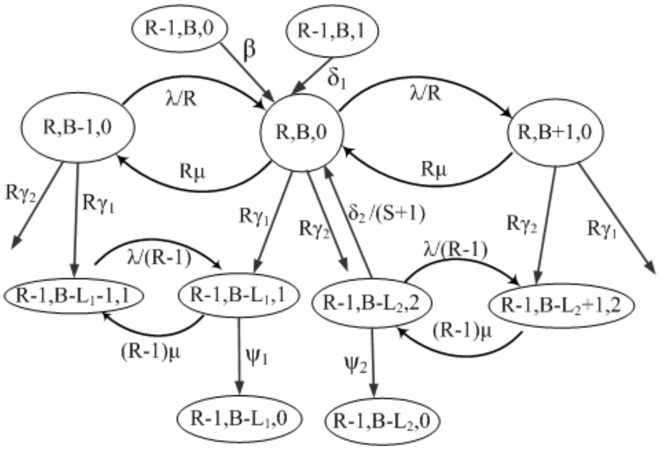

Fig. 2. State transition diagram for NEMO with multiple MRs.

- Departure of a packet: This will lead to the state $(R, B-1, 0)$ with a transition rate of $R\mu$.
- Node failure: This event happens for the MR with heaviest load (with $L_1 = \lceil \frac{B}{R} \rceil$ packets) which will be lost due to the failure. This leads to the state $(R-1, B-L_1, 1)$ with a rate of $R\gamma_1$.
- Link failure: This can happen for any of the active MRs having $L_2 = \lfloor \frac{B}{X} \rfloor$ packets in its queue. The event leads to the state $(R-1, B-L_2, 2)$ with a rate of $R\gamma_2$.

The following events from the following states can lead to the state $(R, B, 0)$:

- Departure of a packet from the state $(R, B+1, 0)$.
- Arrival of a packet from the state $(R, B-1, 0)$.
- Recovery of node failure from the state $(R-1, B, 1)$.
- Recovery of link failure from the state $(R-1, B-L_2, 2)$.
- From the state $(R-1, B, 0)$ and due to the introduction an error-free MR.

When $R_i < N_r$, number of states with R_i MRs is $3(R_iS+1)$, whereas for $R_i = N_r$, it is (SN_r+1). Thus, the number of states with R_i MRs can be expressed as follows:

$$f_s(R_i) = \begin{cases} 3(R_iS+1), & \text{when} \quad R_i < N_r \\ SR_i + 1, & \text{when} \quad R_i = N_r \end{cases} \tag{1}$$

Therefore, the size, n, of the generator matrix, Q, can be obtained as follows:

$$\begin{aligned} n &= |K| \sum_{i=0}^{N_r-1} (iS+1) + (SN_r+1) \\ &= 3\Big(S \sum_{i=0}^{N_r-1} i + \sum_{i=0}^{N_r-1} 1\Big) + (SN_r+1) \\ &= \frac{SN_r}{2}(3N_r-1) + (3N_r+1) \end{aligned} \tag{2}$$

We number the states $(0,0,0)$, $(0,0,1)$, and $(0,0,2)$ as states 1, 2 and 3, respectively. Then states $(1,0,0)$, $(1,0,1)$, $(1,0,2)$, etc. are numbered as states 4, 5, 6, and so on.

For the CTMC shown in Fig. 2, we can determine each element of the generator matrix $Q = [q_{i,j}]$ $(0 \le i, j \le n)$ as follows:

$$q_{i,j} = \begin{cases} \lambda/R_i, \quad j = i+3, B_i \le SR_i \quad \text{(arrival)} \\ R_i\mu, \quad j = i-3, B_i \ge 1 \quad \text{(departure)} \\ R_i\gamma_1,\ j = i - f_s(R_i-1) - (3\lceil \frac{B_i}{R_i} \rceil - 1) \text{ (node failure)} \\ R_i\gamma_2,\ j = i - f_s(R_i-1) - (3\lfloor \frac{B_i}{R_i} \rfloor - 1) \text{ (link failure)} \\ \delta_1, \quad j = i + f_s(R_i) - 1 \qquad \text{(node repair)} \\ \delta_2/(S+1), \quad j = i + f_s(R_i) - 2 + 3X \quad \text{(link repair)} \\ \beta, \quad j = i + f_s(R_i) \quad \text{(new MR introduction)} \\ 0, \quad \text{other } j \ne i \\ -\sum_{k=1}^{n} q_{i,k}, \quad j = i, k \ne i \end{cases}$$

Let us explain each of the transition rates of $q_{i,j}$ in details.

- Arrival: The arrival of packets in any state increases the number of packets in the system by 1 as long as there is buffer space available, i.e., $B_i \le SR_i$.
- Departure: The transmission rate of the system is proportional to number of available MRs at any time.
- Node failure: The node failure happens for the MR with highest load, and $R_i > 0$. This will cause the packets in the failed MR to be lost.
- Link failure: The link failure can happen for any link involving an active MR and the AR when $R_i > 0$.
- Node repair: This increases number of available MR by 1 with no addition in the number of packets.
- Link repair: The link repair can bring a MR into the system with X number of packets, where $X \in \{0, 1, .., S\}$.
- Introduction of new MR: This increments the number of active MRs by 1 without increasing the number of packets in the system.

Once the infinitesimal generator matrix Q have been determined, the steady state probability distribution (π) of the CTMC can be obtained as follows:

$$\pi Q = \mathbf{0} \tag{3}$$

When a packet arrives, if the system is in state $(0, 0, K)$ or state (R_i, SR_i, K), the packet is dropped due to lack of buffer space in the system. Therefore, the dropping probability can be calculated by:

$$\begin{aligned} P_d &= \pi D^T \\ \text{where } D &= [D_0, D_1, \cdots D_j \cdots D_{N_r}], \\ \text{and } D_j &= [0, \cdots 0, 1, 1, 1]_{3(jS+1)}, j = 0, \cdots, N_r - 1 \\ \text{and } D_{N_r} &= [0, \cdots 0, 1]_{SN_r+1}, \end{aligned} \tag{4}$$

The average number of packets $(E(m))$ in the whole system can be determined as follows:

$$\begin{aligned} E[m] &= \pi v^T \\ \text{where } v &= [v_0, v_1, \cdots v_j \cdots v_{N_r}], \\ \text{and } v_j &= [0, 0, 0, 1, 0, 0, \cdots, Sj+1, 0, 0], j = 0, \cdots, N_r - 1 \\ \text{and } v_{N_r} &= [0, 1, 2, \cdots, SN_r] \end{aligned} \tag{5}$$

Hence, we can obtain the average packet delay using Little's law as follows:

$$E[T] = \frac{E[m]}{\lambda_{accepted}} = \frac{E[m]}{\lambda(1 - P_d)} \tag{6}$$

D. Survivability Model with one MR

The transition diagram for NEMO with single MR is shown in Fig. 3 which is a simplified version of Fig. 2. Here, the total number of states is $S + 4$.

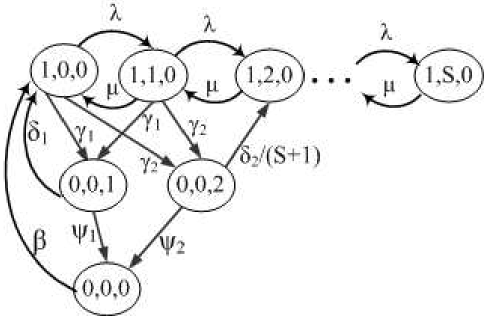

Fig. 3. State transition diagram for NEMO with one MR.

We number the states $(1, 0, 0)$, $(1, 1, 0)$, $(1, 2, 0)$, .. ,$(1, S, 0)$ as states $1, 2, 3, .., (S + 1)$. The states $(0, 0, 1)$, $(0, 0, 2)$, and $(0, 0, 0)$ are numbered as $(S + 2)$ through $(S + 4)$. The generator matrix Q can be expressed as follows:

$$q_{i,j} = \begin{cases} \lambda, \quad j = i + 1, B_i \le S, R_i = 1 \quad \text{(arrival)} \\ \mu, \quad j = i - 1, B_i \ge 1, R_i = 1 \quad \text{(departure)} \\ \gamma_1, \; i \le S + 1, j = S + 2 \; \text{(node failure)} \\ \gamma_2, \; i \le S + 1, j = S + 3 \; \text{(link failure)} \\ \delta_1, \quad i = S + 2, j = 1 \qquad \text{(node repair)} \\ \delta_2/(S + 1), \quad i = S + 3, j \le S + 1 \quad \text{(link repair)} \\ \beta, \quad i = S + 2, j = 1 \quad \text{(new MR introduction)} \\ 0, \quad \text{other } j \ne i \\ -\sum_{k=1}^{n} q_{i,k}, \quad j = i, k \ne i \end{cases}$$

Steps similar to Eqns. (3)-(6) can be followed to compute the steady state probabilities, packet dropping probabilities, average number of packets in the system and the average packet delay.

IV. NUMERICAL RESULTS

In this section, we evaluate the survivability of NEMO using the analytical model developed in Secs. III-C and III-D. The values of the system parameters are listed in Table I which are similar to [2]. We explain the logic behind setting these values to the parameters. The data packet arrival rate is kept 100 packets/sec and the signaling traffic rate is used as one-tenth of data traffic. Node failures happen one in every 500 sec whereas link failures happen twice in every 500 sec. Link recovery requires twice the node recovery time as it might be difficult to detect in the first place. Some failure may be fatal or irreversible with very small rates.

TABLE I
VALUES OF SYSTEM PARAMETERS USED IN NUMERICAL ANALYSIS.

Parameter	**Meaning**	**Value**
λ_d	Data packet arrival rate	100 per sec
λ_s	Signaling packet arrival rate	10 per sec
μ	packet transmission rate	300 per sec
γ_1	Node failure rate	0.002 per sec
γ_2	Link failure rate	0.004 per sec
$1/\delta_1$	Node repair time	10 sec
$1/\delta_2$	Link repair time	20 sec
ψ_1	Irreversible node failure rate	0.00001 per sec
ψ_2	Irreversible link failure rate	0.00002 per sec
β	Rate of introducing an error-free MR	0.001 per sec
S	Queue size	15 packets

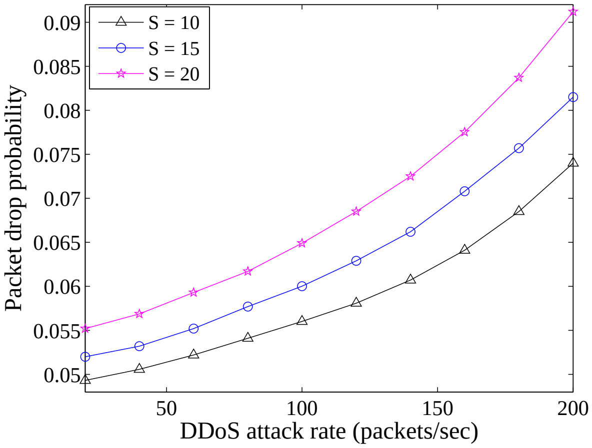

Fig. 4. Effect of DDoS attack strength on the packet drop probabilities for different queue size.

Fig. 4 shows the impact of DDoS attack strength on the packet drop probability at MR for different queue size. We have used N_r = 3 for this graph. It is found that with increasing DDoS attack strength, the packet drop probability increases dramatically compared to its normal values as there is no way to distinguish between legitimate data (or signaling) packets with the DDoS attack packets. In addition, more packets are dropped for smaller queue size as the buffer slots are filled up quickly by the attack packets.

Fig. 5 shows the impact of number of MRs and failure rates on the mean packet delay. It is found that increase in number of MRs reduces the mean delay since long queues are not encountered in a MR; rather packets are distributed among the MRs and get served faster. Moreover, mean delay is higher for higher failure rates due to more packets queued in the active MRs, thereby increasing the delay.

Fig. 6 shows the impact of mean time to recover (MTTR) on average packet drop probability for different data packet arrival rates. In this case, we have assumed the failure recovery time for node and link failures are equal. It is found that higher MTTR causes more packets to be dropped due to the lack of sufficient number of active MRs. In addition, higher data

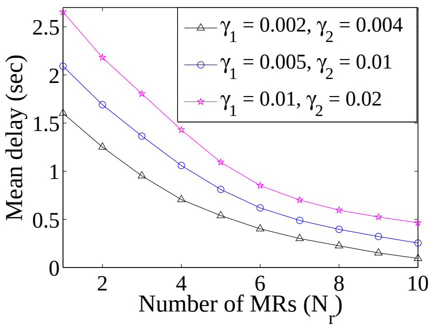

Fig. 5. Impact of number of MRs on the packet delay for different failure rates.

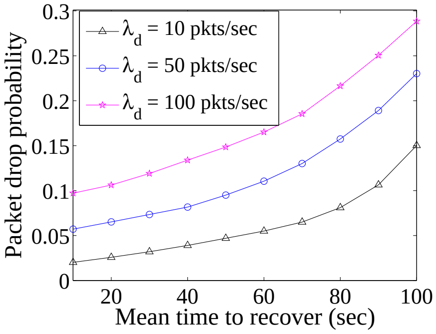

Fig. 6. Impact of MTTR on the packet drop probability for different data packet arrival rates.

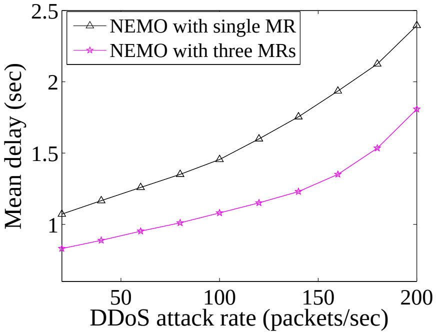

Fig. 7. Impact of DDoS attack rate on mean packet delay.

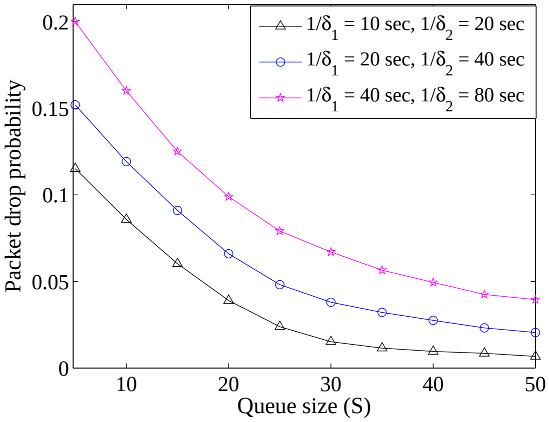

Fig. 8. Effect of queue size on the packet drop probabilities for different mean recovery times.

traffic rate raises the packet drop rate as more data packets are fed into the system, causing more drops.

In Fig. 7, the impact of DDoS attack strength is shown on the mean packet delay for two NEMO scenarios. We have used S = 10 for this graph. Mean delay increases for higher values of λ_a, as more attack traffic causes queues to be filled up with these traffic, raising the delay for all the packets. Moreover, the delay is higher for single MR case, as this means smaller queue size and less processing speed for the incoming packets in the system.

Fig. 8 shows the impact of queue size on the packet drop probability at MR for different recovery times. Higher queue can accommodate more packets, thereby reducing the drop rate. On the other hand, lower recovery time causes nodes or links to be up again, resulting in better performance, i.e., lower drop probability.

V. CONCLUSION

In this paper, we have developed an analytical model for quantitative survivability evaluation of NEMO with multiple mobile routers taking into consideration possible natural or man-made failures as well as DDoS attacks. We have also presented numerical results to validate our model. Our results show that increase in the number of mobile routers improves the performance of the mobile network by reducing the mean delay and drop probability while withstanding attack packets. Our survivability model can be used to perform quantitative survivability evaluation of other host or network-based mobility protocols.

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