Virtual Private Mobile Network with Multiple Gateways for B5G Location Privacy

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Abstract—In a beyond-5G (B5G) scenario, we consider a virtual private mobile network (VPMN), i.e., a set of user equipments (UEs) directly communicating in a device-to-device (D2D) fashion, and connected to the cellular network by multiple gateways. The purpose of the VPMN is to hide the position of the VPMN UEs to the mobile network operator (MNO). We investigate the design and performance of packet routing inside the VPMN. First, we note that the routing that maximizes the rate between the VPMN and the cellular network leads to an unbalanced use of the gateways by each UE. In turn, this reveals information on the location of the VPMN UEs. Therefore, we derive a routing algorithm that maximizes the VPMN rate, while imposing for each UE the same data rate at each gateway, thus hiding the location of the UE. We compare the performance of the resulting solution, assessing the location privacy achieved by the VPMN, and considering both the case of single hop and multihop in the transmissions from the UEs to the gateways.

Index Terms—Location Privacy. Routing. Virtual Private Mobile Network.

I. INTRODUCTION

The information on the position of smartphones and other connected devices is relevant for several location-based services, e.g., navigation, advertisement, and social networking. However, an uncontrolled disclosure of our position and movement is a severe violation of our privacy with consequences at both personal and societal level [1]. Some cases related to the disclosure of position have already been reported in courts, such as covert location-based surveillance of employees, extra charges for rental car clients, contextual evidence gathering, and location-based profiling. Location privacy (also named geolocation privacy) has been studied from a legal standpoint in the last years [2], with a revamped interest associated to the recent general data protection regulation (GDPR) act in the European Union [3]. Also these regulations have highlighted the responsibilities of the mobile network operators (MNOs), once considered as trusted.

The evolving cellular communication standard developed by the third-generation partnership project (3GPP) has significantly strengthened the technical tools to locate and track user equipments (UEs), with the fifth generation (5G) network being able not only to exploit millimeter waves for localization, but also artificial intelligence for its processing through the network data analytics function (NWDAF). Moreover, the MNO can disclose the position information to over-the-top (OTT) operators through the network exposure function (NEF), further threatening our location privacy. The trend will continue in beyond-5G (B5G) networks, where more precise localization techniques will be included, also using frequencies in the Terahertz (THz) band [4].

A. Related Literature

Several works have addressed location privacy, in most cases focusing on network and application layers. A pretty good privacy solution has been proposed in [5], where connectivity and authentication functionalities were decoupled. Other approaches are based on k-anonymity [6] or differential privacy [7]. To limit the leakage of information to location-based service providers, a middle-ware can be introduced [8]. Blockchains can also be exploited to anonymize users [9], satisfying the principle of k-anonymity privacy protection without the help of trusted third-party anonymizing servers. However, in all the existing literature the MNO has been assumed to be trusted and location privacy is defended only against external attackers.

Only recently, a more global vision of location privacy protection has been introduced in [10], considering also the MNO as not trusted. In [10], the concept of virtual private mobile network (VPMN) has been first introduced, where a set of UEs perform device-to-device (D2D) communications that are not accessible to the MNO, while only selected VPMN devices operate as gateways between the VPMN and the cellular network. With this approach, the MNO knows only the location of the gateways and not that of the UEs.

B. Contribution

In this paper, we consider a VPMN with multiple gateways, and focus on the uplink transmission, where VPMN UEs route their packets towards the gateways, which in turn forward them to the next-generation NodeB (gNB) of the serving cell. UE packets may arrive to the gateways either by a single hop, of passing though other VPMN UEs operating as relays. In both scenarios, a first option is to apply a maximum-flow algorithm to determine the transmission rate. However, this choice creates an unbalance of data rates at the gateways, which partially reveals the location of the VPMN UEs: in fact, the maximum rate solution uses close-by gateways more intensively. Therefore, we revise the maximum rate problem by adding the constraint that the same data rates are transferred by each gateway from each UE.
In [10], only very preliminary results on the performance of a possible VPMN are reported, and here we offer a wider analysis of the VPMN, in terms of probability of connectivity of the UEs in a given area, achievable rates, and localization error. Results show that the VPMN offers an interesting trade-off among rates and localization error in typical B5G cellular scenarios.

The rest of this paper is organized as follows. In Section II, we revise the VPMN, consider a possible implementation, and model the channels of the links. Section III addresses the problem of routing for VPMN, recalling the maximum-rate routing and introducing the location-privacy preserving routing. An in-depth evaluation of the considered VPMN is proposed in Section IV, before conclusions are driven in Section V.

II. THE VIRTUAL PRIVATE MOBILE NETWORK

We focus here a VPMN including \( N \) devices, namely \( M \) UEs and \( S = N - M \) gateways, as introduced in [10]. The objective is to prevent the localization of the UEs by the MNO. To this end, the UEs communicate in a D2D fashion, without the intervention of the gNB. The VPMN will then communicate with the cellular network of the MNO through the gateways. An example of VPMN is shown in Fig. 1.

A. Security Assumptions

The MNO is only aware of the list of UEs in the VPMN but it is not able to decode their communications or identify the signals over the air, i.e., associate them to the sender UE. For this later aspect, suitable techniques should be deployed (see [10] and [11]). In the uplink, when a VPMN UE has to send a packet to the cellular network, it transmits it, possibly by multiple hops within the VPMN, to the gateways, which in turn transmit it to the gNB. Note that the communications among UEs will be encrypted with codes not available to the gNB, to avoid localization of the UEs by the gNB. In the downlink, the gNB sends each packet in broadcast to the gateways, which will re-encrypt it and send to the destination UE inside the VPMN, possibly through multiple D2D hops within the VPMN. In the following, we focus on the uplink.

B. VPMN Implementation

Here we do not consider the implementation details of the VPMN: we only observe that at the moment, the 3GPP standard does not allow its direct implementation. Indeed, the D2D communication is strictly under the control of gNB and devices involved in D2D transmissions are localized and identified by the gNB. We could implement the VPMN as a femtocell, where the gateway is the femto-gNB: however, a single femto-gNB would be available, restricting us to the use of a single gateway.

A second option is to use another technology, e.g., the IEEE 802.11s standard that supports the implementation of a mesh WiFi network to implement the VPMN, and the gateway UEs will interface the two networks. Although immediately deployable, this solution has the disadvantage of involving two standards, designed for two different scenarios; in particular, while cellular standards handle well mobility by the handover procedure, WiFi is designed for slowly moving terminals. In any case, we envision that a VPMN can be well defined in future versions of the cellular standard, and this work is a contribution in this sense.

C. Channel Model

All VPMN devices have a single antenna\(^1\) and both the D2D channels among VPMN UEs and the gateway-gNB channels are modeled including the effects of shadowing and path loss in an urban scenario. Two devices (UE or gateways) will be connected if their channel gain value \( \Gamma_{i,j} \) in dB satisfies

\[
\Gamma_{i,j} > \gamma,
\]

where \( \gamma \) represents a suitable threshold in dB. Let \( d_{i,j} \) be the distance between UEs \( i \) and \( j \).

The channel gain in dB is obtained from the addition of the local shadowing component at both the receiver \( z_j \) and the transmitter \( z_i \), and the path-loss of the \( i - j \) link as

\[
\Gamma_{i,j} = z_i + z_j + \log_{10} g_{i,j},
\]

where the path-loss of the \( i - j \) link is

\[
g_{i,j} = \left( \frac{d_{i,j}}{r_0} \right)^{-\alpha},
\]

\( r_0 \) is a normalization factor, and \( \alpha \) is the path-loss exponent. About the shadowing, we consider also its spatial correlation, and in particular the correlation of shadowing experienced at devices \( i \) and \( j \) is [12]

\[
R_{i,j} = \exp \left( -\frac{d_{i,j}}{d_{\text{cor}}} \ln 2 \right),
\]

where \( d_{\text{cor}} \) is the decorrelation distance, dependent on the environment. We collect \( R_{i,j} \) for all the devices into the \( N \times N \) matrix \( R \). Then, let \( z \) be a column vector collecting \( \{ z_i \} \), which can be generated as \( z = Lx \), where \( x \) is a vector of independent zero-mean unitary variance Gaussian variables and \( R = LL^H \) is the Cholesky decomposition of \( R \).

\(^1\)Future studies will also consider devices with multiple antennas.
III. ROUTING FOR THE VPMN

In the following, we will concentrate on the uplink, i.e., the transmission from the VPMN UEs to the gateways and then the gNB, as it can be exploited by the MNO to localize the UEs.

We consider two options for the routing of packets in the VPMN: a) multihop, where packets generated by a UE can be forwarded to a gateway by multiple hops though other UEs, and b) single hop, where UEs transmit packets directly to the gateways. About the single hop, we observe that a UE that is not connected to any gateway is not part of the VPMN.

Time is divided into slots, and one UE transmits in each slot to avoid interference. About the multihop case, the maximum achieved rate on link between devices \( i \) and \( j \) is

\[
\rho_{i,j}^{(\text{max})} = \begin{cases} 
\log_2 (1 + \Gamma_{i,j}), & \Gamma_{i,j} > \delta, \\
0, & \text{otherwise},
\end{cases}
\]  

(5)

where we assumed without restriction a unitary-power additive white Gaussian noise. For the single-hop case we have

\[
\rho_{i,j}^{(\text{max})} = \begin{cases} 
\log_2 (1 + \Gamma_{i,j}), & j \in \{1, \ldots, S\} \text{ and } \Gamma_{i,j} > \delta, \\
0, & \text{otherwise},
\end{cases}
\]  

(6)

where \( 1, \ldots, S \) are the indices of the \( S \) VPMN gateways and links with non-zero rates are only those towards the gateways.

A. Maximum-Rate Uplink Routing Algorithm

The routing solution that maximizes the achievable rate is the max-flow algorithm \[13\] on a graph having a node for each VPMN device, and edges between all connected devices. The weight of the edge between devices \( i \) and \( j \) is its maximum rate \( \rho_{i,j}^{(\text{max})} \).

Note that the maximum flow problem is defined between one node operating as the source and one node operating as the sink, while in the case of multiple gateways we have multiple sinks. In this case, to obtain the maximum flow solution, we add a fictitious node, denoted as super-sink, which is connected to all gateways through edges with infinite weight (rate). Then, we solve the maximum flow problems from each UE to the super-sink, using several solutions available, e.g., the Ford-Fulkerson algorithm \[13\].

B. Location Privacy Assessment

One main design objective for the VPMN is to prevent the localization of VPMN UEs by the MNO. Still, due to the fact that the UEs are connected (possible by multiple hops) to the gateways and the MNO can intercept packets going through the gateways, the MNO has some information on the UE location. We now consider the localization error.

In the following, we assume that all communications in the VPMN are not identifiable and decodable by the MNO, i.e., the MNO cannot use them to obtain the location of VPMN UEs. \[2\] Still, the MNO knows the location of the gateways, using several available localization techniques \[10\]. Moreover, we assume that the MNO can intercept packets going through the gateways, and associate packets to its transmitting UE, e.g., by the Internet protocol (IP) address. Clearly, anonymization techniques operating at the IP level can limit these possibilities.

To assess the localization error, let \( p_i \) be the position of UE \( i \), and let \( \hat{p}_i \) be its position estimated by the MNO.

Localization Error With A Single Gateway: In case of a single gateway, the MNO sees all packets coming from a single position \( p_{GW} \), that of the gateway. Therefore, the best estimate of any VPMN UE position is the gateway position, i.e., \( \hat{p}_i = p_{GW} \). For the single hop scenario, the average localization error

\[
\bar{U} = \mathbb{E}[||p_i - \hat{p}_i||],
\]  

(7)

coincides with the average distance of UEs from the gateway. Still, considering the correlated shadowing model, it is not straightforward to compute the average localization error. Therefore, in Section IV we will resort to simulations for its assessment.

Localization Error With Multiple Gateways: When multiple gateways are present, we can still estimate the average localization error as the average connection distance, resorting to numerical methods. However, we observe that when multiple gateways are present, the MNO can intercept packets and identify the transmitting UE: by observing the data rates coming from the different gateways for a single UE, and knowing the location of the gateways, a better localization can be achieved. For example, in the single hop scenario, if each VPMN UE is connected to the nearest gateway, observing from which gateway packets come, the MNO can significantly reduce the localization error. Similar considerations hold for the multihop scenario, where having multiple gateways allows also a trilateration based on the observed rates at each gateway. This will also be confirmed by simulations in Section IV.

C. Privacy Preserving Maximum Rate Routing

We therefore propose a routing strategy that ensures for each UE that the same data rate is achieved through all the gateways, regardless of the UE position. To this end, we formulate an optimization problem to determine the rate \( f_{i,j} \) on link \( i - j \). First, the objective function to be maximized is the rate from UE \( v \) to all the gateways \( s = 1, \ldots, S \), i.e., (for all UEs)

\[
C(v) = \sum_i \sum_{s=1}^S f_{i,s}.
\]  

(8)

Furthermore, to ensure that no information on the position of UE \( v \) is disclosed by the resulting flows through the gateways, we impose that all gateways have the same rate for each UE, i.e.,

\[
\sum_j f_{j,s_1} = \sum_j f_{j,s_2} \quad \forall s_1, s_2 \in \{1, \ldots, S\}.
\]  

(9)
We obtain the following linear programming problem:

\[
\begin{align*}
\text{max} & \quad \sum_{i} \sum_{s=1}^{S} f_{i,s} \\
\text{s.t.} & \quad f_{i,j} \leq \rho_{i,j}^{(\text{max})} \quad \forall i, j \\
& \quad \sum_{i} f_{k,i} \leq \sum_{j} f_{j,k} \quad \forall k > S, k \neq v \\
& \quad f_{i,j} \geq 0 \quad \forall i, j \\
& \quad \sum_{j} f_{j,s_1} = \sum_{j} f_{j,s_2} \quad \forall s_1, s_2 \in \{1, \ldots, S\},
\end{align*}
\]

where (10b) is the maximum flow constraint on the \(i-j\) link, (10c) is the flow-conservation constraint (the outgoing rate should not be larger than the incoming rate for each intermediate UE), (10d) ensures non-negative rates, while (10e) is the constraint (9) on the same rate for each gateway and each UE.

\[\text{(10a)}\]

\[\text{(10b)}\]

\[\text{(10c)}\]

\[\text{(10d)}\]

\[\text{(10e)}\]

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IV. NUMERICAL RESULTS

We consider an area of 100 m x 100 m, wherein \(N\) VPMN devices are uniformly randomly distributed. For channel modeling, we assume a decorrelation distance \(d_{\text{corr}} = 20\) m and a path loss exponent \(\alpha = 2\). The path-loss normalization factor is \(r_0 = 31.62\) m, corresponding to 10 dB loss every 100 m.

We now assess the performance of the VPMN according to several metrics. In particular, we evaluate the probability that all UEs constitute a single VPMN (i.e., suitable connections with the gateways exist), the localization error by the MNO provided by the VPMN, and the rates provided by the routing algorithms with and without location privacy constraint (achievable rates).

\[\text{IV. NUMERICAL RESULTS}\]

We consider here the probability that the \(N\) randomly dropped devices constitute a VPMN with multihop routing, i.e., they are a connected component where edges are present when condition (11) is satisfied.

We recall that a conforming set \(C = \{(i, j)\}\) is a set of edges for which the \(N\) nodes are connected. We denote with \(\Phi = \{C\}\) the family of all conforming sets. The probability that all UEs are in the same connected component is

\[P_{\text{CONN}} = \sum_{C \in \Phi} \mathbb{P}[\Gamma_{i,j} > \gamma, \forall (i, j) \in C, \Gamma_{i,j} < \gamma, \forall (i, j) \notin C].\]

(11)

Since \(\Gamma_{i,j}\) are correlated Gaussian random variables, \(P_{\text{CONN}}\) is related to the cumulative distribution of a set of correlated random variables, for which no close expression exists, thus we resort to numerical methods for its evaluation.

Fig. 2 shows the probability that all devices are in the same connected component \(P_{\text{CONN}}\), as a function of \(\gamma\) for \(M = 5, 10,\) and 20 devices. We observe that increasing the number of devices increases the connection probability: since the devices are randomly dropped in the same area, dropping more devices will make them closer, thus increasing the probability of being connected. Moreover, decreasing \(\gamma\) also increases the connection probability, with values above 0.9 for \(\gamma = -20\) dB.

Note that \(P_{\text{CONN}}\) can be read also as the probability that a UE finds a VPMN to connect to, given that there are \(N\) devices in the area. Similar results hold also for the single-hop case, not reported here.

B. Localization Error

We now consider the localization error, for the case of single and multiple gateways.
Single Gateway: We consider a single gateway, placed at the center of our map with coordinates (0, 0). Fig. 3 shows the average localization error $\bar{U}$ given by (7), as a function of $\gamma$ for $M = 30, 52, 75, 97, 120$ UEs. We observe that for small values of $\gamma$, where we also have that all UEs are a connected component, the average localization error is very high. For smaller connected components (higher values of $\gamma$) the localization error is reduced. For the multihop scenario instead, a higher number of nodes yields richer connected components, in turn increasing the localization error. In the single-hop scenario, the localization error does not depend on the number of UEs, as the connectivity of each UE to the VPMN does not depend on other UEs. Also, the single-hop scenario has a lower localization error than the multihop case, due to the need of UEs to be directly connected to the gateways, i.e., being closer to each other.

Multiple Gateways: When multiple gateways are present, we have observed that the MNO can infer the position of the UE also by checking which fraction of the UE traffic goes through the various gateways. To better understand this point, we consider a scenario where all devices are on a line: two gateways (with indices 1 and 2) are at positions (0, 20) and (0, -20), while $M = 28$ UEs are on the same line, with uniformly distributed positions in [-50, 50]. The ratio between the rates (solution of the max-flow problem) going through the two gateways is

$$\beta = \frac{\sum_j f_{j,1}}{\sum_j f_{j,2}},$$

which is used to infer the position of the UE. Fig. 4 shows the contour plot of the joint probability density function (PDF) $\phi(p, \beta)$ of the random vector $(p, \beta)$, with $p$ being the position of the UE, and $\beta$ the corresponding value of the ratio (12). Both the single hop and multihop scenarios are considered. For a given observation of $\beta$, its maximum likelihood estimate of the UE position is

$$\hat{p} = \mathbb{E}[p|\beta] = \int p \frac{\phi(p, \beta)}{\phi(\beta)} dp,$$

where $\phi(\beta)$ is the PDF of $\beta$, which can be obtained from $\phi(p, \beta)$ by marginalization. With this procedure, the average localization errors for the single hop and multihop scenarios are

$$\bar{U}_{SH} = 3.9 \text{ m}, \quad \text{and} \quad \bar{U}_{MH} = 26 \text{ m}.$$ (14)

Clearly, in the single hop scenario the PDF of Fig. 4 is much more concentrated (with smaller variance) than the PDF in a multihop scenario, since for the single hop scenario it only depends on the direct links between the UE and the gateways, which in turn mostly depend on the distance of the node from the gateways through the path-loss.

C. Achievable Rate

We now consider the average rate through the gateways, namely, the average of the sum of (8) over all UEs

$$C_{\text{tot}} = \mathbb{E} \left[ \sum_v C(v) \right],$$

where the average is done with respect to the UEs positions and channel realizations for randomly dropped devices in the square area. Fig. 5 shows the average rate for $S = 1, 2, 3$ gateways, and different numbers of UEs, $M$. We compare the performance obtained with the unconstrained maximum-flow (UMF) algorithm and the privacy-preserving maximum flow (PPMF) solution of Section III-B.

First, note that with a single gateway the UMF and PPMF solutions coincide, thus we show a single line per scenario. Then, we note that the single-hop scenario yields much lower rates than the multihop scenarios, where links among UEs are exploited to increase the rate. Lastly, we observe that introducing the privacy preserving constraints has a significant impact on the
rate, in particular for the single-hop scenario, where the direct links of the UEs with all the gateways may not be available, and in this case the rate is zero to avoid location information disclosure. In the multihop scenario, instead, the rate reduction is much less pronounced, making this option more attractive for implementation.

V. CONCLUSIONS

For a VPMN aiming at defending the location privacy of the UEs while ensuring connectivity with the cellular network, we have considered the case of multiple gateways. We have highlighted that using an internal routing algorithm that simply maximizes the VPMN data rate towards the cellular network may reveal information on the location of the VPMN UEs. Therefore, we have derived a routing solution that prevents this information leakage by ensuring that data is collected from each UE with the same rate from all the gateways. We have also assessed the performance of the proposed routing solution, showing that it has a reduced performance loss with respect to the maximum-rate routing.

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