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Reliable Relay: Autonomous Social D2D Paradigm for 5G LoS Communications

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***Abstract*—Next generation 5G wireless networks contemplate to exploit millimeter Wave (mmWave) for a massive increase in data rates but its inherent characteristic of Line-of-Sight (LoS) brings up the challenge of directional synchronization of transmitters and receivers. In this letter, we propose a fusion of Social Internet-of-Things (SIoT) and Device-to-Device (D2D) communications, shaping Social D2D (S-D2D) to tackle mmWave LoS challenge using an independent "Reliable Relay" scheme. We introduce distributed social network of devices and propose two algorithms for social-communication graph formation and autonomous trustworthy relay procedure. Utilizing Reliable Relay, a Non-LoS (N-LoS) device can communicate to 5G networks without compromising the contents privacy. Our analytical model demonstrates that agile Reliable Relay substantially improves the capacity gain and data rate and can be an integral part of existing relay selection schemes. NS3 based simulations validate the proliferation in throughput with minimum additional delays.**

***Index Terms*—Trustworthy Relay, SIoT, D2D, 5G, S-D2D**

I. Introduction

THE directional communication of $5G$ wireless offers massive $1 \sim 10$ Gbps data rates and foresees a roughly $10\times$ increase from $4G$, with extraordinary ~ 100 Mbps edge rate [1]. Not only the high data rates are expected from next-generation 5G wireless networks but also better Quality of Experience (QoE) and 99.999% availability is anticipated. The millimeter Wave (mmWave) spectrum in $3 \sim 300$ GHz bands offer massive data rates and wide bandwidth but it is bounded by the characteristics like limited propagation and penetration which can lead to high outage probability. However, the Non-Line-of-Sight (NLoS) communication do exist for mmWave signal propagation but it is more sensitive to blockages and exhibits low diffraction. Recent studies and experiments show that a mmWave signal drops pathloss value to 40 dB/decade with additional loss of $15 \sim 40$ dB for blockage, whereas under LoS the value is only 20 dB/decade [2].

On the other hand, the Device-to-Device (D2D) communications not only can help avoid coverage holes of 5G using relay based communication but also support expected device-centric architecture [3]. Recent research highly suggest to utilize D2D communication for increase in 5G coverage and user capacity, and introduce the best relay selection schemes [3, 4]. However, such a D2D communication requires agile communication procedure and more importantly trustworthiness in the relay, which are still very under-researched topics. Considering agility, existing research suggests that the centralized relay selection and D2D communications increase control overhead and introduce additional delays, whereas the distributed scheme is an obvious preference due to agility, independence and practicality [5]. Furthermore, the trustworthiness in an independent and distributed D2D communication can be induced by using Social Internet-of-Things (SIoT).

The fundamental concept of SIoT envisions a social network of smart devices, where devices autonomously communicate and establish social relationships which lead to an independent, autonomous and trustworthy network of devices, analogous to Social Network Services (SNS) [6]. The native traits of the subjective SIoT model include autonomous communication proficiency, peer-based privacy and security management modules. The SIoT devices utilize proximity based communications and establish relationships for trust calculation. Existing relationships are Co-Location Object Relationship (CLOR), Co-Work Object Relationship (CWOR), Owner Object Relationship (OOR), Social Object Relationship (SOR) and Parental Object Relationship (POR) [6]. In this letter, we exploit SIoT relationships and introduce Social D2D (S-D2D), which is the fusion of SIoT and D2D communications for 5G networks. We propose a relay selection procedure, i.e. Reliable Relay, which perpetuates the trustworthiness in devices and immensely increases 5G networks capacity gain, data rate and throughput with negligible additional delay. Proposed scheme improve upon existing literature due to these main reasons: (1) Our major focus is to increase 5G coverage using relays and utilize SIoT as an application to solve trustworthiness challenge. (2) We consider existing relay selection schemes and propose possible co-existence using outage probability. In the next section, we model our proposed Reliable Relay scheme using graph theory and introduce graph formation and relay communication algorithms.

II. Proposed System: Reliable Relay

We propose that devices in proximity establish communication links (communication graph) and autonomously communicate to develop social relationships (social graph) which in turn shapes a social-communication graph. The communication ties with social trust culminate Reliable Relay communications, which extend 5G network coverage and capacity.

Graph Formation: Consider a system is populated by a set of N nodes, $V = \{v_1, v_2, ..., v_N\}$, where each of which is capable of capillary communications and 5G communications; however, not all the devices are in the LoS of the directional communications. The devices discover nearby devices using capillary communications and establish communication edges $\varepsilon = \{\varepsilon_1, \varepsilon_2, ..., \varepsilon_M\}$, shaping communication graph $G(V, \varepsilon)$. Subsequently, each device independently utilizes respective communication edges to communicate and establish trust. The trustworthiness of a device ($\psi_{i,j}$) is calculated using a function

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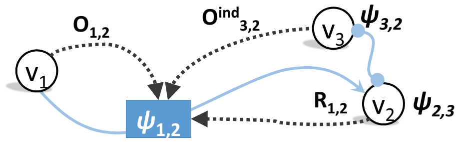

Fig. 1: Trustworthiness calculation process

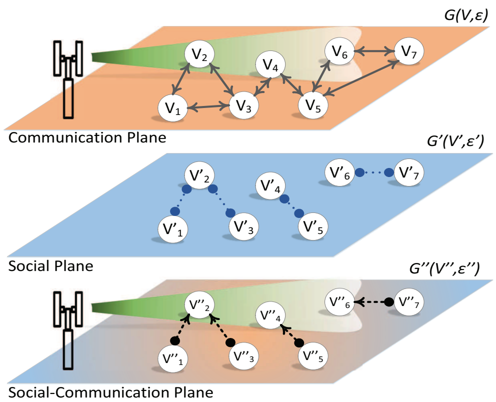

Fig. 2: Social-Communication Plane

of social relationships, centrality of the device ($R_{i,j}$), history of previous direct transactions ($O_{i,j}$) and indirect transactions of common neighbors ($O_{i,j}^{ind}$), as shown below:

$$\psi_{i,j} = (1-\theta-\phi)R_{i,j} + \theta O_{i,j} + \phi O_{i,j}^{ind} \tag{1}$$

Figure 1 further elaborates the trust calculation procedure using above mentioned weighted sum function with θ and ϕ as weights. Each device communicates with the target device and common neighbors to determine device trust and tailor social edges $\varepsilon' = \{\varepsilon'_1, \varepsilon'_2, ..., \varepsilon'_{M'}\}$. A device v_i forms a social edge with another device v_j , if the trust value ($\psi_{i,j}$) is higher than a personal threshold (ψ_τ). Autonomous edge formation leads to a social graph, $G'(V', \varepsilon')$, where the devices with social edges (ε') are denoted by $V' = \{v'_1, v'_2, ..., v'_{N'}\}$.

Reliable Relay Communication: The ultimate goal of the graph formation process is to enable a trustworthy proximity based communication, which is triggered whenever a device in outage (v_i) requires a cellular relay (v_j). A device (v_i) establishes a social-communication edge ($\varepsilon''_{i,j}$) with a relay (v_j), if and only if there exist ($\exists$) a communication and a social edge ($\varepsilon_{i,j}$ *and* $\varepsilon'_{i,j}$). Mathematically:

$$G'' = \{V'', \varepsilon''\} \mid \forall\ \varepsilon''_{i,j}\ \exists\ \varepsilon_{i,j}\ and\ \varepsilon'_{i,j} \tag{2}$$

Each device independently communicates and forms social-communication edges which result in a social-communication graph, $G''(V'', \varepsilon'')$, as illustrated in Figure 2. Algorithm 1 outlines the graph formation procedure which constructs $G(V, \varepsilon)$, $G'(V', \varepsilon')$ and $G''(V'', \varepsilon'')$, sequentially.

Each device preserves nearby device knowledge ($V,\ V'\ or\ V''$) and edge information ($\varepsilon,\ \varepsilon'\ or\ \varepsilon''$), which can be a substantial asset for relay services. Considering the role of initiators, the proposed scheme is majorly divided into two categories, pro-active and re-active. In the pro-active procedure, a relay initiates the process by sending a relay offer message to nearby devices (V'). In response, the devices send the data if there exists a social-communication edge ($\varepsilon''_{i,j}$) to the relay. Subsequently, the relay aggregates the responses and transmits the data. In the re-active process, a device broadcasts a relay request to the nearby devices. Interested potential relays respond to the request and offer relay services. In case of multiple responses, the device can choose on the basis of higher trust value ($\psi_{i,j} > \psi_{i,k} \geq \psi_\tau$) and select v_{relay}. Subsequently, the device sends the data to v_{relay} using $\varepsilon''_{i,j}$. The unavailability of any relay service causes the device to run graph formation algorithm and establish fresh relationships and edges. In case of no social-communication node ($V'' = \{\}$), the algorithm ends. The proposed Reliable Relay communication procedure is outlined in Algorithm 2.

Algorithm 1 Graph formation algorithm

Require: V={v_1, v_2, ..., v_N}
Ensure: $G(V, \varepsilon)$, $G'(V', \varepsilon')$, and $G''(V'', \varepsilon'')$
1: Repeat for V={v_1, v_2, ..., v_N}
2: **if** $distance(i, j) \leq Capillary\_Comm\_Range$ **then**
3:     Establish $\varepsilon_{i,j}$
4:     **if** $\psi_{i,j} \geq \psi_\tau$ **then**
5:         Establish $\varepsilon'_{i,j}$
6:         Establish $\varepsilon''_{i,j}$
7:     **end if**
8: **end if**

Algorithm 2 Relay based communication algorithm

Require: $G(V, \varepsilon)$, $G'(V', \varepsilon')$ and $G''(V'', \varepsilon'')$
1: **if** device is relay **then** act Pro-actively
2:     Broadcast relay services to V'={v'_1, v'_2, ..., $v'_{N'}$}
3:     Aggregate data from V'={v'_1, v'_2, ..., $v'_{N'}$} and send
4: **else** act Re-actively
5:     Broadcast relay request to V''={v''_1, v''_2, ..., $v''_{N''}$}
6:     **if** relay responses > 0 **then**
7:         Repeat for all responses
8:         **if** $\psi_{i,j} \geq \psi_\tau$ and $\psi_{i,j} > \psi_{i,k}$ and $i \neq j \neq k$ **then**
9:             v_{relay}=$v''_{i,j}$
10:         **end if**
11:         Send data to v_{relay} using $\varepsilon''_{i,j}$
12:     **else**
13:         Run graph formation algorithm
14:         **if** $V'' \neq \{\}$ **then** Go to Step 5
15:         **end if**
16:     **end if**
17: **end if**

The relay-based communication relies on the availability of the nearby trustworthy device, whereas trust is a result of relationships (e.g. OOR, CWOR, etc.). Considering a set of total possible owners of size A_{OOR}, from which a device is randomly assigned an owner, then the probability of the device to have the same owner as another device becomes $Pr_1 = \frac{1}{A_{OOR}}$. Similarly, if there are total A_{POR} manufacturers then $Pr_2 = \frac{1}{A_{POR}}$, A_{CWOR} work themes then $Pr_3 = \frac{1}{A_{CWOR}}$, and A_{SOR} social networks then $Pr_4 = \frac{1}{A_{SOR}}$ probability of trustworthy device, respectively. The cumulative probability of a nearby trustworthy device can be summed up as:

$$P_t = Pr_1 + Pr_2 + Pr_3 + ... + Pr_\Omega = \sum_{\beta=1}^{\Omega} Pr_\beta\ , \tag{3}$$

where Ω is the number of different relationships and $\frac{1}{\Omega} \geq Pr_\beta$.

Moreover, if there are L_α number of devices in proximity of relay α then using above probabilistic study, the potential number of trustworthy devices for that relay becomes $L_\alpha \times P_t$. Furthermore, the potential devices participating in Reliable Relay scheme using total λ relays can be computed as:

$$C = \sum_{\alpha=1}^{\lambda} L_\alpha \times P_t = \sum_{\alpha=1}^{\lambda} L_\alpha \times \sum_{\beta=1}^{\Omega} Pr_\beta \tag{4}$$

On the other hand, the uplink Signal-Interference-plus-Noise-Ratio (SINR) (δ_{legacy}) of a device transmitting to the Base

Station (BS) with N other devices, over a quasi-static Rayleigh fading channel having g channel gain with Additive White Gaussian Noise (μ), is [3]:

$$\delta_{legacy} = \frac{gP}{\mu + \sum_{n=1}^{N} g_n P_n}, \quad (5)$$

where P is the transmission power of the device and interference by other N devices is represented by $\sum_{n=1}^{N} g_n P_n$.

The Reliable Relay aggregates the devices (C) which restrains the uplink requests, resulting in less interfering signals. Replacing N with $(N - C)$ in Equation (5), the uplink SINR of a device transmitting in Reliable Relay, (δ_{RR}) becomes:

$$\delta_{RR} = \frac{gP}{\mu + \sum_{n=1}^{N-C} g_n P_n}, \quad (6)$$

where C is estimated from Equation (4).

Respectively, the attainable data rate for a device with assigned bandwidth f, in the legacy system and in the Reliable Relay can be calculated as:

$$\sigma_{legacy} = f \log(1 + \delta_{legacy}) \quad (7)$$

$$\sigma_{RR} = f \log(1 + \delta_{RR}) \quad (8)$$

Complexity Analysis: Moreover, for time and order complexity of proposed algorithms, consider a best case when a graph formation algorithm is not needed and existing relay information is used for relay selection. Using Big-O notation, we can estimate: for pro-active= $O(L)$ because a relay communicates to nearby devices (L) and waits for the response. On the other hand, re-active = $O(1)$, because a candidate relay responds and subsequently selected, successfully. In a worst case, the Pro-active shows same complexity $O(L)$, however, the re-active process becomes: $O(L) + O(N'') + O(count(L_i \cap L_j))$, where N'' is the number of possible relays and $count(L_i \cap L_j)$ represents number of common neighbors used in trust calculation. The complexity for periodic edge update for graph maintenance (in both pro-active and re-active) can be estimated as the sum of multicast to trustworthy devices (V'') and their responses, i.e. $O(1)+O(V'')=O(1+V'')$. However, we believe that the aforementioned complexity, to avoid complete outage is an acceptable deal for a device.

TABLE I: S-D2D scenarios for performance evaluation

	Scenario1	Scenario2	Scenario3	Scenario4	Scenario5
Owners	10	20	30	40	50
Parents	3	6	9	12	15
Work	7	14	21	28	35
Social Network	5	10	15	20	25

A. A case study using outage probability analysis of relay selection schemes fusion

Proposed Reliable Relay scheme not only offers a trustworthy relay selection paradigm but also suggests the blending with state of the art strategies. In this section, we derive a closed-form equation of the outage probability for proposed scheme and combine it with two typical relay selection schemes, i.e. max-min and max-link [7]. Considering that an outage occurs in the Reliable Relay scheme if the trust value ($T_m = arg\ max_{n=1,..,\lambda}(\psi_{i,j_n})$) is less than the trust threshold (ψ_τ), we estimate outage probability (P_{RR}) as:

$$P_{RR} = P(T_m < \psi_\tau) = \prod_{n=1}^{\lambda} \left(1 - exp(-\frac{\psi_\tau}{T_m})\right), \quad (9)$$

Successively, considering independent and identical distribution fading and mutually exclusive nature of events, the outage probability of Reliable Relay with max-min (P_{RR}^{mm}) and max-link (P_{RR}^{ml}) relay selection schemes [8] can be derived as:

$$\begin{aligned} P_{RR}^{mm} &= (\xi)\, P(T_m < \psi_\tau) + (1-\xi)\, P(W^{mm} < \delta_\tau) \\ &= (\xi) \prod_{n=1}^{\lambda} \left(1 - exp\left(-\frac{\psi_\tau}{T_m}\right)\right) + (1-\xi) \prod_{n=1}^{\lambda} \left(1 - exp\left(-\frac{\delta_\tau}{W^{mm}}\right)\right), \end{aligned} \quad (10)$$

where W^{mm} =arg max$_{n=1,..,\lambda}$ (min($\delta_{i,j_n}, \delta_{j_n,BS}$)) = $(\frac{1}{\delta_{i,jn}} + \frac{1}{\delta_{jn,BS}})^{-1}$.

$$\begin{aligned} P_{RR}^{ml} &= (\xi)\, P(T_m < \psi_\tau) + (1-\xi)\, P\left(W^{ml} < \delta_\tau\right) \\ &= (\xi) \prod_{n=1}^{\lambda} \left(1 - exp\left(-\frac{\psi_\tau}{T_m}\right)\right) + (1-\xi) \prod_{n=1}^{\lambda} \left(1 - exp\left(-\frac{\delta_\tau}{W^{ml}}\right)\right), \end{aligned} \quad (11)$$

where $W^{ml} = arg\ max_{n=1,..,\lambda}(\delta_{j_n,BS})$.

The probabilities, P_{RR}^{ml} and P_{RR}^{mm} are represented using closed-form equations and are mathematically tractable. However, the value of weighing factor ξ impacts outage probability to incline towards an only trustworthy ($\xi = 1$) or only SINR ($\xi = 0$) relay selection strategies. An equal distribution ($\xi = 0.5$) causes outage probability to be equally distributed between trustworthy and high signal scheme.

TABLE II: Simulation Parameters

Parameter Name	Value	Description
Center Frequency	28 GHz	5G Network Operating Frequency
Wi-Fi range (D2D)	50 m	Radius of Social D2D communications
Packet Size	1,500 B	Uplink packet size
Inter Arrival Time	10 ms	Packet generation inter arrival time
Simulation Time	10 Sec	Simulation time
Distance	10 ~ 150 m	Distance between devices and BS
Bandwidth (f)	20 MHz	The operating frequency bandwidth
Power (P)	250 mW	Device Transmission power
Antenna gain (g)	15 dBi	Channel gain of BS antenna
Noise (μ)	−101 dBm	Additive White Gaussian Noise for 20 MHz

III. Performance evaluation and Results

Considering analytical explanation mentioned earlier that the total number of attributes affect the probability of finding a trustworthy device, we develop a data set with diverse valuations to observe and evaluate proposed Reliable Relay scheme. Table I delineates our data set which thoroughly spans over five distinct scenarios. Our analysis uses uniform random distribution with equally likely relationship outcomes for all the devices which using Equation (3) obtains ∼ 77.8% probability of trust to a ∼ 15.5% for scenario 1 to 5, respectively. A total of 500 ∼ 2,000 devices are randomly distributed and assigned random attributes from our data set. Subsequently, the simulations settings utilize default 28 GHz 5G network frequency in NS3 mmWave simulator module[1] with Wi-Fi as capillary communications with a range of 50 m. Considering Maximum Transmission Unit (MTU) of UTRAN, the packet size is set to 1,500 B. Other parameters like power, bandwidth, antenna, etc are reflected from [3] and summarized in Table II.

Analysis: Figure 3a demonstrates that the scenario 1 with higher trust, achieves up to 50% ∼ 80% capacity gain, whereas scenario 5 with even a low ∼ 15.5% trust probability accommodates additional 10% ∼ 16% devices, calculated using Equation (4). Overall Reliable Relay surmounts the legacy system by providing coverage to approximately 80 ∼ 400 additional devices over 500 device and approximately 200 ∼ 1,000 devices over total 2,000 devices. Nevertheless, due to reliable aggregation and relay services, the proposed system has an obvious advantage of 10% ∼ 80% capacity gain over legacy

[1] mmWave[Accessed:Mar. '17]http://github.com/mmezzavilla/ns3-mmwave

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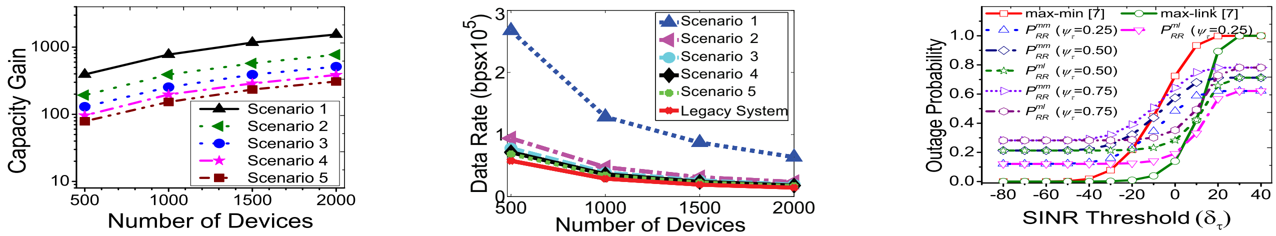


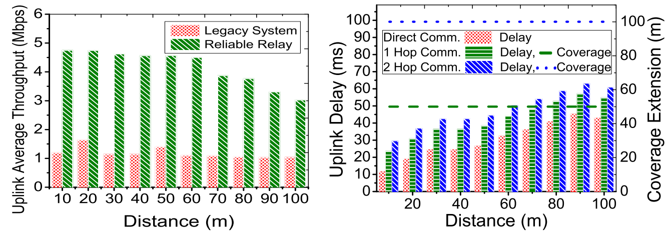
(a) Capacity gain under scenarios (b) Data rate (c) Reliable Relay with max-min and max-link

Fig. 3: Reliable Relay Analytical Results

system. Figure 3b shows the data rate for the legacy system and Reliable Relay, which is calculated using Equation (7) and Equation (8), respectively. It can be observed that the Reliable Relay in scenario 1 obtains maximum achievable data rate of ~ 0.25 Mbps for a device whereas the legacy system only provides ~ 0.06 Mbps. Moreover, the graph trend shows that the increase in the number of devices causes more interference resulting in reduced data rate. Ultimately, the results are as expected that the scenario with higher trust provides more capacity gain and data rate than the lower trust probability.

The outage probability of existing max-min and max-link [7] blended with proposed Reliable Relay scheme using Equation (10) and Equation (11) against δ_τ (SINR threshold) is shown in Figure 3c. Considering weighing factor $\xi = 0.5$ and available relays $\lambda = 10$, each relay is assigned $\psi_{i,j} \in [0, 1]$, $\delta_{i,j} \in [-80, 20]$ and $\delta_{j,BS} \in [-80, 20]$, using random distribution. It can be seen that an increase in ψ_τ increases the outage probability, which infers less availability of trustworthy devices with high signal leads to outage. The ψ_τ defines a trade-off between relay credibility (high ψ_τ) and availability (low ψ_τ). As a whole, the outage probability is more for mixed scenario due to multi-threshold dependency which is the trade-off for a trustworthy and reliable communications.

Simulations: In Figure 4a, the throughput of the legacy system versus proposed Reliable Relay scheme is investigated. The average uplink throughput shows that the proposed scheme has approximately $2 \sim 4$ Mbps advantage over the legacy system. Moreover, with increased distance, the throughput performance slowly reduces due to two main reason of directional communication coverage and pathloss of capillary communications (i.e. Wi-Fi). However, the Reliable Relay scheme clearly provides coverage to additional devices which is apparent from the increased throughput. Considering that no lunch is free, we also observed delays brought about by proposed Reliable Relay scheme. Figure 4b shows that in Reliable Relay communication (5G and Wi-Fi), a one hop communication leads to ~ 10 *ms* added delay, whereas two-hop transmission induces a total of ~ 15 *ms* delay. However, with the cost of aforementioned delays Reliable Relay provides approximately max. 50 m and 100 m coverage extension in one and two hop communications, respectively. For any device, these delays are unquestionably acceptable over the complete communication outage and coverage holes. Moreover, the distance from BS does not increase the delay as long as the capillary communication exist. Considering a wide range of applications, with widely varying periods (ranging from frequent updates at every 100 ms to relatively in-frequent updates at 1 sec), the estimated worst case messaging overhead (assuming the maximum possible relay nodes), associated with the periodic edge updates, lies in the range 0.56% to 5.6%.



(a) Throughput in Reliable Relay (b) Delays and coverage

Fig. 4: Reliable Relay as a Multi-hop Communications Results

IV. Conclusion

This letter proposes and evaluates proposed independent "Reliable Relay" framework for mmWave enabled 5G wireless limitations and coverage extension. By introducing the trustworthy factor in relay selection we bring about an autonomous and self-governing privacy protection paradigm and model, Social D2D (S-D2D). We propose graph formation and relay communication algorithms and evaluate the effectiveness of proposed scheme over five distinct scenarios. Performance evaluation and observations infer that the proposed Reliable Relay scheme increases capacity gain and data rate with negligible delay. Moreover, the analytical study of outage probability reassures that the existing relay based systems can be easily incorporated with Reliable Relay, to achieve more flexible and realistic relay selection schemes.

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